A Roadmap to Sustainability Evaluation: a System Approach from Evaluation Theories

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Declaration of Authorship

I hereby declare that this thesis and the work presented in it are fully my own. I confirm that this work: was done wholly while in candidature for a PhD degree at University of Kent; where I have quoted from the work of others, the source is always properly given and referenced; I have acknowledged all main sources of help.

Signed:

Date:

Abstract

Sustainability evaluation has been widely applied as a tool manage the relationship between the human and the Earth to avoid human activities that jeopardise the survival of all lives and subsequent implementations have been improving sustainability within certain time and region. However, consequently, many measures are proved unsustainable outside suitable spatio-temporal scales. While abundant researches attempted this issue by developing sustainability frameworks that apply wider systems as evaluation subjects or designing compound indexes, limited work recognise the evaluation nature and analyse from the evaluation theories perspective where the issue could be the consequences of having implicit elements in sustainability evaluation.

The issue is attempted following three key research objectives. First, determine the characterisation of evaluation elements by embedding sustainability. Critical literatures of evaluation theories, sustainability, and sustainable development (SD) from nearly all fields of study are collected, screened, and analysed. A group of fundamental evaluation elements are summarised to be applicable for this thesis, as a reflection of evaluation theory basis. Proper evaluation should explicitly characterise this group of evaluation elements by decision makers (DMs) and evaluators. Sustainability objectives, where certain criteria should be defined specifying the sustainable state, would influence the characterisation of all evaluation elements. Thus, we state, in practice, sustainability evaluation is done for a group of necessary conditions towards planet sustainability during which values of key stakeholders including human and non-human lives require demonstration.

Second, construct a framework that could develop explicit sustainability evaluation elements with applicable metrics and measurements. Critical literatures of sustainability evaluation and key heuristic studies are reviewed and a systemic review of 118 sustainability evaluation empirical studies in the energy sector is conducted. It is confirmed the causes to implicitly unsustainable measures from the evaluation perspective are that sustainability evaluations often implicitly place human values in centre but holds shifting stakeholder stances between human-central or universal values, and many evaluation elements are implicit, especially the evaluation objectives and subject when they are not mutually suitable. Noticing that based on stakeholder connections and a criteria of sustainability the evaluation objectives and subject would be explicitly developed, an evaluation framework for sustainability enabling developing explicit and suitable evaluation elements is constructed, forming a roadmap to sustainability evaluation. The roadmap demonstrates a process of explicitly forming an apposite system for sustainability evaluation objectives that is used as the evaluation subject. The sustainability evaluation

framework concludes metrics of material and energy, structure, and value (MSV). Evaluation results are produced for the apposite system and implementations for the initial system. For cross-system evaluation, a group of suitable, EEV, measurements are proposed. Material metric could be treated as classifying renewable or non-renewable materials. Energy metric could be measured by emergy that traces system energy hierarchy with unified unit. Structure metric could be measured by Shannon entropy. The value measurement could be compensated by human pricing while considering the survival of weak stakeholders.

Lastly, the applicability of the roadmap is tested based on the electricity systems of 28 European countries, including the production system and consumption structures. Suggested by the country sustainability objectives of carbon neutral and targetting energy security, a CO2 sustainable electricity production system targetted for 2005 country sustainability evaluation objectives including 10 electricity production technology subsystems is constructed as a sustainable reference system. Country peer ranking is calculated by individual indexes of emergy, entropy, and electricity prices, and compound scores by data envelopment analysis (DEA). It is revealed that the evaluation framework, especially following the proposed protocol, would require mass high quality data and information for linkages of subsystems, providing directions to refine the framework and evaluation results.

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Chapter 1

Introduction

1.1 Background of the Study

Sustainability evaluation gained its importance as a decision-making tool to reach a preferred state of the Earth, managing systems containing sustainability relations, the relations among nature, human, and society on the anthroposphere(Singh, 2006). Widely noted as terms ”sustainability” and ”sustainable development (SD)”, the preferred state is being characterised by the United Nations (UN) with 17 SD goals (SDGs) that include all aspects of the Earth: no poverty, no hunger, good health and well-being, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace, justice and strong institutions, and partnerships (UN-DESA, 2016). As human activities remain extensive and continue to affect the survival of other lives and the survival of future human, implementing the sustainable measures for the suitable time and region remain critical for all parties.

Despite many implementations that has avoided extremely extensive sustainability relations, attributing to many aspects including sustainability objectives, evaluation frameworks, methods, and indexes, sustainability evaluation results have been widely criticised to be unattainable, impractical, and incomparable (Bjrn and Hauschild, 2013, Bykzkan, 2018, Phillis and Andriantiatsaholiniaina, 2001). Currently, sustainability evaluations often focus on sustainability perspective, and in many cases, take methods from multi-criteria decision-making (MCDM) studies. For sustainability objectives, given the Brundtland definition of SD, that is to satisfy the need of this generation with guarantee for the next generation (Brundtland et al., 1987), ”sustainability” is often defined with presumed context as the ”sustainability of something”, such as product design, actions, the natural environment, the ecosystems, the human society, policies, and the Earth (Bowman et al., 2010, Kloepffer, 2008, Li et al., 2017, Steinborn and Svirezhev, 2000, Wolsink, 2010). To cover socio-environmental aspects, sustainability evaluation mainly uses sustainability frameworks that often de-constructs systems as economic, social, and environmental aspects, sometimes also with technological or resource aspects (Pope et al., 2004, Bykzkan, 2018). More recently, this sustainability framework is often used with other evaluation frameworks that constructs wider system construction and define more specific preferences, such as life cycle analysis (LCA), the planet boundary, green energy systems, Industry 4.0 etc. (Asif et al., 2007, Davtyan et al., 2023, Kubilay Karayel et al., 2023, Rockstrm et al., 2009). Lastly, while the measurements are sometimes guided by the sustainability objectives and the frameworks used, nearly all MCDM methods, quantitative and qualitative, are found to be applied (Etxano and Villalba-Eguiluz, 2021, Visentin et al., 2020). Among which, when quantitatively measuring system performance, especially the efficiency metric, DEA would serve as an applicable method that is less influenced by system internal processes (Alvarez-Rodriguez et al., 2019, Thies et al., 2019). However, only focused on ”sustainability”, the concept, many criticisms suggest that a reference system in evaluation that reaches the consent of avoiding the catastrophe of human population is implicit or unknown (Rees, 2010, Tietenberg and Lewis, 2018), which lead to the use of massive variety of indexes including ”scarcity”, ”efficiency”, and ”security” (Ciobanu et al., 2022, Zafra-Calvo et al., 2020). Besides, the system boundary of a suitable sustainability evaluation subject is also implicit or unknown. System developed after LCA or trajectory analysis is seldom being reverified for the evaluation objectives.

Not focused on sustainability, sustainability evaluation practice should also follow evaluation theory basis. Evaluation is a decision-making approach that could be applied to all fields through valuation (Blalock, 1999, Scriven, 1991). Following its general protocols, any evaluation practice could be characterised by some aspects, noting the evaluation elements, including the evaluation objectives, DMs, subject, and methods (Gregory and Jackson, 1992, Melchert and Winter, 2004, Rossi et al., 2018, Scriven, 1991). The quality of evaluation, determined by the DMs, could be further influenced by frameworks, methods, data, and measurements(Farrington, 2003). As the protocols suggest to step-by-step clarify the elements, sustainability evaluation should also be specific and explicit in these evaluation attributes. However, very limited work has analysed current sustainability evaluation from this perspective.

This thesis attempts to develop the characterisation of current implicit sustainability evaluation elements by embedding sustainability, based on its definitions, systematically into a group of more comprehensive evaluation elements. Generalisation to this process of development draws a roadmap to sustainability evaluation and constructs a feasible evaluation framework for sustainability. The practicability of the roadmap, including the framework, the metrics, and measurements, are tested using DEA as the peer ranking method. In this way, this thesis contributes to explicitly justifying the attainability and practicability of the evaluation results for reaching sustainability evaluation objectives, forming explicit reference system for evaluation, by developing the above implicit aspects of sustainability evaluation explicit in the form of evaluation elements.

1.2 Problem Statement

Many past sustainability implementations from evaluation have been applied to relieve the sustainability relations (Ward, 2020, UNDESA, 2022). As noted in 1.1, the applicability of the measures remain an issue that would draw the line between sustainability and unsustainability. Current sustainability evaluation studies attempt this issue mainly from the sustainability perspective. However, we notice, consequently using implicit evaluation objectives and subjects for sustainability evaluation might be causes of the issue.

Firstly, the definition to ”sustainability” in sustainability evaluation is often implied, not limited to containing presumed context. Rooting to linguistic (Freerk Wiersum, 1995) or the system definition (Roger, 2000), having an attribute to be maintained or to be endured to define a sustainable status is necessary. Apparently, such attributes are not explicit in SD and many definitions used in sustainability evaluation. For instance, ”green” often implies considering carbon emission as the attribute (Islam et al., 2022). Although some common preferences that picture planet sustainability are reached, it is still being criticised that conditions of a sustainable state lack theoretical support (Parris and Kates, 2003, Kates et al., 2001, Tietenberg and Lewis, 2018). However, as suggested for general evaluation, proper evaluation objectives should be clear in what or who to be valued with clear value system (Pawson and Tilley, 1997). In this view, the issue that current sustainability evaluations of the same evaluation subject create results that are not comparable (Martin et al., 2018) could be attributed to having implicit evaluation objectives.

Secondly, the sustainability evaluation subject often remains having implicit system boundary. Currently, sustainability evaluation has touched nearly all individuals, processes, and systems containing social-environmental interface. Often regarding as systems with input-output interactions with their external environments, many studies produce more practical and long-term sustainable measures by considering externally related systems (Visentin et al., 2020). System performance related aspects of transformation processes and influences are often included (Greenhalgh et al., 2008). However, evaluation subject systems developed using TBL or trajectory methods such as LCA lacks a verification protocol of to what extent influence has reached out to.

Contingently, lastly, it reveals a structural issue in sustainability evaluation that often, both being implicit, the evaluation subject may not suit the objectives. In past general evaluation having explicit evaluation objectives and subject system boundary, the reference system that could realise or at a better state of the objectives is certain (Mahmoudabadi and Emrouznejad, 2019). However, for sustainability evaluation, where sustainable development goals (SDGs) and country targets are often directly embedded as part of the evaluation objectives (Bottero et al., 2015, Mller et al., 2021), whether the sustainability attributes suits the evaluation subject and whether the system scale of the subject suits the objectives with a reference system remain implicit. Consequently, sustainability evaluations are often conducted for systems that could be incapable of reaching the sustainability evaluation objectives.

1.3 Research Gap

Based on the problems above (1.2), the following research gaps are identified:

1. Systemic and comprehensive observation to current sustainability evaluations by a more comprehensive group of evaluation elements and identify the elements that are implicit and could cause the issues in sustainability evaluation results;
2. Construct a theoretically suitable roadmap to develop explicit evaluation elements to practice sustainability evaluation;
3. Determine the practicability of developing explicit sustainability evaluation elements, following the roadmap and identify the challenges.

1.4 Research Objectives

This thesis aims at constructing a roadmap to sustainability evaluation from the evaluation perspective that more explicitly explains sustainable relations and supports proper implementations of sustainability measures.

Suiting each research gap, the research objectives is to first, comprehensively understand the issues in current sustainability evaluation studies from the perspective of evaluation theories, to determine which elements have often been implicit in current sustainability evaluations. Then, suggested by having implicit elements in sustainability evaluation, based on literature reviews of sustainability frameworks and system performance frameworks and methods, construct a framework that would develop explicit evaluation elements. Lastly, test the practicability of the roadmap with real world case to understand the utility of the roadmap, including its contributions to sustainability evaluation results and the challenges.

1.5 Research Questions

Three research questions are attempted in this thesis:

Q1. *Would there be and what are the differences in characterisation to sustainability evaluation by embedding sustainability into evaluation theory basics?*

Q2. *How to establish an approach that could develop explicit evaluation elements for sustainability evaluation and then, would there be an widely applicable evaluation framework for sustainability evaluation?*

Q3. *Following Q2, how to apply the roadmap developed for sustainability evaluation? And would there be further guidance to its application and further elaborations to the roadmap, the evaluation framework for sustainability, and the measurements through empirical studies?*

1.6 Significance of the Study

By fulfilling the research gaps and attempting the research questions, the key contribution of this thesis is to construct a roadmap of sustainability evaluation that demonstrates explicit evaluation elements and process. It explains the cause of unsustainable actions taken for sustainability objectives from an evaluation perspective. By attempting the problems of evaluation elements in sustainability evaluation, an evaluation framework for sustainability could be constructed. Through testing the roadmap in empirical studies using energy systems, an reference system that could be applied general sustainability evaluation of European countries for their electricity production system and mainly considering the carbon emissions could is constructed. More in general, it demonstrates a more explicit picture of how much external compositions that sustainability objectives would require an initial system to hold and, depending to the sustainable evaluation objectives, to what extent the system influences should be traced and how it would influence the evaluation results implemented.

1.7 Outline of Thesis

Figure 1.1 exhibits the overview composition of this thesis.

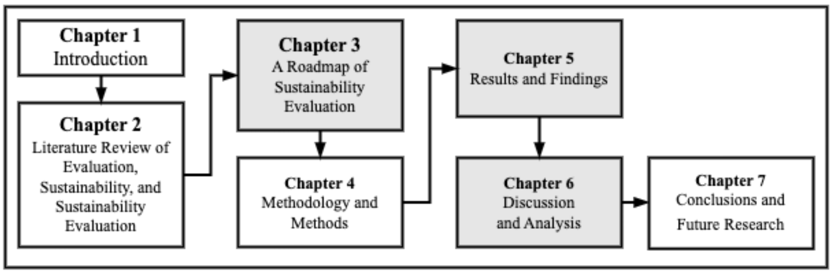


Figure 1.1 Thesis Structure Outline.

Since the thesis focus on contributing from the conceptual and methodological domain of sustainability evaluation, many literature reviews are done in several chapters to thoroughly understand, identify, and confirm the theoretical basis and conceptual issues to be studied. The chapters follow:

Chapter 2 constitutes literature reviews of three key topics, evaluation and its theories, sustainability, and sustainability evaluation. The definitions of evaluation and sustainability are given following respective reviews. Also, especially for sustainability evaluation, a review of 21 systemic reviews of sustainability evaluation by other authors done and a systemic review is done for the energy sector with 108 empirical articles to confirm issues in current sustainability evaluation.

Chapter 3 constructs the roadmap for sustainability evaluation. It is developed using the 3E metrics and measurements of performance evaluation and an evaluation framework, a group of suitable metrics, the MSV metrics, and a group of applicable measurements, the EEV measurements, are proposed and justified, forming a suggested protocol for sustainability evaluation.

Chapter 4 concludes the methodology applied in this thesis and introduces the data, methods, and materials applied in the case studies of the electricity systems of 28 European (EU) countries. Empirical testing focus on the sustainability of electricity production systems of EU28, and the effectiveness of the system. Peer ranking is performed using DEA models.

Chapter 5 presents the results of the empirical case. Chapter 6 presents the discussions and analysis around the indications to continuously following the proposed evaluation framework protocol are drawn and the challenges during the process to construct the apposite system following the roadmap

Eventually, Chapter 7 concludes the thesis. It clarifies the contributions and implementations of the thesis, and introduces the limitations and future directions of this research.

Chapter 2

Literature Review of Evaluation, Sustainability, and Sustainability Evaluation

2.1 Introduction

This thesis overall puts efforts to understand characterisation to sustainability evaluation from the perspective of general evaluation theories, using performance evaluation metrics and measurements especially for systems with frequent outward interactions with external domains such as the social and the natural environmental phase. Thus, we first determine the theoretical foundation of evaluation and attempt to develop references of evaluation theories that could be used more tangibly in later chapters. Then, some evaluation techniques, especially system performance evaluation techniques that could be used in sustainability evaluation are reviewed. Following that, since sustainability is being abusively used for nearly all topics, the definitions and ethical foundations of sustainability and its tangible presentations as sustainability targets, towards the goal of sustainability for the Earth, are reviewed. Lastly, sustainability evaluation, the concept, current issues are reviewed. Especially, a systemic literature review of sustainability evaluation studies in energy sectors is conducted to better present the issues.

2.2 Evaluation and Performance Evaluation

”Evaluation” and ”performance” are two terms that could be applied to nearly all fields with many contextual definitions. Considering the wide application of the terms, this section looks into the definitions of the terms and evaluation related theories, including its composition, characterisation, and techniques that can be applied to all context.

2.2.1 Definition of Evaluation

To identify a suitable definition for this thesis, the definitions of evaluation are gathered from various fields of study, especially in the general form being contextless. During the search of suitable literatures, it is noticed that evaluation is popularly defined with purposes that are influenced by or influencing the action. Table 2.1 presents a group of key definitions of evaluation that is often applied.

The definitions covered the subject to be evaluated, the dimensions to be concerned, and the valuation system to make decisions. Some definitions explain the subject to be evaluated. We notice that it is implied that evaluation is often done for determined evaluation objectives, which are the purposes, and subject while measuring with limited metrics and measurements. When the values are not measurable or the subject has no potential to reach the objectives, the objectives are thought unsuitable (Pawson and Tilley, 1997).

Evaluation would face the challenge in developing and measuring the extensive and intangible aspects such as potentials, happiness, satisfactions, or sustainability. Pawson and Tilley (1997) explains that the *evaluators* influence the evaluation process by their cognitions, including their perspectives and interpretations for the evaluation objectives and the physical state of the evaluation subject. However, the influences of the evaluators and DMs to the valuation process is seldom systemically analysed. Focused on the values created, It is evident that evaluation objectives would mainly influence determining what is meritable, worthwhile, and valuable. Banks (2000) notes that evaluation also serves for deliberation, the measurement of preferences, and even foreseeing the potentials. However, to note, none of the definitions have clarified how evaluation objectives influence the evaluation preferences, the perceptions to the evaluated subject, and the value system applied.

Withholding such concerns of implicitly in connections of aspects of evaluation definitions, we notice among the definitions that evaluation, in general, could be done from external and internal perspectives to the subject being evaluated, developing the system construction within the subject system and/or around the subject. We tend to attribute such differences in the origin of the evaluation objectives. An evaluation done from the internal perspective is usually quite clear that the organisation owners provide clear objectives for the evaluators to set the preferences of evaluation. Carman and Fredericks (2008) concludes that evaluating within an organisation could gather and diffuse resources, serve for external promotion, and observe whether the inner operation follows certain organisation strategy. As a result, organisations conduct internal evaluations for the benefits of its funders and shareholders to improve existing programs, report information, and intro-

Table 2.1 Definitions of evaluation

Definition	Source
A decision-making tool that reaches out to everything. A process to understand the nature of system efficacy. A process to provide criteria for a subject.	Rossi et al. (2018)
”All efforts to place value on events, things, processes, or people” A process that determines and attaches merit, worth, and value to things.	Scriven (1991)
A process that test, refine, and adjudicate theories or strategies to open up a black box of processes.	Stame (2004)
For some funders of system, a process measuring on data gathered by qualitative and quantitative methods to understand how inputs led to outputs and outcomes.	Carman and Fredericks (2008)
The complete process of applying scientific protocols that enables making good quality decisions, which is determined by the quantity and quality of outcomes, and impacts, the potential to improve the decisions	Elwyn and Miron-Shatz (2010)
A process to determine the results and impacts that are meaningful.	Patton (2015, p.39-44)
A process that could include both spiritual and material aspects.	Patton (2015, p.278)
The decision-making tool of a program through understanding how results are achieved by program inputs and outputs.	Greene (1988)
Placing value to the process starting from the implementations until the realisation of the outputs.	Samset and Christensen (2017)
A process that comprehensively and systemically measures the outcomes, the processes, and the influences .	Lucantoni et al. (1994)

duce new potentials. We perceive that evaluating from the internal perspective features the advantage of containing clear objectives and a clear enterprise boundary that demarcates the organisation from the environment setting a clear body to be evaluated within. To note, even explicit evaluation objectives could cause implicitness in forming evaluation measurements when attributes not associated with specific measurements such as satisfaction, accomplishment, development, and stability are contained (Chankseliani and McCowan, 2021, Mackenzie, 2005, Mononen et al., 2016). Shifting the authority to external third parties, external evaluation is appreciated for reporting information and benchmarking with others (Jaafaripooyan, 2014). Multilateral voices need to be heard and communicated with DMs in adopting evaluation objectives and implementing them (Fetterman, 1994). Evaluation with external perspectives, naming external evaluation, is usually applied in topics of public and environmental domains, serving for extensive subjects (Pahl-Wostl, 2002). However, apparently, considering external perspectives in evaluation could easily introduce evaluation preferences that are implicit or conflicting with internal collective objectives and preferences, after which the initial evaluation objectives given for the initial system and the evaluation subject including external aspects or systems may become mutually unsuitable.

Concluding from diverse definitions and varied perspectives, we admit that a general evaluation process, given initial objectives and an initial system, is the process that makes decisions or judgements by determining the value and impacts to anything that is the interest of the proponent based on information gathered. To note, in this thesis, when ”evaluation” is used independently, it means general evaluation that could be suitable for general systems of any context. This thesis attempts to understand evaluation comprehensively considering its subject, the perspectives, and the valuation process.

While searching for evaluation, ”assessment” is noticed to be frequently used alike a synonym of evaluation. However, the terms vary significantly by the decision-making process. Here, such differences are analysed and presented, emphasising the importance of the attempt for decision-making in evaluation.

When reviewing the definitions of evaluation, assessment is often defined in comparison with evaluation. Rossi and Wright (1984) defines assessment as a measurement process that enables decision-making of the studied subject by gathering information around it. Patton (2015, p.278) describes assessment as a decision-making tool by observing a subject and acts as a narrower reference for the tangible or measurable outcomes. Assessment is prominent in scientifically developing and picturing the subject or the system around it, which could produce insightful implementations.

Also containing the process of outlining the studied subject, evaluation is prominent in the process of making judgements by the evaluator using information gained through observation and measuring, during which the decision-making criteria should follow the evaluation objectives (Morrow et al., 2015). Assessment is not featured in having objectives that should suggest, whether in the explicit or implicit form, the values to be measured and the scale of the system to be studied, which are key to evaluation. Good assessment results should be high in quality of observations and measurements. For evaluation, it often requires the evaluators to assess with reference to the context of the studied subject, and judge contingent to the evaluation objectives and the interests of the DMs (Scriven, 1991, Morrow et al., 2015). We understand that perspectives applied for value judgement would significantly alter the scope of evaluation studies (Spellberg, 1994). They set baselines for identifying objectivity and subjectivity in decision-making. Therefore, not all subject assessed, especially differentiated by the value system, nor would all insights by assessment be suitable for the evaluation objectives.

More explicit, systemic, and comprehensive frameworks, better developed methods and techniques for measurement, and higher-quality data would produce better results for both evaluation and assessment. Applying hereditary, comprehensive systemic assessment or evaluation frameworks would produce better verified and rational construction of the studied subject (Stame, 2004). When methods or techniques for observation develop, more comprehensive and precise measurements produce more precise insights or judgements (Rossi and Wright, 1984). Overall, it explains, while assessment methodologies could be applied to evaluation, evaluation features in comprising objectives and preferences of stakeholders into measurement and decision-making, producing targeted judgements.

Although many clarifications have been done regarding the two concepts, the terms are still frequently used in mix. Sustainability studies is one of the topics that most severely discombobulated the two terms. While much research is named sustainability assessment, very often an evaluation process is conducted with leading objectives. Thies et al. (2019) concludes that empirical studies of sustainability assessment apply methods of multi-attribute decision-making (MADM), and multi-objective decision-making (MODM), which both require clarifying preferences and criteria for decision-making. Consequently, much discussion of the empirical studies focuses on the contribution of sustainability decisions made for realising the sustainability goals. Similarly, while LCA serves well as an assessment method that constructs a complete circulated process around a subject (Guinee et al., 2011), many empirical works have silenced the inclusion of sustainability goals in the decision-making phase (Kloepffer, 2008, Blengini, 2009, Stamford and Azapagic, 2014). Thus, noticing that certain value systems and objectives are implied before observation phase even started, we point out that many studies using LCA methods perform evaluation instead.

2.2.2 Elements of Evaluation

Many protocols are proposed for systemically and comprehensively conducting evaluation to produce scientific results, usually reflecting evaluation theories including the definitions and methodologies. Evaluation roughly includes the observation process and the decision-making process. Some elements including the evaluation objectives, stakeholder, evaluation subject, and methods that characterise an evaluation are found to be specified after one attempt and they usually differ by evaluations (Scriven, 1996, Rossi et al., 2018). Thus, in this section, we observe the evaluation protocols designed for general subjects and attempt to conclude some key evaluation elements revealed. This group of elements are regarded as the reflection to the key indications of the evaluation theories that could be directly applied to specific form of evaluation.

General Evaluation Process

Vast work illustrates certain procedures to follow so as to practice fine quality evaluation(Lucas, 1971, Rossi and Wright, 1984, Scriven, 1991, Gregory and Jackson, 1992, Neely et al., 1995, Atkinson et al., 1997, Rossi et al., 2018), including conceptual and practical protocols and empirical examples. Concluded in and from these literatures, the following six questions are universally asked during evaluation, not necessarily in the order or exact form presented:

1) Who proposed the evaluation, who is/are the owner(s) of the subject to be evaluated, and who are the DMs and the general stakeholders?

2) Based on the system state, what is the purpose of evaluation? What are the objectives that are attached by the influencers to the evaluation?

3) What is consumed and required in evaluation? Are there additional costs for data collection?

4) What is the paradigm of the evaluators? How will the system be deciphered for evaluation?

5) What measures are used for evaluation?

6) What method can be used to analyse and aggregate information for decision-making?

These questions touch many issues that characterise an evaluation which are developed specific upon answering and conducting the evaluation. In the first question, four groups of participants, the stakeholders, in evaluation are included: those who proposed to conduct the evaluation, those who could make decisions for the evaluation, the owner of the evaluated subject, and the participants of the evaluation and the evaluated subject. It has been recognised that compositions of the stakeholders could alter the collective evaluation preferences and values (Mark and Shotland, 1985). The second question mainly queries the evaluation objectives. Frequently given by owners, governments, inspectional organisations, the evaluation objectives would determine the initial system and/or its good outcomes (Rossi et al., 2018). It could also contain internal targets such as production and the profits (Scriven, 1991, Neely et al., 1995, Rossi et al., 2018), and external targets such as governmental policies (Singh, 2006). Here, it is implied that an evaluation subject should be determined. Evaluation could be done for different subjects all being clear bodies, including an organisation, an institution, an enterprise, for desired outcomes (Gregory and Jackson, 1992). In question four, it is suggested that the evaluation subject could be mainly identified by the evaluators. Then, it is noticed that evaluation is supported by resources and techniques. Evaluation, especially done by human, require data, labour, money, and other auxiliaries (Singh, 2006). And lastly, for decision-making, measures and methods are required.

In practice, a collective protocol of evaluation, integrated, exhibits as Fig. 2.1 (Melchert and Winter, 2004, Rossi et al., 2018). Evaluation could be demonstrated as a process that attempts to develop specific contents for the aspects contained in the above questions.

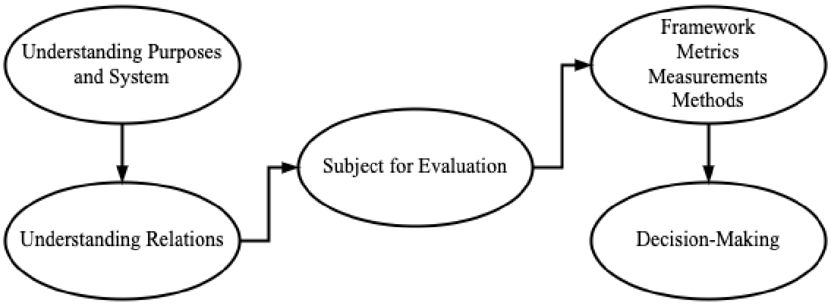


Figure 2.1 The Evaluation Process

Given the evaluation objectives, it is often by default to expect the subject for which the evaluation is proposed to realise the objectives. In this thesis, this system defined in the evaluation objectives is termed the ***initial system*** for better separation with the evaluation subject, the system that is measured in evaluation. How the evaluation objectives are engaged with the initial systems to result in changes in the indicators of good outcomes are clear in many evaluations: revenue and profits suggest the operation status of companies (Fukuyama and Weber, 2015, Mahmoudabadi and Emrouznejad, 2019); grades of students indicate education outcomes (Chankseliani and McCowan, 2021); temperatures and lighting degrees create building environment suitable for human living (Konis, 2013). The judgemental criteria is clear with values of human, let it be owners or users. Also, the initial system is crucial in evaluation by generally containing important stakeholders and their values which influences decision-making. The owners with the power to control the evaluated subject are often prioritised for their preferences and benefits (Fetterman, 1994). All DMs, evaluators, and other stakeholders would constitute the value connections and construct the physical structures around it (Atkinson et al., 1997, Fetterman, 1994). It has been recognised that more sufficiently analysing stakeholder influences on evaluation could produce more satisfying results for the DMs (Mark and Shotland, 1985). As FuiHoon Nah et al. (2001) points out, understanding the composition of stakeholders and how their objectives are aggregated to the overall objectives of the organisation could identify the faultiness and inefficiencies in the operation of an organisation.

However, often in practice, initial systems are directly used as the evaluation subject, which may not be suitable. In many evaluations the realisation of evaluation objectives by the initial system could be unclear or unattainable: patient satisfaction could be systemically influenced by multiple attributes of hospital performance (Kotiadis et al., 2013); agricultural production is a collective outcome of ecosystem conditions (Pagotto and Halog, 2016); and more commonly, sustainability of a thing, a process, and a system could be indicated by indicators covering nearly the whole system composition (Hiremath et al., 2013, Mori and Christodoulou, 2012, Thies et al., 2019). The integration of multiple indicators (Singh, 2006, p.21) and the inclusion of external objectives (Aguinis, 2009, p.59-64) could result in unsuitable use of the initial system as the evaluation subject mainly in system scale. When evaluation is merely done over the initial systems in this case, the decisions made for benchmarking or improvement could be unable to be achieved or simply meaningless (Banks, 2000). Thus, as Fig. 2.1 indicates, to comprehensively adopt evaluation objectives, it require efforts to understand the linkages between the evaluation objectives and the initial system.

As externalities are being recognised to be highly influential to the evaluated subject, using more metrics and conducting network analysis linking the evaluated subject with its external bodies are found to serve for better quality decision-making, which are still two main challenges of evaluation studies (Rossi et al., 2018). Ex-ante evaluation expands the time scale of the initial system with predictions to its future outcomes (Samset and Christensen, 2017). Performance evaluation has evaluation metrics including efficacy, efficiency, and effectiveness, measuring both the internal transformation and external influence mechanisms of the initial system (Lucas, 1971, Connell, 2001). Sustainability evaluation could be done by the life cycle perspective (Blengini, 2009, Guinee et al., 2011) or considering more aspects of social and environmental impacts (Cohen et al., 2002, Chankseliani and McCowan, 2021). It is noticed that the initial system and the evaluation subject, the subject that is eventually being measured and used for decision-making, could be eventually holding different system boundaries. In other words, in such evaluations, the evaluation subject is implicit.

An explicit evaluation subject, especially through network construction methods, hence, should be determined by the evaluation objectives, explaining how they are realised. More specifically, for complex system with colliding values, stakeholders play deterministic roles for the system boundary of the evaluation subject. For general systems, the triggers to all criteria and actions are the participants of the initial system and other stakeholders that are linked to them (Seuring et al., 2008). The cognition of the stakeholders, mainly the evaluators and DMs, would determine the boundary of the evaluated system (Mark and Shotland, 1985). To note, it is also in this process that some externally attached evaluation objectives could be found to be unattainable at all. The relations could be limited by technologies and techniques to understand all key relations or the developed evaluation subject could be too large to be measured (Pawson and Tilley, 1997, Morrow et al., 2015). This occurs often in sustainability evaluation (Fonseca et al., 2020).

Contingently, frameworks, measures, and the method for evaluation is constructed or selected. These aspects are sometimes directly determined in the evaluation objectives. For example, given the need to conduct life cycle sustainability evaluation for palm oil production, the initial system is the process of transforming from palms to the bottled oil products while other processes supporting this initial system such as the supply of palms and other materials are identified based on the life cycle perspective (Chavalparit et al., 2006). Similarly, when life cycle sustainability evaluation is done for products, it is the process from the production of the product to the destruction that is evaluated, not tracing from earlier nor tracing till later stages (Kloepffer, 2008).

For overall evaluation, the portrait to the evaluated system by the framework, the selection and projection of evaluation indicators, and the accuracy and consistency of monitoring are all expected to influence the quality of decision-making (Lucas, 1971). The preferences set for these aspects are usually greater quantity of outputs produced, higher efficiency of the transformation process, and more efficient data collection and monitoring (Lucantoni et al., 1994). The fundamental criteria for selecting or constructing a suitable framework is that it should be capable of reaching the objectives and explaining or reflecting the relations (Seuring et al., 2008). In other words, the measures of evaluation, the dimensions to be assessed and indexes to be monitored, should be derived from the framework, or can be attributed clearly into the framework. When objectives contain expectations for the improvements of the initial system, the evaluation framework should be directive for the measures and the indicators, for example, through including extended dimensions or subsystems or introducing the need for collecting additional data (Pope et al., 2004). However, the application of evaluation methods seems to be relatively independent from the frameworks. Through the selection of various quantitative or qualitative methods, it is more targetted at better reflection of the evaluation objectives (Thies et al., 2019). As Thies et al. (2019) concludes, MADM, multi objective decision-making, and DEA are the most popularly applied methods in operations research and they are popularly conducted associating with AHP, outranking, TOPSIS, weighted average and other qualitative or quantitative methods. Hence, the determination of evaluation methods, unless being stated in the objectives, mostly depends on the pursuit of evaluation, including but not limited to classify, to set the preferences, or to compare the efficiency of transformation. Additionally to note, although the selection of evaluation methods is theoretically independent from the evaluated system, methods thrive differently in fields of research where one method can be more widely accepted in one discipline than the other (Thies et al., 2019, Hiremath et al., 2013, Weiss et al., 2015, Holden and Hyer, 2005).

With the completion of all stages, evaluation that targets at decision-making through the assessment of the evaluated system can be done. After judgements are made for the evaluated system, information can be carried out in the way of feedback to the DMs or practical implementation to the initial system (Melchert and Winter, 2004). This marks the end of this or this routine of evaluation.

Basic Elements of Evaluation

As a conclusion to the process that evaluation should go through, the following ten fundamental elements are identified that should be clarified after evaluation which are presented in Table 2.2. To note, depending on the contents the objectives of the evaluation disclose, some elements that appear later in the table can be determined earlier regardless of the process of evaluation.

Table 2.2 Basic Elements of Evaluation

Process of Evaluation	**Elements of Evaluation**	**Explanation**
Understanding system and purpose	Lead of evaluation	The body that proposed the evaluation.
	Evaluation objectives	The preferences or prioritisations in evaluation.
	DMs of evaluation	The body that holds to the power to make decisions.
Understanding relations	Key stakeholders and general stakeholders	Actors in and related to the initial system.
	Evaluation subject	The evaluated system.
System for evaluation	Evaluation resources	The support needed to conduct evaluation.
Selecting framework, measures, and method	Evaluation framework	The conceptual framework applied.
	Evaluation measurement	Evaluation methodology.
	Evaluation method	Method used for performance appraisal.
decision-making	Result and feedback	The report of evaluation results.

Acknowledging evaluation from the perspective of an evaluator who mainly determines the perspective to conduct evaluation, the originator of the evaluation determines the fundamental world-view that the evaluation lies in, justifies the proposal of the evaluation objectives, and triggers evaluation for the initial system. Being the body who proposes the need for evaluation, lead of evaluation reveals some instinctive preferences of the initial system that are independent from the evaluators. These preferences determine part of the evaluation objectives that lower authorities need to contribute to or some conditions to be satisfied. Often, it influences perspectives of the evaluator in the clarification of the evaluation objectives and the formulation of the relations in the initial system and the evaluated system. For example, when the central government proposes financial performance evaluation of banks, actions of all banks are evaluated as the contribution towards national development goals and different from regional targets, the fluidity of capital among regions are also part of the evaluation focus (Singh, 2006, p.10-11). Similarly, regional financial bodies are regarded as directly contributing to the regional targets proposed by the regional governments whose interests can be different from the national ones containing more regional preferences for industries (Singh, 2006, p.12). To note, although it is recognised that the proposal of the objectives from the lead of the evaluation can be the outcomes of the implementation of managemental strategies or activities on the greater dimension (Seuring and Gold, 2013, Aguinis, 2009), since not all evaluations need to be led by certain strategy or guided by a managemental structure, the cut-off point for evaluation is signalled by the explicit proposal of an evaluation attempt.

Contingent to the lead of evaluation, the evaluation objectives illustrate, in the explicit or implicit form, the key aspect that the evaluation focus on and provide preferences, including the screening of key inputs and procedures to be observed (Guba and Lincoln, 1981, p.4). Objectives are usually associated with different groups of players, naming stakeholders (Seuring and Mller, 2008). While each stakeholder may hold individualised pursuits, the preferences of evaluation determine that some objectives are more respected than others (Pawson and Tilley, 1997). Hence, the clarification to evaluation objectives also means understanding the composition of the DMs of the evaluation and the KSs of the evaluated subject. Slightly different from traditional perception to DMs, the DMs in evaluation are not only the DMs for the initial system who holds the power to set the initial preferences but also those who hold the power to make decisions for the evaluated system. Similarly, the KSs for the evaluation are the stakeholders who cause significant influence to the initial system, meaning that they should be contained in the evaluated system, and those who are the influencers to the evaluating process. In other words, it is necessary to understand that the initial system, the evaluated system, and the process of evaluation have different participants who may have multiple roles in evaluation. Since the evaluated subject may hold a system boundary greater than the initial system, the DMs identified for the evaluated system may be different from that of the initial system. Also, although evaluators are indeed part of the KSs, the level of influence from the evaluators can be different for different types of evaluation. In empowerment evaluation, evaluators can be the DMs or even the lead of evaluation (Fetterman, 1994). More contributing to the evaluation process, in other types of evaluations, evaluators are usually merely part of the DMs since they determine the world-view, the methodologies, and the methods for evaluation (Scriven, 1996), but they may not be the originators.

Given the existence of the initial system, the lead of evaluation, the objectives of evaluation, and the DMs in evaluation outline mechanism of the initial system and the overall direction that the evaluation tend to prefer. Noticing that stakeholders are the triggers in the operation of any system (Seuring and Mller, 2008), drawing the linkages among the stakeholders and links to the initial system forms the group of KSs and general stakeholders consisting of the evaluated system. In this way, the substantive focus for the evaluation, the most important program concerns, and questions, are outlined by the stakeholders (Greene, 1988).

Following that, the evaluation subject can be developed as the evaluated system, explicitly presenting not only the mechanisms and the linkages, but also the boundary that separates the evaluated system from its greater environment. Since the evaluated system is bound to the objectives of evaluation, the subject can be anything, spreading to all fields of research. For example, Chen (1996) focuses on educational programs; Lucantoni et al. (1994) examines the traffic on road within a city; Mio et al. (2018) studies performance of the routes of chemical production; Xian et al. (2016) looks into the performance of air particle emissions; Mahmoudi et al. (2019) concerns the energy and environmental performance of electricity plants; and Brown and Ulgiati (2004) delves in the utilisation of natural resources. The scales of the evaluated systems cover a company or a group of companies (Arvey and Murphy, 1998), one or more industry sectors (Shao et al., 2019), and one or more countries (Suzuki and Nijkamp, 2016), which are any scale of system that is under the evaluation interest. More importantly, the subjects are defined with clear system boundary that contains all the elements of evaluation from the initial system, the stakeholders, the linkages drawn from the stakeholders, and the indicators used to reflect all information. Given the examples of evaluation subjects, the initial system can have explicit boundaries such as programs, production routes, companies, and countries. Systems such as the natural resources, air particle emissions have implicit boundaries that cannot be clearly separated from the surrounding environment. However, the extent to which these systems reach out to is clarified once the measures and indicators used are determined.

Upon clarifying the subject of evaluation, what supports the evaluation need to be identified to know the cost attached to evaluation. Acting as an assessment tool to the initial system, in some cases, obtaining, recording, and managing key performance indicators, which can be additional tasks for business operation, cause massive burden to its operation (Ohlig et al., 2020). Often, evaluation is done requiring more resources. It consumes materials and labour to reach the decision-making process and creates impacts. The impact from evaluation can be feedback to the operation of the initial system. It influences the reputations of the institution, and it also acts as an appraisal tool that attracts more resources for the organisation (Carman and Fredericks, 2008).

Then, the framework that suits and demonstrates the evaluated system is selected for modelling. According to Elwyn and Miron-Shatz (2010), in evaluation, after processes including identifying the background information of the problem, affective forecasting to the problem, constructing the preferences to the problem, measures around the problem are integrated into a decision-making model. This model is the framework. They also state that by looking into the background of the subject, the more information is captured and introduced to the DMs, the more rational and acceptable decisions are made for the suitable system which contains the relationships of attributes and consequences around the initial system. In other words, framework can be a determinant for the scale of the evaluated system as it may introduce new dimensions or aspects to the perspectives of the evaluators. However, not all frameworks can be genuinely adaptive. Some frameworks are designed to a certain context, such as the air particle emission-sink model (Meinshausen et al., 2009), supply chain management (Rao and Holt, 2005), and the green economics (Cato, 2012), respectively established for air particle diffusion, supply chain, and the economic market. Consistency of the context naturally implicitly justifies the suitability between the evaluated subject and the framework applied. However, frameworks including the TBL (Savitz, 2013), the SDGs (UN-DESA, 2017), and and the changes of ecosystems (Begon et al., 2006) are not specific for certain context and still lacks justification for the suitability in applying to the initial system and the evaluation objectives.

The methodology, methods, and the measurements to be used in evaluation are determined by more practical aspects aside from the capability to represent the dimensions of the evaluation framework. Typical evaluation methodologies include qualitative, quantitative, formative, and summative (Scriven, 1996, 1991). Indeed, evaluation research can also be done using mixed methodologies and methods (Blalock, 1999). Evaluation methods are more varied. Mackenzie (2005), Pawson and Tilley (1997), and Thies et al. (2019) list many qualitative, quantitative, and mixed methods including interviews, case study, regression, DEA, and portfolio analysis. Holding the capability to explain part of the features of the initial system, the selection of the evaluation methods seems to be mostly free from the evaluated system. For example, for electricity production process, all above methods are applied (Yellishetty et al., 2011, Sueyoshi and Goto, 2013, Zurano-Cervello et al., 2018). What seems more important is the application and the treatment of collective indexes. Indeed, evaluation methods and indices should, eventually, serve for rational decision-making. For example, as Siche et al. (2008) introduces, for the indication of some compound concept such as sustainability, aggregated metrics such as the environmental sustainability index (ESI), ecological footprint (EF), and the environmental accounting indexes including emergy yield ratio (EYR) and the environmental loading ratio (ELR) are popularly used. These indexes can be aggregated through algorithms or systemic unification following certain physical measurement. To calculate ESI, the indicators composing the indexes have different units that need to be standardised and summed. For EYR, by calculating all the materials and information using the unified measure, emergy, the flow of energy is traced. While all methods, measures, indexes, and the aggregation of indices have pros and cons, their proper use can be determined by the quality of the decisions made for the evaluation objectives and the system scale of the evaluation subject.

Eventually, the feedback of evaluation marks an end or a cut-off to a routine of evaluation where the decisions made, and conclusions arrived at from evaluation is reported or implemented. Singh (2006, p.20) notes that in such cases of periodic evaluation, the results from the previous evaluation can become the input of the next. And in terms of the quality of the decisions made, as Blalock (1999) mentions, when the improvement of performance is also within the interest of evaluators, evaluation results from previous ones are coherently critical. Evaluation can be periodic and repetitive which would serve for better monitoring of the initial system and for making long-term decisions.

Overall, while it is claimed that clear illustration to the ten basic elements of evaluation marks the completion of one routine of evaluation, it also tackles or provides rational explanation to five general issues that exist in evaluation (Guba and Lincoln, 1981, p.3): 1) confusing measuring and evaluating; 2) implicit and non-solid paradigm of inquiry to the evaluation problems; 3) biased appraisal towards individual differences; 4) the bounded relationship between the orientation and the objectives from the cultural background where some methods of standardisation naturally accompany the relations; and 5) the assumption that evaluation results ought to fit industrial ideologies or common sense. We notice, explicitly developing the elements in 2.2 should identify the above general issues in evaluation and provide references to the limitations of the evaluation implementations.

Perspectives of Evaluation

The definitions of evaluation set a fundamental consent that evaluation contains two stages, assessment and decision-making, and not until quality decisions are made, the protocol is not yet to end. And, although the basic elements of evaluation provide a clear outline of evaluation, there is no clear reference to determine the boundary of the evaluated system. What is clear is that the perspectives of the KSs and the linkages among the stakeholders are critical in setting the boundary. On top of this, while realising that evaluation is being popularly classified according to different criteria, the stance of internal or external perspectives determines some evaluation objectives. Quite obviously, when internal evaluation is done, the main objective is to diagnose within the organisation for improvement. When external evaluation is done, a naturally accompanied objective is to benchmark the organisation or system on the planet or among its competitors. Here, different forms of evaluation (Appendix A) are classified and compared following the clues from the evaluation elements, including the position of the DMs, within or outside the evaluated system, and the perspectives of the evaluators.

Evaluation is mainly categorised in comparative forms on different criteria. Such categorisation mainly demonstrates a theoretical or methodological feature of evaluation. In the past, evaluation has been divided into explicit and implicit forms and further considering the role that evaluation plays, evaluation can be formative or summative (Scriven, 1996). From the rationale and observation to the system, when system constitution and its boundary is explicitly presented, evaluation for such system is explicit and can be done using summative methods for decision-making. Differently, implicit system constitution and boundaries allows for the use of formative methods that can more explicitly present the system supporting evaluation (Gawronski and Bodenhausen, 2014). Theory-based and method-based evaluation is probably the most widely applied categorisation. Method-based has its intrinsic advantage in data availability but the linkage between the evaluation objectives and the results of the evaluation is not always tight (Stame, 2004). Similarly, result-based evaluation calls for result-based diagnosis to making judgements that can be preferably supported by collective data (Nielsen and Ejler, 2008). For theory-based evaluation, although creating new challenges in data collection, opens the black-box for programmes with vision following some logical linkages and gains more explainable and justified results while detecting the deficits in evaluation as evaluation methods get sophisticated (Stame, 2004). Based on the time when evaluation is done, evaluation can be divided into traditional post-event evaluation when it is done after the system operates and performs some actions and ex-ante evaluation which is to evaluate with anticipations for the future (Banks, 2000). Divided by different foci of evaluation framework typology, Chen (1996) proposes four division of evaluation including process-improvement evaluation, process-assessment evaluation, outcome-improvement evaluation, and outcome-assessment evaluation. Target-based and target-free evaluation can be separated by whether evaluation objectives are straight forward and present clear system to be evaluated (Scriven, 1996). Slightly different from method-based evaluation, there is the method-oriented evaluation that process around chosen methods, which highly depends on what is measured (Carman and Fredericks, 2008). On the methodological domain, evaluation can be categorised to qualitative, quantitative, and a mixture of both (Patton, 2015). Evaluation can also be divided according to the researchers' world-views and research interests. To describe the nature of system process and the conduction of strategy, a popular form of evaluation is the stakeholder-based evaluation by Mark and Shotland (1985) that gives voice to whomever involved in the process. Stakeholders, the players in the system, when being regarded as the subjective selection of the researcher to the objectively involved group of people, participate in culture-based evaluation that reflects the context they perform in (Gregory and Jackson, 1992). On the contrary, when the evaluation objectives focus more on power control, as a form of subjective context (Gregory and Jackson, 1992), sponsor-oriented and system-resource based evaluations become more useful. When the evaluation subject is focused to a program, with specific customer and service routine, Pawson and Tilley (1997) attributes them as program evaluation. When the power of evaluation is performed by both the external evaluators and the internal evaluators, Fetterman (1994) calls this as empowerment evaluation. Focused on the performance of a system, performance evaluation specifies the dimensions of the system to be evaluated (Lucantoni et al., 1994). However, for example, performance evaluation, the term ”performance” could define specific dimensions or objectives to evaluation. The combination of performance research and evaluation research is reviewed in later section with the realisation that performance evaluation in nature can be a type of comprehensive evaluation.

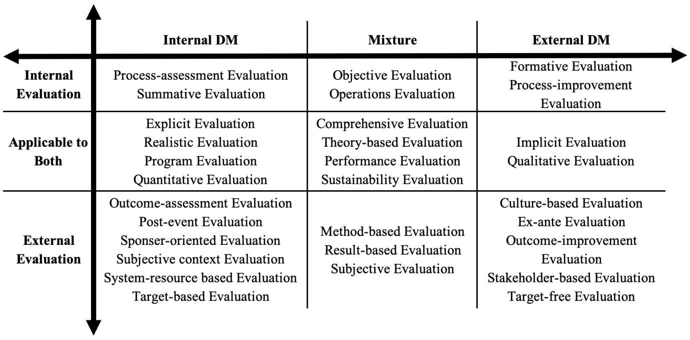
From the criteria used for categorising forms of evaluation, it is quite obvious that the following three questions are popularly asked:

1) What is the purpose/objective(s) of evaluation?

2) How is the evaluated system assessed?

3) What method is used for making decisions that are appropriate?

The first question realises, from past evaluation experience, that the purposes and objectives often contain information over the values to be held in the evaluation and the system studied. The second question requires clarification to the determination of the subject of evaluation. It can be given in the objectives, can be deciphered by the perspectives of the evaluators, or can be clarified in some other ways. Whichever way would determine the features of the evaluated system, mainly the boundary of the system to be either explicit or implicit. The third question focuses on the consistency with the evaluation objectives, the suitability of the scale of system to be evaluated, and the representativeness of the method applied. It explains that explicitness or implicitness of the system boundary and the internal or external evaluation perspective are some reflections of different theoretical foundations of various forms of evaluation noted above. The results are shown in Fig. 2.2.



	Internal DM	Mixture	External DM
Internal Evaluation	Process-assessment Evaluation Summative Evaluation	Objective Evaluation Operations Evaluation	Formative Evaluation Process-improvement Evaluation
Applicable to Both	Explicit Evaluation Realistic Evaluation Program Evaluation Quantitative Evaluation	Comprehensive Evaluation Theory-based Evaluation Performance Evaluation Sustainability Evaluation	Implicit Evaluation Qualitative Evaluation
External Evaluation	Outcome-assessment Evaluation Post-event Evaluation Sponser-oriented Evaluation Subjective context Evaluation System-resource based Evaluation Target-based Evaluation	Method-based Evaluation Result-based Evaluation Subjective Evaluation	Culture-based Evaluation Ex-ante Evaluation Outcome-improvement Evaluation Stakeholder-based Evaluation Target-free Evaluation

Figure 2.2 Categorised Forms of Evaluation

All attributed forms of evaluation may not be independent from each other. All evaluations are done indifferently for explicit systems with preferences that provide standards or preferable outcomes indicating judgements that are better. Internal evaluation relies on clear strategies and expectations from the organisation and just reflection to the real state of the system. Processes, programs, and operations are systems whose most of the basic components are explicitly presented. Within such, given a clear boundary of system, evaluation can focus on the assessment of the process and using summative methods concluding from the history performance (Scriven, 1996, Chen, 1996). When the objectives contain anticipation to future, often targeting on improvement and development, formative methods enable prediction based on past experience (Scriven, 1996). Different from that, external evaluation allows for the inclusion of subjective perspectives from the evaluators and the DMs (Scriven, 1996). Sponsor-oriented and system-resource evaluations highly depend on the evaluators' subjective judgement to the DMs' strategies and suggestions (Mark and Shotland, 1985, Gregory and Jackson, 1992), which could be too subjective(Chen, 1996). Compared with the internal perspectives, the objectives of external evaluation highly depend on the world-view of the evaluators. It allowed evaluators to focus on some aspects of the evaluation including the method, the result, the culture, the future impacts, stakeholders. As the practicability of evaluation becomes one criteria for judging its quality, Pawson and Tilley (1997) points out that realistic evaluation eventually needs to reflect the inner structure and the outer influences of a specific system. It is recognised that although some systems can be open to the environment, evaluating such a system, in the end of the day, needs an at least relatively clear system boundary that contains the open system but eliminates evaluation to some extent. Traditional evaluations of organisations and institutions easily determine the system boundary following the enterprise boundary (Singh, 2006). Sometimes, the word attached before "evaluation" such as "program" directly sets program evaluation to concentrate on the program, which could be an enclosed system. Systems can be evaluated using both qualitative and quantitative methods. Quantitative evaluation eventually determines an explicit boundary of the system through quantified indexes (Scriven, 1996). However, as Gawronski and Bodenhausen (2014) demonstrates, evaluated systems may always contain implicit compositions that can only be partially reflected not clearly nor directly observed. Qualitative evaluation hence often discovers aspects that could be implicit (Patton, 2015). Eventually, the most conceptually universally justifiable form of evaluations stand in the middle on both dimensions, that is comprehensively considering the internal and external perspectives and acknowledging that systems can contain explicit and implicit components.

The metaphor for the implicit aspects in evaluation is also contained in the objectives. When the evaluation objectives specify a system boundary, it is already explicit, but more often, information is partially suggested in the words attached to evaluation. Theory-based evaluation presumes that the evaluation objectives and the system evaluated could be demonstrated by the theory applied (Stame, 2004). Hence, freedom is given to the selection of theories that explain the mechanisms of the studied system and hence, system boundary is specified according to the theory followed with the derivation and selection of suitable indicators. Similarly, comprehensive evaluation attaches the pursuit of systemic overview, logical linkages, sufficient information collection, and rational justification to the results, and also other aspects that perfect the evaluation (Chen, 1996). Although, comprehensive evaluation is the most appreciated form of evaluation, due to the limitation in cognition, the theory of causation is on the harder pathway to be comprehensively complied (Pawson and Tilley, 1997, p.24). Thus eventually, the implicit system boundary expands to the cosmos, that is everything linking with the studied subject.

Slightly different, sustainability evaluation and performance evaluation stands for the form of evaluation that attempts to demonstrate some features to be evaluated. Evaluators must define sustainability as it determines the interpretation of sustainability aspects in evaluation, the objectives, and the mechanisms that some indicators would maintain (Markevich, 2009). To emphasise, when a specific subject to be evaluated is not clearly defined in the objectives, it might no longer be suitable to directly apply the organisation boundary to form the evaluation subject. For example, although focusing on crude palm oil production, its environmental sustainability evaluation reaches out to the ecosystems during the process from the production of original material until the sole production and distribution (Chavalparit et al., 2006). Resultantly, sustainability evaluation to any production system cannot neglect why, how, and how much influences are caused to the surrounding processes that critically supports the system contained in the evaluation objectives or determined by the DMs. As the context of sustainability amplifies, it becomes a necessary process to first of all identify the boundary of the system for sustainability evaluation.

Similar to sustainability evaluation, by putting ”performance” in front of evaluation, its evaluation objectives focus on the performance of the system studied, influencing the aspects observed, and the variety of performance indicators of different data types (Lucantoni et al., 1994). Unlike programme evaluation that directly clarifies the body of evaluation, during which the extend to which the system reaches out to could have clear cut-off (Chen, 1996), the determination of the body of performance evaluation may, too, highly depend on the understanding to the paradigms and methodologies associated with performance research. Blalock (1999) notes the issue from two aspects. As the definition of performance extend from outcomes to impacts, the process being evaluated extends, with wider coverage of associated processes and longer range in time. Also, due to such extension, the lack of more systematic consideration on measurement on its performance causes flawed evaluation that resulted in misguided policy setting and judgements.

Therefore, for both sustainability evaluation and performance evaluation, when the evaluation objectives contain specific system to be evaluated that enables full reflection of the sustainability or performance mechanisms, the system boundary of evaluation subject is explicit. However, more often, the system or process mentioned in the objectives are not sufficient for sustainability or performance evaluation. For example, Weitz et al. (2018) observes that the sustainability goals are multilateral and can be conflicting which by achieving one doesn’t necessarily mean the realisation of sustainability. Assisting the derivation for the suitable system boundary for evaluation, the typology of evaluation can also focus on some logic linkages within the system. Such forms of evaluation includes target-free evaluation (Scriven, 1991), culture-based evaluation (Gregory and Jackson, 1992), and the stakeholder-based evaluation (Mark and Shotland, 1985). Rarely such form of evaluations directly provide explicit system boundary to be evaluated. Instead, a criteria is given to draft the proper system. Mark and Shotland (1985) illustrates the decisive role of stakeholders in evaluation as the origin of the formulation of evaluation questions, the creation to the performance of the observed organisation, the implementation of evaluation activities, and the determination to value judgement by evaluation. In other words, stakeholders are the players of the operation system and the players of the evaluation process. Hence, linking evaluation research with performance research, performance evaluation (originally using ”assessment” by the author) is the process of evaluating the behaviours, outcomes and impacts around the players. Eventually, apparently, it is probable that different forms of evaluations, such as sustainability evaluation, performance evaluation, and stakeholder evaluation, can be applied together for better quality assessment and decision-making.

2.2.3 Performance Evaluation

The definition of performance follows a historical development to include more systemic and enteral aspects. Table 2.3 exhibits the definitions of performance by different attributes.

Table 2.3 Definitions of performance

Definition	**Source**
Performance is...	
Actions:	
a set of behaviours relating to the targets and internal units.	Murphy and Kroeker (1988)
the observable behaviours of people that are relevant organisational goals.	(Campbell et al., 1990)
measurable actions.	Campbell et al.((1993, p.35-70))
potential to achieve objectives and targets through intentional actions.	Lebas (1995)
valued contribution to achieve organisational goals, where the stakeholders provide perspectives for the targets and the remarked aspects include performance planning, control, measurement, and rewarding.	Melchert and Winter (2004)
intentional actions often from DMs that are related to the process.	Ermolayev and Matzke (2007)
Outcomes:	
the extent a system is meeting the cherished objectives.	Hurst and Jee-Hughes (2001)
conducting tasks under the situation of allowing for the optimal outcomes.	Baldvinsdottir et al. (2003)
the consequences of actions related to the targets.	Sonnentag and Frese ((2005, p.4-19))
Multiple attributes:	
outcomes, efficiency, quality, and effectiveness.	Harkema (1999)
outcomes, productivity, and efficiency.	Faulk II (2002)
measurable and dynamic attributes of system.	Rynes et al. (2005, p.4-19)
quantitative and qualitative reflections of system.	Paucar-Caceres (2009)
outcomes, efficiency, and impacts.	Sroufe (2003), Rynes et al. (2005, p.40), (Rich et al., 2010)

Applying the definition that performance include efficacy, efficiency, and effectiveness attributes in this thesis, the origin of intentional purposes tend to explain the value system behind judging performance. Murphy and Kroeker (1988) notes that the width and depth of perspectives of the performance observers may draw different relations linking the actions and the results. The being of stakeholders in drawing the links stands out. Also, the purposes are also influenced by some external direct or indirect factors such as the environment and the culture (Rynes et al., 2005, p.6). Thus, we understand that performance has internal and external perspectives and could be influenced by stakeholders.

Inheriting definitions from ”performance” and ”evaluation”, *performance evaluation* is an evaluation process which adds merits and value, around the performance metrics of a system that could be determined by performance management strategies or cognitions, making judgements on how well the system performs and implementing decisions to reach better achievements (Ferris et al., 1994, Judge and Ferris, 1993, Elwyn and Miron-Shatz, 2010). Rooting from performance research and evaluation research, it should be a disciplined field of study that is rational in performance measuring and decision-making (Blalock, 1999). Empirical studies reveal that systematic investigation following some logic often leads to better evaluation results (Ferris et al., 1994, Song et al., 2006). However, it is often being criticised of improperly conducted by attaching unsuitable targets or lacking systemic coherence between the objectives and the indicators (Mackenzie, 2005, Lucas, 1971), especially when the evaluators directly use given performance indicators, not sufficiently considering the information carried (Lucantoni et al., 1994).

Internal and External Performance Evaluation

Attaching the perspective of evaluation, performance evaluation done from the internal view and the external view exhibit clear differences in the evaluation elements. The main contribution of engaging evaluation from an internal perspective is that it clearly explains the origin of evaluation objectives of the initial system under organisation performance management, and hence present more internal typical features compared to external evaluation.

The implementation of organisation management strategy can be clearly reviewed through performance evaluation from the internal perspective, simply calling it internal performance evaluation in this thesis (Amaratunga and Baldry, 2002). This strategy provides information of managing conditions that lead to the organisation performances (Lebas, 1995). This means that objectives are given by DMs from the organisation for internal research, planning, financial management, and operation purposes (Simpson, 1985), and there is a clear boundary of organisation within which implementations are carried out and for internal stakeholders (Aguinis, 2009, p.2-4)

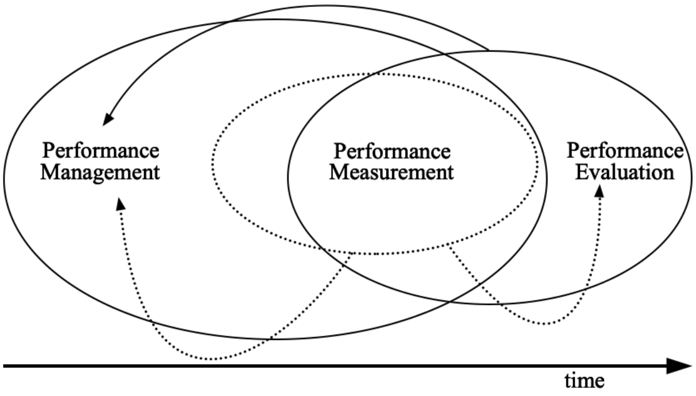


Figure 2.3 Performance management, performance measurement, and performance evaluation are twined.

Figure 2.3 presents the the relationship among performance evaluation, including internal and external perspectives, performance management, and the relevant measures. The aspects are openly intertwined. Internal performance evaluation often apply sufficient management information (Lebas, 1995). With respect to the control of organisation to the evaluated initial system, the organisation boundary, and the availability to internal performance evaluation information, featuring elements of internal performance evaluation is concluded in Table. 2.4.

Table 2.4 Basic Elements of Internal Performance Evaluation

Elements of Evaluation	Features of Internal Evaluation
Lead of evaluation	Often the owner or leader of the organisation that contains the initial system.
Objective of evaluation	Often present necessity to understand status of the initial system within the organisation.
Decision maker of evaluation	Must include member within or have control over the organisation.
Key stakeholders and general stakeholders	Actors in and related to the initial system and extends within the organisation.
Evaluation subject	The evaluated system contain the initial system but often doesn't extend beyond organisation boundary.
Evaluation resources	Provided by the organisation.
Evaluation framework	Framework is chosen under the focus for performance indication.
Evaluation measurement	Measurement system are often constructed case-specific.
Evaluation method	Usually independent from other elements.
Result and feedback	Supporting evaluation objectives, contributing to the management strategies of the organisation.

The DMs for internal performance evaluation should, apparently, also be the DMs of the management. The inclusion of internal DMs acts as a necessary condition for internal performance evaluation, supporting decision-making and successful conduction of the evaluation. Also noticing that performance management holds the function of a planning, management, and evaluation for the organisation target(Blalock, 1999), it also assists the determination of the evaluation framework. Commonly implemented frameworks using the internal perspective include the results and determinant relationships, logic models, causal models, the balanced scored card (BSC), and the European Foundation for Quality Management excellence model (EFQM) (Brignall et al., 1991, Fitzgerald et al., 1991, Millar et al., 2001, Kaplan and Norton, 1996, Hendricks and Singhal, 1996, Lebas, 1995). Beer's firm performance measurement framework of actuality, capability, and potentiality is also one of the kind (Paucar-Caceres, 2009). Atkinson et al. (1997) proposed a stakeholder-based design with respect to the influence of activity participation which is tested to be capable of capturing environmental impacts (Mark and Shotland, 1985, Pahl-Wostl, 2002). Upon recognising the complexity of organisation mechanisms, as Kloot and Martin (2000) and Lebas (1995) conclude, strategic performance management, by following fabricated linkage of dimensions of logic under certain strategy, provides rational evaluation perspective with performance measurements that supports comprehensive and better decision-making.

Perhaps the most critical contribution of the performance management framework to internal performance evaluation is the establishment and justification to the selection of performance measures, or when it is systemically done, the *performance measurement system*. In Figure 2.3, as Lebas (1995) studies, performance management and performance measurement has an intertwined relationship. This means that fine performance management structure not only clearly understands the derivation of the performance indicators that can be used for internal performance evaluation(Blalock, 1999), but also takes the resources needed for evaluation into organisation planning. Traditionally, financial indicators are believed to directly advise the performance of corporations. However, since performance now is determined to include more dimensions, performance measurement system should also be able to quantify actions, outcomes, and measurable indications of efficiency and effectiveness (Neely et al., 1995). A causal model must exist either explicitly or implicitly that demonstrates the achievement of performance (Lebas, 1995). Atkinson et al. (1997) points out that the connections among the stakeholders are critical for internal performance evaluation as a great proportion of managerial information influences the quality of financial data that can be measured. This might have been the main cause that flawed the tradition internal performance evaluation focused on actions and results. Aside from connections of stakeholders, to capture the implicit aspects of performance, the causal model can be built on tracing the transformation of elements or product, seeking the impacts on the natural, social, or cultural dimensions, and many others (Kloot and Martin, 2000). Such methods are often categorised as the inventory analysis or trajectory analysis. A more conceptual method is the soft system methodology (SSM) that tackles problems involving the measurement for the performance reaching out to external impactsPaucar-Caceres (2009). By opening up the black-box through some linkages and methods, contributions of organisation behaviours to its performance can be comprehensively reported (Amaratunga and Baldry, 2002).

While comprehensive reporting of performance information is found to significantly improve quality of internal performance evaluation, to guarantee the continuity of the conceptual framework is also challenging. Leading to flawed performance evaluation, many empirical studies mistreats the relationships between the organisational objectives and the performance actions (Aguinis, 2009, p.2-4). Also, as performance management structures embed more public sectors to reflect impacts of organisation outcomes, the relations of the outcomes with quality service, stakeholder satisfaction, and the continuous improvement of the organisation are hard to measure (Blalock, 1999). In other words, implicit and intangible evaluation objectives are challenging for internal performance evaluation.

Without definite power of control over the organisation and guaranteed accessibility to all organisation information, external performance evaluations requires understanding and modelling to the initial system based on accessible data so that the performance measures are derived and the measurement system with indicators of actions, outcomes, and external impacts is constructed(Jaafaripooyan, 2014). Its main contribution is that only the external perspective can illustrate the impacts caused by collective organisation behaviours and optimises distribution of resources with external parties (Zhang et al., 2021, Yu and Ma, 2015).

The trigger of external performance evaluation is also the lead of evaluation. With some understanding to the initial system, popular groups of proposing external performance evaluation include the government, large organisations (Singh, 2006), non-governmental organisations (UNDESA, 2020), or simply some researchers (Ghosh and Neogi, 2018). Apparently the lead of external performance evaluation usually has the power to assign or to determine the group of evaluators. With uniform examination from ”external” evaluators, external performance evaluation is believed to hold better comparability across systems that hold similar features under the evaluators’ perspectives (Jaafaripooyan, 2014).

The evaluation objectives are often partially externally oriented. Simpson (1985) illustrates the objective of external performance evaluation, expanding from internal performance evaluation, as ”Included are not only institutional objectives, which range from general statements of institutional purposes to more specific instructional, research and public service goals, but also professional and personal objectives. Of relevance also are the goals of those the institution serves, and of the larger community within which the institution operates.”. It is also concluded that the objectives should also provide information on the significance of value orientation, the boundaries for accepting responsibility, and the conceived alternatives. Such implicit aspects were not problematic in internal performance evaluation since system operation determines some objective, the boundary of system, and some indicators to be used. For example, energy use, thermal and visual comfort are some aspects that under the current state, is already expected for the performance of shading devices. When photovoltaic techniques are applied, the energy consumption, changes in energy efficiency are indicators believed to reflect the performance of applying the technology (Ghosh and Neogi, 2018). However, since the lead of external performance evaluation inevitably touches external objectives, typical evaluation objectives are given by government or related schemes, and social and natural responsibilities (Libeer et al., 1996, UNDESA, 2020). As a result, it can be a concern that whether the objectives are suitable or not, when the boundary of the system and the range to take up external responsibilities can be too large. This suggests that it is even more important in external performance evaluation to clarify the difference between the initial system and the evaluated system to suit the objectives. Eventually, as some objectives are more preferred than others, it is important to seek the suitable balance between the evaluation objectives and the individual ones (Srour et al., n.d.).

The clarification to the DMs are more significantly influenced by the cognition of the evaluators in external performance evaluation. In external evaluation, the DMs are often different from the group of people that applied the results of the evaluation to the initial system (Singh, 2006, p.27). For a given initial system, its out-ward influences can be categorised to two main part, that actively created from the transformation process of the internal process, and that passively to the external environment (Zhang et al., 2021). To determine the boundary to which the impacts reach out to, evaluators understands the DMs for the initial system and for the impacts. Therefore, it can also be claimed that it is the constitution of the DMs that determine the boundary of the evaluated system. And also, as DMs often sit within the organisation in internal performance evaluation, we recognise that in external performance evaluation part of the DMs sit outside the organisation, for example the external leads of the evaluation. Following the analysis to the clarification of evaluation objectives, the clue for implicit boundary of the evaluated system may originate from blurred specification to the DMs in evaluation. Being the key group of DMs, evaluators identify the stakeholders relevant to all of the objectives on the basis of the initial system (Mark and Shotland, 1985). Quite obviously, an external perspective to the initial system does not necessarily indicate that stakeholders within the initial system can be regarded as the same group since different level of stakeholder engagement is highly linked with levels of management targets(Gruman and Saks, 2011). Since preferences and objectives often associate with stakeholders (Greene, 1988), the determination of KSs and general stakeholders assists understanding the collective evaluation objectives and the break-down of the collective objectives to each groups of stakeholders(Taouab and Issor, 2019). In the same time, accordingly, the purpose of evaluation can be clarified, varying from mere decision-making to performance appraisal and others, suggesting the aspects to draw feedbacks for evaluation (Fetterman, 1994). Apparently, stakeholders of the initial system are more likely to be part of the KSs in the evaluated system.

Following the general process of evaluation, the linkages among the stakeholders need to be drawn to suit the evaluation objectives forming the evaluated system. The evaluated system presents the feature of containing the key process of the initial system, linking with external communities, and forms a clear evaluation system boundary (Ayele et al., 2021). The DMs can determine the boundary of the evaluated system by concerning the subsystems that are relevant with the initial system. For example, impacts from the initial system may be associated with other subsystems such as the managerial information system, coordination system, and organisation engineering (Lebas, 1995). In a word, for performance evaluation that concerns the impact from the initial system, there would be an inclusion of other systems to the initial system so that the aspects of impact can be captured in the evaluated system. To note, this does not necessarily result in greater system scale of the evaluated system comparing with the initial system.

Aside from general resources that need to be provided for evaluation introduced in Section 2.2.2 and different from internal performance evaluation where performance data can be extracted from management data, external performance evaluation, at least, requires additional labour of the evaluators to conduct evaluation(Yu and Ma, 2015). For example, as Singh (2006) presents in the financial report of many banks, the environmental cost to reach sustainability targets proposed by governments are mainly associated with additional data collection and project cost for third-party evaluation. Since the authority is shifted to external evaluators or evaluators that must hold external perspective even to their own institution, external performance evaluation is believed to support neutrality for the evaluation results, without bias to any evaluated parties (Yu and Ma, 2015).

Following clear understanding to the evaluation context, a critical action to be done is the selection of performance aspects(Lucantoni et al., 1994), or to say the performance evaluation framework that suits the evaluated system. The framework that explains the mechanism of the evaluated system can be context based. The mission, vision, targets, and strategies observed at different scales, such as the organisation, unit, team, and individual levels, are different with unique benefits pursued at each level(Aguinis, 2009, p.59-64). However, more crucially, the selection of the performance evaluation framework needs to be sufficient. There are cases when the context-based frameworks are unable to reflect all aspects of effectiveness since some dimensions can be lacking (Singh, 2006, p.11). In this way, the main function that a suitable external performance evaluation framework should hold is guidance and governance (Yu and Ma, 2015).

Although the selection of evaluation methods is genuinely free, following latest definition of performance with three dimensions, methods need to be capable of aggregating them. Additionally, there are preferences to methods in different industries. When reducing system risk becomes of the focus of performance evaluation in financial sectors(Singh, 2006, p.45), COMPAS is a method that is popularly used(Jackson and Mendoza, 2020). Fluid models are often used to evaluate the accuracy of air particle flows(Chang and Hanna, 2004, Walther et al., 2002). Also, when organisation performance is the focus, balance scorecard, the EFQM appraisal models are applied. More quantitatively, meta-analysis and data envelopment analysis (DEA) are very commonly used methods to evaluate(Arvey and Murphy, 1998, Neves and Loureno, 2009). Additionally, DEA is prominent in directly reflecting efficiency. Similarly, the selection of the measurements or the construction of the measurement system is guided by the performance evaluation framework (Neely et al., 1995). External evaluation includes the process of understanding the evaluated system and the internal and external observation to establish or select the suitable performance indicators (Ayele et al., 2021). Perhaps for any types of evaluation, while measurement system should be comprehensive, the application of indicators is not the more the better. Quantity and degree should be both reflected in the performance measurements (Yu and Ma, 2015). Also, it can be noticed that there are indicators that there can be indicators for system features that contribute to performance, too. Time can be exhibited in different forms of indicators such as the duration or periodic observation (Singh, 2006, p.20). System structure can be presented qualitatively in words like transformation(Scoones et al., 2020), using weights(Thies et al., 2019), in entropy(Purvis et al., 2019), or other forms. On the other hand, accountability can be hard to trace and attribution to causes can be too complicated when too many indices are used in evaluation (Singh, 2006, p.9).

2.2.4 Evaluation Techniques for General Systems

General System

Before understanding the techniques applied, we need to understand the features of the evaluation subject, a general system that can be independent from its application context. targeting on organisations, they are regarded as closed systems isolated from the outer environment by the organisation boundary (Houghteling et al., 2006). However, as organisations present much features of open systems, Katz and Kahn (1969) opens up general system as an open system fundamentally featured with input-output transformation process, forming an I-O model.

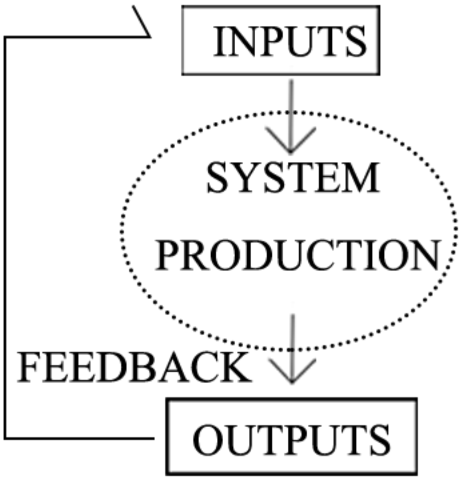


Figure 2.4 Input-Output Model

Katz and Kahn (1969) concludes that I-O system is composed of input, output, throughput (transformation), feedback, and environment, where each composition is well separated either internally or externally by the organisation boundary. Inputs are the resources absorbed from the environment that await to be consumed by the system. Outputs are the creations of products from the system that may contain desirable and undesirable parts which would be released back to the environment. Throughput is the process of transforming inputs into outputs within the organisation. Environment is all elements outside the system boundary that influences or can be influenced by the system. And feedback is the continuous exchange of information with externals to assist the system adapt to the dynamic environment. Hence, the general system of an I-O model (Figure. 2.4) suggests a clear system boundary formed by input, output, transformation, and feedback that are manageable while environment lies outside the system boundary. This forms the root conceptual model of organisation as other researchers illustrate organisational systems in ways different from Katz and Kahn (Ramosaj and Berisha, 2014).

While general system hold fundamental I-O model composition, as Shaw (2009) concludes there are four universal elements that general systems hold, the transformation process, hierarchic structure, purposeful function, and inner control. Associated with these elements, Kondraske (2011) concludes the elements into relevant system attributes including structure, function, behaviour, and performance. It is specially emphasised that performance, the capability of the system, is different from behaviour, the actions of the system, as it deals with objectives and interests of the system. Traditionally, the system objectives that guides functionality and performance of the system comes from management strategies mainly in the form of demand (Ermolayev and Matzke, 2007). However, the capability of what the system can do is an inverse aggregation of performance capacities from lower management level limited by performance resources (Kondraske, 2011). Hence, as performance extends beyond outcomes and purposeful actions, this system attribute is linked with consequences hierarchically created by the system structure, function, and actions (Harald and Rainer, 2020). '

Soft Systems Methodology

Performance criteria determines the aspects of system performance to observe and measure and high relevance with evaluation objectives and the constitution of the evaluated system is critical for quality decision-making (Lior and Zhang, 2007). Embedding performance evaluation as a process measurement in performance management, the balanced scorecard (BSC), the performance prism, and the European Foundation for Quality Management (EFQM) excellence model are some typical frameworks and methodologies for general organisations. BSC breaks down the realisation of long-term organisational visions and strategies into four top-down sequential perspectives including financial, customer, internal process, and learning and growth (Kaplan and Norton, 1996, 1998). Then, the realisation of strategic performance is deciphered into measurement indicators following linkages drawn by strategy map that connects aspects within each perspectives with the ultimate financial outcomes of the organisation (Kaplan, 2009). Using other methods to attach weights to the indicator and the dimensions, preferences are quantified and organisation performance is measured under BSC (Balaji et al., 2021). Claiming that stakeholders, especially the managers, set organisation strategies with the values they carry, the performance prism models organisation performance from five facets, stakeholder satisfaction on the top, stakeholder contribution at the bottom, and three side facets of strategies, processes, and capabilities (Neely and Adams, 2000). As Neely et al. (2002) describe the prism as a different scorecard, the implementation of the five facets also require mapping to understand how stakeholder satisfaction is realised based on stakeholder and task interface by asking who, what, and how. This process of querying who, what, and how is a mapping reference that suits any general system. More focusing on the aspects that an organisation could manipulate, EFQM excellence model provides a methodology and a framework for organisational self-assessment where organisational performance is presented in enabler criteria including leadership, people management, policy and strategy, resources, and processes, and result criteria including people satisfaction, customer satisfaction, society impact, and business results (Porter and Tanner, 2013). Given importance to each criteria category and all aspects, organisational performance is assessed through scoring and organisation performance is evaluated with implementation to the reality from the results of assessment (Wongrassamee et al., 2003). Other methods also include strategic measurement analysis and reporting technique, performance measurement questionnaire, results and determinants matrix, and consistent, integrated, and dynamic performance measurement processes (Pun and White, 2005).

Following traditional organisation production relations, these methodologies share the purpose of rationally implementing organisational strategies with clear organisational boundaries that determines the subject to be evaluated (Ermolayev and Matzke, 2007). This boundary has assisted in the determination of internal people satisfaction with external customer and social satisfaction, which the stakeholder influences from people within the organisation is apparently stronger than the external ones. Also, these frameworks share the idea that there are causal-effect linkages between strategic objectives and internal stakeholder behaviours and organisational processes, and between organisational processes with the external outcomes (Wongrassamee et al., 2003), which form the human-task interface in general systems. Such attempts to form clear system boundary for performance evaluation and causal-effect mechanisms are also presented in frameworks of agricultural system performance evaluation models (Tilman et al., 2002), city air diffusion models(Gong et al., 2012), societies(Eizenberg and Jabareen, 2017), and energy production systems(Sueyoshi and Goto, 2014). However, as external stakeholder influences are stronger in systems with natural mass exchange interface and social welfare services, especially with system objectives to respect the externalities, the system boundary that system performance reaches out to expands (Bititci et al., 1997). SSM is one of the contextless frameworks that is applicable for general systems by letting the system to ”speak out” the composition and mechanisms of its own and it, too, requires additional methods to be used for quantitative implementation to obtain performance scores.

Soft systems methodology (SSM), being an interpretivist problem structuring and organisation process modelling approach, deals with and diagnosis systems or situations that are intricate and complicated (Checkland, 1981). By recognising the power of stakeholders in situations, it is an action research where the analyst can intervene with the members of the system studied through continuous negotiation and renegotiation and to understand the system status, it allows for systemically developing the indices for evaluation (Checkland, 1999, Paucar-Caceres, 2009). Initially, starting from the seventies, Checkland (1999) has conceptualised SSM into *four main activities*:

1. Finding out about a problem situation;

2. Formulating some relevant purposeful activity models;

Table 2.5CATWOE Elements

	Explanation
Customer	Directly influenced by system output, both good and badly.
Actor	Conductors of activities in system.
Transformation	Production of transforming inputs into outputs.
Weltanschauung	World-view that attaches meanings to activities in system.
Owner	Controls the system; have the power to create or destroy the system.
Environment	Environment the system lies in; the environmental constraints that need to be fulfilled.

3. Debating the situation, seeking systemically desirable and culturally feasible changes, and the accommodations between conflicting interests which will enable action to be taken;

4. Taking action to improve the problem situation.

Set on these principles activities, it is developed as an never ending learning cycle (loop) of describing, perceiving, acting, feedback, questioning, justifying, and improving which constantly communicates across the real world and systems thinking around the world. The existence of the problem can be sensitive to conditions, such as a certain group of stakeholders. After determining a problem, important relationships contained in the situations are observed with the stakeholders or from the perspectives of them or their systems (Checkland, 1999). The logic behind SSM allows for any stakeholder to hold the perspective of a manager, having the power to interact and influence some aspects relating to them (Ameyaw and Alfen, 2018) . Clear definitions and statements of values would determine what is problematic. Recognising that problem situation can inherit impact through interpersonal connections, expressing the situation can identify new problems that would not suspend as a preliminary stage (Checkland, 1999), which may result in a massive problem system. Step 3 calls for providing the ”root definitions” that formulate and characterises the problem situation, usually constructing it to a system. Usually, the root definition of a system can be given through defining six major factors, the CATWOE elements (Checkland and Poulter, 2010).

Taking the first letter of each element, CATWOE defines customer, actor, transformation process, weltanschaunng (the world-view), owner, and environment (Table.2.5). In practice, it is usually the user of the concept who characterises and determines the CATOWE elements in SSM (Dortmans et al., 2006). And to note, although determined by the user, the CATWOE elements is not merely describing features of a system limited to human players as none of the functional explanations to the factors are limited to human actors.

The construction of the conceptual model could follow different criteria. One typical and genuinely suitable model is the PQR model, ”doing P by Q in order to contribute to achieve R” (Checkland, 1999). It continuously asks the question of what to do (P), how to do it (Q), and why (R). Aggregated linkage of these purposeful activities explain the occurrence of transformation process (Kotiadis et al., 2013). In Checkland's (1999) words, the actions are intentionally taken "to be the system named in definition" and hence, in principle, the models forms from these actions are not "model of X" but rather the model that are "relevant to debate about X". This guarantees internal validity of SSM conceptual models in its relevancy to the problem core and competency to understand the problem system, but systematic research into the reality needs to be done to be externally valid (Pala et al., 2003). Thus, step five should be comprehensive and systemic besides including important relations by comparing the conceptual model with the characterised problem situation (Kotiadis et al., 2013). Very often. structured performance measurements are used such as the 3E measurements, which is introduced in the following section. It is a diagnostic step that adjusts the conceptual model from system thinking with the real word. Step six amends the conceptual model and it is tested to change the initial problem in step seven. Without definition to how the adjustment to the conceptual model from step four should be done, many conceptual or empirical, quantitative and qualitative methods are used. Emes et al. (2017) sets the criteria for filtering conceptual model initiated approaches using results from discreet interview with the participants of the system. Besides, stakeholder-based value focused thinking, observation to system reality, simulation, scoring, ranking, weighting are also some typical methods used (Franozo et al., 2021, Emes et al., 2019, Augustsson et al., 2019). Although SSM is an never ending routine of learning process in principle, finishing a 7-step SSM, ending at taking actions in the real world, usually marks the completion of one SSM routine (Pala et al., 2003).

Additionally, we realise from the elements of evaluation (Table. 2.4) that using SSM for system performance evaluation would clearly present the mechanisms that distinguish the initial system and the evaluated system. One the one hand, SSM, building a complex construction of the system linking with stakeholders, needs to be directed by the evaluation objectives. Connell (2001) criticises from past performance evaluation studies using SSM that when evaluation criteria, usually presented in the form of evaluation objectives, with structuring strategies and implementation are hardly differentiated from the system mechanism and attributes the cause of such chaos to the insufficient clarification to the evaluation objectives and stakeholders. Stakeholder involvement influences how the evaluation objectives can be achieved and how the SSM model can be implemented. As Checkland (2017) notes the difference, evaluation for diagnosis purposes is usually an external understanding to the system and for management purposes would focus more on the actions that can be pro-actively carried out by the system. It means that we need to be clear of whether it is internal evaluation, external evaluation, or a combination of both that is done, adapting to the evaluation objectives. On the other hand, especially in step five of SSM, viability of the SSM model is considered as a restriction to the evaluated system. Concluding performance of a viable system as actuality, capability, and potentiality, Beer's viable system model provides a different set of measures that is parallel to 3E (Paucar-Caceres, 2009). Often compared with it, it emphasises that performance of system needs to be quantifiable and measurable to be evaluated (Beer, 1995). Many studies treat this challenge as multi objective decision-making through aggregation of quantitative and qualitative data (Franozo et al., 2021, Cao and parikhani, 2020, Kotiadis et al., 2013). Besides, the viability of SSM models needs to consider whether the evaluation objectives can be achieved mainly through examination to the impact of the initial system by linking with other systems (Paucar-Caceres, 2009). As performance is defined with the dimension of system influences, it is an aspect lacking suitable reflecting although it constructs the problematic situation and contributes to completion of system objectives (Ledington and Donaldson, 1997). The learning loop of SSM, after understanding the dimensions of transformation and outcomes, impacts from the initial system is usually the extension of variety features around the system (Kotiadis et al., 2013). Hence, the evaluated system, especially when evaluation objectives include aspects of measuring system performance, can be regarded as the expanded system from the initial system.

For any general system of I-O models, the three Es, efficacy, efficiency, and effectiveness, respectively demonstrate one aspect of performance criteria linking with universal system attributes (Shaw, 2009). 3Es performance criteria is also the set of answers to each one of the elements in PQR model (Table. 2.6). Efficacy illustrates the outputs of the system. Outputs are can be desirable or undesirable, as an result of the purposeful activities (Harald and Rainer, 2020). In other words, the model is still an I-O model even if the input of resources is not producing the anticipated outputs. Efficiency cares about the quality of transformation. Mingers et al. (2009) demonstrates a transformation process with best efficiency as producing the current outputs by consuming minimum resources. Generally, it is quantified as output(s) over input(s), however with different decision-making for reaching the "best efficiency" (Cooper et al., 2011). Effectiveness cares about the connections of the evaluated system with the world-views around it. Checkland (1981) notes that effectiveness can be identified by continuously answering "is it the right thing to do". Mingers et al. (2009) notes it as the contributions of the evaluated system to the wider system or environment. However, effectiveness is difficult to measure in two ways: it contains comprehensive and complex aspects, and influences can be unpredictable. Effectiveness can be reflected from but not limited to social, cultural, and political aspects (Checkland, 1999). It also includes parts that are related to the natural environment, the living and non-living aspects of the universe aside from human (Tietenberg and Lewis, 2018). Regardless of the context effectiveness can reach out to, in many scenarios, the consequences of system behaviours and system potentials are only realised after it is done, even if being efficacious and efficient in conducting the activities (Paucar-Caceres, 2009). This suggests the application of ex-ante evaluation or using ergodic measurements for system performance evaluation.

Table 2.6 Performance Criteria 3Es and Explanation

	3Es	Explanation
P-What	Efficacy	Is the transformation by purposeful activities in the model producing the outputs?
Q-How	Efficiency	Are the outputs of the transformation process produced by minimum resources used?
R-Why	Effectiveness	Do the outputs and the transformation follow expectations in Weltanschauung?

As shown in Figure. 2.5, the system boundary of an I-O system contains efficacy and efficiency. The infrastructure for completing transformation and containing the inputs and outputs forms an explicit boundary of the initial system in evaluation that separates the organisation from other bodies and the environment (Shaw, 2009). However, to note, when understanding system performance using SSM, the aspects that are strongly influenced in the outer environment would form an open system boundary with the aspects of effectiveness that contains the I-O initial system. In performance evaluation, this is the boundary of the evaluated system that awaits to be explicitly presented.

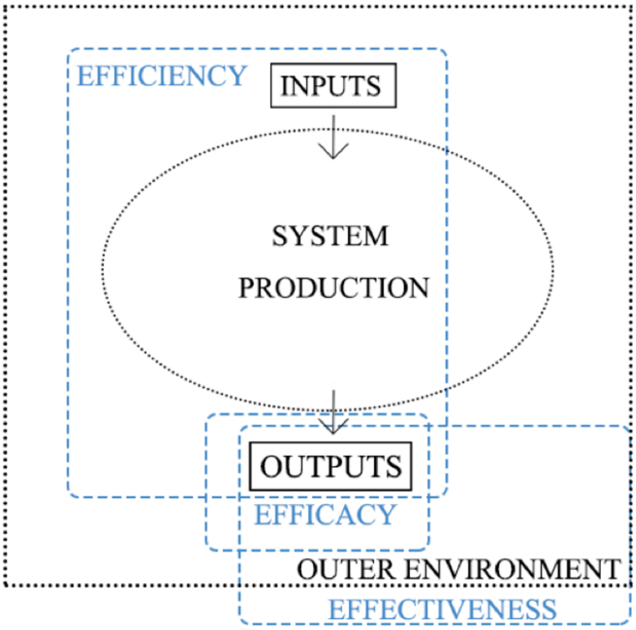


Figure 2.53 Es in an I-O System

As more aspects are identified from the world-views, qualitative compositions of the social systems add more ”E”s to the 3Es. Morality and aesthetics are respectively introduced as elegance, and ethics (Ameyaw and Alfen, 2018, Kotiadis et al., 2013). However, such aspects can be contained in the evaluation objectives, this thesis focus on 3Es to demonstrate system performance. Recognising that it is the system and its stakeholders who bring the objectives and preferences in performance evaluation, the 3Es measurement doesn't biased towards any aspect of system performance. Checkland (1999) only denoted system performance as comprehensive consequences that can be reflected in the 3Es. Hence, as Paucar-Caceres (2009) claims, the quality of decision-making for improving system performance using, for example SSM in combination with 3Es, can be improved by method improvements such as indicator selection and data collection. This thesis thus attempts to apply SSM in combination with 3Es as the indication of system performance for system sustainability evaluation.

General System Measurements

General system attributes suit all systems regardless of system scale or context. Among such attributes, sustainability has been concerned to be relevant to system structure following thermodynamic view, under which entropy is a popular measure for structure. Besides, while energy is widely recognised as the fundamental support to life, we introduce a measure of energy accumulation from the system, emergy. Lastly, since general systems contain stakeholders and purposeful functions of the system, the origin of the purposes or system objectives, values, is reviewed. Thus, different from indicators such as CO2 emission for which systems without CO2 emission would not suit, entropy, emergy, and value are measures that are suitable for any system.

2.2.5 Entropy

Before clarifying what entropy is, being a term originated in thermodynamics, it can be easier to understand what role it plays during transformation in a system. Within a system, when the discharge of gradient of free energy occurs, two things can happen, either work is done or the work is not done. What is more observable is when work is done, free energy is being replaced by another form of free energy. It is being compensated. In the other case, it is uncompensated. When work is not done but free energy gradient is still discharged, free energy turns into for instance, heat that levels up the temperature of the system, where no further change is brought to the system. In the real world, the discharge of free energy gradient cannot be fully compensated. Entropy hence is the part of free energy gradient that cannot be transformed to useful work(Sherman, 2018, p.91-128). On more general sense, Rudolf Clausius defines this ”equivalence value” of heat (as heat over temperature) that was later called ”the transformational content” of a body to entropy, using the wording similar to energy, noting in S(Clausius, 1865). For a closed system that contains only reversible processes, the Clausius equality holds as $\oint \frac{\delta Q}{T} = 0$ where its line integral is path independent, entropy is given as:

$$dS = \frac{dQ}{T} \tag{2.1}$$

where Q is the heat expressed in the form of energy, and T is the temperature at the uniform state of system. Throughout time, many interpretations have been attached for entropy due to different formation of the concept. It can refer to the direction of spontaneous changes in a system, and since the increase of entropy is naturally irreversible some also say it is ”an arrow of time” (Ben-Naim, 2008). Developing from molecule systems, it is a measure of chaos (Wehrl, 1978). Deciphering entropy for information and signals, it can be the uncertainty in information transmission (Gu, 2017). On the wider scope for the society and life, it is measure of disorder or disorganisation that may trigger life and death (Sherman, 2018). That is to say, the spontaneous processes in life brings about the world today.

Most physical properties such as energy and heat are tangible or observable or can be measured by tangible quantities. For example heat is measured in temperatures. Unlike them, entropy has gone through massive debate to be accepted as a physical property since itself is intangible and cannot be directly measured (Ben-Naim, 2010, p.1-6). It is only the phenomena of entropy change and the natural tendencies of the spontaneous changes that can be widely observed at both macro and micro scopes. Without other disturbances, heat transfers from hot to cold body until the temperatures are equivalent; gas spontaneously fills the space it is given and ends up evenly distributed; and the Brownian movement of molecules in a liquid that eventually reaches a status of dynamic stability when the density gradient disappears (Ben-Naim, 2010, Sherman, 2018). In deed the status of equilibrium sets some ending point to the changes and following the Zeroth Law that equilibrium status is transmissive, spontaneous activities are thought to be following some directions of the gradient and hold some condition of reaching to a stabilised status (Ben-Naim, 2010). As the Le Chatelier’s principle suggest when a closed system arrives at equilibrium where conditions are stable to time, thermal free energy in the system is reduced to zero which no more thermal gradient exists (Sherman, 2018). Characterising the tendencies of the changes, Clausius declared two laws of thermodynamics and another that is sometimes called the third (Sherman, 2018, p.91-128):

1. The energy of the universe is constant;

2. The entropy of the universe tends to a maximum.
3. Entropy of a pure substance is zero at absolute zero.

Thus, focused to the second law, there are different ways of formation. Entropy and its properties are described in different scopes of problem and base theories. Boltzmann entropy for probability and Shannon entropy of information are the two most out-breaking kinds.

Relating entropy with the "number of states of the system"(Ben-Naim, 2010, p.6-10), Ludwig Boltzmann formulated measurement for entropy from the perspective of probability of using W to note the probability of cases, written in:

$$S = k_B \log W$$

,where k_B is the Boltzmann constant that equals to $1.380649 * 10^2 3J/K$ and the base for log can take different values that determine different units for entropy. Before quantum mechanics, describing the tendency of spontaneous processes using the term "most likely to happen" brought great challenge to understand (Ben-Naim, 2008). Developed on Boltzmann entropy, Gibbs entropy holds for reversible systems written as(Bein, 2006),

$$S = -k_B * \sum iP_i logP_i.$$

Introducing possibilities into entropy, Shannon entropy describes the average level of information carried by a random variable (Shannon, 1948). For a random variable P, p_i is the probability that it is going to happen, Shannon entropy, using the letter H, is written as,

$$H = H(P_1, P_2, ..., P_n) = -\sum_{i=1}^{n} p_i logp_i \tag{2.2}$$

, where the information sample of probabilities $\sum_{i=1}^{n} p_i = 1$ (Shannon, 1948, Bromiley et al., 2004). Here, in this thesis, we apply the letter S indifferently for all types of entropy. In linking with information, Shannon entropy can be regarded as a measure for signalling (Bein, 2006, Gray, 2011). The creation of disorder and order are both reflected in a dynamic sense where Prigogine (1989) suggest that, for a system state far from equilibrium, entropy can be the dynamic indication that can be deterministic in the long term or over macro scale systems. Thus, linking with the society, the concept of dissipative structure is demonstrated with the exchange of entropy.

Dissipative Structure

The dissipative system, first introduced by I. Prigogine, is used to explain the linkages and organisation within an open system that is far from equilibrium which is dynamic and continuously exchange energy and matter with the surrounding environment (Prigogine, 1980, p.77-102). Concluded by Yin (2016), dissipative structure of featured by continuously measured entropy production rate within the system and its exchanges rate with the surrounding environment over time. The author also noted the understanding to dissipative structure can be the energy structure inheriting the organisation of matter and the matter structure resulting from the organisation of energy flow. It is an illustration to the mutual interactive space structures of mass and energy. An prerequisite that describes dissipative structure is the system need to be far from equilibrium, not under nor near. According to Jantsch (1980), far from equilibrium is the source of dynamic orderliness and order is destroyed in systems near or under equilibrium. As thermodynamics develops and the recognition to the structural influence of information, an dissipative system is an open system that is far from equilibrium with fluctuant and continuous exchange of materials, energy, and information with the outer environment Yin (2016). Here, we mainly focus on macro or mesoscopic systems as violations to the second law is naturally observed in small infinite systems on short time scales whose sustainability need to be defined differently (Wang et al., 2002).

By definition of entropy production, the entropy change over the system boundary is (Purvis et al., 2019, Weber et al., 1989),

$$\frac{dS}{dt} = \frac{d_iS}{dt} + \frac{d_eS}{dt} \tag{2.3}$$

, where the total change of entropy for the system dS is constituted of two parts, the entropy production within the system S_i and the entropy exchanged with the outer environment S_e. This suits the exchange of entropy over general systems in the nature where ecosystem participants of producers, consumers, and regenerators all exists in the system (Weber et al., 1989).

As the second law of thermodynamics states, the internal entropy of an isolated system, under the natural state, naturally and continuously increases (Ott and Boerio-Goates, 2000) and thus, using t as the time,

$$\frac{d_iS}{dt} > 0$$

,would always hold while the sign for $\frac{d_eS}{dt}$ can be positive, zero, or negative (Jrgensen et al., 2000). Dissipative system as an open system with exchange of mass and energy over the boundary, the entropy exchange in the physical form can be written as (Ben-Naim, 2008),

$$\frac{dS}{dt} = \frac{d_eS}{dt} + \frac{d_iS}{dt} = \frac{dQ}{T} + \frac{d_eS_m}{dt} + \frac{d_iS}{dt}$$

, where entropy changes by energy differences follow equation 2.1 within which T is the temperature at the state of exchange and S_m notes the entropy associated with matter exchange.

To reach system stability under some orders created by nonequilibrium inevitably requires the dissipation of entropy from the inner system to be balanced by the energy and mass brought in from the external environment. Thus, if the system reaches dynamic equilibrium at ecosystem climax, $dS = 0$, where internal production of entropy is balanced by the external entropy flow (Zhang et al., 2006). To note, when $\frac{dS}{dt} > 0$, we are at a state of consuming the materials and energy from the ecosystem and possibly causing degradation in the ecosystem structure. As Prigogine (1980, p.77-102) notes, the steady state is arrived, by neglecting the micro reversible processes within the system, when system attributes remain at relevantly constant level and the fluctuations or oscillations within the system would only rotate around the steady state not changing its core attributes, which include the function of the system, the space-time structure of the system.

Within variety of explanations, Nicolis and Prigogine (1977) attributes the successive dissipation of thermodynamic entropy to the outer environment as the phenomena of self-organisation in complex open structures. By indicating self-organisation, Prigogine (1989) further illustrated that a dissipative system presents the dynamic feature of having "attractors" that represents the objectives of the chaotic complex system given in different dimensions. These attractors with objectives that are directive to the chaotic system are sensitive to initial conditions and are not regionally consecutive, suggesting the spatio difference of values in the chaotic system. He also concluded, as the feature of dissipative system, that dissipative systems inherit historical system conditions connecting the past and future (Prigogine, 1980, p.103-130). Yin (2016) further notes, it is a system that holds self-organisation, in the form of certain stability to its system time-space structure, and the the tendency of evolution as interactions with the external environment continues.

2.2.6 Emergy

System metabolism suggest the inclusion of energy across all beings and processes. Energy, illustrating the current work contained in a product or process has been a good reflection of the function role of population and the operational status of the ecosystem (Odum, 1971, p.103). Besides, exergy has been used as the maximum amount of work that may be obtained from a system by bringing it into equilibrium with its environment (Dincer and Cengel, 2001). However, different from energy and exergy, emergy, generally noted as Em, is used to exhibit the amount of work that needs to be done to produce products or services (Odum, 1996).

Emergy is also defined as the total available energy already used, both directly and indirectly, to create a service or product, noting to be the "memory" of energy (Odum, 1971, p.121-124). From the energy perspective, emergy for the same product can be different if different production pathways are taken (Brown and Ulgiati, 2004). Emergy analysis attributes all emergy inputs to Earth into three sources, the sun, the tide, and geological deep energy and defines solar emjoules, whose unit is noted as $solseJ$, as the basic unit for emergy, assuming $1sol \quad seJ = 1seJ = 1J$. Thus, the input emergy for solar, tide, and geological deep energy are all equivalent to $1seJ$ (Odum, 1996). Turning all sources into the collective thermodynamic unit can be regarded as a treatment to not bias towards human values such as using monetary units for natural capitals (Brown and Ulgiati, 2004).

The estimation of emergy of a product is based on the thermodynamic foundations of energy and materials used during its production which must require detailed mechanism of how it is produced. It inevitably requires the analysis for the detailed emergy flows during the transformation, constructing a network similar to emergy inventory. According to Siche et al. (2008), emergy analysis starts from the identification of all material and energy inflow into the initial system. To note, this suggest that emergy analysis, too, requires a clear system boundary that separates the external environment from the system. Principally, the inflows need to be traced until all are expressed in the form of solar emergy, the treatment can be simplified by using a conversion factor, transformity, estimate the emergy inflow of materials and services that are intermediate products between the solar energy and the production system. Noting as Tr, it is defined by the ratio of product emergy to its energy, whose unit is seJ/J, and can also be regarded as a factor indicating the quality of a product (Brown and Ulgiati, 2004). It follows the expression of,

$$E * Tr = Em$$

, where E is the energy of the product.

According to Brown and Ulgiati (2004), there are also several sustainability indicators developed using emergy measures. Percent renewable is defined by the emergy of total renewable sources to total emergy inflows. Emergy yield ratio is the total output emergy over total emergy of non-renewable inflows. Environmental loading ratio is the overall non-renewable and slowly renewable emergy inflows over renewable inflows. And emergy sustainability index is the emergy yield ratio over environmental loading ratio. Many studies have been done using such indicators and have found some implementations of sustainability to be problematic with the emergy benchmarks (Brown and Ulgiati, 2002, Zvolinschi et al., 2007). In the same time, other decision-making assessments could also follow emergy analysis to indicate sustainability such as developing new environmental factor or LCA (Ingwersen, 2011, Lior and Zhang, 2007). As Ingwersen (2011) concludes, emergy analysis could also be appreciated as a perspective for constructing sustainability index since sustainability eventually is a balance between global input and output of the biosphere.

2.2.7 Value

Value has always discussed on a philosophical domain. Here, we focus on the issue of values that step across social-environmental interface without reaching to ethical or moral cognition domains. The most commonly seen form of value, or the valuation system, is the capitalism value (Marx, 1867). Under the massive category of capitalism, it is noted that values are associated with production in the market and distribution of products (Garegnani, 1984). Thus, it is presented for us the market pricing of labour, machinery, products, and the higher pricing of rare natural resources. Furthermore, as social cognitions develop, the origins of profits can be found in social product, technology, and labour, which through market exchanges, the surpluses of values on top of necessary consumption accumulate even more (Garegnani, 2018). While many criticisms focus on illustration to the product relationship for determining capital profits, wide consent is seen for the composition of capitals. Labour, apparently, is not the only determinant to market pricing. However, we need to realise that capital pricing of valuation is full of human preferences, which are problematic in sustainability relations.

Mulia et al. (2016) introduces Kant's Categorical Imperative to state there are values and dignity beyond capitalism valuation system. Under such notion, it strikes the necessity to recognise the value of nature which Marx has illustrated that capitalists heavily depend on free services of nature, not only in the form of resource extraction but focused to the services by water, sun, and soil (Huber, 2017). This is often named with nature's services (Gretchen C. Daily, 1997). Recognising that the functional value of nature could eventually enter human market exchange, many of the services of the ecosystem are capitalised as types of resources (de Groot et al., 2012). Again, we realise, although it could be unreasonable to do so, such value of nature's services could be presented based on the appreciation of human. Aside from functional value, nature's services also provide instrumental values of aesthetics such as landscape and scenery (Loft et al., 2015). However, as Daily et al. (2000) states, beyond the instrumental values of the ecosystems, the nature holds intrinsic value can in its nature could not be capitalised. It is being describes as the existence of a natural being would hold its intrinsic value

(Bowman et al., 2010). The intrinsic value is believed to be fully independent from ecosystem's services (Washington, 2013, p.39). Some also emphasise that we have not recognised the importance of the intrinsic value due to limited cognition (Jax et al., 2013). And thus, respect is called for the independence of evert biome (Kumar, 2012).

Beside the instructional values and the intrinsic value of nature, there are also cultural values that are associated with the nature. Inherent value from history is, indeed, critical for human social well-being (Loft et al., 2015, McKenzie, 2004). Thus, under the current social-environmental interface, instructional value and cultural value could be included under the human valuation system, however, the intrinsic value may stand on another dimension that cannot be judged. Hence, we see that with respect to the intrinsic values of nature, strong sustainability sets the lower bound for them as non-declining.

2.3 Sustainability and Sustainability Evaluation

2.3.1 Towards Definitions

Sustainability and Sustainable Development

Table 2.7 shows a collective group of definitions to sustainability and its synonyms.

The lexicographical definitions supported the development of later definitions (Gruen et al., 2008). It implies some attributes should be measured and defines the preferred state of the attributes: maintaining desirable or undesirable attributes within some range. Dealing with undesirable attributes, many sustainability assessment and evaluation studies regard successful reduction of undesirable processes or products as better sustainability (Emrouznejad and Yang, 2016, Li et al., 2013, Salazar-Ordonez et al., 2013, Commission, 2019*b*). For desirable attributes, the temporal and spacial benchmark of suitable conditions to maintain them are studied (Costanza and Patten, 1995, Greenhalgh et al., 2008).

The system definition suggests a fundamental presence of system sustainability where later definitions could be regarded as developed on this basis. It demonstrates sustainability from the perspective of attributes in system where contextual demonstration of a sustainable state of system matters (Speelman et al., 2007). System performance attributes such as ”continuation”, ”institutionalisation”, ”resilience”, ”stability”, ”persistence”, ”maintenance” (Gruen et al., 2008), can be some explicit sustainability attributes on different systems.

Compared to these definitions, SD focus more on the preferred state of the Earth from the perspective of human. It ultimately constructs human culture and

Table 2.7 Definitions of sustainability and sustainable development

	Definition	**Source**
Lexicographical:		
Sustainability	the quality of being sustainable	Oxford English Dictionary (OED Online, 2020*a*)
Sustainable	”capable of being endured or borne; capable of being maintained or continued at a certain rate or level”	Oxford English Dictionary (2020*b*)
System Sustainability:		
	”attributes stay within an acceptable range of states”	Roger (2000)
In applications:		
Sustainability	continuous resource extraction from the nature	Freerk Wiersum (1995) Gretchen C. Daily (1997)
	the preservation for the ecosystem structure	Pauly and Christensen (1995)
	avoiding rapid changes in the structure	Resnick and Hall (1998)
	state within the planet boundary	Tilman et al. (2002) Rockstrm et al. (2009) Hou and Al-Tabbaa (2014)
	the capability of being able to continuously consume natural resources to conduct actions creating product that may trigger imbalance to the regional ecosystem	Sheehan et al. (2003)
	reduced resource use, environmental damages, or human activities	Glavi and Lukman (2007) Gagliano et al. (2015) Commission (2019*b*)
	the state of no depletion of capitals in business liquidation	Dresner (2008, p.3-4)
	simultaneous good performance of indicators on social, economic dimensions	Welch and Venkateswaran (2009)
	the capability of producing steady continuous outputs from an institution	Sterling (2010)
	system state that constantly provide provisioning, regulating, and cultural services	Mononen et al. (2016)
	a state of balance between respecting social-environment relationships and pursuing organisation profits	Papoutsi and Sodhi (2020)
SD	”the development that meets the needs of the present without compromising the ability of future generations to meet their needs”	Brundtland et al. (1987)
	guarantee the well-being for the future generation under ecological constraints	McMahon and Mrozek (1997)
	understanding why inputs are provided to maintain the system and create consequences	Santillo (2007)

humanity (Kashima, 2020). SD puts the sustainable state of human in the centre and could be regarded as applying the root definition of sustainability to the systems that we live in. It is recognised that challenges have arose to traditional theories on infinite expansion of economy and political growth and that further developing the human society requires respecting the limitations that social development may face (Vos, 2007).

Some definitions to SD understands it as a unified term. SD is defined as a dynamic process that seeks for maintaining continuous production while meeting some expectations (Freerk Wiersum, 1995). Contributions to the society and the nature are expected to be simultaneous. Thus, SD objectives should alter from time to time by regions and indicators should also suit (Xu et al., 2020, Tsalis et al., 2020, Kwatra et al., 2020). Global sustainability can be better indicated with the integration of technological improvements and the progress of development (Batie and Healy, 1980). The development of human well-being and its capability should be both guaranteed. Some definitions regard SD as a combination of two terms with different context. To sustain relates to the natural environment and to develop relates to society and economy (Parris and Kates, 2003). Often, the part of conditions and materials that are supportive to human activities are named ”natural resources” which are transformed into economic capital units (Spiertz and Ewert, 2009). This thesis also applies this definition to resources. Through the discourse of ”development”, the resources needed by the society, the capitals, and justice become more human focused pursuits of sustainability (Vallance et al., 2011).

Some common human values are reached for SD. Over time, the human society for the future generations should at least remain as well of as the current serving for the accessibility to resources and preserving value of the nature (Tietenberg and Lewis, 2018). To note, seemingly a metaphor, human plays the decisive role in setting the explicit restrictions for preserving resources and values. Another consensus is that SD and sustainability is an ubiquitous objective, aspect, culture, or on whatever level of impact it holds that need to be observed comprehensively with the integrity of various aspects (Vos, 2007). By separating the human society from the natural environment, society is regarded as a sub-system nested in the natural environment with massive amount of and frequent interactions (McKenzie, 2004). If the nature is regarded as a bigger system, society is a subsystem of the nature that has been attached with additional objectives for sustainability of the minor system from the environment.

Often regarded as a new social definition, SD is frequently used in mix with sustainability as it may have suggested the same context in empirical researches. Similar to sustainability, SD is also abusively applied to different agendas by almost everyone (Schwarz-Herion and Omran, 2015, p.3-7). Becker (2012) defines ”modern sustainability” as the ability of continuance that initiates human behaviours and life relating to this generation, the future generation and the nature. Apparent shadowing to SD can be observed. Egilmez et al. (2013), based on the manufacturing sector, believes that better performance of SD indicators contribute to the global sustainability. Similarly using SD to restrict the complexity of system sustainability, Franks et al. (2011) claims that principles for SD originate from resource and social sustainability and Moran et al. (2008) proposes that unified measurement of SD indicators contributes global sustainability. In the process of decision-making, since valuation of human capitals is done more explicitly, global sustainability is more heavily valued in financial units of both capitals (Baumol and Willig, 1981) or social well-being and cultural pursuits (Hart and Milstein, 2003). However, to note, a general concern for sustainability, regardless of the context, is that it is only a characteristics of an imaginary preferred picture rather than definition (Costanza and Patten, 1995), containing implicit relations.

To this point, we notice, currently, when majority of sustainability evaluations done for the social-environmental relations, the expectations for sustainable objectives originate from SD, rather than raw definitions where SD is implicit and for global context. For example, McMahon and Mrozek (1997) defines sustainability given the context of macro economy as ”the ability to maintain or to increase well-being over time”. Linguistically comparing with the basic definition, well-being substitutes the position of the genuine word ”attributes”, attaching expectations from the researchers or industry planners. For more general systems including the energy sector, Lior and Zhang (2007) demonstrates sustainability from the perspective of thermodynamics using system performance measures. The foundation for reductionism is also set that one or more indicators are believed to be serving for better sustainability when they are reduced (Gonzalez-Garcia et al., 2018). From the opposite perspective, how well the reduction for some reluctant processes is achieved and how well some desirable process is maintained are popular questions to be answered to conceptualise sustainability (Pope et al., 2004).

The root definition of using system attributes as a reflection of sustainability leads to the result that the necessary conditions leading to better sustainability are derived instead of the sufficient conditions of realising sustainability. Apparent enough, the later can be impractical. In the mean time, as the root definition has not defined a context that sustainability suits for, it is not at all clarified that attaching a context to sustainability means applying the root definition of sustainability to a certain sub-system. In other words, certain measurements need to be drawn to locate to a sub-system. For example, the sustainability of an industry can be defined as the time that the price the corporates needed to enter a new industry remain stable (Panzar and Willig, 1977, Baumol and Willig, 1981). System sustainability is reflected by a single attribute. Applying to the Earth system, a more local system in the cosmic, typical terms explaining the concerns for such limitation attached by the two foundations include ”environmental corridor”, and the ”planet boundary” associating with better clarification to what aspect or quantity to sustain(Adedoyin et al., 2020, Rockstrm et al., 2009). However, different understandings are drawn for the relationships leading to abundant statements around planet sustainability. Le Blanc (2015) concludes that sustainability of the planet is about different mapping of the overall system of the planet Earth and its sub-systems including the ecosystems, the social systems, and their relationships.

Understanding that, currently, sustainability is mainly concerned for key influences over the plant Earth, relevant to human living, we define in this thesis that sustainability indicates *system sustainability for systems on the Earth within which some attributes should be clarified to be maintained within certain range*. In association with the components of general systems (Chapter 2), all systems on Earth to be studied for sustainability are expected to hold material and energy basis.

From this perspective, many attributes have been claimed to be able to reflect sustainability. Allen and Hoekstra (1993) notices that sustainability is not mere human concept but rather a state of system with spatiotemporal features. Maintaining the key spatiotemporal features of a system could be regarded as reaching sustainability. Smith et al. (2011) emphasises that since the state of true sustainability is not yet known, it would be more valuable, regardless of environmental, economic, or societal interfaces, to focus on the changes of and contributions to the attributes. It has been long understood that sustainability would never be reached by only considering human livings and benefits, as Becker (2012) notes, sustainability requires the localisation of all beings and it is certain that individual would not be able to reach it. Hence, we notice that sustainability could be the maintenance of certain attributes while focusing to certain system and eventually, such effort may require collective contribution of many supportive components aside from the system itself.

Issues in Definition

As more insights are developed from the Brundtland report definition, it is gradually recognised that SD is a complex term that actually not even the Brundtland report definition have defined clearly of what it is (Schwarz-Herion and Omran, 2015, p.3-7). Due to the limited features in its definition, SD is being criticised of being fuzzily defined and sometimes with exhausting paradigms (Phillis and Andriantiatsaholiniaina, 2001, Blhdorn, 2016). We recognise that understanding SD as one term or the compound of two terms places different priority to human economic and social activities. As our culture develop towards the harmony of social-environmental relationships, the integration of planet sustainability and human development may lead to a state of the system, planet Earth, featured under the root definition of sustainability. As Ll (1991) concludes, recognising the influences from social factors, SD would eventually arrive at two interpretations of either suggesting sustaining growth, indicating development, or achieving ecological and/or social sustainability. Here, it can be recognised that it may not be the problem that SD is unclearly defined, but rather that Brundtland report has provided a more clear statement of applying sustainability of a grand human centred system. It identifies three key sub-systems that are critical to human and some objectives that human shall target. However, as Zeng et al. (2020) points out, when the objectives of SD are embedded to the natural environment, although the implemented approaches ease the damage to the natural environment, they cannot hinder artificial destruction to the nature. Therefore, by clarifying some necessary conditions contributing to better global sustainability, the concept of SD acts as a clearer implicit illustration that can be related to the definition of system sustainability, that is to maintain the system attributes of the planet. Such perceptions are in fact already widely embedded but not often displayed by researchers. A typical example is that the three pillars of sustainability, the key sub-systems, need to be simultaneously under good performance to be reaching SD (Jeurissen, 2000*b*) and more explicitly, Schwarz-Herion and Omran (2015, p.3-7) notes that SD is the stability of the three sustainability pillars.

To establish a clear ground for perceiving SD, the following five aspects that features SD can be concluded (Moore et al., 2017) : 1) a defined period of time is given for the context; 2) the system, including the programs, processes, or implementations of strategies, is continuously delivered in the time of being; 3) the freedom for individual behaviours is allowed so that some actions can be unsustainable; 4) the changes in the system actions and the individual behaviours may evolve or adapt; and 5) the system continuously produces benefits for the system and/or the individuals. In this way, SD covers the problem of time scale of long or short, spacial problem of global or regional, and the relations within the system and its linkage to the outer aspects. More importantly, as natural resources become exhausted and ecosystem is convinced to be a basic unit of environment constitution, SD, aside from the process that used to be of focus, also lies in social and ecological sustainability (Ll, 1991). SD mainly systemically addresses the concerns for aggregating environmental sustainability with social and cultural parts (Elkington, 1998). Consequently, SD is genuinely perceived as a multi-dimensional concept that emphasises integration and dynamic balance among the three key featured sub-systems of the Earth, economic, social and environmental aspects, to ensure inter-generational and intragenerational equity (Kwatra et al., 2020) . In measurement, economic sustainability takes the advantage of being able to be directly measured using financial indicators (Singh, 2006). Unlike economic aspect, according to McKenzie (2004), social sustainability is defined as a life-enhancing condition and the process within communities that can achieve that condition. It targets at creating healthy and liveable communities that are equitable, diverse, connected, democratic, and provide good quality life through formal and informal processes, systems, structures, and relationships. Consequently, to what extent, on the scale of time and space, to sustain and to develop await to be answered by researchers taking care of both the natural environment and social development.

Although SD identifies three key pillars, its insufficiency towards global sustainability is also widely discussed. The three pillars indifferently provide a framework of sustainability. However, as the processes concerned within the three subsystems are complicated, while on the one hand some system features are lost in using the three independent aspects, on the other hand, it often need to set different criteria for applying different indexes for these processes (stergaard et al., 2020). By applying sustainability to human, SD requires achieving a great mixture of objectives for human benefits in nearly all aspects and meanwhile, protecting the nature. Pursuing a consecutive paradigm for SD and respecting the being of all systems, the mixture of multiple objectives leads to the inquiry of whether it is sustainability or SD that is pursued (Eizenberg and Jabareen, 2017). As more attention is given to extended aspects of the natural environment, it becomes more challenging to hold a consistent view of SD. Also, as the social-natural relationships fabricate, while the three sub-systems may still stand as the most important subsystems, there are other systems that may need to be considered for SD, as a context based concept. Giddings et al. (2002) concludes from the objectives of global sustainability and SD that human society never hold a sole stance in setting what is sustainable and what is not, especially in social and cultural ideologies. These include the targets of feminism, equality, and justice, which differ from time to time (Giddings et al., 2002, Zafra-Calvo et al., 2020, Tsalis et al., 2020). Attributing that alteration of the social and cultural notions to political and social issues (Giddings et al., 2002), to more comprehensively identify the key subsystems, Reed (2008) demonstrates determinative role that stakeholders play to link the system and identify the key attributes from social aspects and the artificially perceived aspects of the nature.

Anthropocentric sustainability mainly faces challenges to truly achieve global sustainability from human. As the understanding to the relationships between human and the environment fabricate, key unsustainable problems to be dealt with alter. Very often, this ubiquitous concept of sustainability is being criticised with unclear statement for what, who, when, where, and how, and concerns arose in the sufficiency of reflection (Scoones et al., 2020, Papoutsi and Sodhi, 2020, Vadn et al., 2020). According to McMahon and Mrozek (1997), sustainability can be contextualised as a problem of determining how largely the economic system relates to the earth system, following the physical hierarchy of the economic system, the Earth, and the Solar system. Following the time line, sustainability was adopted for sustainable economy in the nineteenth century; after 1800, aesthetic aspects are included (Schwarz-Herion and Omran, 2015, p.3-7); and currently, the impact from the natural environment have become greater than ever (Toya and Skidmore, 2007). Apparently, cognitions to the features of social-environmental relationship are different on global and regional scales and as Kates et al. (2001) points out, the spatio scale of the problem studied and the changes in the world are two main directions set for continuously re-thinking the pathway for human development. Above that, unlike the system definition of sustainability, "sustainability" with the planet context is not clearly defined. Although illustrated using the term definition, most are likely to be statements around global sustainability. Systems approach to sustainability has not been following any systematic rigour, resulting in confounded and underspecified recommendations (Porter and Crdoba, 2009). Concluding from wide empirical studies, old sustainability objectives may fail for preserving the current status and thus both new and old objectives need to alter in accordance to new environmental and social challenges (Barbier and Burgess, 2020). Since, sustainability is a system feature that is directed by a collective value aggregating different values (Hart and Milstein, 2003), anthropocentric sustainability fails to be sustainable on the strategic level as human value singularly leads the collective value.

Recognising that regardless of values of all sources, economy, politics, or the nature, all impacts from all actions would eventually result in the nature (Kates et al., 2001), *true sustainability*, of the Earth, becomes the final objective to be achieved through re-demonstrating the development of human society (Vos, 2007). Sustainability, still with the planet context, thus become closer to the system definition and the perceptions to social-environmental relationships become more systemic and comprehensive with the collective cosmocentric value of a sustainable planet that is more conservative in balancing the social and environmental pursuits. In its composition, economy, society are all sub-systems of the nature. Becker (2012, p.9-11) concludes for modern sustainability, it is an orientation, a norm towards what need to be strived about the fundamental social-natural relationships. Using more neutral words, Scoones et al. (2020) describes sustainability as a process of transformation that the construction of the continuous actions guided by cognition to the social-environmental relationship is systemic and stable. Setting a baseline, a necessary condition to sustainability is having a sustainable growth path being dynamically efficient (Stavins et al., 2003). The lines between sustainable actions, improving actions, and unsustainable actions are more clearly drawn given the concept. On the belief that "life is fundamentally one", sustainability requires renewable or regenerative consumption and production (Smith et al., 2011). Different from such sustainable actions, improvement of technology efficiencies for consuming fossil fuels beyond its regeneration are actions of better sustainability not realising it, which still lies in the range of "false sustainability". Similarly, urban sustainability is the balance between urban life and the wild life that eventually forms a regenerative society (Marvuglia et al., 2020). Eventually, a whole system design that illustrates the state of the system on different scales would assist reflecting true sustainability(Markevich, 2009).

Sustainability Evaluation

Sustainability evaluation differs from the simple combination of the objectives ”sustainability” with the process ”evaluation”. Over the time, sustainability evaluation is bound with many descriptives for protocol for the evaluation process, understandings to sustainability objectives, and determination of preferences in sustainability relations and the optimality. This section hence reviews the definition of sustainability evaluation and the features of sustainability objectives and preferences in evaluation that is also scattered in the literatures of nearly all fields of study and all types of articles.

Putting the word ”sustainability” in front of evaluation, sustainability evaluation can be defined following evaluation process and the understandings to sustainability. We would define in this thesis that sustainability evaluation based on our definition is a decision-making tool for DMs to understand the performance through values and behaviours of system attributes that are maintained over time. In other words, it is a form of evaluation that contains objectives linking with sustainability. This is a comprehensive illustration with the following definitions to sustainability evaluation. Allen and Hoekstra (1993) describes sustainability evaluation as understanding the performance of sustainability related behaviours and policies, in which ”sustainability” is determined by the evaluation objectives held such as being environmentally and socially friendly. Outcomes, efficiency of resource use, and impacts are important dimensions mentioned. More from the decision-making point of view, sustainability evaluation is a general system evaluation tool used by DMs to achieve SD and preferably under an optimal approach (Devuyst, 2001, Verheem, 2002). The values in sustainability evaluation needs to be understood from different actors of the target system as they place values on the value tree on the paradigm of sustainability (Karger and Hennings, 2009). Koziolek (2011) further characterises sustainability evaluation process as understanding the current system status and the maintenance and evolution potentials of such status over time. To emphasise, DMs are especially important in sustainability evaluation. As previously reviewed, we recognise that KSs construct the sustainability relations of the system and DMs, who are also part of the KSs, determine the evaluation objectives and preferences in evaluation. In sustainability evaluation, DMs determine both.

Since DMs of sustainability evaluations are often human groups, we often find sustainability evaluation to be the evaluation of global sustainability. Given such context, sustainability evaluation is also popularly defined based on sustainable development targets or human benefit directed sustainability frameworks. Kates et al. (2001) defines sustainability evaluation as the decision-making tool for obtaining long-term financial support for a system. Verheem (2002) regards sustainability evaluation as identifying the optimal approaches that contribute to SD. As it is recognised that sustainability of human system require global basic support system such as a healthy natural environment and stable human population (Brown et al., 1987), Bottero et al. (2015) states that sustainability evaluation is the comprehensive decision-making process considering three macro aspects of sustainability, economic, social, and environmental. More recently, Campos-Guzmn et al. (2019) considers sustainability evaluation as the decision-making towards realising sustainability objectives using multi criteria decision-making tools so that different aspects of the natural world can be integrated. To note, noticing that a global sustainability context has been attached to system sustainability in the above definitions of sustainability evaluation, we recognise the importance of adapting evaluation objectives to the system evaluated.

Besides the differences in the definitions of sustainability evaluation, its synonyms present more variety. Due to the robust use between evaluation and assessment, sustainability evaluation is used in mix with ”sustainability assessment” (Kluczek, 2017) even though significant amount of empirical work has emphasised the quality of the sustainable decisions made from observations. Especially, when the use of LCA method is attached, the decision-making study is often called life cycle sustainability assessment instead of life cycle sustainability evaluation (Kloepffer, 2008, Egilmez et al., 2014). The mixed use has become so genuine that the two terms are more likely to be equivalent with each other. Another lexicographical replacement occurs for ”sustainability”. Besides ”sustainable development”, which replaces sustainability as a form of definition, ”environmental friendly”, ”green” are also some words indicating the evaluation concerns for social-environmental relationship (Deuble and de Dear, 2012, Li, 2013). Such replacement of wording for sustainability often differentiate according to industry.

2.3.2 Stakeholders and the Analysis

In the construction of sustainability relations, DMs indeed play the central role (Ayres et al., 2001), especially in clarifying the ethics and the targets to pursue. Moreover, sustainability relations, in its context, raise the concerns for the trade-offs, the externalities of human activity systems, and the imperfections in the treatment to nature’s services and their pricing. Reed (2008) points out that most environmental problems that we face today are caused by the participation of the stakeholders of human and other natures and hence, their needs need to be respected systematically. Especially with sustainability objectives attached, unlike past business processes, the participation of stakeholders is not explicit (Penzenstadler et al., 2013). For such an open system with many implicit players involved, the reflection to the interests and characteristics of stakeholders are often inadequate(Grimble and Wellard, 1997). Also, stakeholders in sustainability are often aware of the relevant issues and the goals but not all take the pressure and responsibility for the implementation of actions(Silva et al., 2019). Upon realising such features of sustainability issues, stakeholder analysis (SA) that classifies the key stakeholders, supports the understanding of the individual and institutional concerns serves as an excellent tool that assists the construction of sustainability relations and avoids marginalising some important interests of important stakeholder groups, especially in systems with environmental externalities(Grimble and Wellard, 1997, Prell et al., 2009).

Strong and Weak Stakeholder Influence in Sustainability

For example in the process of managing natural resources, the stakeholders cover all the players of the system from generating to policy management, and from the past time of being to the future, including small farmers, small resource users, the policy makers, planners and admins, the future generations and the wider society(Grimble and Wellard, 1997). These groups of people are categorised based on the interest or stake in a issue or system they share(Grimble and Wellard, 1997). Some define stakeholders as the people of a system that has the power to determine the realisation of the objectives(Penzenstadler et al., 2013).

Mainly dealing with different groups of human participants, stakeholders are classified in different ways. The criteria for classification include the power, influence, and legitimacy(Prell et al., 2009, Grimble and Wellard, 1997). For sustainability, the classification criteria is often set on the functional construction and influence to the system which can classify the stakeholders to the DMs, the key stakeholders (KSs), the primary stakeholder, the secondary stakeholders, and the interfered parties. DMs (DMs) in the issue or system holds the power to make decisions leading to productivity and structural changes of the system(Reid, 1981). Others may define DMs, in more modern way, as people who make decisions or participate in the decision-making process and are aware of the impact of the decisions made and this can lead to including the participants of the decision-making system and the decision-making tool itself(Wierzbicki and Wessels, 2000). DMs are especially important in the issue of system pursuing sustainability as the valuation process inevitably bias towards the values of DMs(Alarcon et al., 2010). DMs are also named as the active stakeholders that actively influence the system while another group is the passive stakeholders that are influenced by the system(Grimble and Wellard, 1997).

Sometimes containing DMs, KSs often contribute to the structure of the process or system. We also characterise KSs as the stakeholders, including the involved ones who may provide motivation, sources of control and expertise, and the influenced ones with sources of legitimation, whose interests are prioritised by the DMs considering their power, legitimacy, and urgency of stakeholder engagement (Vos, 2003). KSs includes the leaders, the members, and all the groups that guarantees the conduction of the process(Hanson et al., 2009). KSs can be determined in many ways. KSs can be the groups of players that mainly contribute to the complete operation of the system(Penzenstadler et al., 2013). Some also include parties that contribute to the transparency of the organisation(Epstein and Roy, 2003). When attempting to achieve the sustainability targets that can be determined by the DMs, natural components can become groups of KSs, too, having the valuation passively attached by other groups of KSs (Dale et al., 2019). More importantly, different from functional classification, KSs are more of groups of stakeholders that matches the pursuit of performance evaluation. It is the components of the KSs that forms a network of players that is capable fully of representing the efficiency, efficacy, and effectiveness of a system where other functional classification of stakeholders may fail to capture the players of some performance aspects(Mathur and others, 2007, Penzenstadler et al., 2013). Here, we follow the definition of KSs that without it, the functionality of the system would be affected Wang et al. (2014), De Luca et al. (2017), regardless of being human groups or not.

Divided by the contribution to the initial system, that is the system in real operation, stakeholders include primary stakeholders who have stronger devotion to the system and the secondary stakeholder who have weaker contribution. Wheeler and Sillanp (1997) defines primary stakeholders as the actors, regardless of the organisation boundary, having direct control of essential supports, including materials and services, crucial to the organisation. Garvare and Johansson (2010) states that secondary stakeholders are the players that indirectly provide essential support to the organisation while they may still be crucial to the valued products or services of the system so that they are more than parties of interest. In content, primary and, case sensitive, DMs and part of primary and secondary stakeholders can constitute KSs. However, it is important to consider not only the constitution of the system from stakeholder's perspective, but also the influences from the same perspective since, in practice, the derivation for even the primary stakeholders can be insufficient as some are kept silence but is critical and influences the measurements(Silva et al., 2019).

The influences of stakeholders are judged on the influences to the decision-making of the system. On the one hand, strong influence of the stakeholders is lead by strong level of engagement. This is often achieved through louder expression and the higher acceptance to the opinions from the stakeholders (Haddaway et al., 2017). On the other hand, aside from having the capability to clearly exhibit the pursuits, strong stakeholder also have more direct and tangible influences to the decisions made, let it be setting the strategy and objectives or the implementation of the objectives(Bohren et al., 2012). This means that the direct actors of the system are more likely to cause strong stakeholder influences. This thesis categorises such stakeholders with strong influences and are capable of clearly expressing their interests are categorised as *strong stakeholders*. Different from the active and direct strong influence, weak influence from stakeholders are silent in the expression of the pursuits and, commonly seen passively, a compensation is made to them from the system(Bohren et al., 2012). Mark and Shotland (1985) concludes this as a feature of stakeholders that the various objectives and information demanded by different stakeholder groups may exceed the original interest of the research system. Therefore, with the classic organisation boundary, treating the organisation as a system with input-output transformation, the strong and weak influences can come from within the organisation boundary and the surrounding environment where the organisation lies. As Figure. 2.6 shows, strong stakeholder influences often come from primary stakeholders and perhaps part of the secondary stakeholders while although some primary stakeholder may not strongly express their opinions or ideas, being respected by the system DMs and putting their pursuits into the objectives of system operation, eventually have strong influence to the system. Such stakeholders with strong influence but low voices to the system is collectively categorised as *weak stakeholders* in this thesis.

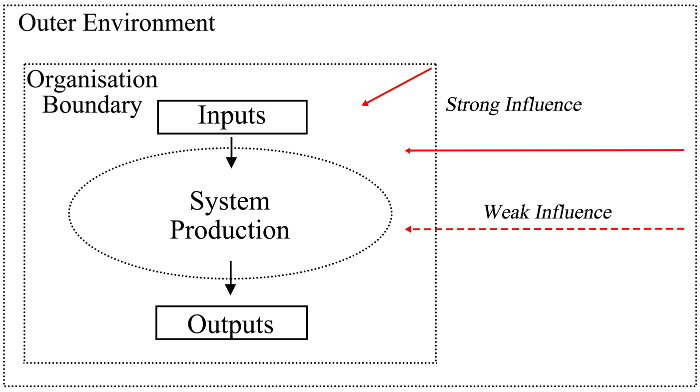


Figure 2.6 Types of Stakeholder Influence to System

The strong and weak influence of stakeholder can be different and become more complicated as the issue becomes dealing with open systems and expanding to global scale, the relations of the influences can change. In dealing with the intricate relations in sustainability, it is an open system that touches the global scale that needs to be pushed forward from actions to cultures. Since KSs determine the conduction of the system, they play the important role of having the power to initiate sustainability objectives and relevant implementations (Hanson et al., 2009). Hence, for global sustainability, primary and secondary stakeholder induces another division of stakeholders with weak influence, the interested parties(Garvare and Johansson, 2010). The expansion of the the interested groups develops into a cultural and structural support for sustainability, as a result of different stakeholder influences (de Bakker et al., 2019). The interested parties may develop into a state of containing more and more varieties of identities in the stakeholder community that prevents the pursuit of sustainability from failing(Hanson et al., 2009). It suggests, even within the social system, weak stakeholders would often hold interests opposite from the collective voices of the strong stakeholders, forming social sustainability relations. Including more aspects, sustainability is often divided into an issue of three dimensions, social, environmental, and economic(Savitz, 2013). With respect to the support of nature's services to all activities on the planet (Gretchen C. Daily, 1997), there is a clear division of social and environmental aspects. The social stakeholders are more concerned with different human groups and environmental stakeholder consider more adequately for other living beings. By only considering for one group of stakeholders may result in biased sustainability relations.

The production system of the organisation develops sustainability based on continuous demand and supply that forms the flow of consuming resources for the creation of products and values(Garvare and Johansson, 2010). Within organisational sustainability, the primary stakeholders are mainly different human groups that cause strong influence to the system and some secondary stakeholders who are also different human groups that indirectly interact with the organisation. As organisational sustainability expands to regional sustainability, external secondary stakeholders can influence the system, which may include the organic parts from the regional environment. However, there are differences in the level of expression for the benefits of these secondary stakeholders. The pursuits from social aspects are clearer and more frequently expressed by human actors while those of other actors in the natural environment are mainly expressed through the shadow impacts to the environment(Ferreira et al., 2020). The characteristics of such external secondary stakeholders are that they indeed in their physical nature cause strong influence to the performance of both the regional and organisational sustainability, but their wills lack representation from the perspective that doesn't bias towards the benefits of human actions, which are often the organisational profits. Haddaway et al. (2017) calls for the recognition to the systemic bias to the louder stakeholders through improvements in methods and hearing equally for the stakeholders that stay in silence. This is especially important when the silenced stakeholders hold strong influence.

Stakeholder Analysis

Stakeholder analysis (SA) is a method often used to understand the stakeholders and the strength of linkages among the stakeholders that underpin the system. It is a holistic approach or procedure to follow that constructs understandings to a system and knowing the impacts of changes to and from the system through identifying the key actors or stakeholders and assessing their interests (Grimble and Wellard, 1997), originating from the idea of comprehensively identifying the individuals, groups, and organisations with interest and potential influence to the system, including the policies, actions and processes that construct the system (Crosby, 1992, Walt, 1994). In its functions, it is a decision-making tool that is often used for policy setting, organisation management and development, especially in cases where contacts with intangible aspects, such as cultural connections, are strong and frequent (Brugha, 2000). Since SA is not a process that must be done by actors from the system (Prell et al., 2009), it needs to be noticed that SA, in its nature, is biased and influenced by transparency of information and the expression of stakeholders (Haddaway et al., 2017).

Observing the pursuit for sustainability from the perspectives in SA where all systems are physically open systems, there are two main questions to be dealt with in the complex issue of sustainability, the objectives or valuations and the boundary of the open system pursuing sustainability, in other words, the extend to which the system studied actually influences. SA first of all assists to understand the values in the system by recognising the differences in stakeholders linked with the studied process or system that some are obvious while some are not or may remain unrecognised and this complicate network of values formed by the stakeholders can be mainly classified into explicit and implicit objectives(Mathur and others, 2007, Reed, 2008). Gradually tracing the importance of the explicit and implicit objectives by identifying the key stakeholders among the actors, recognising that social and ecological system are open and complicate, the boundary that is usually partially explicit and implicit is constructed(Reed, 2008). In this way, a fundamental system model that has the potential to be sustainable is found for sustainability evaluation.

However, the special issue of sustainability also requires attention in some aspects in SA. While identifying the stakeholders in sustainability relations, although it is concluded that traditionally stakeholders claim a common interest among themselves (Mathur and others, 2007), not all actors in social and natural system can guarantee their voices are clearly heard as the actors can be human, the non-human living bodies, the non-living entities, and the future generations of all the groups so the identification for stakeholders and their importance to the preferences in the system need to be done by understanding the mutual influences among the groups of actors and how much the decision-making process is influenced(Reed, 2008). Yuan et al. (2010) further suggests that when sustainability is observed with performance measures, in combination with SA, the objectives in the system can be divided to three levels of a system of objectives that mainly comes with the stakeholders, the attributes of objectives with part of the priorities, and the importance level of each objective. Eventually, SA serves as a systemic tool for scanning the current and future system of the planet, let it be the global system or the regional systems, including the aspects of environmental planning and policy setting(Brugha, 2000), continuously integrating preferences with system compositions (Bal et al., 2013, Metcalfe, 2008)

Eventually, a big group of stakeholders with their importance to the evaluation objectives is formed following the framework used to identify the stakeholders and hence sub-groups of stakeholders may be formed. However, in time, the 3 steps are gradually developed better in detail. In the first step, aside it is proposed by other researchers that, along with stakeholders, the issues and strategic objectives and the dimensions of the problem can be identified, too(Metcalfe, 2008, Prell et al., 2009). While the initial stakeholders involved with the system are usually explicit, these issues, from the beginning can be implicit(Prell et al., 2009). Also, many other methods or frameworks suiting the research interests are applied in association to more comprehensively identify stakeholders including soft system methodology(Wang et al., 2014), social network analysis(Doloi, 2012), system entropy(Yuan et al., 2010), and frameworks including the dimensions of sustainability, the CATOWE and other more focused to the context(Atkinson et al., 1997, Wu et al., 2011, Brugha, 2000, Persson and Olander, 2004, Doloi, 2012, Bal et al., 2013). Wang et al. (2014) concludes four principle features of stakeholders including the time and context for identifying stakeholders, the formation of complex network of stakeholders, the dynamic change of roles of stakeholders, and a screen to the wills of stakeholders. The second step is, in other words, understanding the preferences of the stakeholders and how they are influencing the system preferences, which management manners and structures may be considered to capture the characteristics of all stakeholder groups(Prell et al., 2009). Many methods are taken to complete the process including mere discourse(Atkinson et al., 1997), a typology matrix(Mark and Shotland, 1985, Atkinson et al., 1997), degree of centralisation(Doloi, 2012) etc. Lastly, the stakeholders are prioritised according to their influences to the decisions made for both the current system and the potential future, forming a network of connections among stakeholders(Prell et al., 2009).

When applying SA to sustainability context, the need to the expand the current system on the temporal and spatio scales is clearly proposed. To conduct SA with sustainable objectives, the fundamental processes are upgraded with comprehensive analysis of gradually analysing four relations, the top-down control to the system, the instantiating generic and physical being, the bottom-up influence and feedback within and outside the system, and the iterated synergy of stakeholders(Penzenstadler et al., 2013). In this way, the stakeholders involved can be classified into dimensions of individual level containing human capitals, social sustainability for regional communities, environmental sustainability for the well-being of ecosystem services, and the technical sustainability for continuous evolution for human infrastructure(Penzenstadler et al., 2013). Hanson and Salmoni (2011) also calls for the cognition to the power that is indirectly caused by informing and educating the stakeholders of sustainability issues. Also, it is important to recognise that different from traditional decision-making, decision-making for sustainability, given the extending objectives and implicit system boundary, the strength of influence from the stakeholders can be described by their ability to take action when their needs are not met(Foley et al., 2011). Epstein and Roy (2003) points out that on principle, stakeholders deal with systemic aspects of the ethics, the governance, the transparency of system, the returns and operation of the system, the value of products and services, and external environmental issues.

Without specific context, Penzenstadler et al. (2013) states that SA process can be completed by identifying and analysing the relationships among the stakeholders following the four types of relations. Bal et al. (2013)concludes a 6-step protocol of SA for sustainability, including: identifying all key stakeholders, relating the stakeholders with sustainability objectives, prioritising the stakeholders, managing stakeholders, measuring performance of stakeholders and the management process, and actioning for sustainability and other objectives. Following similar routine, Dale et al. (2019) promotes another 6 relations to find stakeholders involved including defining the scope of the initial system, prioritising available indicators according, the establishment of targets both sustainable and not, determine the value of indicators, analysing the trends and trade-off, and identifying the practices that are good. The generic list of stakeholders include those affecting the system, those affected by the system, and those who may be interested to the system(Mathur and others, 2007, Dale et al., 2019). (Mathur and others, 2007) designs 12 questions to be asked for identifying stakeholders for assessing the sustainability of a system covering aspects based on the generic list of stakeholders including ownership, responsibility, profession, beneficiaries, representation, consumption, and linked authorities. Additional 5 aspects are adopted for sustainability objectives: the affected but silenced groups, the impacts and affections from the non-living units in the environment, the cultural associations, and the representatives to the fully voiceless groups such as the non-human entities and our future generations. Therefore, conducting SA for sustainability needs the cognition to the limitation how SA is done for input-output systems we perceive now. Concluding the above four processes, there are several aspects to be respected for doing SA for sustainability:

1. The generic stakeholders, naming the *initial stakeholders*;
2. The different types of relations linking with the initial stakeholders;
3. The silenced human entities linking with the initial stakeholders;
4. The non-human entities linking with the initial stakeholders;
5. The future generations of both human and non-human entities;
6. The objectives and importance of the objectives associated with the above stakeholders.

The first three aspects describe the operation of the initial system from a wider perspective that enables the identification to some stakeholders with weaker voices and weaker influence to the system based on the original boundary that can be easily and often explicitly perceived. The fourth aspect looks into the influence of human activities with the natural environment where more bodies of stakeholders, both human and non-human, may be affected by the influenced environment. Later, the representatives that give voice to the future generations and future status of the environment is concerned. Eventually, the objectives for the wider linkage of the stakeholders can be analysed. In this way, conducing SA for sustainability will end up with a bigger network of stakeholders that are formed across the space and are linked with each other in time. Among these stakeholders, a group a them with strong stakeholder influence are determined as key stakeholders that should hold unified consent to delivering and performing sustainability strategies, goals, and measures(Bal et al., 2013). All stakeholders consisting a wider system that is capable to sustain will form a new input-output system that is, in its scale, bigger than the original simple system.

2.3.3 Sustainability Evaluation Objectives

Given the complexity and wide coverage of sustainability, there are two main originations of sustainability objectives, societal guided objectives and system relation derived objectives. Sustainability objectives cover more than mere aspects that are understood by human, but also many aspects that are yet to be discovered (McRae et al., 2016). The origination for sustainable development goals (SDGs) defined by UN is believed to be the conflicts that arose during urbanisation as environmental and cultural changes are impetuses by human governments and hence the sustainable targets, after urbanisation have altered the living conditions to the current state we live in, are different for regions and communities, for mega cities and smaller towns (Norman, 2019, p.21).

The objectives derived based on system relations, calling them *system objectives* in this thesis, are appreciated as it provide clearer reference to how the objectives are proposed and the suitability to the context and scale of the system (Grunda et al., 2011). This subsection reviews the origination of the sustainability objectives from two aspects, the given goals from external institutions, mainly the SDGs by UN, and the other objectives.

Sustainable Development Goals

Sustainable development goals (SDGs) listed by the UN is probably the most commonly used reference of a framework and a series of indicators for sustainability. Established on top of the planet boundary framework (Norman, 2019, p.35), the SDGs are being regarded not only as a framework that can be adopted by all countries in settling critical problems on the aspects of people, prosperity, peace, and partnership, but also a big set of suggestions of indexes and indicators to different aspects (Norman, 2019, p.29). On a wide range of issues associating with human and planet well-being and leading a common agenda for 2030, 17 SDGs include removing poverty, no hunger, clean water and sanitation conditions, good marine condition, good on-land environment, good health and well-being, affordable and clean energy, quality education, gender equality, decent work and economic growth, industry innovation and infrastructure, reduced inequalities, sustainable cities and communities, responsible consumption and production, climate action, peace, justice and strong institutions, and good partnership for the targets (UNDESA, 2017). Noticing the changes in the perceptions towards the 17 goals and the changes of the world, it is more popularly regarded as an agenda that marches towards better sustainability whose content would alter and perfect from time to time (UNDESA, 2020). Water, air, and medical health problem are the direct issues caused by the COVID-19 pandemic (Mukherjee et al., 2020). Aside from that, increasing regional conflicts, the collapsed lifestyle for schooling students, lose of employment, and the creation of hunger and poverty are more jeopardising social aspects that heavily affect human well-being (UNDESA, 2020). It is anticipated to be including more aspects in the future as the valuation to human and planet well-being completes.

The greatest contribution of SDGs would be developing the past human culture and lifestyle from only pursuing the economic benefits to seeking for the well-being of human including more suitable living conditions for current and the future parties. The SDGs present the common consent of stronger governmental roles during the transformation towards more sustainable planet (Norman, 2019, p.143). The SDGs also bring the sight for future stakeholders and the linkage of the future generation with the youth of this generation(Mori Junior et al., 2019). It guides current researchers to look into the mechanisms and the features of the system transformation processes of the planet where TBL is one attempt of breaking down the complex planet system to three subsystems (Beyne, 2020). Being a whole framework of targets, Lozano-Daz and Fernndez-Prados (2020) concludes that sustainability objectives, even though categorised to different aspects, interacts with all levels of systems on the planet that cover many system performance aspects such as the outcomes, and responsibilities.

More importantly, SDGs and the associated list of indexes and indicators provided by UN serve as a pool indicators for wide application. It is Not only demonstrated in detail the clarifications to the targets and indicators of various issues to be dealt with on the planet (Allen et al., 2020), but also the implementations of sustainability into strategies, policies, and practices into the mechanisms of operating, recording, and reporting, and tracing accountability by wide coverage of indicators (Mori Junior et al., 2019). This thrived the empirical studies based on reductionism where the contribution of one negative indicator linking to one SDG is often studied on temporal and spatio dimensions (Beyne, 2020). Besides, Parris and Kates(2003) suggest that the selection of sustainability proxies would vary in the system scales, driving forces, policy responses of the studied system and the selection of scientific theories and frameworks and negotiation during observation. Kwatra et al. (2020) concludes that good sustainability indexes should contain indicators that are highly indicative to sustainability or SD, theoretically relevant to sustainability issues, user-friendly in explanation of indexes, capable to indicate trends over time, sensitive to changes in the circumstances, scientifically valid for measuring, clearly defined, have clear data sources, and have precise, sufficient, and cost-effective data.

Although SDGs have guided many studies, policies, and social activities towards global sustainability, global sustainability is still yet to be achieved, practically speaking and partially due to the theoretical limitations. Even before the pandemic, the world has not arrived at a point where most countries are on the SD track (UNDESA, 2020). For theoretical limitations, on the one hand, SDGs and relevant applications are criticised to be heavily data-driven. As Allen et al. (2020) indicates, the SDGs that are better supported by data availability of the listed indicators by UN and data-driven analysis are more discussed than intangible objectives. It has been criticised that evaluation of sustainability have been abusively done on the national and local level where relevant data is more abundant (UNDESA, 2020). Not only has it been noticed that how micro-scale indicators are aggregated to macro-scale indicators is less discussed, but also the issue is been made prominent as global and local indicators used differ significantly (Norman, 2019, p.100-125). Already calling for better understandings to data integration, additionally, the COVID-19 pandemic also created the problem of data availability since global data collection in many countries is being disrupted (UNDESA, 2020). On the other hand, due to the screening of some SDGs among all, operational measures suggested for SD cannot reach consensus. Ll (1991) notes that SDGs are illustrating our living conditions from various aspects where some are but some are not mutually exclusive. Hence, prioritising one or some SDGs among others can trigger unsustainable outcomes (Weitz et al., 2018). Typical dilemma is among decent work and economic growth, good on-land and marine environment, and the affordable and clean energy where the living conditions are being detrimentally affected by economic growth and the technology is not yet ready to support the energy consumption. Comprehensively understanding SDGs, we need to be aware that even the full achievement of SDGs doesn't necessarily indicate the realisation of global sustainability (Giannetti et al., 2020).

Other Objectives

Directly attaching SDGs to all systems could be unsuitable to study the sustainability of some regional systems. Different from selecting one or some external sustainability objectives, deriving objectives for a system respects the constitution of the system and induction to sustainability. This requires deconstruction to the system structure and understand how the attributes of the system can stay within some range so that objectives are given on such basis. It is also applicable for using SDGs as reference indicator system.

The traditional targets given present its insufficiency to realise sustainability in aspects including systemic aggregation of objectives on different scales and the adaption to present understanding to sustainability or SD. Developed on Elkington's illustration to SD through TBL, it can be said that SD is achieved by good performance and dynamic balance among the three pillars (Kwatra et al., 2020). However, we now notice, sustainability objectives are not mutually exclusive as being divided by the boundaries of economic, social, and environmental subsystems. Besides, as the objective of SD becomes guaranteeing the well-being of human, SDGs contain aspects such as happiness that are cannot be quantified by any currently used development indexes (De Neve and Sachs, 2020). Bell and Wulf (2019, p.210-220) points out sustainability objectives include the formation of sustainable lifestyle for human with the recognition to the limitation of market pricing. As Silva et al. (2019) attributes, the collective objectives of a system is the aggregation of individual objectives from stakeholders rather than preferences to subsystems since there would always be stakeholders whose benefits are not satisfied. On the other issue, more present illustration to the target of sustainability is to "maintain the equilibrium and stability of our integrated socio-environmental system" (Fu et al., 2020), which also calls for integration and balancing of scattered objectives to systemically realise sustainability. However, SDGs are, instead of being discreet division of objectives in independent fields, a net work of objectives that are strongly or weakly linked with each other where only some are independent in its own fields (Zhao and Yang, 2017). The situational analysis method for SDGs, the sustainable critical paths, indicates the need to integrate relevant solutions on the pathways with the context where sustainability research lies in (Giannetti et al., 2020). Hence, SDGs is more of a guiding tool for governments and organisations to form a common sustainability picture. Under constructivist view, global sustainability should be analysed with systemic approaches as SDGs are interlinked across categories and interactions in the form of trade-offs and diminishing efforts have the potential to shift away burden in mainly socio-environmental system equilibrium or stability (Griggs, 2019).

On the basis of the mechanism that achieves individual targets, both explicit and implicit ones, system objectives could be regarded as collectively integrating individual objectives. Systems with transformation process contain directions and values of transformation, which are often contained in the objectives of the system(Shaw, 2009). Sustainability objectives is more complicated containing objectives of the system performance which requires demonstration to efficacy, efficiency, the current influences, the anticipation to future efficacy, efficiency and influences, also the effectiveness(de Vries et al., 2003). Apparent enough, the collective sustainability objectives are the results of aggregating individual expectations of beings in the social-environmental relations when system attributes are perceived into performance evaluation dimensions. Meanwhile different human groups hold their interests and stakes in the society, sustainability urges the recognition that both people and the environment, including the species of animals and plants and the non-living cycles, have their interests and stakes(Haddaway et al., 2017). Hence, the determination of sustainability objectives, even if choosing them from the SDGs, can be done following the connections of all strong and weak stakeholders in sustainability relations. To note, systematically deriving the stakeholders serves as a method of identifying the silent groups and their stakes (Silva et al., 2019).

Taking an example of selecting among SDGs from the derivation of system stakeholder drives, the process of determining system objectives also clarifies the implicit stakes that are weakly expressed and the boundary of the system to which its influence mainly reach out to. Noting the feature of adjusting and thriving from time to time, SDGs can be understood as the systemic inheritance from the historical transition of the planet (Schwarz-Herion and Omran, 2015, p.9-15). And hence, in the greater scale, it is a problem that can be simplified by the famous slogan ”one world, many places”, demonstrating global sustainability achieved by stabilised structural construction by the sub-global regions or bioregions holding different characters and sizes. Figure 2.7 demonstrates an example of such inheritance that describes the derivation of the SDGs and the nature of the systemic synergies within. The natural drivers introduces explicit outcomes of the limit to which the nature’s services can provide and takes up all the causes and results of climate change. The natural drivers hence affect the social drivers where some explicit undesirable ones include the creation of conflicts, the fight for profits, agricultural farm practices, and climate change inactions. As the outcomes of such problematic social drivers in the food supply system, there are problem of regional and global conflict, poverty, hunger, obesity and unhealthy lifestyle, food waste, inefficient use of resource and resource depletion, and partially as a result of the above tangible issues, the intangible problems include the lowering of the yield of original nature's services, and further climate change. Concluding the complex system inheritance from the natural drivers, the SDGs directly list the indicators of the outcomes of the stakeholder connections. It is indeed a good simplification to the complex issue of sustainability by considering only part of the system as any production system can be too complex and time consuming to be evaluated comprehensively with respect to all of its linkages (Grunda et al., 2011).

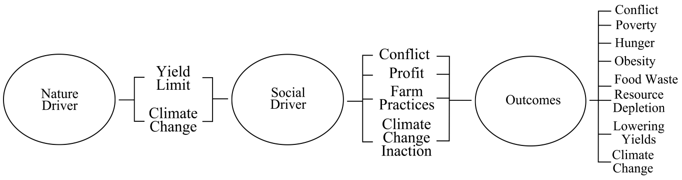


Figure 2.7 Outlined drivers and outcomes of current world food supply system. Adapted fromSchwarz-Herion and Omran (2015, p.141-154)

Considering that the main types of drivers under the mechanisms of planet sustainability are natural and social, it is also the main bodies of the nature and the society that sustainability tend to negotiate among. Inheriting the concept of stakeholders, as Mathur and others (2007) states, they are defined in two ways, by the definition or classification of the stakeholders themselves or by the project team in their cognition, and it is after the clarification to the stakeholders the different objectives and valuation methods are introduced to the system. Also noticing that many environmental influences are caused by unintentional activities of human(Haddaway et al., 2017), sustainability assessment or evaluation, given the objective to better demonstrate the social-environmental relations, prefers the derivation of stakeholder by the assessment or evaluation team. To note, the limitation of human cognition may become unavoidable at the current state of technology since the languages of other species are yet to be deciphered. Moreover, we need to recognise that sustainability objectives for any system would eventually cross its system borders reaching out to outer landscapes and cultural societies (Roger, 2000). The outcomes that can be concluded to SDGs are not only linked with one type of drives, but are also connected with the drives. When one driver alters, the dynamics of the system and downstream outcomes may alter accordingly. Although sustainability or SD is now popularly studied in regions, dividing the planet to Europe, America, or the Middle-East, focusing on historical proposal to and implementation for sustainability objectives, we are under the transition from historical geopolitical state towards more collaborative sustainability state (Schwarz-Herion and Omran, 2015, p.9-15).

Sustainability Objectives and Preferences in Evaluation

As we recognise as evaluation is indeed a purposeful activity with objectives that must include decision-making for an existing initial system, it is bound with certain objectives and successful conduction of an evaluation activity is supported and limited by the elements of evaluation (Table. 2.2). Hence, for sustainability evaluation, we need to first of all understand how the sustainability objectives given for the initial system influence other elements of evaluation.

We understand from Chapter 4 that sustainability objectives mainly place requirement over the dimension of time, or some quantities related to the changes across time, and both SDGs or sustainability objectives are mainly set based on the social-environmental relationship constructed for the initial system. Thus, sustainability evaluation for general systems often means to perform decision-making over some outcomes that the system is already producing, and adding sustainability attributes in the evaluation objectives depending on the definition of sustainability taken for the evaluation.

Sustainability evaluation objectives can be different from conceptually determined sustainability objectives such as the SDGs or the sustainability objectives. They are influenced by the sustainability objectives and they also need to be influenced by the evaluation elements which are case sensitive. Respectively contingent to the limitations of SDGs and sustainability objectives, explicit sustainability objectives should clearly explain whether the evaluated system has the potential to sustain over the attributes set by the objectives and concern the limitations of the system's collective values mainly of whether the evaluation outcomes follow a true pathway towards sustainability. In other words, sustainability evaluation objectives can be physically unsuitable for the initial system. The evaluated system for sustainability evaluation could often result as an expansion of the initial system over sustainability attributes. Besides, sustainability objectives could also be influenced by evaluation DMs, stakeholders, resources, and methods. Evaluation objectives in general, in many cases also naming it goals or targets, are often multiple for a system influenced by the aspects that the system objectives attempt to contribute to, the actors and relevant actions implemented in the system, and the measurement units during evaluation (Hon, 1998, Hill, 1973). Inclusive for sustainability objectives, they can be practically unsuitable for the initial system. Consequently, numerous different sustainability objectives are used in evaluation. Some set sustainability objectives as conservation to natural capital, maintenance of total equity, level of advancement on ecologically friendly structural adjustment, and the degree of globalisation, or some systemic sustainability objectives for specific context including pursuing better cost-benefit efficiency, reaching stability between cost and profit, avoiding excessive inflation or recession, creating a stable basis for operation of economy (Erickson and Gowdy, 2007, p.36-52). Others would set it as, more widely considering economic, social, and environmental subsystems, the realisation of minimizing resource use while guaranteeing minimum social and economic well-being thresholds (Mller et al., 2021). Apparently, to deal with such unsuitability between sustainability evaluation objectives and the initial system, the initial system needs to be adapted to the sustainability objectives and perhaps, some aspects of the sustainability objectives would also need to be adjusted to be practical for evaluation.

Inheriting the influences from sustainability objectives to the evaluation elements, we need to recognise the power of stakeholders in sustainability evaluation, especially the DMs and the KSs. As Pope et al. (2004) puts it, while sustainability assessment is context dependant on the interest of DMs and the main indicators are those capturing the physical existence of the observed object and the target of assessment, the preferences and measures for assessment is highly influenced by the objectives. However, attributing the contribution to the actors in sustainability relations, according to Devuyst (2001, p.9), sustainability evaluation objectives are usually reflecting the DMs' and KSs' interests over what activities need to be implemented and what need to be avoided for the realisation of sustainability. Furthermore, DMs generally determine the implementation of actions from evaluation (Reid, 1981). In accordance with strong and weak stakeholders in sustainability relations, DMs and KSs together determine the preferences of evaluation. To note, evaluators, part of the DMs for evaluation, also takes the responsibility to determine optimality, methodologically. Triggering a flow that constructs a network of influences in evaluation, DMs not only determine the suitable sustainability objectives, but also selects the suitable proxies of indicators through negotiation with other stakeholders and the driving forces linked to the initial system (Parris and Kates, 2003). Consequently, we recognise that through DMs, sustainability objectives could influence the composition of all evaluation elements throughout the whole process.

To shortly conclude, sustainability evaluation objectives, on top of evaluation objectives that are not related to sustainability nor global, social, economic, environmental sustainability, bring changes to the set of evaluation elements that can be determined by the system boundary of the initial system. As sustainability may not be suitable for all systems, sustainability objectives, too, may not be always suitable for directly evaluating the initial system (when the evaluated system is the same as the initial system). To mutually accommodate between sustainability objectives and the initial system, the evaluated system, notably its system boundary, for sustainability evaluation can be different from the initial system; the original sustainability objectives may require adjustment or additional assumptions to suit the status and values of the KSs; and the connections of the stakeholder need to be respected. Concluding from the elements of evaluation, such stakeholders include the lead of evaluation, the DMs, and the KSs, where in sustainability relations, they are not bound to be only human.

2.3.4 Frameworks Used in Sustainability Evaluation

Although sustainability evaluation has been done for a great variety of contextually different systems, given the context of what we today perceive as sustainability, that is mainly the state of global harmony between human society and the natural environment, several typical frameworks are applied. These include the triple bottom line (TBL) sustainability pillars, the ecosystem stability model, and the planet boundary. The application of these frameworks vary clearly according to field of study of the researchers where TBL is more applied by environmental economists, the ecosystem stability model is more popular with ecologists, and the planet boundary framework is more popular with engineering fields. These frameworks can be determinant to or directive for sustainability evaluation methods such as the conceptual model constructing methods of SSM, LCA, energy flow, material flow analysis, and the ecological footprint, and the evaluation methods such as DEA, scenario modelling, or regression (Ness et al., 2007).

Triple Bottom Line

Observing systems form the perspective of auditing, environmental auditing, and social and ethical accounting, TBL framework illustrates that sustainability, or rather SD, is at least relevant to three subsystems within the social-environmental relationships including the economic, social, and environmental aspects (Elkington, 1998). The three aspects are also relatively named profit, people, and the planet or equity, ethical, and economic aspects (Goodland, 1995).

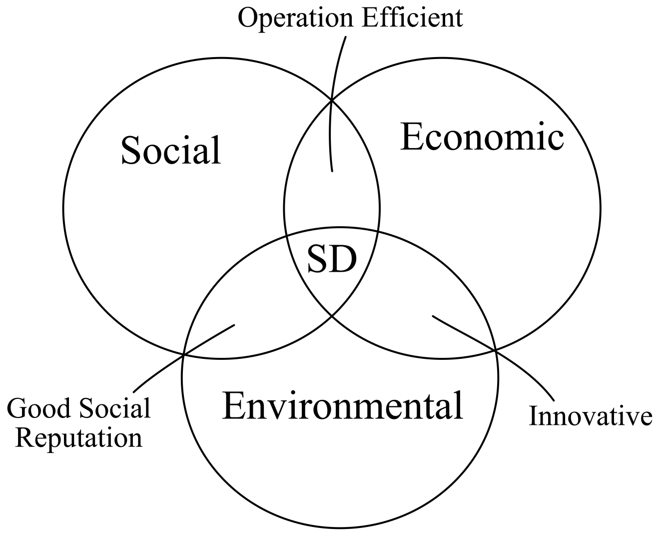


Figure 2.8 Triple Bottom Line

As Figure 2.8 exhibits, it is the good performance of the three pillars that can be regarded as standing on the pathway to SD. According to Elkington (1998), the three pillars can contain aspects that are both independent or interdependent with other two pillars. To note, it has not been mentioned whether one subsystem is more important than the others. Although the collective criteria for achieving SD is better clarified as simultaneously performing fine on the three aspects, it is also recognised that part of the objectives within the subsystems are conflicting with each other. For instance, attaching a business organisation context, having good sustainability performance under TBL for the business means achieving economic prosperity, reaching high level of environmental quality, and standing in line with social justice in the same time (Jeurissen, 2000*a*). It is found that the benefit of performing better in SD becomes more apparent in the long run. Besides the central target of SD, TBL also believes that the situations that lie in the intersections of any of the two aspects also has its sustainability sweets that meets the basic human needs (Savitz, 2013). It is demonstrated that social and environmental achievements relate to the contribution of business social reputation. Social and economic achievement relate to more efficient of business operation. And economic and environmental achievement relate to higher level of contribution in innovation. Thus, it s apparent that on the one hand, sustainability objectives can be set on different sustainability sweet pots under TBL, and on the other hand the application of TBL would conceptually require clear presentation to the preferences for achieving SD.

Another typical illustration of TBL, mostly regarded as demonstrating SD under strong sustainability, the three pillars are regarded as nesting subsystems on top of the other. According to Cato (2012), environment sits on the bottom layer, social subsystem sits on top of the environmental aspect and economy lies on top of the social pillar. This nesting relationship of the three pillars respect the observation that all economic activities rely on social construction and all societies are contained in the natural world. It also reveals the preferences of TBL that was implicit. TBL, describing the natural world using two human central pillars of economy and society, perceives the realisation of SD under human benefits. As Grunda et al. (2011) observes from empirical studies of sustainability evaluation, while TBL aspects probably guided most sustainability evaluations, it is more likely that the studies are biased towards concerning the socioeconomic impacts of activities on the environment. The evaluation indicator system developed on the basis of TBL, such as sustainability frameworks of SDGs including the wedding cake model and the SDG pyramid, inevitably prioritise human actions and social welfare (Giannetti et al., 2020). Instead of retrieving back to the definition of sustainability, the empirical studies often directly focus on TBL aspects, let it be considering all the subsystems or selecting one or two out of the three.

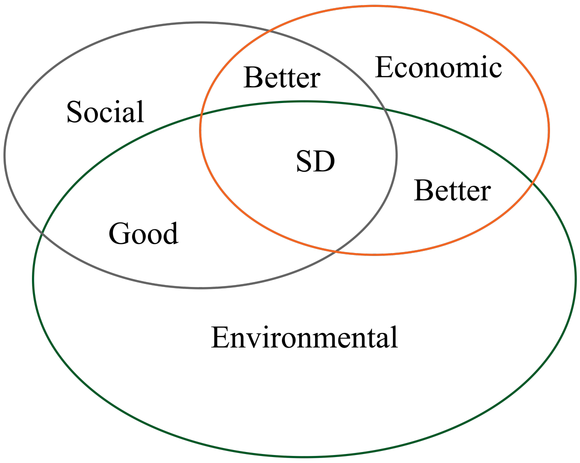


Figure 2.9 Triple Bottom Line with nesting relations

Figure 2.9 shows a Venn diagram of TBL with nesting subsystems which clearly presents the biases that TBL framework could bring to sustainability evaluation. The combination provides better indication for a systematic description of SD. While claiming sustainable development should be considered from the three aspects, it also suggests that environmental resource and energy availability and capacity etc. are, in the most explicit form, limitations to social aspects, and social restrictions give limitation to economic activities which is usually regarded as the desired gaining from the system.

As Pope et al. (2004) concludes, sustainability evaluation using TBL framework mainly present two drawbacks. First, as the simplest form of deciphering the subsystems is to consider them independently, the evaluation would eventually focus more on the competing interest of the three pillars instead of the interdependencies crossing the borders of the subsystems. Second, as indicator are usually being justified as desirable or undesirable within the subsystems, the evaluation often follow reductionism or resource management objectives for decision-making and consequently systemic synergies among the indicators lack discussion. The need of systemic measures to be used for measuring SD under TBL is proposed. For example, the treatment of many systems due for sustainability evaluation as urban systems considering the urban well-being, urban mobility, green networks, sustainable culture and heritage, and climate change for cities would better disclose the interdependent consequences among the three pillars (Norman, 2019, p.72-99). Besides, although TBL framework expresses the aspects that human activities involve, the nesting relationship with the environment lacks reflection as most of the restrictions are being expressed from the aspects of human society and the limitation of environment to the society is not well presented (Giddings et al., 2002). He then argues that the context covered by the social and economic aspects, more concisely, is human activity and well-being. This idea proposes that due to the complex system that is being considered for sustainable development, on the one hand is the consideration that whether it is a system whose scale is big enough to be assessed, and on the other hand is the proposal that the system observed, due to the impact of human activities and different pursuit for well-being, may have been much bigger than considered. As Kumar et al. (2017) concludes, many other subsystems with its own objectives are introduced in many sustainability evaluation studies including the technology aspect, system collective aspect, potential aspects relating to system function. We need to realise that the operational measures of SD has the potential of unable to reach consensus because many of the objectives are mutually exclusive ones relating to the living conditions of the subsystems (Ll, 1991).

Hence, it can be recognised that although the TBL framework provide fine reference for SD by dividing the natural world into three important subsystems that have frequent interactions with the anthroposphere, it is not the same as evaluation frameworks where objectives and the evaluation preferences are both explicit. In this way, perhaps TBL is more suitable as an observational framework and to conduct sustainability evaluation using TBL, we need to be aware of its biases and the importance of the determination of evaluation preferences. Thus, the power of evaluators and other DMs would present to be determinant for such sustainability evaluation.

2.3.5 Ecosystem Stability

Different from TBL framework of decomposing the natural world into subsystems, ecosystem stability framework constructs the natural world through different ecosystems. Ecosystem stability is said to be possessed when the equilibrium of the ecosystem could maintain as the mature ecosystem within which the functions and characteristics of the ecosystem would not alter. Figure. 2.10 presents a combination the complex system cycle and ecosystem succession within the system cycle introduced by Odum (1971, p.4-7) that together describes the position of ecosystem stabilised state in the system cycle. In the ecosystem sustainability frameworks, the basic unit that could march towards sustainability is an ecosystem (Jelinski et al., 1992). It cannot be ecologically sustainable when any singular sustainable indicator is not concerned with its linked ecosystems.

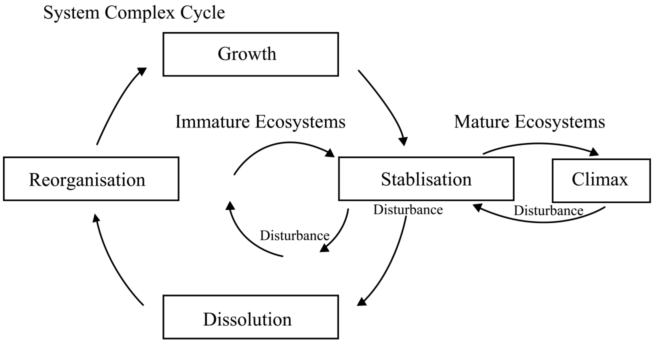


Figure 2.10 Complex System Cycle and Ecosystem Stability

Ecosystem continuously undergoes the general complex system cycle of growing in system scale and complexity until reaching an equilibrium state with the system external environment and when destructive or creative destruction occur to the system, it dissolutes and goes through reorganisation in the system structure and system functionalities may alter (Odum, 1971, p.4-5). The dissolution, reorganisation, and growth states present a state of immature ecosystems that it can be evolutionary in its composition with creativity of new species and new ecosystem functions. Mature ecosystems are consistent in its system key structure and key functions. Illustrated as the homeothesis under the fixed structure (Odum, 1971, p.6-7), continuous disturbances in mature systems develop structure and functionally stable ecosystems to continuously shift between the equilibrium state with the climax state. The climax state contains the largest number of species who are mutually efficient in the use of the limited resource in the system. The energy flow networks, such as the food web, of in the mature ecosystem continuously interact with the non-organic environment and thus could maintain its status for centuries without destructive damages (Odum, 1971, p.108-116). Hence, sustainability evaluation based on ecosystem stability framework would form a system whose boundary is determined by the key ecosystems specified by the evaluation objectives. Besides, by describing sustainability as the stability of ecosystem associated with the initial system, ecological upper bounds of capacity of all beings in the related key ecosystems are attached. The claim that sustainability challenges mainly concern the capability of nature's services is recognised (Gretchen C. Daily, 1997).

Although sustainability contextually defined to the stability of ecosystems, ecosystem stability is still measured from a great variety of measurements. Constancy, resilience, and persistence are popular terms that are used to specify stability but has thrived with further debates (Grimm and Wissel, 1997). In other cases, some measurements indeed become very explicit. Holden and Hyer (2005) uses the maintenance of ecological footprints in the sustainability evaluation objective related ecosystems to represent level of system stability. Moran et al. (2008) replaces ecological footprints with the minimum required land to support the evaluated ecosystems since minimum biodiversity in the ecosystems has the base requirement of space. Indifferent with TBL, evaluators and DMs would also need to determine the measurement for ecosystem stability. However, ecosystem stability framework guarantees the sustainable potential based on the basic unit of ecosystem, turning sustainability objectives from potential blue prints into ecologically achievable interests.

2.3.6 The Planet Boundary

Also recognising that the planet ecosystem holds all human and non-human activities, the planet boundary framework summarises the challenge that the planet Earth face today into several aspects. These aspects are focused to the environmental problems that arose during the industrial revolution since human activities have significant altered the balances of, for example, water, land-use, and atmosphere (Vitousek et al., 1997). Jelinski et al. (1992) concludes the new industrial ecosystem that created such outcomes into three types, consuming limited resource and creating limited waste, consuming resource and energy and creating waste, and only containing energy flows. On the one hand, it brings the concern for limited resources that can be consumed by the regional industrial ecosystem. On the other hand, it emphasis the fact that the creation of waste would not be eliminated unless the transformation within the industrial ecosystem is managed.

Collectively summarising severe environmental systems that altered significantly, the planet boundary framework is set on the fact that the basic systems that satisfy the living of creatures, are believed to hold a dynamic level of tolerating the quantity of materials where over stepping the boundary will lead to irreversible damages to a series of ecosystems (Rockstrm et al., 2009). Relevant to ecosystem stability, the upper boundary the planet boundary framework believes that the planet should operate within is the maximum carrying capacity, that is the maximum capacity of species under the climax state of the ecosystem stability framework. According to Odum (1971, p.126-132), the maximum carrying capacity is the max amount of biomass that can be supported by the ecosystem that when the entropy of the whole ecosystem exceeds the system dissipation, a reduction in system size or a crush is expected to occur. In its empirical estimation, maximum capacity is linked with the population of the species and its reproduction rate. Thus there would be an optimal scenario under the planet boundary framework where materials are consumed in the most efficient form resulting in the maximum amount of species that can be held. Besides, the series of ecosystems are described as different environmental problems that the human face today. These aspects include climate change, ocean acidification, stratosphere Ozone depletion, Nitrogen and Phosphorus cycle, land-use change, fresh water, biodiversity, and aerosol loading and air pollution.

The system determined by the planet boundary is not a static system with fixed tolerance. The definition clearly indicates that the level of tolerance to different issues are different. As Rockstrm et al. (2009) notes, planet boundaries exist for all systems on Earth but the level of tolerance over one issue can be different from other regions. For example, the tolerance to air pollution highly depends on the regional capability of air particle diffusion (Chang and Hanna, 2004). Geographically, basins would always have lower tolerance to air pollution than coastal regions. Even for one region, when landscape alters in time, its tolerance levels also change. Besides, the collective expectations of dealing with the aspects and the concerns to different boundaries alter as our cognition to environmental reality change. The collective expectations for a sustainable planet changes from being fine in one of the aspects to the well-being of the planet (Norman, 2019, p.37). The concerned aspects within one type of boundary also change. For example, to deal with air pollution, the problems of aerosols expanded from toxic aerosols to $PM_{2.5}$ and climate change brought by CO_2 (Norman, 2019, p.103). The different boundary cycles are complex within its subsystems and are open to be linked with other boundaries. Besides, as regional conflicts become more observable and innovations are brought to industry, new boundaries are set for biosphere integrity and novel entities which concerns the artificially created things that are new to the natural environment (Norman, 2019, p.27-29). Eventually, as Steffen et al. (2015) concludes, the planet boundary framework actually defines a safe space for massive amount of transformation for humanity.

Ecosystem boundary framework takes the advantage of conceptually better for global sustainability as it neglects the cause of the actions and focus on the end-user side of collective environmental influences. While sustainability assessment framework like TBL would call for diversified analysis to the separate aspects of social activities and then integrate the conclusions to achieve SD, the frameworks based on ecosystem like the ecosystem boundary attempt to treat the influences of human activities indifferently for all species across divisions of ecosystems (Thies et al., 2019). In other words, human have to live in a world even if ocean acidification is not caused by human, although the main cause for many of the environmental conditions mentioned in Rockstrm et al. (2009) are greatly deteriorated by human activities.

As Odum (1971, p.94) notes, "*most human have difficulty in determining when enough is enough*", the Great Acceleration is indeed an historical example that human, without feeling satisfied, have conducted activities that surpassed the ecological boundaries. The planet boundary framework also describes the global characteristics of sustainability that we pursue for the well-being of human community. Any change to the ecosystem would always result complex and hierarchical (Walther et al., 2002). We could not anticipate all global influences of the actions taken in the past and we also could not fully expect which bodies would be influenced by the actions. As Bonnedahl (2019, p.4) attributes, climate change is the aggregated and accumulated consequences of human activities where all activities should be accounted for historical responsibilities. And there are cases such as urban ecosystems where high intensity of human activities of urbanisation have changed the original balance of the natural ecology and formed completely new balance within the cities (Grimm et al., 2008) and we could not anticipate retrieving back to the state where cities are underdeveloped. However, as all material and energy would leave continuous traces in the ecosystems on their paths, the hierarchical impacts to ecosystems is able to be traced following the materials and energy flows (Begon et al., 2006). Hence, connected by the materials and energy, the environmental issues concerned by sustainability objectives, especially ones that may jeopardise human well-being, would always be a global not local or regional issue (Steffen, 2005). It is apparent that the planet boundary framework would indifferently demonstrate the problems contained in a global system and thus, regional problems may not be able to be answered under the framework. Implementations of actions such as technology improvements would benefit the sustainability of the wealthy regions than the poor regions as energy subsidies are not guaranteed in the poor regions (Odum, 1971, p.88). It can be noticed that aside from the ecological capacity that act as the upper bound for beings in the social-environmental relations, the asymmetrical presence of resources, technology, and information would also determine the upper bound of sustainability well-being.

Similar to SDGs, by determine clear problematic cycles of environmental issues, the planet boundary framework has directed many empirical studies dealing with one of the problems or evaluating sustainability using collective indicators dealing with more than one environmental boundaries. Wu et al. (2011) concentrates on the land-use change to assess the SD of urbanisation. Connecting biodiversity, marine water conditions, with stratosphere Ozone depletion, Worrest and Hder (1989) evaluated the impact of Ozone depletion to marine organisms including marine food web, the fisheries, and the composition of species. Considering dimensions of environmental system, environmental stresses, human vulnerability, social and institutional capacity, and global stewardship, the environmental sustainability indexes, for example ESI-2005, evaluated with 21 indicators with 76 variables (Ness et al., 2007, Siche et al., 2008). Focused on resource consumptions within the boundaries, ecological footprints acts as an accounting tool that estimates resource consumption and waste assimilation requirements of a system with frequent human activities (Wackernagel and Rees, 1998, p.10). Sustainable national income and the human development indexes are also some relevant indexes where the planet boundary clearly explains the planet sustainability issues the indexes are linked with (Moran et al., 2008).

2.4 Sustainability Evaluation: An Overview

2.4.1 Introduction

This section intends obtain insights for the key words associated with sustainability evaluation, the popularly evaluated subjects, the trends of studies, and the issues in sustainability evaluation through observing and comparing among systematic reviews of literatures published as academic articles.

2.4.2 Data and Method

This critical review is done for selected literatures that would provide sufficient information forming overall understandings towards the discussion of evaluation elements in past sustainability evaluation.

Through open search using the Scopus database and Google Scholar for systematic literature reviews of sustainability evaluation, 21 articles are selected to be studied in detail. Table 2.8 presents the fundamental information and the key contents of the articles. Just like empirical studies of sustainability evaluation, the systematic reviews of sustainability evaluation are also wide spread in various fields of studies observing very different issues that are not concentrated to evaluation or elements of evaluation. Hence, it would be impossible to even fully study all systematic reviews of sustainability evaluation. However, it is judged that each article would contain discussion to the characteristics of all or part of the evaluation elements previously listed in Table 2.2.

Table 2.8 List of systemic review articles reviewed

Year	Author	Title	Review Perspective	Highlights
2007	Bhringer and Jochem	Measuring the immeasurable A survey of sustainability indices	Measurement	A survey of sustainability indexes focused on conceptual and technological integration.
2009	Wang et al.	Review on multi-criteria decision analysis aid in sustainable energy decision-making	Methodology	A methodological review focusing on methods and measurements on sustainability pillars.
2011	Poveda and Lipsett	A review of sustainability assessment and sustainability/environmental rating systems and credit weighting tools	Measurement	A methodological review focused on measurement systems of sustainability evaluation, proposing the contingency from objectives, frameworks, methods, to measurements.
2012	Searcy	Corporate sustainability performance measurement systems: a review and research agenda	Measurement	A review of different performance measurement systems.
2016	Adams et al.	Sustainabilityoriented innovation: A systematic review	Methodology	A methodological review that introduces the frameworks of sustainability oriented innovations.
2015	Velten et al.	What is sustainable agriculture? A systematic review	Conceptual and Policy	Systematic review of agricultural sustainability over the concepts and their formation.
2017	De Luca et al.	Life cycle tools combined with multi-criteria and participatory methods for agricultural sustainability: Insights from a systematic and critical review	Methodology	Systematic review of agricultural sustainability methodologies, focused on frameworks and methods.
2018	Bykzkan	Sustainability performance evaluation: Literature review and future directions	Evaluation	Systematic review of sustainability performance evaluation from business stance covering sustainability evaluation objectives, subjects, frameworks and methods.
2018	Threr	A systematic review of the literature on integrating sustainability into engineering curricula	Evaluation	Systematic review of evaluating sustainable courses as a contribution to sustainability in higher education.

Year	Author	Title	Review Perspective	Highlights
2018	Sierra et al.	A review of multi-criteria assessment of the social sustainability of infrastructures	Evaluation	Systematic review of social sustainability evaluation works focused on the practice of sustainability evaluation.
2018	Martin et al.	Life cycle sustainability evaluations of bio-based value chains: Reviewing the indicators from a Swedish perspective	Measurement	Systematic review and development for measurements and indicators to be included in LCA on greater scale.
2019	Lampridi et al.	Agricultural sustainability: A review of concepts and methods	Evaluation	Systematic review of agricultural sustainability analysing the stakeholders and methods.
2020	Visentin et al.	Life cycle sustainability assessment: A systematic literature review through the application perspective, indicators, and methodologies	Evaluation	Systematic review of sustainability evaluation focused on life cycle framework methods.
2020	Braithwaite et al.	Built to last? The sustainability of healthcare system improvements, programmes and interventions: a systematic integrative review	Evaluation	Systematic review of healthcare sustainability evaluation studies that covered many elements of evaluation.
2020	Elshall et al.	Groundwater sustainability: a review of the interactions between science and policy	Conceptual and Policy	A conceptual review to critical articles for lead and objectives of ground water sustainability, extending to the evaluation stakeholders.
2020	Javanmardi et al.	Exploring grey systems theory-based methods and applications in sustainability studies: A systematic review approach	Methodology	A systematic review of sustainability evaluation integrated with grey systems theory.
2021	Luo	Environmental sustainability of textiles and apparel: A review of evaluation methods	Methodology	Systematic review of sustainability evaluation in textile and apparel industry focused on frameworks and methods.
2021	Etxano and Villalba-Eguiluz	Twenty-five years of social multi-criteria evaluation (SMCE) in the search for sustainability: Analysis of case studies	Evaluation	Systematic review of SMCE in sustainability evaluation, covering the methodologies, methods, and stakeholder participation.

Year	Author	Title	Review Perspective	Highlights
2021	Kiani Mavi et al.	Sustainability in construction projects: A systematic literature review	Scientometric	A conceptual review to the sustainability evaluation of construction projects, focusing on the implementation of sustainability to the theme of construction projects.
2022	Mio et al.	Performance measurement tools for sustainable business: A systematic literature review on the sustainability balanced scorecard use	Evaluation	Systematic review of sustainability evaluation in business over the conceptual and modelling level.

2.4.3 Article Description

The 21 articles studied cover a timeline from 2007 to 2022, with varied focus of sustainability evaluation studies conduced. Although the studies observe some similar trends of sustainability evaluation, they also revealed different issues associated with sustainability evaluation. Among the issues, we emphasise that most reviews focus on one or some elements of evaluation. The general trends of sustainability evaluation and the issues are discreetly analysed in subsequent parts.

As shown in Table 2.8, the focus perspectives of the systematic reviews could be roughly classified into scientometric, conceptual, evaluation, methodological, and measurement. Conceptual systematic reviews are the studies that, based on systematic selection of the articles, qualitatively describe the features of the articles studied and are, in the articles observed here, associated with collective comparative analysis providing insights for sustainability policy setting. For systematic reviews that are classified as holding evaluation perspectives, they are observed as indifferently considering the concept of sustainability, the frameworks, and the measurements, providing judgements on the quality of sustainability evaluations done.

From the perspectives applied in the systematic reviews, it proves our previous recognition to sustainability evaluation that it is a value-led evaluation that present to be debatable over both the conceptual formation of sustainability relations and the practice of evaluation over the techniques. The scientometric review by Kiani Mavi et al. (2021), focused on the sustainability performance of construction projects, points out that the definition to sustainability, SD, and sustainable construction has not reached consensus over the definitions and, technically, the suitable measurements. It is pointed out that conceptual unification and finding the suitable measurements, even if the measurements are theme-based, are the most studied issues in sustainability research. Besides, the reviews done from the evaluation perspective, mentioning the process and quality of sustainability evaluations (Braithwaite et al., 2020, Bykzkan, 2018, Etxano and Villalba-Eguiluz, 2021, Lampridi et al., 2019, Mio et al., 2022, Sierra et al., 2018, Threr, 2018, Visentin et al., 2020) tend to propose similar division in research perspectives of empirical studies. Thus, it may have explained meaningfulness of the in-depth reviews done for the concept of sustainability (Elshall et al., 2020, Velten et al., 2015), methodology domain of sustainability evaluation (Adams et al., 2016, De Luca et al., 2017, Javanmardi et al., 2020, Luo, 2021, Wang et al., 2009), and the measurement domain (Bhringer and Jochem, 2007, Martin et al., 2018, Poveda and Lipsett, 2011, Searcy, 2012).

2.4.4 An Overview of Sustainability Evaluation

The articles have presented some general consensus for sustainability evaluation. Sustainability has been widely recognised as a value-based concept influenced by the stakeholders. Also, alike evaluation, sustainability evaluation is also applied to wide variety of fields wide a great variety of methods. However, many have proposed the sustainability evaluation should target for systematic frameworks with high consistency from the conceptual level to the practice domain. Such trends are analysed in this section.

Sustainability evaluation is found to be popularly done throughout the years across wide variety of fields of study, especially applying more systematic methods on the evaluation subject including life cycle or ecological footprints of products and processes. The scientometric analysis generally identify sustainability evaluation to be a topic with boosting popularity of empirical studies that is widely applied to different thematic fields of studies. A scientometric survey of sustainability and SD studies indicate that relevant research boosted since 2005 (Olawumi and Chan, 2018). Alike such overall trends in sustainability studies, sustainability evaluation also thrived with continuous increasing number of articles in many thematic fields of studies. Since the declaration of SD by the UN in 2005, steep increase of sustainability evaluation empirical studies are done for implementations in higher education (Threr, 2018). Agricultural sustainability evaluation thrive with steady growth and in 2016, the interest boosted (Lampridi et al., 2019). The focus of agricultural sustainability evaluation is more focused on forestry-based products, biomass, and biofuels instead of industrial products and processes. Systematic evaluation to the primary production process and the ecosystem's services are more valued for agricultural sustainability. For social sustainability evaluation for urban infrastructures, the increase in the interest of empirical studies is slow (Sierra et al., 2018). Such trend is being explained that the intangible aspects of social sustainability aspects that are hard to measure creates technical challenges for evaluation. Evaluation techniques, especially the frameworks, the methods, and indicators, are found to be continuously holding great research interest. Bykzkan (2018) concludes that since 2007, in performance indicator studies, more interest is attached to analytical work of sustainability, compared with conceptual and literature reviews. Empirical studies based on life cycle frameworks and associated tools continuously boost since 2014 (Visentin et al., 2020). Other methods with steadily increasing interest include the Gray System Theory and the sustainability balanced scorecard, suiting for qualitative and quantitative analysis (Javanmardi et al., 2020, Mio et al., 2018). It could be recognised that the focus of sustainability evaluation would mainly focus on widened topics, the development of the concept of sustainability and the frameworks, and the technical aspects of evaluation. Thus, we respectively conclude for insights that for these aspects in the articles.

Although many studies identify that sustainability evaluation involves nearly all fields or industries, the majority focus on environmental aspects of ecology, energy and resources, and technical development. Sustainability evaluation is most popularly done in study categories including ecology, environmental sciences and engineering, energy, resources, civil engineering, green technology, construction, chemical engineering, and computer science Olawumi and Chan (2018). Focusing to social multi-criteria evaluation, the popular topics include rural and urban planning, agriculture, resources management, energy, land-used change, and other industries and biological problems (Etxano and Villalba-Eguiluz, 2021). Holding similar focus, for construction project sustainability evaluation, Kiani Mavi et al. (2021) also points out the popularity in information technology, project performance management, and stakeholder management. Focused on sustainability oriented innovation, Adams et al. (2016) reveals that industries recognise that sustainability is a multi-industrial issue which multiple industries simultaneously hold interest for one sustainability implementation evaluated. The review by Martin et al. (2018) also concluded that considering product sustainability, energy, construction, and commodity products are the most evaluated ones. Indeed, it follows the fundamental conflict in sustainability relations between human and primary production processes requiring free natural inputs.

More explicitly presenting expectations for harmonious social-environmental relations out of the conflicts in the wide thematic fields, sustainability or SD targets are proposed by the UN and governments. These targets are being frequently directly applied as the evaluation objectives (Braithwaite et al., 2020, Bykzkan, 2018, Etxano and Villalba-Eguiluz, 2021, Luo, 2021, Sierra et al., 2018, Velten et al., 2015, Visentin et al., 2020). (Braithwaite et al., 2020) analysed that much greater proportion of sustainability evaluation for healthcare system would not demonstrate clear definition to sustainability in respective empirical work. It is being genuinely pointed out in the reviews that it is conceptually preferred for the stakeholders, especially the DMs, to determine the objectives. However, in practice, as many empirical studies apply Analytical Hierarchical Process (AHP), the stakeholders more often participate in evaluation for determining the weights of indicators instead of the objectives chosen from the proposed ones. Perhaps from the perspective of feasibility, some also suggest that sustainability evaluation objectives are often determined by the evaluation frameworks applied (Adams et al., 2016, Poveda and Lipsett, 2011). Also focusing on the evaluation perspective, some studies conclude that sustainability evaluation objectives also contain expectations for quality of evaluation results. Martin et al. (2018) suggests that sustainability evaluation objectives with systematic perspective produced more feasible implementation suggestions. Javanmardi et al. (2020) concludes that sustainability evaluation objectives include thematic ones and those for the quality of sustainability assessment. Kiani Mavi et al. (2021) further suggests that evaluation objectives are usually set as producing more feasible evaluation results over economic, social, and environmental aspects, and thus thematic objectives applied differ by the scope of the evaluation subject. Together, it could be recognised that sustainability evaluation objectives are often treated with targets given by authorities and sustainability evaluation could only be done for limited selection of objectives. Also, sustainability evaluation objectives in empirical studies often neglect the quality of evaluation results. Consequently, many studies suggest that the results produced from sustainability evaluation are insufficient for ecosystems, are not comparable, or are unable to reach global consensus (Braithwaite et al., 2020, Bykzkan, 2018, Threr, 2018, Elshall et al., 2020). Overall, for any system, evaluating for a wider system with better sustainable reference is regarded as capable of producing better evaluation outcomes.

The focus of insights from the review articles focus on systemic process of sustainability evaluation, mainly discussing the consistency between the evaluation objectives and the frameworks, and the consistency of use of measurement guided by the framework. The most common framework used for sustainability evaluation is considering the economic, social, environmental aspects of the subject (Adams et al., 2016, De Luca et al., 2017, Javanmardi et al., 2020, Kiani Mavi et al., 2021, Lampridi et al., 2019, Martin et al., 2018, Poveda and Lipsett, 2011, Searcy, 2012, Velten et al., 2015, Visentin et al., 2020, Wang et al., 2009). This is a compound system suggested under the TBL framework. Its application is also often associated with other subsystem attributes such as technology (Kiani Mavi et al., 2021, Searcy, 2012, Wang et al., 2009) or used in compound with thematic frameworks (Adams et al., 2016, Kiani Mavi et al., 2021, Poveda and Lipsett, 2011). As previously mentioned, Adams et al. (2016) and Poveda and Lipsett (2011) have arrived at a conclusion that evaluation frameworks would determine the sustainability evaluation objectives. This conflicts with the conceptual process that we analysed previously for appropriate evaluation process (Chapter 2) that evaluation is usually guided by explicit evaluation objectives and determines the suitable framework that could be applied. We recognise that it could be the thematic frameworks that would influence the evaluators' decisions for adjusting the evaluation objectives. Focused on innovation process, Adams et al. (2016) concludes that evaluating innovation would concern with optimization activities or transformation activities, which would associate with different measurements for different objectives combining with sustainability objectives. Similarly, Poveda and Lipsett (2011) presents the combination of different thematic frameworks with sustainability assessment frameworks which could be integrated to serve for sustainability evaluation. In some fields, some thematic frameworks integrates sustainability attributes into the context (Braithwaite et al., 2020, Elshall et al., 2020, Mio et al., 2022, Threr, 2018). However, replacing sustainability with considerations for economic, social, and environmental concerns is being heavily criticised for missing integrated values. Some emphasise social environmental synergies such as green brand (Luo, 2021); some concern for the risk of sub-optimisation implementations in finding more sustainable substitutes for exhaustible sources (Martin et al., 2018); others concern the suitability of the scale of the evaluated system with the division of subsystems (Kiani Mavi et al., 2021). Seemingly to develop for more integrated system, other commonly applied contextless frameworks, aside from the TBL frameworks, include LCA, ecological footprint, emergy analysis, and the planet boundary (Bykzkan, 2018, De Luca et al., 2017, Etxano and Villalba-Eguiluz, 2021, Kiani Mavi et al., 2021, Luo, 2021, Martin et al., 2018, Mio et al., 2018, Searcy, 2012).

For the consistency between frameworks and methods and measurements, a consensus is reached as the framework would influence the applicability of methods, and both the framework and the method would influence the use of measurements. The framework mainly guides the criteria selection, and the use of independent or compound indicators, which would associate with the selection of weighting methods, decision-making methods, and the aggregation methods. The selection of methods seem to be relatively unrestricted. According to Braithwaite et al. (2020), the quantitative methods often serve for cost-effective evaluations and evaluations using organisational or system data. Qualitative and mixed methods are associated with stakeholder engagement through surveys, interviews, case studies, behavioural experiments (Braithwaite et al., 2020, Mio et al., 2022). Comparatively, quantitative analysis thrive, being believed to hold better subjectivity. Generally, the decision-making methods include weighted sum method, correlation and regression, LCA and associated methods, BSC, DEA, TOPSIS, AHP, ELECTRE, PROMETHEE, NAIADE, VIKOR, grey relational analysis, fuzzy set, etc. (Adams et al., 2016, Bhringer and Jochem, 2007, Braithwaite et al., 2020, Bykzkan, 2018, De Luca et al., 2017, Etxano and Villalba-Eguiluz, 2021, Javanmardi et al., 2020, Lampridi et al., 2019, Luo, 2021, Martin et al., 2018, Poveda and Lipsett, 2011, Searcy, 2012, Sierra et al., 2018, Visentin et al., 2020, Wang et al., 2009). To note, eventually, there are high similarity in the measurements used. It is pointed out in many studies, especially containing analysis for AHP method, that the stakeholder value, although conceptually being recognised to be critical in sustainability relations, would only mainly participate in the determination of weights. Stakeholders, especially the DMs and the key stakeholders has not participated enough in indicator selection. Searcy (2012) concludes that in sustainability evaluation, measurements are often selected case-by-case by the themes and frameworks. Lampridi et al. (2019), Martin et al. (2018), Poveda and Lipsett (2011), and Threr (2018) also deduced similar statements. Luo (2021) and Bykzkan (2018) would emphasise the integration of measurement selection with the evaluation objectives and consensus among DMs. As Bhringer and Jochem (2007) concludes, currently, the use of frameworks, methods, and measurements in sustainability evaluations would depend on the theme of evaluation, and no such general rules exist for method selection, nor would there be rules for inputs variable commensurability.

Conclusively observing the general trends, it could be seen that the focus of sustainability evaluation are the concept of sustainability and the development of evaluation techniques. Besides, it is widely accepted that sustainability and sustainability evaluation would be a field of study with great variety of themes, applicable frameworks taking from thematic backgrounds or from sustainability studies, and methods of evaluation. However, holding an evaluation perspective in this thesis, we recognised that, past literature reviews tend to miss out discussion on one or more elements of evaluation as listed in Table 2.2. Such issues are analysed in the following section.

2.4.5 Issues in Sustainability Evaluation: from the Elements

While current sustainability evaluations has been found with some general trends and focus, this section attempts to understand such trends and identify systematic issues from the evaluation's perspective. Thus, analysing the attributes of basic elements of evaluation that is concluded in Chapter 2, Table 2.9 presents the results of whether the elements are analysed or discussed in the selected articles.

As analysed in the general trends, the focus of analysis is conceptually from the objectives to the framework construction and technically deriving suitable methods and measurements from the framework. Analysis regarding evaluation framework, method, and measurements are covered in most articles among the 22. Besides, as measurements used in evaluation could be influenced by the evaluation objectives, the data available, the frameworks, and the methods, what lies in the centre of the technical domain is the need for a suitable evaluation framework that would be able to systematically integrate all elements.

Presented by the counts of articles, the second concern would be the consid-

Table 2.9 Elements of evaluation analysed in sustainability evaluation reviews.

Author	**Lead**	**Objectives**	**DMs**	**KSs**	**Subject**	**Resource**	**Framework**	**Measurement**	**Method**	**Results**
Adams et al.	-	+	-	+	+	-	+	+	+	-
Bhringer and Jochem	-	-	-	-	-	-	-	+	+	-
Braithwaite et al.	-	+	+	+	+	-	+	+	+	+
Bykzkan	+	+	+	-	+	+	+	-	+	+
De Luca et al.	-	+	-	+	-	-	+	+	+	-
Elshall et al.	-	+	+	+	+	+	+	+	+	+
Etxano and Villalba-Eguiluz	-	+	+	+	+	-	+	-	+	-
Javanmardi et al.	-	+	-	-	+	-	+	-	+	-
Kiani Mavi et al.	-	+	+	+	+	+	+	+	+	+
Lampridi et al.	-	-	+	+	+	+	+	+	+	-
Luo	-	+	-	-	+	+	+	+	+	-
Martin et al.	-	+	-	+	+	+	+	+	+	-
Mio et al.	+	+	+	+	+	+	+	-	+	+
Poveda and Lipsett	-	+	+	-	-	-	+	+	+	-
Searcy	-	-	-	-	+	-	+	+	+	+
Sierra et al.	-	+	+	+	+	+	-	+	+	-
Threr	-	+	+	+	+	+	+	+	+	+
Velten et al.	-	+	-	-	+	-	+	+	-	-
Visentin et al.	-	+	+	+	+	+	+	+	+	-
Wang et al.	-	+	-	-	+	-	+	+	+	-
Cnt.	3	19	12	13	19	11	20	18	21	8

erations to stakeholders, especially for DMs and KSs. Many articles have pointed out to more comprehensively include the engagement of such stakeholders. The DMs could include governance bodies, institutions, clients, project managers, top managers of firms, practitioners, external experts, and researchers(Elshall et al., 2020, Kiani Mavi et al., 2021, Mio et al., 2022, Poveda and Lipsett, 2011, Sierra et al., 2018, Threr, 2018). To emphasise, these DMs are the DMs for the evaluation which would take different functional roles in decision-making. Some may determine the final implementations taken for the subject (Braithwaite et al., 2020); some may determine the measurements used (Bykzkan, 2018); some may present different values for the objectives (Etxano and Villalba-Eguiluz, 2021); some may only participate in determining the weights for decision-making (Visentin et al., 2020). Sustainability benefits might not alter the preferences of DMs unless they are linked with the primary benefits of the DMs. As for the KSs, being a much wider group of stakeholders than DMs supporting the operation of the evaluated system, their preferences and functions are widely emphasised in the studies. However, the key issues for considering the engagement of KSs in sustainability evaluation are two fold: on the one hand, the weak stakeholders, both human and nature who are unable to make their voices sufficiently heard, require much attention by the DMs or evaluators and the comparability between their values and the values of the strong stakeholders is hard to integrate (Adams et al., 2016, De Luca et al., 2017, Etxano and Villalba-Eguiluz, 2021, Kiani Mavi et al., 2021); on the other hand, even among the KSs with known values, the values are hard to reach harmony and would influence the indicator selection (Martin et al., 2018, Visentin et al., 2020). The integration of stakeholder values and preferences seem to be a long-term issue in sustainability evaluation.

More importantly, especially over the lead of evaluation, only one study included discussion to full elements and including that, only three have considered the origin of the sustainability evaluation objectives. Braithwaite et al. (2020) notes that sustainability is a collective value of the world that mainly depend on governmental authorities and international organisations and the majority of studies inherit the definition to sustainability from those given by such authorities or typical studies related. Based on the context of health systems, they concluded that some leading organisational bodies promoting sustainability values include World Health Organisation, the Organisation for Economic Cooperation and Development (OECD), and the World Economic Forum, together with the governments of member countries. Consequently, they identify that for health care systems, sustainability evaluations apply evaluation objectives that mainly consider safety, quality, and lower-cost health care services to the serving population and, also by many governmental departments, sustainable healthcare system evaluation frameworks should be applied. Conclusively, by Mio et al. (2022), it is usually the international organisations, governments of all scales, scientific teams, and the top management groups of organisations or institutions who propose the need for sustainability evaluation. Aside from the three studies, we concluded the possible lead of evaluation that are implied in the reviews (Table 2.10).

Table 2.10 Possible lead of evaluation of sustainability evaluations.

Year	Author	Lead of Evaluation
2007	Bhringer and Jochem	International organisations, Governments
2009	Wang et al.	International organisations, Governments, Academics
2011	Poveda and Lipsett	International organisations, Governments, Academics, Communities
2012	Searcy	n.a.
2016	Adams et al.	International organisations, Governments, Academics
2015	Velten et al.	International organisations: Nature Conservation and Nuclear Safety, Greenpeace, Monsanto, UNEP, WHO, WWF, Governments, Academics, Farms
2017	De Luca et al.	n.a.
2018	Bykzkan	International organisations, Governments, Academics, Business owners
2018	Threr	International organisations, Governments, Academics, Institutions
2018	Sierra et al.	Governments
2018	Martin et al.	International organisations, Governments, Academics
2019	Lampridi et al.	International organisations, Academics, Governments (national, regional, local), Farm owners, Technicians
2020	Visentin et al.	International organisations, Governments, Academics
2020	Elshall et al.	International organisations, Governments, Academics
2020	Javanmardi et al.	International organisations, Governments, Academics
2021	Luo	Academics
2021	Etxano and Villalba-Eguiluz	International organisations, Governments
2021	Kiani Mavi et al.	International organisations, Governments, Academics, Project clients

n.a implies for technique reviews that has not implied at all for potential lead of evaluation.

Aside from reviews focused on evaluation techniques (Searcy, 2012, De Luca et al., 2017, Luo, 2021), all others implied that sustainability evaluation would hold the needs for policy setting, sustainable lifestyle governance, or purely academic research. Kiani Mavi et al. (2021) reported that the majority of the empirical studies are funded by governments and both Braithwaite et al. (2020) and Etxano and Villalba-Eguiluz (2021) exhibited that in their sampled articles reviews, around half of the studies are funded by governmental research institutes. Besides, a scientometric study of sustainability studies showed that the top co-wording of sustainability and SD are, ranking from high to low frequency, ”system”, ”management”, ”indicator”, ”framework”, ”energy”, ”performance”, ”impact”, ”climate change”, ”environment”, and ”design” (Olawumi and Chan, 2018). Kiani Mavi et al. (2021) also presented through clustering analysis, that sustainability evaluations often associate with words including management, planning, performance, design, and innovation. Hence, we understand the lead of sustainability evaluation, who are often also the determinants of the objectives that are directly applied in sustainability evaluations, might have determined the current insight to sustainability that it is a kind of lifestyle, a form of collective value that may not be limited to individuals.

Eventually and most importantly, as the objectives are mainly given by the international organisation and governments under managemental purposes, we recognise that these evaluation objectives are set to recover to certain time. As previously reviewed in Chapter 4, the UN mainly sets the SDGs over conceptual level where many harmful indicators are developed for application based on reductionism. As Visentin et al. (2020) conclude, UN has also set a scope of sustainability evaluation studies over time that the emissions levels would mainly recover for 2005 level or 1995 level. Meanwhile, perhaps noting the insufficiency in such evaluation objectives, Martin et al. (2018) notes that sustainability evaluation objectives should always hold broader perspective for the evaluated subject. Others would present sustainability evaluation objectives, similar to sustainability targets, to be continuously changing. Minimum livelihood is applied for social sustainability (Etxano and Villalba-Eguiluz, 2021) and others also present that sustainability evaluation objectives would differ according to the stakeholders (Luo, 2021, Mio et al., 2022). However, we notice that, for whichever sustainability evaluation objectives taken, the baseline system for a sustainable picture is imaginary. As previously analysed in Chapter 4, a key criticism to sustainability has been that the concept itself seem to be blue print of the world. From the evaluation perspective, calling such baseline system a reference sustainability system, it remains to be a critical issue in presenting a sustainable or nearly sustainable reference system to derive suitable sustainability implementations so that evaluation results could become comparable.

2.5 Sustainability Evaluation Element in Energy Sector

2.5.1 Introduction

Among all topics of sustainability evaluation, the energy sector is probably the most traditionally and also currently studied sector. Energy is the necessity of life (Washington, 2013, p.5-14) and the whole industry sector covers the process of finding energy sources, extracting, refining, and delivering the refined sources to production, supply, consumption and the sustainability objectives of efficient, clean production and secured energy supply (Odum, 2007, Marvuglia et al., 2020). Besides, the whole industry of energy must face the negotiation brought by temporal ethical gaps and geographical connections (Bonnedahl, 2019, p.77-95). Thus, this section collects empirical studies of sustainability evaluation within the sector to understand in detail current presentation of sustainability evaluation elements.

2.5.2 Data and Method

The systemic literature is done by collecting and screening empirical studies of highly discussed sustainability evaluation studies. Based on the Scopus database, run in July, 2019 and renewed in July, 2020, the articles are screened by excluding conference papers, the articles that are not approachable, and the articles that are not in English. Then, due to the large amount of articles, the cut-off point is set 50 times where for articles published in recent 3 years above 45 are also selected, with respect to newly published articles (Threr, 2018). Then, bad citation articles are artificially excluded. Eventually, 108 relevant articles of empirical sustainability evaluation studies are obtained (see Appendix C.1 for list of articles).

The articles are thoroughly viewed according to the elements of evaluation identified from review Section 2.2.2, respectively starting from the lead of evaluation, the value paradigm for evaluation, and consecutively to the indicators used for evaluation.

2.5.3 Article Descriptives

This section presents the statistical descriptives of the selected sustainability evaluation empirical studies screened, mainly from the perspectives of years and journals. According to Figure 2.11, sustainability evaluation has been performed since 1968 and most highly cited articles are publicised since 2007. Although SD is a concept that has been proposed by the UN in the 1980s, sustainability has been a topic of evaluation studies since the 1960s with growing popularity since then.

Also, it confirms that the publication of the Brundtland report has significantly emphasised sustainability and SD in evaluation practices. It also suggests that many later evaluation researches would be done on the basis of studies done between 2008 and 2014. The definition to sustainability evaluation, the construction of frameworks, and development of evaluation methods could be heavily guided by past evaluation practices done during the period.

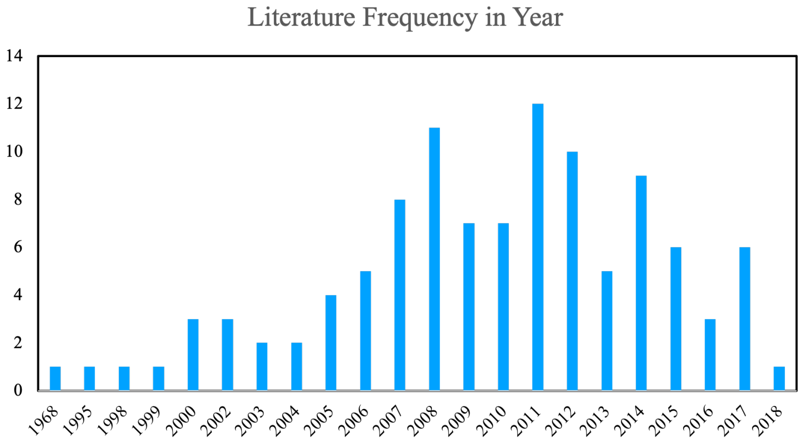


Figure 2.11 Count of Article Frequency in Years.

From the perspective of journal articles that published the empirical studies, it is apparent that heated topics include environment, ecology, and SD, consistent with that revealed in Section 2.5. In the chosen articles, construction, industry, SD and climate change, ecosystem, transportation, and tourism seem to be heated topics. It indicates that the sectors of energy consumption are heavily studied and the influences of energy could be wide spread in various fields, including the industries, the ecosystem, and specific projects. It confirms that sustainability evaluation could be performed for wide fields of study. The contextual background of sustainability evaluation could be largely different when sustainability or SD is defined in contextual way.

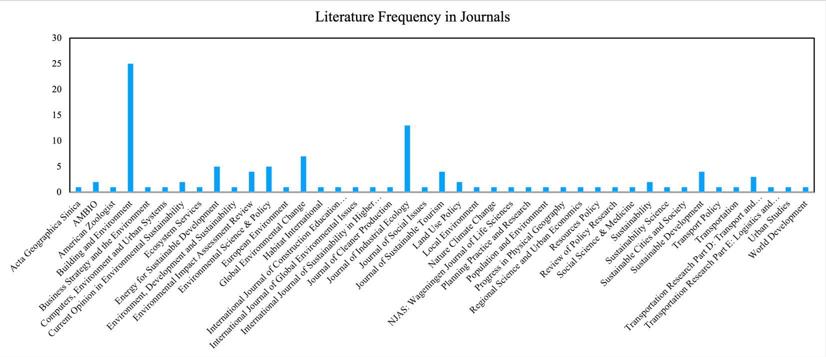


Figure 2.12 Count of Article Frequency According to Journals.

Confirming that the overall trends of the studied group of articles are consistent with past analysis, as the information carried by the descriptives of the article distributions could be limited, the following sections look into the contents, mainly from two perspectives, the evaluation elements in sustainability evaluations and the roles of stakeholders in the sustainability relations demonstrated in the studies.

2.5.4 Lead of Energy Sustainability Evaluation

All the articles are analysed for each one of the elements in Table. 2.2, including the lead of evaluation, the objectives, the DMs, the KSs, the evaluation subject, resources for evaluation, the evaluation framework, measurement, methods, and the results. Since energy sector, too, is a wide field of study with varied context, the analysis focuses on the features presented in each element.

First of all, among the articles, the lead of sustainability evaluations are inevitably human. This may be that the accurate communication is only capable among human communities and it is the collective values of the society that may have revealed the problematic situations between the urban world and the natural world. Evaluation, being a strong reflection to the interest of the evaluator, only exhibit certain problems under certain perspectives (Lebas, 1995). Thus, the sustainability values being evaluated or being pursued in evaluation would be always biased by human cognition. However, we attribute that the outcomes of such technical limitation over communication with non-human stakeholders would be more direct and significant over the stances of the DMs, which would be analysed in the following section.

The lead of evaluation could be roughly divided into external authorities and organisations or internal institutions. Sustainability evaluation could be lead by external academic groups, intrigued by governmental authorities, and national and international organisations (Holden and Hyer, 2005, Lundy and Wade, 2011, Ozaki, 2011, Stagl, 2006, Wu et al., 2016). Ozaki (2011) evaluates the public opinions towards sustainable lifestyle. Lundy and Wade (2011) observes social technology development in urban sustainability where the need for technological development has been widely recognised as welcomed social advancement. Stagl (2006) and Wu et al. (2016) perform national level sustainability evaluation for energy and technology based on targets proposed by international organisations. Holden and Hyer (2005) performs sustainability evaluation for fuels by measuring for the ecological footprints, targeting for providing suggestions for regional authorities. All such studies of sustainability evaluation lead by external groups often tend to form comparative results for policy management. Also typically, many studies focus on conducting sustainability evaluation serving for internal management purposes. Berardi (2012) and Jim and Tsang (2011) evaluates the energy consumption efficiency for specific buildings or functional modules using internal data of building construction. For slightly larger system, Bohdanowicz et al. (2011) evaluates for the contributions to sustainability by projects. The leads of internal sustainability evaluation would often include owners of the evaluated subject, even if the evaluation could be done by third party academics.

The different originations of lead of sustainability evaluation could influence other elements of sustainability evaluation, especially, the objectives, which would guide the compositions and preferences of the evaluation. Although determined by possible objectives given by the lead, the above-mentioned internal evaluation could also be done from the external perspective when internal resources and stakeholders are not necessary. Thus, understanding that sustainability evaluations are generally lead by different groups of people, after acknowledging that sustainability evaluation would be inevitably biased by human cognition, what matters more is the DMs determined in evaluation and the objectives of evaluation that would bring much difference to the sustainability relations considered in the evaluation.

2.5.5 Stances of DMs

This section analyses for the 108 articles over the stances of the DMs. The stances are categorised as universal and human central, where we also noticed that human central stances also present different biases. The results of article counts are presented in Table 2.11.

Just alike past evaluations, a great many sustainability evaluations are done under organisational objectives, as being more cost-efficient and more environmental friendly would both improve sustainability (Fitzgerald et al., 1991, Bauer et al., 2017). Sustainability evaluation with such objectives determined by the DMs would only consider the valuation to social-environmental components under human values. Without consideration to the values of other species, such

Table 2.11 Percentage of types of decision maker stances in sustainability evaluation empirical studies.

Stances of DMs		**Article Cnt.**	**%**[1]	Explanation to Stance
Universal		7	6.42	Not biasing to human interests.
Human	Partially Universal	4	3.67	Limitations of human interest lead sustainability evaluation is recognised.
	Environment	46	42.20	Evaluated under human interests, mainly concern environmental issues and interests.
	Economic	15	13.76	Only concern economic interests.
	Social	22	20.18	Evaluated under human interests, extending to social externalities and well-being.
	Equally concern 3 pillars	15	13.76	Equal treatment to environment, economic, and social interests.
Sum		108	100	

[1]. The total number of article is 108.

studies could be categorised as holding human central stances by its DMs. On the other hand, we notice from Brown and Ulgiati (2004) and Woodwell and Whittaker (1968) that, underlying in the energy industry, nature itself is also a massive complicated production system that is not guided by human interest but produces desirable outputs that human need. Also, conceptually, as Holden and Hyer (2005) concludes, sustainability evaluation resources, measurements, and indicators should be adaptable for all aspects of sustainability relations, including human impacts, ecological presence of the natural world, and the thermodynamic patterns embedded. Hence, the DMs are capable to hold the *universal* stance that the valuation system itself is not fully determined by human values but also considering the values of other species.

Among the articles studied, the majority DMs hold human central stances. The proportion of sustainability evaluations lead by human interests exceeds 90% where only 7 articles stood on the universal stance. Indeed, sustainability evaluation thrive being human central. The results stand with the previous claim that we are attempting to contribute over limited conditions to plant sustainability. In other words, in sustainability evaluation, holding human central stances would not fully fail the evaluation, but it is more likely that the evaluation is only suitable for limited situations as important value links not among human are missing.

Shown by 42.20% , the key concern of sustainability is human respect to the environmental conditions. The concerns scatter over fundamental living conditions in the energy sector. For example, Sheehan et al. (2003) evaluated energy and environmental performance of biomass fuels. It is noticed in their work that the transformation from biomass to energy fuels brings heavy CO_2 emission and downstream environmental impacts. Differently, Deuble and de Dear (2012) evaluates the living condition of human through ventilation, temperature, noise and lighting and collectively target for energy saving. Cultural and aesthetic values are not popularly discussed with environmental concerns. However we also notice from 13.76% and 20.18% that during sustainability evaluation decision-making, these values that are currently mainly serving for human interests could be valued above other concerns. These include and are not limited to leisure and recreational functions (Bohdanowicz et al., 2011, Sandstrom, 2002), historical and aesthetic functions (Sandstrom, 2002), tourism availability (Becken and Patterson, 2006, Taylor and Ampt, 2003), stakeholder physical and mental well-being (Keirstead and Leach, 2008, Duchin, 2008, Jin et al., 2006), transportation convenience (Huang et al., 2009, Taylor and Ampt, 2003), individual economic gains (Hertwich, 2008), cost-benefit capital management (Langston et al., 2008, Berges et al., 2010, Deng and Wu, 2014, Tatari and Kucukvar, 2011), cultural attitudes (Wolsink, 2010, Liang et al., 2014, Masera et al., 2005). Thus, it needs to be recognised that sustainability evaluation decisions made based on human cultural and aesthetic values is not flawed. However, it needs to be recognised that its contributions to sustainability under the current techniques are limited as cultural and aesthetic values need to be understood with mature communicational techniques among all beings. We recognise that efforts have been made by mainly governmental bodies standing on human central but partially universal stances attempting to bring wider attention to the values of non-human beings.

Indicatively, the 7 articles with universal stances suggest some treatments to values that can be applied for conducting sustainability evaluation for universal stakeholders. The collective sustainability objectives can be measured using quantities with uniform units such as energy, emergy, or the ecological footprint (Brown and Ulgiati, 2004, Ingwersen, 2011, Frey et al., 2008, Wood and Lenzen, 2003). Human interests are presented as part of the sustainability objectives that would influence the composition of the evaluated system. Differently and more ambitiously, Vanham (2016) and Bjrn and Hauschild (2013) study more neutral ecosystems such as the water cycle or the energy cycle of the natural world. Besides, Woodwell and Whittaker (1968) acknowledges that the natural environment itself is an I-O system and also a consumer of its own products.

It is suggested that taking universal stances by the DMs would mean the sustainability evaluation would base on larger systems and hence, great challenge is proposed for sustainability evaluations standing on universal stances over evaluation resources. As the system become complex, some data in the ecology system are not recorded and would require estimation or need to be eliminated from the evaluation (De Meester et al., 2009). Also, since some records that should be conceptually studied are not approachable or some may not be necessary (Wolsink, 2010), better understanding to the indicators would be necessary and developing more suitable measurements remain problematic.

2.5.6 Evaluation Objectives, Frameworks, and Measurements

Following the evaluation elements, the objectives practically set for sustainability evaluation, the framework, the dimensions of metrics described by the frameworks, and the measurements are analysed for all 108 articles. Especially for the energy sector, typical evaluation frameworks include the resource management (Asif et al., 2007, Blengini, 2009, Gonzalez-Garcia et al., 2018), the TBL (Sheehan et al., 2003, Riahi et al., 2017, Klein et al., 2005) and special TBLs (Deuble and de Dear, 2012, Ozaki, 2011, Noppers et al., 2014, Pelletier and Tyedmers, 2011), industrial or urban ecology (Hertwich, 2008, Sandstrom, 2002, Li and Mak, 2007, Chavalparit et al., 2006), environmental accounting (Becken and Patterson, 2006, Brown and Ulgiati, 2004, Ingwersen, 2011), and ecosystem succession or the planet boundary (Westley et al., 2011, Woodwell and Whittaker, 1968, Frey et al., 2008). Only presenting typical articles above, Appendix C.2 presents the statistical counts of articles that are classified in each type.

For presenting collective features of sustainability evaluation objectives, contextual narratives are transformed into general forms for its evaluation subject and objectives. For example, the production of wood fuels (Bailis et al., 2015) and power generation (Sheu, 2008) are both concluded as transformation systems containing, to the least common, the sustainability objective of minimising negative environmental impacts. To note, one performance of evaluation could hold multiple sustainability evaluation objectives. Also, the framework used for sustainability evaluation and the associated indicator system structure constructed, and the measurements used are analysed. The results are presented in Table. 2.12.

Table 2.12 Frameworks, objectives, and measurements in sustainability evaluation.

Sustainability Evaluation Framework	**Applied General Subject**	**Sustainability Objectives**	**Dimensions**	**Metric**	**Measures**
Resource Management (Operational level objectives)	Construction life cycle Energy flux Transformation system Global sustainability targets	Maximise profit Energy saving: reduce embodied energy Energy saving: reduce energy consumption Minimise negative environmental impact Enhance emission control Efficient material use, reuse, and recycling Optimise management for transformation Well use of nature's services	Material	Primary resource	Transformational material supply Durable materials consumption Total consumption Space for production
				Recycled resource	Recyclable materials consumption Resource collected on-site Gross credit Recycling potential
				Resource property	Resource productivity Resource extraction rate
				Product	Product service time Product service type Production quantity
			Energy	Demand	Exergy Emergy Demand
				Consumption	Consumption intensity or rate Electricity consumption Natural gas consumption Peat-coke consumption Diesel consumption Embodied energy
				Capacity	Production mix (Res and Non-res)[1]
				Transformation	On-site energy production Energy budget Energy saving Energy saving design
				Energy Efficiency	Primary consumption to on-site energy production Energy efficient equipment installed capacity
			Economic	Cost	Total cost Installation cost

Continued

Sustainability Evaluation Framework	**Applied General Subject**	**Sustainability Objectives**	**Dimensions**	**Metric**	**Measures**
					Transportation cost Operational cost Waste treatment cost Storage cost Carbon price
				Capital production	GDP Total revenue Net Profit
				Impact	GDP growth Level of corruption Financial risk
			Social	Demographic	Population Migration
				Global	International trade level Internation environmental policy
				Stakeholder	Energy consumption pattern
				Food	Food demand
				Transportation	Distance to target place Average road speed Area of pavement Pavement lifetime
			Environmental	Climate change	Global temperature increase CO_2 emission GHGs emission Global warming potential (CO_2e) CO_2 emission reduced CO_2 emission intensity
				Toxicity	Human toxicity Eco-toxicity
				Air pollution	CO emission NO_x emission SOx emission VOCs emission PMs emission N2O emission CH4 emission NH3 emission Winter and summer smog Ozone depletion potential
				Acidification	Acidification potential (H+) Mass of SO4-
				Solar	Solar radiation
				Land	Land cover and use change Soil moisture Soil temperature
				Water	Eutrophication potential (PO4-) Precipitation
				Chemical	Chemical discharge
				Waste	Total waste generation Solid Waste generation Waste water generation Waste recycling impacts
				Human commodity	Temperature Urban heat island effect Amount of daylight Daylight sufficiency
			Sustainability	Direct index	Material efficiency Reduced total CO_2e emission Regional variance Stakeholder satisfaction
				Aggregated index	Energy and environmental performance score Environmental performance weights Bio-physical performance score
TBL (Compound systems)	General system or process Equal importance for 3 pillars Overall evaluation for 3 pillars	UN SDGs Reduce CO_2 emission Enhance GHG sinks Sustainable product selection Enhance stakeholder sustainability participation Minimise long-term management requirement Implement long-term objectives Benchmark subsystems of urban metabolism	Economic	Cost	Life cycle cost Import Equipment cost Transportation cost Construction cost Long-term management cost Production cost Clean up cost Waste disposal cost Environmental tax Air emission cost

Continued

Sustainability Evaluation Framework	**Applied General Subject**	**Sustainability Objectives**	**Dimensions**	**Metric**	**Measures**
					Effectiveness of support for civil society initiatives Cost per person
				Product	Product quantity Product price Property value
				Value product	Additional income for rural population
				Economic efficiency	Investment pay back period Reduced time in transformation
			Social	Infrastructure	Accessibility to public facilities Human service capacity
				Equity	Justice Social resource distribution Social sustainability ethics
				Institutional	Social responsibility Policy (on different levels)
				Security	Social resilience to natural catastrophe Tax revenue
				Food	Food security
				Transportation	Average speed on road
				Community livelihood	Counts of pedestrians and cyclists Residential density
				Labour	Employment Job creation Employee Income
				Technology	Energy certificate Production mix (Res and Non-res)[1] Energy efficiency R&D Investment
				Education	Number of schools
				Safety	Regional average human lifetime Deaths from natural catastrophe Community risk Traffic deaths or injuries Worker's risk on-site Insurance cost
				Cultural	Heritage sites Streetscapes Symbolic values Sustainable lifestyle
				Stakeholder responses	Mitigation Adaptation Stakeholder engagement Stakeholder demand Stakeholder influence Organisation reputation
				Other	Time spent for evaluation
			Environmental	Resource	Biocapacity Fishery Grazing Forestry CO_2 uptake land Resource conserves
				Environmental load	Total consumption Quality material consumption Recycle or reusable material consumption Energy consumption (primary, secondary) Remaining contamination (area of land)
				Climate change	Climate change policies CO_2 emission Global warming potential (CO_2e) 100
				Air pollution	SOx emission VOCs emission Number of people impacted PM formation potential
				Waste	Waste generation Toxic waste generation Solid waste generation
				Land	Land use Urban scale Land degradation (ha) Protected area Area for redevelopment Land coverage for transportation
				Water	Water consumption Water harvested on-site Sea level rise
				Direct indicator	Production quantity Product lifetime Reduced secondary contamination

Continued

Sustainability Evaluation Framework	Applied General Subject	Sustainability Objectives	Dimensions	Metric	Measures
					Cost saved from sustainability implementation Stakeholder satisfaction Ecological footprint
				Aggregated index	Risk (spatial, temporal, social) Overall danger Resilience Sustainability performance scores System performance score Sustainability performance weights Stakeholder preference determined weights
Special measurement in TBL	TBL interlink aspects	Improve quality of life Enhance community livelihood Encourage green product through cognitive and normative implementation	Social environmental	Land	Land product productivity Land use change by conflict
				Green value	Cognition to sustainability issues Awareness to impact of climate change Environmental norms
			Environmental economic	Product	Green product functionality
			Social economic	Uncertainty	Risk controllability
	TBL and EKC	Enhance sustainable energy consumption concerning global economic and environmental background	Social economic	Development	GDP per capita Purchasing power parity Market exchange rate Secondary energy use to GDP
				Energy	Electrification (%)
			Environmental-economic	Environmental impact	Emission per capita (kg/cap) Emission intensity (kg/USD) Emission concentration (kg/m^3)
	TBL and technology	Energy security: alternative production Improve technology, economic, environmental benefits Adoption of green innovations	Technology	Energy security	Technology efficiency Technology compatibility Technology reliability Technology durability
				Land	Suitable land for technology implementation
				Product	Functionality and efficiency Production quantity Recycling rate Emission reduction rate
	TBL and institutional	Relief to national specific problems Effective support to investment and policy	Institutional	Governance	Sustainability policies on different scales
				Education	Capability for learning
				Project	Project release
				Appraisal setting	Mechanism for monitoring and assessment for sustainability
				Feedback	Stakeholder feedback for policies
	TBL and resource management	Improve social-psychological acceptance to implementations Improve bio-physical efficiency Improve survival of the planet	Resource management[2]		
2D TBL	Social environmental	Reduce energy consumption Reduce environmental impacts through social controls Reduce social environmental risks Enhance use of nature's services Improve attitude to environmental implementations	Social	Demographic	Gender Age
				Infrastructure	Paved road area per capita Drainpipe line length per capita Utility land area per capita Hospital density Primary school density Shops/restaurant density
				Institutional	Sustainable energy policy
				Transportation	Public transportation availability Transportation efficiency
				Technology	Installation of emission remove equipment
				Energy	Fuel consumption Raw material consumption Electricity consumption per capita Natural gas consumption per capita
				Resource	Water consumption per capita Off-site resource consumption On-site resource consumption
				Safety	Fire accidents per ha Health risks Traffic safety (by accidents) Respiratory illness Heat flux reduction
				Culture	Coverage of decoration
				Stakeholder responses	Environmental attitudes Satisfaction
				Energy	Embedded energy Energy supply distribution
				Solar	Solar radiation

Environmental

Continued

Sustainability Evaluation Framework	**Applied General Subject**	**Sustainability Objectives**	**Dimensions**	**Metric**	**Measures**
				Climate change	CO$_2$ emission
				Air pollution	SO2 emission VOCs concentration PM2.5 emission Ozone depletion potential Smoke reduction
				Wind	Wind velocity
				Waste	Waste water generation
				Land	Brown space area Green surface area
				Water	Surface water eutrophication Harvested rain water
				Human commodity	Temperature Ventilation Relative humidity Lighting Noise level Area with unacceptable noise level
			Sustainability	Direct indicator	Non-renewable resource consumption Energy saved CO$_2$ emission reduced Acceptance to energy saving implementation Stakeholder satisfaction
				Aggregated indicator	Environmental quality (standard set by social well-being) System performance score
	Environmental-economic	Promote sustainable lifestyle	Economic	Product	Local capital increase Global capital increase
			Environmental	Land	Required land for production
	Social-economic	Cost management to green products	Economic	Cost	Total cost
				Product	Transaction price
				Value product	Green price
			Social	Product	Product ownership (stakeholders) Product service time
			Sustainability	Direct indicator	Long-term total cost
Industry/Urban Ecology (System functional division of subsystems)	Environmental protection implementations Performance of cities Transformation network Water, energy, land network Urban ecology stakeholder responses Human-nature ecosystem	Promote economic influence of sustainable product consumption Sustainable resource extraction or production Reduce network resource use Enhance industrial emission control Improve organisational environmental awareness Control environmental outcomes Reduce network environmental impact Efficient use of nature's services Improve human/social well-being Maintain urban human-nature relations Industrial ecosystem stability Improve social/urban metabolism Sustainability of urban cities	Transformation	Resource	Total consumption Durable material used Recyclable materials used Energy supply Water consumption
				Recycling	Waste recycled
				Technology	Technical infrastructure coverage Transformation Capacity Technology change
				Product	Total industrial production Embodied energy in product Storage capacity Biomass production Biogas recovered from waste water Bioenergy production
				Efficiency	Energy consumption per unit GDP Resource use intensity
			Economic (local, global)	Contextual	Economic growth Value-added
				Cost	Lifecycle total cost Installation cost Operation and management cost Maintenance cost Labour cost Carbon cost
				Productivity	GDP to labour
				Value product	Income Fuel price Electricity price Government sustainability strategy
				Bio-economic pressure	Total exomatric energy metabolised over working time
				Demographic	Population Average body mass Industry categories Urban structure and functions Urban scale growth Cultural identity City identity and character
				Global	Importance level of green implementation to sustainability Sustainability initiatives
				Institutional	Appraisal mechanism for environmental practices

Social/Human
(local, global)

Continued

Sustainability Evaluation Framework	Applied General Subject	Sustainability Objectives	Dimensions	Metric	Measures
					Environment and energy policy Governance transparency
				Food	Population access to food Food consumption Food demand
				Transportation	Car ownership Distances to facilities
				Land	Density of parks Human service Human activity concentration Availability of green space management plans Natural equity
				Labour	Employment Total quantity of human activity
				Technology	Innovation R&D investment
				Energy	Electricity supply Fuel consumption Production mix (Res and Non-res)[1] Installed capacity of energy plants Energy consumption share by activity Consumption pattern
				Education	Education ratio PhD concentration
				Safety	Worker injuries Fatalities due to large accidents Human toxicity potential Radiation impacts
				Stakeholder	Stakeholder connections (local, global) Stakeholder engagement Stakeholder influence
				Environmental awareness	Aware to environmental goals Aware to environmental implementations
			Ecosystem (local, global)	Resource	Stocks and reserves Exergy Freedom to implement environmental practices Accessibility to technology and funding for environmental practices Time for environmental practices
				Ecosystem services	Exomatic energy supply Exomatic energy consumption Yield growth rate per year Biomass potential
				Stability	Degree withstand environmental and climatic changes Mineral decomposition rate Expected time for atom decay
				Biodiversity	Biodiversity species level Regional biodiversity
				Meteorology	Climate zone Wind velocity Precipitation Regional temperature
				Air condition	CO_2 emission GHGs emission Local air pollution reduction
				Acidification potential	SO2(gas) emission equivalent
				Waste	Total waste production Waste water production Radioactive waste water Waste biomass production Waste discharge amount
				Land	Land use (renewable, degraded) Size of green space Habitat continuity Deforestation per year Soil chemical status Fertiliser use
				Animal	Animal production system
				Water	Fresh water reserve Eutrophication potential (PO43̂-)
				Toxicity	Terrestrial eco-toxicity potential Pesticide use
				Noise	Local noise reduction
				Direct indicator	Cumulative exergy Ecological footprint Carbon footprint System exomatic energy consumption rate Local exomatic energy consumption rate System social metabolism rate

Sustainability

Continued

Sustainability Evaluation Framework	**Applied General Subject**	**Sustainability Objectives**	**Dimensions**	**Metric**	**Measures**
					Reduced waste discharge rate Emission intensity Stakeholder sustainability satisfaction
				Aggregated indicator	Eco-indicator 99 Environmental load System synergetic reduction of GHGs Weighting methods System performance (3Es)
Environmental Accounting (Unified construction of systems using emergy measures)	Industry emission control System sustainability	Reduce energy use Control carbon dioxide emission Use of renewable energy Maximum performance from human and biosphere interfaces System sustainability: continuous energy production	System composition	Materials	Material types Quantity Emergy Exergy
				Service	Service types Service quantity
				Production	Utility Welfare Investment
				Transformation	Consumption activity intensity Activity transformity Exergy efficiency
			Value	Capitals	Environmental capital Human capital Social-organisational capital Manufactured capital Credit capital
			Energy use	Energy	Energy intensity Total energy consumption Production mix (Res and Non-res)^1
				Emergy	Emergy yield ratio
			Environmental	Emission Environmental load	CO_2 emission Environmental load ratio
			Sustainability	Direct indicator	Energy per unit CO_2 emission Emergy sustainability index Environmental compatibility factor
Ecosystem Succession Planet Boundary (Unified integration of Earth systems)	Social-ecological systems General transformation system	Enable system transformation of technology Development under environmental boundaries Continuous system transformation (system sustainability)	Natural world	Nature's services	Solar energy input Carbon sink Soil recovery Oxygen production Water purification Air pollution diffusion Primary production Wild life habitat Biodiversity (habitat, plant, animal, water) Land cover variety
				Cap	Harvest limit Degraded land Disturbed plants Enrichment ratio Biomass capacity
				Metabolism	Endogenous change of hydro cycle Endogenous change of carbon cycle Endogenous change of population Endogenous change of climate
			Value	Value	Intrinsic asset value Recreation and aesthetic value
				Economy	Economic growth
			System transformation	System	Respiration Production efficiency Production mix (Res and Non-res)^1 Electricity production Fossil fuel consumption Nuclear fuel consumption
				Air	CO_2 emission CO_2 exchange rate GHGs emission Air pollution
				Heat	Temperature
				Land	Soil fertility degradation Land cover change
				Water	Humidity Water cycle Water categories Waste water generation Water contamination
				Infrastructure	Presence of roads Sewage system coverage

Human

Continued

Sustainability Evaluation Framework	Applied General Subject	Sustainability Objectives	Dimensions	Metric	Measures
				Agriculture	Crop production systems
				Education	School rankings
				Safety	Crime rates
				Innovation	Available land Capital incentives
				Cultural	Protected land Restoration projects
			Sustainability	Direct Indicator	Net primary production Fisher information index Entropy-based sustainability score Ecological footprint Water footprint Emergy Product transformity

1. The production mix indicates the method of energy production which usually include non-renewable technologies of fossil fuel (oil, gas, coal etc.) combustion and nuclear. The renewable technologies include solar photovoltaic, geothermal, wind, biofuels, hydro, and tide. Although there are other ways of production, they are not specifically categorised in the table nor concerned in this thesis.

2. When TBL framework is used with resource management frameworks, the additional dimensions used in the framework besides economic, social, and environmental aspects are contingent with those under the resource management framework. Hence, they are not separately presented.

Connecting frameworks with objectives

The main frameworks of sustainability evaluation relating to the energy sector can be concluded as resource management, TBL, industry or urban ecology, environmental accounting, and ecosystem succession or the planet boundary. To note, limited by other elements of evaluation, the conceptual frameworks used to observe the evaluated subject can be different from the the frameworks that are eventually used in evaluation. While the majority of evaluation studies are done using the TBL framework with urban ecology and resource management following up, it can be seen that the sustainability objectives present different focus by the frameworks while the measurements used under each framework show high similarity.

Resource management seems to mainly deal with processes whose system boundaries are relatively explicit following the production relations. Production, construction, energy, or their life cycle flows clearly present statements to what the researcher define as being sustainable or contributing towards global sustainability. From its sustainability objectives, the solid ground is apparently set on the transformation process or system and thus, sustainability objectives often seem more likely to be additional objectives attached to the process for cost benefits or system functional benefits. We notice that among the articles analysed, the majority attach sustainability objectives as additional social or environmental concerns. Typical examples are product based sustainability evaluations such as high-tech materials (engl et al., 2008), buildings (Blengini, 2009), green products (Kosareo and Ries, 2007), supply chain(Sheu, 2008), and on the global scale, energy based development analysis (Kriegler et al., 2017). However, as it can be seen in the articles within which sustainability objectives are systemic derived, the cap of nature's services, the planet boundary, are often recognised to be apparently affecting the transformation system. Jim and Tsang (2011) recognises the reduction of energy consumption for heating and cooling through embedding green roof. Besides, Koroneos and Dompros (2007) recognises the limited capability of treating wastes for production company and the limited capability for purification by the nature. Comparatively, the sustainability objectives attached to the evaluation often requires the process of understanding how the objective is linked to the evaluated subject while the later naturally determines the core environmental concerns. Overall, resource management framework as a management tool embeds managemental pursuits into the evaluation objectives with clear preferences for decision-making.

More severely, TBL presents heavy bias to evaluating under sustainability objectives that are externally given. This can be explained in a way that TBL framework mainly serves as an sustainability assessment tool through the three aspects (Savitz, 2013). Merely looking at the evaluation objectives, they are bound with specific problems for the three pillars. While the UN SDGs can be clearly categorised to different subsystems, economic concerns include production demand and management requirements; social concerns include human well-being and mainly satisfaction to sustainability implementations; and environmental concern currently mainly focus on climate change and pollutions. In other words, TBL is now mainly used for evaluating SD through economic growth, social well-being, and reducing environmental impacts and it is not unified in the evaluation preferences for the three pillars. This may explain why sustainability evaluation using TBL could also be done by mainly concerning two out of the three aspects. In the same time, TBL thrive in mainly two ways. Some researchers concern that the three subsystems of TBL is insufficient to cover all the key issues for the evaluated subject and hence attaches other measurements including technology and governance. Besides, much concern is attached to the interlinking parts of the three aspects. Social environmental aspects mainly reflect sustainability from cognitive and normative aspects which would influence the demand for green products, the aspects that would be environmental-economic. However, as Basiago (1995) points out, whether environmental-economic products are just for sustainability should be put under criticism. Reflecting environmental-economic relations with more explicit forms, TBL is used with the environmental Kuznets curve (EKC). The meso-scale evaluation mainly provided cross-regional suggestions for more renewable energy consumption (van Ruijven et al., 2008).

Differentiating from industrial or urban ecology, the system derived sustainability objectives are more popularly applied. In some senses, under these frameworks, sustainability is more popularly regarded as an outcome of system performance where the evaluated targets become more varied in network presence instead of focusing to only transformation processes. Or to the least, as Bjrn and Hauschild (2013) states, indicators such as eco-efficiency are in fact compensations to global systemic indicators. However, comparing with fully systemic frameworks, industrial ecology and urban ecology frameworks hold the common characteristics that sustainability decisions are made by regarding the society as an organic body in the nature with intentional functions. Both recognises that it is mainly the social stakeholders who are deterministic in sustainability evaluation decision-making. Besides, both set the objectives of systemically improving resource use efficiency and reducing negative environmental impacts as the historical inheritance of accountability from the Great Acceleration, during which the natural environment has already being changed to a completely different state where cities and the relations with the natural wild environment are completely different from the state before the acceleration of human activities (Steffen, 2005). Focusing on slightly different aspects, industrial ecology sets objectives more based on the industrial transformation system. Thus, efficiency resource use and emission control are popularly set as sustainability objectives for the transformation network. In the same time, urban ecology looks into more intangible aspects over the human-nature interface where efficient resource use and emission control are usually the compensated sustainability objectives for realising social well-being. However, it is clearly recognised in industrial or urban ecology framework that systemic changes are always linked with different aspects on regional and global scales. Economics, society relations, and ecosystem services and problems are always indirectly influenced by regional problems, especially linked by the requirement to sufficient land to load all activities (Gawel and Ludwig, 2011). In later analysis, we regard industrial ecology and urban ecology as equivalent concepts mainly using the term urban ecology.

Environmental accounting, seemingly more like a method to illustrate transformation processes, is regarded as a framework for sustainability evaluation as it holds different perspectives in the objectives from other systemic frameworks. Contingently, the sustainability evaluation objectives also cover efficiency energy use, emission control, better performance of transformational systems over the human-nature interface, and sustainability in the form of security for the transformation system. The system performances are being evaluated from the perspective of total energy or material needed for the support for the current system. The network constructed for evaluation, that is the evaluated system is being generally guaranteed for the potential to sustain over the accounted standard. In this way, although not explicitly stated, environmental accounting evaluation base decision-making on the benchmarking of system performance over the accounted standard.

Eventually, probably holding the most solid physical stance for sustainability evaluation, ecosystem succession and the planet boundary frameworks willingly describe extraction and consumption of natural materials and energy as nature's services and respect the upper limit capacity for nearly all materials and forms of energy and builds the evaluated system on such perspective for sustainability evaluation. To note, even if the evaluated system is constructed under relative neutral stance for all beings in the natural world, the decision-making during the evaluation can be human value lead (Westley et al., 2011, Basiago, 1995), changing the dominant stakeholder in the evaluation. The slight difference between the two framework is that the planet boundary framework describes capacity, resilience, stability,which all makes up the sustainability of the ecosystem, as the upper bound that guarantee the living of the organisms on the planet while ecosystem succession describes the dynamic changes of the structure of the ecosystem and the dynamic systemic changes of the upper bound. Limited by evaluation techniques and resources, the sustainability objectives for the two frameworks also present similarity. Thus, we also regard ecosystem succession and the planet boundary as same concepts for the categorisation of evaluation frameworks, mainly using the name planet boundary. Overall, under the categorisation of different frameworks, sustainability evaluation objectives present high similarity since the objectives attached to the system are commonly unified by human values for social well-being and those that are systemically derived tend to be different clarifications to the attributes of sustainability.

Dimensions of frameworks and measurements

The dimensions covered in the evaluation mainly attempted at reflecting the transformation process or system, the initial system, and the related attributes around it and the environmental issues caused by the initial system or the relevance to the environmental issues that we intentionally desire to deal with. How to open up the black box of system transformation and the creation of relevant influences resulted in different categorisations from dimensions to metrics and measures.

We realise that the measures used are quite similar across frameworks where the difference mainly lies in systemic measures relating to the world view of the frameworks. Aspects relating to the transformation process share the same measures, including material and energy supply, consumption, and production of energy, product, and waste outcomes. It can also be noticed that the measures for environmental issues share the same metric. Resource supply, nature's services, environmental load, biodiversity, water, land and soil, air condition and pollution, climate change, acidification, eutrophication, solar and lighting, heat, and radioactive issues mainly cover all interests of researches. Similarly, economic values cover the consumption and accumulation of capitals and societal constructions include aspects of social well-being such as demographics, social infrastructure, institutional aspects, human safety, societal security, labour, cultural values, and intangible aspects such as stakeholder responses and satisfaction. Apparently, most of the fundamental measures are covered in the SDGs by

UN. However, these descriptive measures for the physical and cultural status of the natural world could belong to different metrics or dimensions under different frameworks. Merely on the level of measures, environmental related capitals including the carbon price, waste treatment cost, environmental tax, tax revenue, green price which are mainly included in the dimension of economic aspects, could have different interpretations. While popularly, environmental taxation is regarded as a cap to economic growth (Erickson and Gowdy, 2007, 37-52), even under TBL, tax revenue can be treated as an indicator for social security relating to the social capability to be environmental resistant. Over metrics, while resource management and TBL frameworks note environmental issues as environmental aspects of sustainability, the system connection between on-site influences and the off-site influences would not be understood as well as putting it under ecosystem aspects such as the urban ecology or under system compositions like environmental accounting and the planet boundary. This is mainly caused by the amount of consideration to the interlinking interfaces of, for example the society and the natural environment, if the they are intentionally separated as two subsystems of the natural world. Comparative studies using different frameworks found better indication for sustainability implementation from the systemic view than evaluating using isolated subsystems (Doan et al., 2017, Berardi, 2012). Berardi (2012) concludes that while resource management would neglect environmental aspects that are outside the transformation system where sustainability implementations from TBL could expect better performances, the collective quality for ecological, economic, and social aspects are still not well evaluated by TBL. Doan et al. (2017) further tests on product based sustainability evaluation that sustainability implementations from TBL would not result in better implementations than industrial ecology through the construction of energy convectional system crossing the social-natural interface. TBL framework itself also thrives with special measurements of including the interlinking aspects.

Besides, the placement to energy related indicators and metrics vary significantly. Resource management regards energy as the other input for transformation beside materials. Under TBL, energy related cost are considered as capital inputs, and relevant mix and capacity are regarded as part of social construction. This is more clearly presented in TBL using two dimensions of social and environmental. Primary energy fuel and energy consumption are included under social aspect and relevant outputs such as embedded energy in product and energy distribution are put under the environmental category. Special treatment separates technology from TBL pillars and embeds related aspects of energy security and production efficiency. Urban ecology contain energy related metrics and measures in almost all dimensions. To demonstrate the transformation process, energy supply lies under system resources, energy production mix lies under transformation technology, and secondary energy source production can be included in the products. In the meantime, energy prices are well categorised into the economic aspects. Under the human interface, energy consumption and consumption pattern are regarded as social structural reflection. Energy is also related to the ecosystem interface in terms of reserves. Environmental accounting even more heavily respect the energy flow through the transformation system. It can be done using indicators such as emergy and exergy, where accumulation of energy through every node in the system is analysed and evaluated. Similarly treating energy in systemic way, planet boundary relates energy with nature's services, the system transformation, and the outcomes of system metabolism.

From the perspective evaluation, the different placement to energy related indicators and metrics could be the result of different evaluation preferences. Both environmental accounting and the planet boundary clearly sets the evaluation preference to the better performance of system metabolism within which must contain material and energy fluxes. Industrial ecology and urban ecology also explicitly prefer during evaluation decision-making for social well-being and continuous production under the world-views, reflecting in terms of relevant indicators the existence of institutional strategies. Material and energy fluxes often sets the structural basis that explains the network built for sustainability evaluation. Without such requirement for understanding the mechanism of system, resource management and TBL frameworks, especially TBL, has not embedded any evaluation preferences. As often seen, TBL is used for evaluation without any network construction process and merely for the initial system (Chen et al., 2008, Noppers et al., 2014, Stagl, 2006, Masera et al., 2005, Tabares-Velasco and Srebric, 2012). In this case, the evaluated system remains the same as the initial system. In quantitative evaluation, the preferences for sustainability decision-making are presented in sustainability aggregation indexes such as the environmental performance weights, system performance weights, and the performance weights given by stakeholders. These frameworks are often compatible with perspectives that can be used to understand the transformation system which can be attached with LCA, adding the life cycle perspective that is thought to be intentionally better for indicating sustainability (Berardi, 2012, Campos-Guzmn et al., 2019). In fact, resource management and TBL would not conflict with any criteria for constructing a network of social metabolism. It can be observed that sustainability evaluation using resource management can be product life cycles (Deuble and de Dear, 2012, Altomonte and Schiavon, 2013, Azhar and Brown, 2009), monetary flow (Berges et al., 2010, Tatari and Kucukvar, 2011, Deng and Wu, 2014), production structure (Kriegler et al., 2017, Konis, 2013, Riahi et al., 2017, Wu et al., 2016), emission traces(Welz et al., 2011, Huang et al., 2009), heat or energy flux (Jim and Tsang, 2011, Gagliano et al., 2015), and stakeholder engagement (Park and Boo, 2010, Wiek et al., 2012). Consequently, the evaluated system can be different from the initial system based on the extension over specified preferences and we notice, illustration to sustainability objectives change when for example using LCA with TBL by attaching terms such as ”life cycle” or ”long-term” before the original objectives.

Among the metrics and measures used, it can be seen that structural contributions and influences from world view values to sustainability are widely recognised. Contextual metrics include the demographics and infrastructure of social construction, the meteorology conditions of regional environment and biomass capacity of the regional environment. It can be directly seen from indicators in urban ecology, environmental accounting, and the planet boundary, especially under the category of transformation and environmental related dimensions, the use of exomatic energy supply, exergy, environmental yield, and nature’s primary production recognises the capacity of the natural environment and the fact that the natural world itself is a bigger transformational process. Thus, the capacity is linked with the rate of recovery or reproduction which can be expressed in measures including purification rate, diffusion rate, recovery rate, and the endogenous changes within different ecological cycles. The use of Fisher’s information indicator, entropy based weights, emergy, distribution of social equity, mix of production, distribution of energy supply which are used under all frameworks indicates that it is recognised in current sustainability evaluations that sustainability performance is linked with system structural compositions across time, space, and resource rarity, however, is very limited.

Aside from limitations of reflecting system structural attributes, evaluators recognise the influence from human values to sustainability implementations and the compositions of values. Sustainability evaluation objectives from all frameworks include aspects of stakeholder participation and the enhancement to sustainability values. Although cost benefit values are the most widely and explicitly measured value by human evaluators, other values are also presented in different forms. In the economic form, the interlinking sector of social-environmental aspect of special measures using TBL concerns the level of green value, which allows for added price for green products (Ozaki, 2011), or as additional cost of green price (Noppers et al., 2014). In the non-economic form, the intrinsic values are respected in the form of non-declining natural assets (Frey et al., 2008), or as part of the resources that need to be reserved for non-human stakeholder in the natural ecosystem cycle (Vanham, 2016). Besides, the cultural and aesthetic values are recognised through the preservation for wild life habitats, land scape, street views, and heritage sites (Pauliuk and Mller, 2014, Gssling and Peeters, 2015, Gober, 2010). The evaluation to values contained within the natural world is very limited and we need to recognise such limitations brought by only holding the capability to more comprehensively measuring human economic values.

Indicators to sustainability

Sustainability decision-making can be done with separate decisions made for each sub-systems. For example, Masera et al. (2005) evaluates the sustainability influence of cooking stoves from aspects including energy use, GHG emission, user satisfaction, cleanliness, ease of operation and maintenance, investment cost, operating cost, and self-reliance. Under the assumption that each one of the aspect would contribute to the sustainability performance of the product, implementation suggestions are given for each separate aspects. Also, in the sustainability evaluation of an university (Amaral et al., 2015), suggestions are respectively given for TBL pillars from economic, social, and environmental aspects. As Lundy and Wade (2011) notes, although sustainability implementations are proposed for each subsystem, how much the implementations could contribute to the overall system is still under query.

Bringing the focus to sustainability decision-making with explicit criteria or indicators, as presented in Table. 2.12, the indicators can be roughly categorised into two types, direct indicators and aggregated indicators. We regard direct indicators as using only one measure to directly indicate sustainability. Ecological footprint is regarded as one of the type as transformation is done for all the footprints and hence, at the stage for decision-making, it is the accumulated ecology footprints that is directly used for sustainability decision-making. Different from that, aggregated index would require quantitative treatments to form collective sustainability scores or index values.

Sustainability indexes present apparent connections with the evaluation objectives while the direct measures present the attributes that evaluators regard sustainability are concerned on explicitly. Under resource management, higher material use efficiency, the amount of reduced CO_2 emission, regional variances of production, and stakeholder satisfaction from interview responses are used. The aggregated index are performance scores of bio-physical performances and energy-environmental performances. The aggregation is done through weighted sum where the weights are given by different methods. On top of that, general TBL also uses the quantity of production, lifetime of product, quantity of secondary contamination reduced, cost saved from sustainability implementations, and ecological footprint of outputs. In 2-dimensional TBL evaluating social and environmental aspects, the amount of non-renewable resources consumed, amount of energy saved from sustainability implementation, and stakeholder acceptance to sustainability implementations are used. Over the social and economic aspects, long-term system cost is used to indicate different status of sustainable development. The aggregated sustainability indicators show the intentions of evaluators to reveal more systemic information. System risks are aggregated from three dimensions over space, time, and social aspects. Similar indicators include danger and system resilience. Besides, aggregated scores of sustainability pillars, system performance, and environmental quality are calculated. The weights are determined through factor analysis and analytical hierarchical process with suggestions from stakeholders. Environmental quality mainly follow the standard for human commodity. Using more system indicators, urban ecology framework include articles that use cumulative exergy, carbon footprint, system and local exomatic energy consumption rate, system social metabolism rate, the amount of waste discharge rate reduced, and system emission intensity, and stakeholder satisfaction. The aggregated indicators also contain some system performance measurements. While Eco-indicator 99 and environmental load are calculated from nearly all issues of the natural environment, systemic synergetic reduction of GHGs aggregates the climate impacts of GHGs. Most importantly, sustainability can also be indicated through system performance measures. These include outputs, efficiency, and effectiveness. As Gawel and Ludwig (2011) concludes, from the perspective of system performance, there is no method that suits well for sustainability that is practical, available, and reaches general consensus. Under environmental accounting, only direct indicators are used, including energy per unit of CO2 emission, emergy sustainability index, and environmental compatibility factor, within which the later two concerns the ratio of consumption of renewable sources to the nonrenewable sources and environmental yields. The articles reviewed using planet boundary framework also only used direct sustainability indicators. These include net primary production, Fisher information index, entropy, ecological footprint, water footprint, emergy, and product transformity.

We notice that many articles report better quality decision-making for sustainability implementations with systemic measures (Gawel and Ludwig, 2011, Nijkamp and Pepping, 1998, Thrn et al., 2010, Ramaswami et al., 2012). However, for aggregated sustainability indicators, different weights produce very different scores (Pushkar et al., 2005). While methods and quantitative treatments are further analysed, we realise that sustainability evaluation, especially in obtaining the system performance scores, can be sensitive to components of the evaluated system, the standard on which sustainability decisions are made, and the qualitative or quantitative methods used.

2.5.7 Sustainability Evaluation Methods

Sustainability evaluation can be done quantitatively, qualitatively, or the combination of both in its methodology. As the selection of articles focus on empirical studies, quantitative analysis is found in all studies, some for decision-making (Wu et al., 2016, Noppers et al., 2014, Bailis et al., 2015), some for statistical analysis supporting qualitative findings (Chen et al., 2008, Wiek et al., 2012, Wolsink, 2010). Table2.13 concludes the methodological features of the articles analysed.

Following Table 2.12, the methods are classified according to the sustainability indications in different framework dimensions (separates) or using sustainability indexes (uniform). The respective operations research method relating to the indication of sustainability indexes are analysed under method category with the number of articles for each method. Following the evaluation elements, we realise that there can a difference between the initial system of the evaluation interest and the evaluated system and hence, whether network construction is done and the criteria used to describe the social metabolism relations are concluded under network construction. Eventually, as the popular perspective of life cycle brings insight into system hierarchy, which mainly concerns the down stream relations, trace up category analysis the studies that look into the upstream linkages of the initial system. Eventually, as other associated methods for evaluation system assessment is concluded under the associated analysis.

Table 2.13 Sustainability evaluation features in index and evaluation network construction, and methods.

Sustainability Index	**Method**	Cnt.[2]	**Network Construction**	Cnt.	**Trace Up Cnt.**	**Hierarchy Cnt.**	**Associated Analysis**	Cnt.
Separated[1]	MODM	62	Production	5	2	3	Scenario modelling	2
							Case study	3
			Product life cycle	7	3	6	LCA and LCIA	7
			Process life cycle	9	7	7	LCA and LCIA	5
							Case study	2
							Other qualitative	2
			Material energy flow	9	3	5	LCA and LCIA	1
							Scenario modelling	3
							Ecological footprint	1
							Environmental accounting	1
							Case study	1
							Other qualitative	2
			Material flow	5	3	4	Scenario modelling	2
							Other qualitative	3
			Stakeholder	7	1	2	Meta analysis	1
							Scenario modelling	1
							Case study	3
							Other qualitative	2
			Monetary flow	1	0	0	Scenario modelling	1
			n.a. [3]	19	1	0	Correlation analysis	1
							Regression	1
							Scenario modelling	6
							Case study	7
							Other qualitative	4
Uniform[1]		46						
	AHP	1	Material energy flow	1	0	0	LCA and LCIA	1
	ANN	1	Material energy flow	1	0	1	Regression	1

Continued

Sustainability Index	Method	Cnt.	Network Construction	Cnt.	Trace Up Cnt.	Hierarchy Cnt.	Associated Analysis	Cnt.
	DEA	1	Material energy flow	1	0	1	LCA and LCIA	1
	Index	18	Product life cycle	2	1	1	LCA and LCIA	1
							MODM	1
			Process life cycle	2	2	2	LCA and LCIA	2
			Material energy flow	4	4	4	LCA and LCIA	2
							Emergy	1
							Environmental accounting	1
							Footprint analysis	2
			Material flow	3	3	2	Scenario modelling	2
							Case study	1
			n.a.	1	0	0	Case study	1
	MODM	4	Production	1	0	0	Survey	1
			Product life cycle	1	1	1	LCA and LCIA	1
			Material flow	1	0	1	Environmental accounting	1
			n.a.	1	0	0	Scenario modelling	1
	Regression	2	Stakeholder	1	0	0	Survey	1
			n.a.	1	1	1	Scenario modelling	1
	SAW	17	Production	3	1	2	LCA and LCIA	1
							Scenario modelling	1
							Survey	1
			Process life cycle	5	3	5	LCA and LCIA	5
			Product life cycle	1	1	1	LCA and LCIA	1
			Material energy flow	3	3	3	LCA and LCIA	2
							Scenario modelling	1
			Material flow	2	0	2	Scenario modelling	2
			Monetary flow	1	0	0	Regression	1
			n.a.	1	0	1	LCA and LCIA	1

1. Sustainability performance of the evaluated system is usually reflected in more than one dimension. Separated sustainability index concludes the studies that doesn't attempt to collectively provide sustainability implementation suggestions but instead, discusses implementations within each dimension. Uniform indexes contain the sustainability indexes presented in section 2.5.6 and includes indexes (referring to direct indexes in Table 2.12), and other operation research methods.

2. Cnt. is short for count, indicating the number of articles accounted for the category.

3. n.a. is short for not applicable. This includes the big proportion of the evaluation studies that do not attempt to reconstruct the evaluation system and conducts evaluation directly over the initial system.

Overall, evaluation methodology doesn't seen to be limited by the evaluation frameworks. However, it can be influenced by evaluation objectives. Typical fully quantitative work applies DEA given the sustainability objectives for enhancing emission control and improving energy consumption efficiency (Wu et al., 2016). Liang et al. (2014) evaluates the sustainability performance of living space through surveys and transforms the results into environmental quality indicative data aggregated with simple average weights (SAW). Chavalparit et al. (2006), in turn, analyses energy flow and systemic CO2 production through palm oil production with quantitative measures including energy consumption and emission intensities and concerns social aspects using qualitative discourses. Such tendency is found in most articles.

Also, apparently, sustainability evaluation covers fields of study beyond operations research. The majority of articles attempt to provide sustainability suggestions according to different dimensions under respective evaluation framework used. To roughly conclude, these studies can be regarded as treating sustainability evaluation as problems of multi objective decision-making (MODM). As Thies et al. (2019) describes, MODM are not problems of choices but respecting potentially mutually conflicting objectives together. We see that the majority of sustainability evaluations are done directly for the initial system, which means that the suitability between sustainability objectives and the evaluated system are not widely concerned.

The network construction criteria can be mainly categorised into seven types. Production indicates the production relations contained in the initial system. It is different from the studies categorised into ”n.a.” based on the complexity of production relationship revealed. Those that are regarded as not performing network construction either base the production relationship by I-O model without or with limited concern to technological mechanism of how the outputs are produced. Many quantitative methods such as correlation analysis, regression and modelling approaches are used to understand potential system linkages. Thus, we see that following production relations from life cycle perspective, upper stream production relations can be considered in the evaluation (engl et al., 2008, Spiertz and Ewert, 2009). Also, on-site production performance could be evaluated by modelling approaches (Konis, 2013). Product life cycle and process life cycle are mainly criteria accompanied with LCA or LCIA and hence the proportion of studies that constructs system hierarchy is high. However, under product life cycle criteria, there are studies that only consider that down stream hierarchy of the product life cycle, especially when the product is directly extracted from the nature such as biomass and solar energy (Sheehan et al., 2003, Asdrubali et al., 2015). Material and energy flow indicates the networks that are constructed by transformational process of both materials and types of energy. Associated methods include systemic ecosystem analysis of ecological footprints and environmental accounting. There are also cases when the network is constructed following material of one type. It can be wastes from production (Franks et al., 2011), industrial supplied resources (Gssling and Peeters, 2015), or biomasses (Thrn et al., 2010). Slightly different, monetary flow is separated from material flow as this criteria would not suit all general system. Lastly, stakeholder connections is also an important criteria which determines for whom the sustainability objectives should target for. Quite high proportion of qualitative methods are associated to understand stakeholder cognitions and opinions.

Different from separated sustainability implications,for sustainability evaluation attempts that used sustainability indexes, we could almost state that net work construction is necessary. The rare use of analytical hierarchy process, neural networks, and DEA could be caused by the selection of article as we did not focus on quantitative evaluations using operations research methods. However, we understand from many reviews (Thies et al., 2019, Mori and Christodoulou, 2012, Kumar et al., 2017, Kwatra et al., 2020) that they are popular methods used for sustainability performance evaluation and DEA is an important quantitative method for efficiency measurement. Besides, we notice that the use of direct indexes and using SAW for aggregating different dimensions for sustainability performance indication is rather popular with varieties of criteria followed for network construction. It is also apparent that for the use of direct index for sustainability or aggregating them through SAW, it is important to construct complete system transformation structure both tracing up and drawing down stream hierarchy. Among the studies using SAW, the influence of weights are rather important to the scores obtained (Pushkar et al., 2005). Some use simple addition, which can be regarded as equal weights (Blengini, 2009, Pons and Aguado, 2012). Others determine weights through stakeholders,(Liang et al., 2014, Onat et al., 2014, Gonzlez et al., 2013), production, emission, or available mass proportions (Huang et al., 2009, Batidzirai et al., 2006, Stazi et al., 2012, Stamford and Azapagic, 2014), coefficients from modelling analysis (Deng and Wu, 2014, Che et al., 2002). Zellner et al. (2008) also adjusted the weights by variances. Also, environmental accounting measurement, emergy, can be categorised according to types within the framework and aggregated through SAW to form a systemic direct sustainability indicator. We recognise that the selection of method doesn't seem to be limited by any current evaluation frameworks for sustainability but hold its own advantages and disadvantages as quantitative treatments.

Overall, it can be seen that understanding system hierarchy would suggest better sustainability implementations, the proportion of studies tracing the complete ecological cycles including the upstream causes to the initial system is relatively limited compared to the down stream influences. It proves the dilemma described by (Gawel and Ludwig, 2011) that LCA and LCIA, from the perspective of system performance, has the tendency of describing efficiency and effectiveness of system performance in better details. We claim that the changes to the components of 3E performance aspects brought by developing initial system to the evaluated system need to be recognised and included in sustainability evaluation as part of contribution to sustainability performance.

2.5.8 Human Central Sustainability Evaluation

Following the previous analysis over each key element of evaluation and identifying the features of sustainability evaluation studies for elements not mentioned, such as the results and implementations, Table. 2.14 exhibits the features of sustainability evaluation present by the 108 articles of sustainability evaluation in the energy sector.

Table 2.14 Elements of sustainability evaluation in energy sector

Elements of Evaluation	**Features in Sustainability Evaluation**
Lead of Evaluation	All evaluations are human lead. Often proposed by managemental or inspectional bodies such as managers of organisations, governments, and NGOs.
Evaluation Objectives	Sustainability objectives can be: chosen from SDGs, determined by lead of evaluation, or out of system performances of the initial system. Could imply sustainability criteria and evaluation subject system boundary.
DMs	In most cases, only human or group of people has the power of decision-making.
Key Stakeholders and General Stakeholders	General stakeholders include human, and other living and non-living beings in the environment. KSs are determined by the evaluation objectives and/or the context where initial system lies in. KSs could present outside the system boundary of the initial system.
Evaluation Subject	The *evaluated system* which focuses on the initial system and contains explicit linkages with the initial system. Can be any system from a transformation process to complex ecosystem. Could contain compositions outside the initial system.
Evaluation Resources	Labour, capital, and resources consumed by stakeholders for evaluation, including available data.
Evaluation Framework	Frequently used ones include resource management, TBL, the planet boundary, and network modelling.
Evaluation Measurement	Determined by evaluation objectives and framework and focus on the evaluated system. Fineness and effectiveness of measurements are often determined by the world view and values of the evaluation context.
Evaluation Method	Could be qualitative, quantitative, or a mixture of both. Techniques include regression, correlation, DEA, case study etc. and depend on evaluation objectives. Indicators are case sensitive and can be single, collective, aggregated, or concerned multi dimensional.
Evaluation Results and Feedback	Decision quality depends on the world view and implementations depend on lead of evaluation and the DMs.

Describing the elements from a top-down perspective, we recognise that most current sustainability evaluation is human central. The key determinant to the human central position is that the lead of evaluation and the DMs for evaluation are mainly human. Human groups propose the need for sustainability evaluation under the ultimate objective to be in harmony with other beings on the planet with human DMs who decide the sustainability implementations to be taken. Although attempts have been made for ecology central evaluation, we notice the evaluation subject are still widely determined by the power control over entities or administrative boundaries. The recognition to the fact that the DMs could take universal stances could be better recognised. Also, such influence in the stances of DMs would bring challenges to other elements including the evaluation resources, frameworks, measurement, and methods.

To simply describe, we realise that the sustainability evaluation objectives have multiple sources and for one evaluation practice, the objectives could be the aggregation of respective objectives from different sources. SDGs is probably the most widely referenced sustainability objectives for evaluation, mainly by selecting one or more out of the seventeen goals. However, it is not the only source of sustainability objectives that are referenced. Some governmental indexes such as the sustainable development index, the environmental sustainability index, eco-indicator 99, and human development index, all have their own objectives and indicator systems forming the indexes (Bauer et al., 2017, Onat et al., 2014, Welz et al., 2011, Abeysundara et al., 2009, Ness et al., 2007). To emphasise, sustainability evaluation objectives, which are explicit, could create implicit aspects in further evaluation. For example, without clear definition to sustainability under the framework of socio-economic pathways, Kriegler et al. (2017) attempts to evaluate sustainability of energy intensity under the fossil duel development scenario with concerns to the three subsystems in TBL. Although outcomes of the scenario is explicitly presented, it is not clarified in the evaluation over what aspects sustainability or SD could be achieved. The most explicit indication is that energy efficiency and waste treatment technologies would contribute towards SD, implicitly presenting the sustainability objectives over the preferences to the technosphere. Differently, Bailis et al. (2015) presents the baseline set for sustainability as the carbon footprint of wood fuels where sustainability of the wood fuel extraction is explicitly targeted as reproductive relationship with the local forest. Typically, we notice it is more likely that the evaluators or the DMs would determine the suitable sustainability preferences and criteria.

The fact that, limited by communication, the DMs in most sustainability evaluations are human, and to be discreet, certain groups of human. During system operation, many non-human factors are able to change the system. Westley et al. (2011) notices the limitations brought to technology transformation by environmental capacity. Bailis et al. (2015) recognise the limitation to the scale of food fuel production by natural reproduction where over extraction inevitably results in the turn over of the forest's function to provide wood fuels. Vanham (2016) further realise that planet boundaries are simultaneously attached to water-food-energy-ecosystem complex. Wood and Lenzen (2003) reveals the structurally uneven and unsustainable distribution of ecological footprints over space. The presentation of the decision-making capability of non-human beings are mainly in the form of restriction to human activities. However, if we are hypothetically able to fully communicate with other beings such as monkeys, monkeys could become the group of strong stakeholders who are able to explicitly express their interest in sustainability evaluation. When these monkeys also hold strong stakeholder influence to the sustainability evaluation objectives, under evaluation theories, they could also be part of the DMs. Eventually, to the very extreme scenario, the sufficient condition of true sustainability, that is the sustainability of the globe, could be able to be discovered when all beings, human beings, non-human living beings, and the non-living beings, are mutually able to express their own sustainability values. Hence, currently, sustainability evaluations are indifferently human centred as DMs are mainly human and the sustainability decisions made from evaluation would always follow human values. What we can do, as has already been attempted mainly by ecologists, is to concern the benefits of other species as possible.

Apparently administrative and organisational boundaries are still the most widely applied system boundary that forms the evaluated subject. Very often, the evaluated system is set to entities (Asif et al., 2007, Gonzalez-Garcia et al., 2018, Langston et al., 2008, Liang et al., 2014, Konis, 2013, Pons and Aguado, 2012, Amaral et al., 2015), cities (Blengini, 2009, Chen et al., 2008, Batidzirai et al., 2006, Jin et al., 2006, Ramaswami et al., 2012, Nijkamp and Pepping, 1998, Zellner et al., 2008), regions (Becken and Patterson, 2006, Bailis et al., 2015, Gssling and Peeters, 2015, Kennedy, 2002, Giljum et al., 2008, Xu et al., 2000, Gonzalez-Garcia et al., 2018, del Ro and Gual, 2004, Gober, 2010), or countries (Klein et al., 2005, Chavalparit et al., 2006, Sandstrom, 2002, Stagl, 2006, Koroneos and Dompros, 2007, Masera et al., 2005, Stamford and Azapagic, 2014, Taylor and Ampt, 2003, Che et al., 2002, Abeysundara et al., 2009), or bound with industries (Hertwich, 2008, Wiek et al., 2012, Ozaki, 2011, Berardi, 2012, Sev, 2009, Yellishetty et al., 2011, Ingwersen, 2011, Wu et al., 2016, Thrn et al., 2010, Zvolinschi et al., 2007). However, the evaluation subject, especially at the stage of decision-making, could have a system boundary that is artificially made clear. For example when using quantitative methods, although the indicator system may be able to construct a massive system that relates to many critical aspects of ecosystems, the decision-making is mainly made over one, such as the green house gas emission (Welz et al., 2011, van Ruijven et al., 2008). In other cases, global indicators or dimensions of global indexes are used for national level research (Holden and Hyer, 2005, Gonzlez and Garca Navarro, 2006, Giljum et al., 2008). The system boundary of the evaluated system could be directive for the selection of evaluation frameworks and measurements.

However, while much effort is done to guarantee consistency between the evaluation subject and decision-making elements (the frameworks, measurements, and methods), the suitability of the evaluated system with the sustainability evaluation objectives is often neglected, especially when the system boundary is implicit and linked with the unclear indication to sustainable state. Although not directly said, Asif et al. (2007) adapts sustainability objectives of energy saving, efficient material consumption, reuse, recycling, and undesirable emission controls. Setting the context to construction and further determining the types of air particles to be evaluated, including CO_2, SO_x, and NO_x, it applied life cycle analysis to understand the energy and material use of the building and evaluates the complete process. Many empirical attempts using LCA implicitly undergoes the process of adapting the evaluation subject with the sustainability objectives, probably due to the speciality of the assessment method (Blengini, 2009, Kosareo and Ries, 2007, Sheu, 2008, Duchin, 2008, Gerilla et al., 2007, Koroneos and Dompros, 2007). Especially, Koroneos and Dompros (2007) presents the fact that the evaluated system of sustainability evaluation faces geographical linkages where outputs can be produced on site and off site. Thus, bringing the suitability between evaluation objectives and the evaluated system composition and scale in to light, we could identify that evaluation approaches can be flawed when the objectives are not suitable with the evaluated system. Evaluating based on the perspective of reductionism and resource management is a treatment that weakens the such unsuitability. As the conceptual model of many studies state (Sev, 2009, Gssling and Peeters, 2015, Berges et al., 2010), inheriting the exceeded environmental loads of attributes such as CO_2, water consumption, energy consumption, food consumption, and land cover change by human activities, the reduction over these attributes would always be more friendly to social well-being and the natural environment. In this way whether and how regional changes contribute to the achievement of the actual sustainability objectives is simplified to regional problem. To note, we are unable to know whether such treatment are more strict or more soft over sustainability objectives. From the systemic view, as Gawel and Ludwig (2011) presents, environmental issue such as landscape change face severe challenge in indirect impacts which would always result as a dilemma where global problem cannot be finely dealt with on the regional scale, and although in the implicit form, it is suggested that measuring landscape change using system performance attributes such as effectiveness would better indicate indirect outcomes.

2.6 Chapter Summary

In this chapter, the definitions of terms ”evaluation” and ”sustainability” are proposed or developed. For evaluation, this thesis applies the definition that for general context, is the process of making decisions through valuation and concerning impacts to anything the proponent has interest in based on the information attainable. For sustainability, it means system sustainability for systems on the Earth within which some attributes should be clarified to be maintained within certain range. Through the critical reviews, many issues in sustainability evaluation are confirmed. Sustainability evaluation often has implicit evaluation objectives, due to defining sustainability. Also, many stakeholder related evaluation elements are implicit in sustainability evaluations, which are often done for evaluation subjects that has a system boundary unsuitable for the sustainability evaluation objectives.

Chapter 3

A Roadmap of Sustainability Evaluation

3.1 Introduction

This chapter presents the construction of a roadmap of sustainability evaluation. Based on Chapter 2, the issues in current sustainability evaluation are first analysed, and summarised into respective issues in evaluation elements. Then, with clues of stakeholder perspectives on values and evaluation objectives, the process to develop explicit evaluation elements is presented. Subsequent sections include an evaluation framework for sustainability that could contain and present explicit evaluation elements, a group of feasible measurements that is applicable, and the roadmap is presented in the form of a protocol for sustainability evaluation.

3.2 Features of Sustainability Evaluation

Based on the results from Section 2.5, this section first analyses the features of an expected sustainable system. These features should suit the reference system for sustainability evaluation. Then, matching the definition of sustainability, evaluation, and performance used in this thesis, the ”attribute” is defined. Lastly, the features of a system suiting the sustainability evaluation objectives are analysed.

3.2.1 Features of A System Meeting Sustainability

Sustainability System Performance

Past understandings to sustainability is mainly done under the attempt of breaking down overall system into subsystems, such as economy, society, and the environment, and then aggregating them. However, we recognise critical faultiness to sustainability from the composition, conflicts, and the ethics in the social-environmental relations. As the popular criticism notes, the main ethical right violated by using human values for sustainability evaluation is the right of living for other species which it is not legitimate to be determined by any parties of human (Kuhlman and Farrington, 2010). Limited by human knowledge, sustainability researchers are yet to find a value system that suits all beings in the natural world. Regarding monetary valuation as the outcomes of measuring human preferences, there is no suitable system for valuing natural capitals (zkaynak et al., 2004). Moreover, it needs to be respected that regardless of the ethical foundations, the natural world is a physical mechanism that carries all beings and their activities (Pacheco, 2014). In other words, sustainability is never about the aggregation of contextual subsystems but rather about the system presence itself. Besides, as Landrum (2018) concludes, system perspective to sustainability could be stronger than WS and weaker than SS as system synergies can shift some detrimental influences to both human and the nature.

System attributes linking to sustainability is apparently not mutually exclusive from system performance measurements, but using performance measurements can well assist the presentation of the composition and transformation of the system, and understand how the system functions and creates the downstream impacts. The requirements of deciphering system composition and system impacts are prominent under both physical and human constructions. McMahon and Mrozek (1997) clearly states that valuations and preferences in sustainability are philosophical issues linking to biases in the system, and hence, entropy, the directional indicator of system disorder, naturally discriminates the proposition of ”waste” and ”pollution” and explains the only energy source for the Earth is the solar energy or that from the outer Earth. However, as the author points out, the nature of entropy is not currently accepted as an available type of economic good. Further, as Rees and Wackernagel (2012) points out, the dissipation of entropy from the society would always be towards higher levels in the system hierarchy. Hence, system attributes needs to consider its linkage, not merely the inner connections, but ought to be towards outer ecosphere. Within artificial construction, Le Blanc (2015) notes, although SDGs provide directional development of the Earth, the multiplicity of linkages among SDGs could result in unexpected outcomes and impacts. Bonnedahl (2019, p.145) demonstrates the influence of sustainability and sustainability objectives as attaching a cap for economic development and the local accessibility to power, resources, and expertise. Hence, systemic attributes contributing to sustainability also requires to look into potentials.

As some sustainability evaluation or assessment theoretical and empirical works have done, system mechanism, the potentials, and impacts to the outer space can be analysed with performance measurements. Korhonen and Luptacik (2004), Fan et al. (2016), Suzuki and Nijkamp (2016) attribute these aspects to dimensions of performance measurements such as efficiency, efficacy, and the impact (effectiveness). Frankly, system performance measurement provide good indicator selection hierarchical structure for sustainability. Furthermore, in the review by Kwatra et al. (2020), the address to sustainability is mainly done through systemically constructed consensus-based indices which are generally constructed following top-down performance strategies of SD. The indices translate SD on different dimensions into regional performance of relevant systems and hence they call for integration of more application of bottom-up approaches in the selection of indices, especially for impact related ones. In the past indication to SD using monetary indicators, Erickson and Gowdy (2007, p.176-192) points out the necessity of correct valuation and better integration with present economy, mainly treating the intangible aspects. Bonnedahl (2019, p.289-301) concludes that complex SD indicators should fulfil the clarification to the sustainability objectives to achieve, the mechanisms and support that system transformation is realised, the outcomes of the system, and the impacts back to the system's embedding background. Cato (2012) notes that objectives attached to indicators can be presented in the objective of evaluation or as boundary conditions for activities.

In the same time, as system performance measurements are not subject to any system properties, it can be applied with other system property indicators that don't discriminate systems contexts, including emergy (Brown and Ulgiati, 2004), entropy (Rees and Wackernagel, 2012) etc. Georgescu-Roegen (1986) supportively pointed out that system attribute indicators are also suitable for binding actions with prospects from system stakeholders. In the end of the day, we need to recognise, sustainability, more precisely the sustainability of the planet Earth, has always been a system feature based on comparison where we are only able to find a relatively better reflection than the past(Schwarz-Herion and Omran, 2015, p.3-7).

Sustainable System Structure: Stabilisation not Equilibrium

Practical conceptual statements to sustainability indicates that sustainability is a global system property of a transformational system and the associated objectives are only achievable on the cosmic level. The implementations of sustainability objectives either recognises the limitation brought by containing the world-view to a subsystem or attempts to expand the dimensions of the world-view by attributing observations to system attributes. We have noticed, for example, the education system cannot reach sustainability without consistent contribution to providing equal access for the consumers (Chankseliani and McCowan, 2021). Also, sustainability of the planet cannot be achieved by merely pursuing economic growth but also introducing the aspects from the society and the natural environment (Elkington, 1998), where this can be also insufficient. However, it doesn't mean true sustainability is not approachable from subsystems. Chankseliani and McCowan (2021) claims that when each subsystem reaches equilibrium or is maintained under a balanced state, a necessary condition for sustainability can be reached. Hence, sustainability would always end up being a global matter that connects the subject for observation with the rest of the world. For global sustainability, Rees (2010) describes it as the presentation of a combative game of all species since the genetic predisposition to expand the population is shared. In this sense, contemporary illustration tend to demonstrate sustainability as the transformational activity using different approaches. Scoones et al. (2020) concludes that structural, systemic, and enabling approaches are respectively appreciated in different aspects of revealing the fundamental changes, explaining intentional actions, and fostering human agencies and valuations. Especially, Bulkeley et al. (2012) emphasises the importance to taking historical inheritance into consideration. To understand the structural features of sustainability, researchers concentrate on physical quantities of energy and entropy from the thermodynamics to address sustainability under instinctive activities in nature where stabilisation is more practical.

Non-equilibrium Energy

As sustainability has been popularly accompanied with words such as ”maintain”, or, in the energy sector, ”reproduce” (Ellabban et al., 2014), sustainability is widely demonstrated as the reproduction of materials. From the perspective of energy, as Massotte and Corsi (2015, 147-148) defines, sustainability is successively reproducing the dissipated energy, where on the macro state of SD, it is the maintenance or the restock to production materials. Standing on the managemental structure of Earth, considering its linkage with the outer space, we may need to notice that naive condition for energy equilibrium between the human society and the natural environment may not be achievable with the law of conservation of energy, $\sum U = 0(universe)$, where U is all energy forms (Ott and Boerio-Goates, 2000). The consumption of energy, due to the limitation by human technology, is, as a result, one way flow, with mechanical loss. Energy is constantly released into the outer universe during human activities mainly in the form of heat from sources including friction.

To regain 1 bit of information, according to Fleissner and Hofkirchner (1994), one phenomena that holds for any types of entropy including the thermodynamic, the figurative, and the information entropy is that the order generated is hard to push up the amount of free energy in any activity regardless of the types of materials consumed. Merely using the form of Boltzman entropy and take the base of 2. On the thermodynamic level, it can be described in relation to heat change by Clausius' second law of thermodynamics (Ott and Boerio-Goates, 2000),

$$dS = \frac{dQ}{T}$$

, where Q is the heat difference in the unit of J that i uniform energy notation can be noted as E_Q, and T is the temperature of the system (K). Hence, the energy needed for $1bit$ of difference in order, $1S$, and the equivalent mass of 1bit order by applying Einstein's energy equivalent $E = mc^2$ are respectively,

$$E_Q = dS * T$$
$$m = \frac{E_Q}{c^2}.$$

To understand the magnitude of intentionally recovering targetted information or energy loss, under stander condition of air pressure, taking $T = 2.7316 * 10^{-2}K$ and $c = 3.0 * 10^8 m/s$, the estimated change in mass is $m = 3.03511 * 10^{-19}g$, which is still uncontrollable under current technology. Keller (2009) illustrates that the root cause of failure to such self-organisation is the intentional recoveries. As Surrey et al. (2001) notes, open systems reach their steady state of self-organisation through dissipative systems not reaching thermodynamic equilibrium but rather under dynamic balance of kinetic parameters, that are the indicators of energy and material exchanges.

Human Directed Planet

For many years, the natural environment is thought to be well explained by Odum brothers as an massive heat engine (Odum, 2007). However, with the recognition of contributions of mutually influential structural changes brought by exchanges of mass, energy, and information as the structure of the society that we live in, dissipative system is thought to be a better explanation to the natural world, a world where the living beings are mainly different from the non-living ones as they are irreversible in time (Prigogine, 1980, p.212-214) and exchangeable in information (Odum, 2007).

Describing the ecosystem and the human society as dissipative systems thrive with the belief that sustainability or the sufficient conditions of system stability seem to follow the stability of dissipative system far from equilibrium. The chemical and biological cycles that we live in or support life on Earth are inevitably under the balance of self-organisation and dissipation of entropy (Keller, 2009). Besides, biological systems are abundant with irreversible processes and directional behaviours (Ulanowicz and Abarca-Arenas, 1997). The networks of energy flow and material flow formed in the natural world are no where near equilibrium, being sufficient to be regarded as far from equilibrium systems (Ulanowicz, 1986). As Yin and Herfel (2011) and Ulanowicz (1986) conclude, the natural world formed of energy and material flux network is sufficient to be modelled by dissipative system that it is consisted by relevantly independent compositions on microscopic or mesoscopic levels, it requires continuous provision of energy and material to maintain the system existence, and its system structure is a developing one that is to the least greater than the sum of its components. Eventually, Yin and Herfel (2011) further notes, the steady state of the natural world is not reached at equilibrium state without production of entropy but with constant entropy exchange through energy, material, and, to more modern view, information. In extreme system of economy, as McMahon and Mrozek (1997) introduces, in the extreme example when technology becomes fully efficient, economic system becomes self-enclosed and consequently, the entropy of the semi-closed system would increase within the system. But due to technology efficiency loss, economic system would always remain incomplete and open that its sustainability inevitably require extension to bigger systems to be stable. In the formulation of such dissipative society or planet, by indicating the source of entropy the temperature difference between the hotter Sun and the colder Earth, the compound sustainability target is (Kleidon, 2020),

$$\frac{dS}{dt} = 0 \tag{3.1}$$

, where as a balance with the internally increasing entropy production $\frac{d_iS}{dt}$, the dissipated entropy to the outer environment follows $\frac{d_eS}{dt} < 0$. According to Rees and Wackernagel (2012), putting the context to human society and the surrounding environment, this can be noted as the resultant entropy, the waste and disorder, released to maintain orders in the society. From the opposite perspective, unsustainability, as an emergent system property, is a reflection that can be seen in any system to the interaction between contemporary techno-industrial society and the ecosphere (Rees, 2010). Sustainability, on the dimension of energy and material flux, can be illustrated as the provision of sufficient energy and materials to fulfil the gap generated by entropy production. Attaching entropy exchange to urban ecosystems, the system entropy production or removing can be set by urban metabolism. According to Zhang et al. (2006) and Lin and Xia (2013), entropy can be classified as sustaining input entropy, imposed output entropy, regenerative metabolism entropy, and destructive metabolism entropy which respectively describe entropy flows of natural resource imports, pressures caused to non-human interfaces, treatment to pollution, and the discharged wastes or pollution to the environment. The entropy balance reaches under such categorisation is also regarded as reaching a stable structure.

In sustainability issues, human values are central to the sustainability relations and the determination of values to create orders in the society, which acts as the ”attractors” causing intentional entropy change. Ito and Montini (2019, p.221-233) concludes that sustainability relations, currently lead under human benefits and valuation system, has been adversarial where one party is preserved on the expense of other associating parties. Although the UN sets different sustainable targets based on ecological environmental protection framework (UNDESA, 2017), the completion of social and economic sustainable targets are prioritised for satisfaction (Apostolopoulou and Cortes-Vazquez, 2019, p.210-220). Additionally, it can be inappropriate in determining the sustainable targets and the use of indicators can be inconsistent as retrofitting indicators can always be developed or found as intangible sustainable objectives become better clarified (Pombo et al., 2016). Apparently, global sustainability requires demonstration to all objectives associated with all attractors on the planet to fully understand the true gap of entropy in energy, material, and information interactions with the cosmos. Hence, in nature, we need to recognise sustainability directed by human values would always be insufficient for planet sustainability from the entropy perspective.

Stakeholders of Sustainability

The beings in sustainability relations include human beings, the living ones, and the non-living ones. Under the TBL framework of considering sustainability for three subsystems, stakeholder analysis can be done for each minor system where each include the three types of beings, contingently arriving at the conclusion that TBL may not be suitable for demonstrating or evaluating sustainability as it neglects some connections crossing the borders of the subsystems. Besides, the TBL framework of SD leaves the collective objectives to be pursued within each subsystem to be demonstrated by every case of analysis. The initial phrase ”good” (Jeurissen, 2000*b*) is not a specific definition to a good state of the system. Especially for evaluative processes for sustainability, DMs may introduce objectives different from those brought by system stakeholders (Ma et al., 2020). Sustainability, from the stakeholder’s perspective, is the process of transition dealing with stakeholders from all levels, within which include all human actors such as the state, private enterprises, public private partnerships, the scientists and inventors, multinational NGOs, think tanks and round table groups, media, cultural players of writers, actors, dancers, musicians, painters, and religion groups

(Schwarz-Herion and Omran, 2015, p.107-113). However, due to technical limitations, the objectives or values of the weak stakeholders, such as the silenced human groups or other species and non-living cycles, cannot be clearly understood. Consequently, it seems that stakes are only associated with human groups while other beings are regarded as elements linked with the interests (Reed et al., 2009). Sustainability should be viewed with consistent perspectives influencing the ethical foundations of sustainability and, at least, with respect to the weak stakeholders holding strong influence to the initial system.

The roles of nature actors are often translated according to their functionality and load to the form of nature's services, the planet boundary, and the environmental load. Although it has successfully revealed the overloaded human activities in the short time after the Great Acceleration, sustainability implementations can be flawed under the biased value judgement to the roles of nature actors and not embedding, not fully but measurable, systemic functions that nature actors hold.

Taking the role of nature actors as the nature's services, the market formed by individual preferences under the neoclassical economics is weak, in its principle, to measure the physical distribution and scarcity of certain living and non-living beings (McMahon and Mrozek, 1997), or in more familiar term "resources" . In such market, the values of goods and services are decided by instrumental purposes (Le Blanc, 2015), the result of integrating customer preferences. It needs to be recognised that the stakes of each group of stakeholders, even if assuming to be containing sustainability pursuits, are contributing to the construction of peaceful living environment for the sake of themselves (Schwarz-Herion and Omran, 2015, p.107-113). On such basis, it is claimed that social valuation could only explain the creation of social values (Haddaway et al., 2017). The creation of social values could simultaneously result in the decrease of values for some nature actors aside from human. Consequently, not only is social reformations are heavily based on people's wills not sustainability frameworks, but also frameworks of sustainability are often flawed by people's wills, the implementations we take and the transformations led by economic profits that we under go can be shifting away from true sustainability Schwarz-Herion and Omran (2015, p.187-189). The 2018 constitution in Ecuador demonstrated the "rights for nature" for containing its values that are not currently understood by human (Loft et al., 2015). Indeed, we recognise that sustainability observations or evaluations are inevitably limited in its valuation towards nature actors.

However, it is currently sure that with the concerns for other species and the reproduction of non-living materials, some value baselines need to be set for nature actors. The common ground for all human stakeholders that relief the hazardous social-environmental relationship include lower energy cities, better innovation and creation reaching for the sustainability target of energy efficiency and zero-emission (Hamdan et al., 2021). Besides, SDGs are good references of common targets that would lean towards better sustainability. Moreover, including many different groups of human stakeholders, citizens and consumers, resource owners, and industry are more focused on achieving sustainability objectives on the product level while research and government focus more understanding the concept and promotion of lifestyle (Dieken et al., 2021).

Besides, although the values of nature actors is a hard judgement to make, their inclusion in the studied system presents stability and resistance to fluctuations caused by human activities and purification to the pollution emitted. As Schellnhuber (1999) defines the Earth system, it is a planetary level complex system containing constant evolution and transition though frequently interactive biotic and abiotic constituents. From an energy perspective, biotic natural actors can be categorised as producers, consumers, and decomposers that forms the basic cycle of lives in the ecosystem (Odum, 1971). Meanwhile, abiotic nature actors are mainly suppliers and receptors. For example, soil is a fundamental supplier of space, the nutrients, and water (Roger, 2000). The atmosphere is mainly a source of space, oxygen, and a sink of pollutants and heat (Chang and Hanna, 2004). Taking cities and the Earth as two key stakeholders, cities are: over energy, huge consumers of energy; over materials, enormous nutrient intake and concentrated release, nodes of material distribution through transportation; and over information, concentrated pods of human activities, innovation, and knowledge (Norman, 2019, p.26). Hence, social actors cannot be viewed of its sustainability without interactions with the nature actors since sustainability is mainly about reaching dynamic relevantly steady state where social actors and nature actors mainly stand on two sides of the balance. Thus, Lohmann (2019, p.234-247) promotes the importance of human DMs to stand on the middle ground with concerns for the rights of commons where lives of other species needs to be carefully studied before they are heavily affected by human activities.

Previous reviews recognise the criticisms over sustainability that paradigm collapses occur as sustainability objectives or their indicators are not suitable with the system studied or when sustainability indicators are not adoptable for system implementation. Such consequences of unsuitability between the conceptual world and the real world can be attributed to the inconsistency of the collective perspectives held by the system stakeholders or the DMs if the process is a sustainability evaluation.

In accordance with the development of understandings to sustainability, system observation hardly ever faced the problem of paradigm shifts since construction of the system and the valuation for system components are mainly based on their instrumental value, that is in other words the market value. To note, it is already seen in the development of stakeholder analysis that stakeholders hold different objectives and such objectives can be different from group to group. However, by having all of them as human stakeholders, as proposed (Metcalfe, 2008), feedback and communication are important tools to assist the adaptability between conceptual objectives and the real world implementation. Thus, although some stakes can be mutually contradicting, eventually the system objectives can explicitly result as the compromised objectives among all (Haddaway et al., 2017), where the mechanism of balancing among objectives can be observed. However, the scenario changes when environmental aspects are introduced to the system. The status-quo of global sustainability indicates that continuously making decisions based on instrumental value for all components including the nature actors fails for sustainability. Hence, the inclusion of the inherent values among communicative groups and the intrinsic values of that are independent from utility of the materials and living beings inevitably cause internal confusions of the sustainability objectives (Loft et al., 2015). The aggregation of the sustainability objectives can no longer be a balance among instrumental values of stakeholders and as environmental concerns intensify and amplify and thus anthropocentric perspective can easily become shifted to holding universal perspectives for environmental concerns which flaws sustainability decision-making since unprecedented stakeholder participation of natural actors are intentionally neglected. As Chakraborty et al. (2019) notes, paradigm shift is ought to occur since the interest of the stakeholders eventually forms a web of interests that suggests the need of structural changes to obtain the capability to embed multiple objectives. The system potential to realise sustainability objectives becomes a very important aspect that a system should hold once sustainability targets are assigned and consistent perspectives would guarantee the solidity of foundations of such sustainable system potentials where system performance measurements can be used in association.

Consequently it needs to be realised that holding consistent cosmocentric perspective to sketch the natural world has theoretical advantages in the observation to sustainability, especially in the formulation of the collective system objectives and the mechanisms leading to system performances. It guarantees the consistency of paradigms taken for every stakeholder and their objectives even with the existence of weak stakeholders who cannot explicitly express their objectives. Besides, the beings and their relations constructing the social-environmental relation network is understood based on physical existence of the real world, not an artificially purposeful cut-off to form the system boundary. Apparently, any random element could be able to draw a complex network involving different living and non-living beings, the connections among stakeholders is one criteria which can be followed that could embed multiple objectives associated with the stakeholders. However, apparently recognising that universal perspective would inevitably result in forming a grand complex system serving for sustainability, system comprehensiveness may need to be compensated for practicability for observation or evaluation.

The System for Sustainability Evaluation

As being analysed in each of the sections, a conceptually sustainable system can be different from a system that is practically feasible for sustainability evaluation. The system for sustainability evaluation inherits the feature of a conceptually sustainable system that its system boundary should contain the capability of realising sustainable objectives over some critical attributes. In the meantime, the final system to be evaluated can be restricted by data acquisition, interests of the evaluation DMs, and limited evaluation resources.

Sustainability evaluation is a form of evaluation that can be internally or externally performed with both internal and external evaluation DMs and as an evaluated system, the evaluated system for sustainability evaluation would also result explicit in its elements, especially the system boundary for the evaluated subject. In the meantime, sustainability as a system feature can be indicated using system performance measurements as sustainability objectives often look at the system's potentials, improvements, and influences. Recognising that effective integration of sustainability into organisation requires actions that exceed organizational boundaries (Seuring and Gold, 2013), general agreement is reached that sustainability of the initial system needs to be studied by expanding it so to understand its externalities and perform better quality decision-making.

However, sustainability objectives are often externally given to the initial system without the guarantee that the objectives are capable for the initial system. Purposeless expansions would present the sustainability in greater scale but still would not guarantee explicit presentation to the realisation of the evaluation objectives. On the greatest scale of the planet, for whom has human economic growth has been suppressed and off-set is not fully revealed and confirmed (Apostolopoulou and Cortes-Vazquez, 2019, p.200-209). The social-environmental relationship is fabricated and its descriptions can be sensitive to evaluation objectives. According to Ayres et al. (1998), social or ecosystem stability cannot be guaranteed, as economic theories suggest, by optimising the margin of the capitals. It is noticed that, under the extreme "ecosystem friendly" case, merely increasing the natural capital may not consequently arrive at a preferable sustainable circumstance. A preferred sustainability state seem to be between economic growth and protecting natural environment. Besides, Ackerman et al. (2007, p.7-35) points out that different from the short-term direct conflicts between human industry and ecosystems, as a long term issue, unsustainability can be the accumulation of unsustainable or not so sustainable impacts. The instance of environmentally induced cancer diagnosis presents the detrimental impact to human individuals by the historical activities that affected the environment. Hence, the tendency of viewing the world on the conclusion that economic growth may not be compatible with environmental protection (Bonnedahl, 2019) can be the consequence of such excessive short-term social-environmental relations and the accumulative impacts. Hence, given the aim of strategic decision-making, the frameworks and methods in sustainability evaluation have and should attempted to provide explicit content as to what aspects are evaluated and to what extent(Vinodh et al., 2014) which better adopts sustainability evaluation objectives. The expansion to the initial system is a process of adopting the sustainability objectives to the initial system so that the system boundary of the evaluated system for sustainability evaluation is explicit and meets or have the potential to meet the evaluation objectives.

The linkages between the sustainability evaluation objectives and the initial system can be developed based on the involvement of stakeholders. Given the initial system and the initial sustainability evaluation objectives, questions need to be answered to be explicit in the elements of evaluation (Table 2.2) to draw the system boundary for the evaluated system:

1) How is sustainability defined and demonstrated by the evaluation objectives?

2) What is the composition of the initial system?

3) What attribute(s) determine a basic scale of reaching a sustainable system?

By clarifying the understanding to sustainability and the attached sustainability evaluation objectives, the perspective that constructs the world and understands values within can be determined. Consistent with such perspective and with known components of the initial system in the social-environmental relationship, new objectives and limitations brought by DMs to the evaluated system require presentation (Ayres et al., 2001). This guarantees a system with structure that can be capable to sustain without collapse of stakeholder stances. Apparently, as stakeholder engagement expand under sustainability goals, stakeholder connections would eventually inevitably include the whole cosmos (Chakraborty et al., 2019). The natural actors connect all activities. For example, sustainability of urban cities that consider the changes brought to the land scape, bio-cycle, and non-bio ecosystems, link with sustainability of the planet regardless of cities' sizes (Norman, 2019, p.36). However, as an evaluation activity, we are limited by the strength of linkage to evaluation objectives and the evaluation resources. Thus, certain attributes can be chosen to eliminate the evaluated system to a smaller self-enclosed system with a new system boundary that is eligible to be assumed explicit. Ayres et al. (1998) jots it as a compromised treatment of environmental aspects towards strong sustainability. The idea of focusing on one or more key aspects to form a smaller system for evaluation has been applied for a long in many empirical studies, although not necessarily under the target of SS. In social context, this includes products (Thies et al., 2019), construction phases (Berardi, 2012), logistic processes (Sheu, 2008), and social well-being (Ramaswami et al., 2012). In the ecological context, such include key services of certain ecosystem (Dietz and Neumayer, 2007), the original distribution of resources and the structure and function of ecosystems (Clark, 2007, p.67-109), energy flow or accumulation (Odum, 1996), and various species and masses that are near their ecosystem's carrying capacities (Odum, 1971, p.126-132). Thus, relevant to evaluation, the attribute that determines the scale of the evaluated system for sustainability evaluation could be explained through the linkages with evaluation objectives and the evaluation resources and present an explicit system boundary for evaluation.

3.2.2 Sustainability Criteria

We decompose the definition of sustainability in this thesis, the sustainability for systems on Earth with energy and/or material fluxes, into two critical aspects for sustainability evaluation: the attributes, which are the necessary conditions, used to proxy sustainability, and the ranges that the attributes should be maintained within. The attributes, naming them *sustainability criteria*, are the criteria that approximate sustainability and are the baselines for developing sustainability relations in the evaluation. And, by stating the acceptable ranges, it determines the preferences in the evaluation over the sustainability criteria. Again, to emphasise, sustainability objectives are set for the sustainability criteria that are contained in or influenced by the initial system, being different from typical evaluation objectives for which the initial system itself often already hold the potential to realise it.

Previous chapters have specified the leading role of evaluation objectives in evaluations, determining or suggesting references for specific and explicit evaluation elements. As a decision-making tool, evaluations results are usually expected to improve or alter the current status of the initial system. Even ex-ante evaluation anticipate decision-making for an existing status bearing higher risk of implementation (Samset and Christensen, 2017). In this sense, we regard the sustainability evaluation objectives initially given by the lead of evaluation to be explicit. This is indifferent for sustainability evaluation. More importantly for sustainability evaluation, contained in the definition to sustainability, when the evaluation objectives specify or imply a possible sustainability criteria, this attribute should be included. When the evaluation objectives have not implied it, the sustainability criteria could be chosen by the evaluators.

In many current sustainability evaluations, carbon neutrality is a typical implied sustainability criteria that is widely concerned and linked with the sustainability objectives of climate mitigations. Even when the initial system feature with functional units of carbon removal and carbon storage, the necessary distribution to wastes and products always connect the initial system with external systems that can be traced with energy exchange and material transportation (Muis et al., 2010, Jungbluth et al., 2008, Blengini, 2009). The I-O initial system very often requires upstream systems to supply the inputs and downstream systems to distribute the outputs. However, in many cases, such sustainability objectives strictly following the definition is very commonly compensated into the form of reducing CO2 emissions which sets a baseline judgement that it is already excessive (Muis et al., 2010, Wang and Li, 2018). Even with the change in the objectives, it would not alter that wider systems together contributes to the emission of carbon (Biswas, 2014). Moreover, as Lal (2002) suggests, considering the interactions between carbon with weak stakeholders and the system components in sustainability evaluation, an even more wider system could be developed. Thus, as evaluation preferences can be held in external wider systems for the sustainability criteria that together regulate the sustainability criteria with the initial system, sustainability evaluation objectives are expected to contain elements to define the supportive criteria to be evaluated for the initial system.

The feasible sustainability objectives should consider the initial system compositions and relations with critical elements including the sustainability criteria. And, good sustainability criteria should defined with evaluation preferences in the sustainability objectives that could be traced demonstrate the mechanism to maintain the criteria within the acceptable range. We notice that sometimes, sustainability objectives are proposed with less relevance to the system functions while in other times, the sustainability objectives are highly linked with the system functions. Some determine sustainability criteria by the key structures and functions of ecosystems (Odum, 1971). The key components of ecosystems has the potential to maintain over time. The planet boundary framework determined sustainability preferences to be not causing non-recoverable changes, which could be indicated using some specific chemical elements or atoms (Rockstrm et al., 2009). In cases of sustainability evaluation for primary production systems, heavily protective measures often turn out to be acceptable. For example, as over harvesting of nature products results in directly observable degradation of the natural forest (Woodwell and Whittaker, 1968), protective measures to maintain the harvest rates of natural sources are prioritised before yearly economic profits. Although sustainability is recognised as the collective synthetic consequences of direct and distance measures, attaching external expectations to distant initial systems are often queried by the effectiveness and necessity of the measures (Allan, 2020). Feasible sustainability criteria for realistic sustainability evaluation should be able to be traced across systems to demonstrate the regulations over the criteria, especially when the initial system is not a primary production system. Also, as many necessary conditions could be developed for the criteria, the sustainability criteria would be more convenient to be applied if it remains across systems. However, defining too many sustainability criteria can lead to developing a system that is too massive for evaluation.

To note, we need to recognise that, as development has proceeded till now, some sustainability objectives can be unachievable or are limited by other elements of evaluation. De Neve and Sachs (2020) suggests that full destruction of some human non-sustainable constructions can be unrealistic even though the contribution of such approaches can be huge for reaching the maintenance of the sustainability criteria. For example, it is apparently impractical to demolish mega cities in exchange for environmental recovery. Besides, obvious at the stage, evaluation can be limited by the stakeholders, the accessibility of resources, and methods, when sustainability objectives are given too ambitious or not feasible enough, the evaluators and the DMs need to continuously communicate to adjust them or further define them. Since in many cases, the characteristics or part of them are implied in the sustainability evaluation objectives, we call them the explicit sustainability evaluation objectives when the initial system and elements relating to sustainability criteria are explicitly defined.

3.2.3 The Apposite System: Expected Features

The initial system usually has known boundary that contains system components, the transformational relations, and stakeholders that together serve for certain functions. In many cases of performance evaluation, the system boundary of the evaluated subject could be defined by the organisation boundaries. For example, when evaluation is done for banking branches, the evaluated subject system boundary is drawn as the banks (Mahmoudabadi and Emrouznejad, 2019); when it is done for hospitals, the land use and administrative participation together draw the organisation boundary of the hospital (Jaafaripooyan, 2014); when performance evaluation studies part of a building, the building's roof could be regarded as a sub-system however with defined functional separation with other compartments of the building (Shan and Hwang, 2018). When the initial system is a program, program sets the system boundary based on the participants and length of the program (Greene, 1988). As evaluation requires clear presentation of the elements, eventually it is done with determined evaluation subject that draws explicit system boundary containing preferred characteristics of evaluation objectives, stakeholders, and resources. To mention, in the evaluation that directly uses the initial system boundary, besides that it is often suitable enough for the evaluation objectives, the system boundaries of the initial system is also clear enough be used to identify all evaluation elements in demonstrating the relations and limitations.

Given sustainability evaluation objectives and feasible clarifications for evaluation elements including the lead of evaluation, the DMs, and the sustainability criteria that could identified from the evaluation objectives, we define that a suitable subject for evaluation is a system that contains potential to maintain the sustainability criteria. We name it an *apposite system*, for the sustainability evaluation objectives. Alike past evaluation practices, the apposite system is expected to be eventually presented with explicit system boundary with clarified stakeholders, system transformational relations, and components. We recognise that the apposite system developed is also an I-O system that could include new stakeholders including DMs and KSs, and system components including inputs, outputs, transformational relations. Besides, sustainability is expected to be reflected using multiple indicators or compound indicators (Chapter 2). Integrating the evaluation objectives into the evaluation subject, the apposite system should serve as the evaluation subject in sustainability evaluation.

Just alike any other forms of evaluation, the DMs in evaluation determine the preferences of evaluation which can be influenced by internal opinions of the initial system and external world-views. Many values and preferences are associated with stakeholders. Hence, for sustainability evaluation, as linked subsystems together contribute to the maintenance of the sustainability criteria, on the one hand, the interests held by the DMs of the linked systems should be considered; on the other hand, as non-human species, mainly animals, are often important actors in the social-environmental relationships, and could contribute significantly to the changes over the sustainability criteria, especially when attributes of the natural environment are included. However, due to technical limitation in understanding the opinions of the weak stakeholders, their preferences over the sustainability criteria cannot be accurately known, especially when compared to the preferences of strong stakeholders. For example, the use of corn stovers as biofuels is appreciated as a form of renewable energy sources, while the harvesting of corn stovers also influences the soil and associated carbon cycle of at the site of corn field (Sheehan et al., 2003). The influence to soil quality and soil fertilisation further influences the species within the ecosystem (Odum, 1971). Also, the preferences for strong stakeholders in different subsystems associating with the sustainability criteria can be different. While national electricity generation widely target for reducing or phasing out the use of coals (IEA, 2020*b*), the coal generation mainly attempt for efficient and low-carbon production (Sueyoshi et al., 2018). The electricity generation and coal extraction systems could be contained in the same apposite system if the sustainability evaluation is done for the electricity generation systems. Thus, the apposite system for sustainability objectives should be able to associate the collective values and the differences in the values of subsystems or the stakeholders within the subsystems. To deal with the weak stakeholders and more silenced strong stakeholders, we could compensate for their living and well-being. We treat the basic living space and requirements for the living of the weak stakeholders in this thesis as the compensation to the values that the weak stakeholders may hold and allow for suitable space for ”unsustainable” factors. In this way, we understand that the values held by the DMs in the apposite system for the sustainability evaluation objectives, both within the initial system and the external values, are associated with the stakeholder connections centring the initial system and recognise the difference caused by geographical distributions of the stakeholders. Together, the explicit value by strong stakeholders can be expressed and compensations are made for the values that could be potentially held by the weak stakeholders, although with a relatively low standard.

Overall, the apposite system to be served as the evaluation subject should be a wider input-output system with determined using explicit sustainability objectives in its characteristics, the DMs which may include new parties, wider KSs, system components, and explicit system boundary. It should present the potential to reach sustainability under the definition of the sustainability criteria with reasonable presentation to the values and preferences of weak stakeholders. Eventually, it is a system that could be explicit in all evaluation elements including the resources and, eventually, the indicators that are available to be used for evaluation.

3.3 Sustainability Evaluation Roadmap Construction

Consecutive to previous descriptions, we collectively perceive that sustainability evaluation would suggest developing clear sustainability evaluation objectives, steady stances of DMs and evaluators during the evaluation, the values that are perceived as influential to the decision-making of the initial system, and the criteria for sustainability and associated preferences. It it also recognised that, not limited to sustainability evaluation, for evaluations of any system, eventually, the evaluation elements should be set and clear, especially with the evaluation objectives and the determination of system boundary indicating the subject of evaluation (Chapter 2). We notice that the issue of not finely defining sustainability and guaranteeing consistent stances of stakeholders are the key issues that could cause further flaws to sustainability evaluations. It is recognised that some critical information that would define sustainability is instead implied in sustainability evaluation practices. This implicitly alters the definition of system sustainability to the one that we imply in this thesis, containing global or planet context. Also, as sustainability evaluation can be done for great variety of systems in different fields, the evaluation roadmap for sustainability should be able to suit systems of all scales and contexts.

Thus, conducting sustainability evaluation from the perspective of system performance, SSM, a system analytical approach to understand the problematic situation that is identified in sustainability evaluation, can be imposted among many system performance assessment methods. We implement 3E measurements for system performance. However, it needs to be recognised that vision and expectations for system performance can be unachievable during the development of evaluation measures for system with value-based, durable, and developing objectives (Pun and White, 2005). The procedure for constructing the roadmap for sustainability evaluation follows:

1. Understanding the evaluated systems in current sustainability evaluations from 3E perspective and proposing the dimensions of evaluation framework for sustainability that is universal;
2. Developing the apposite system for the sustainability evaluation objectives;
3. Identifying new features in overall evaluation elements particular to sustainability evaluation and proposing possible treatments for sustainability evaluation.

3.3.1 3E Performance Metrics in Evaluated Systems for Sustainability

The system boundary is drawn by the inputs that entered the I-O production, the transformation process, and the outputs produced. Under the view of business operation, these are the aspects that can be controlled or altered by the DMs of the initial systems. For such an I-O system, we attach the system performance aspects and the performance evaluation window shown in Figure 3.1. Here, system performance can be measured by 3Es including efficacy, efficiency, and effectiveness, and efficiency is defined under the common energy efficiency form of purposeful transformation.

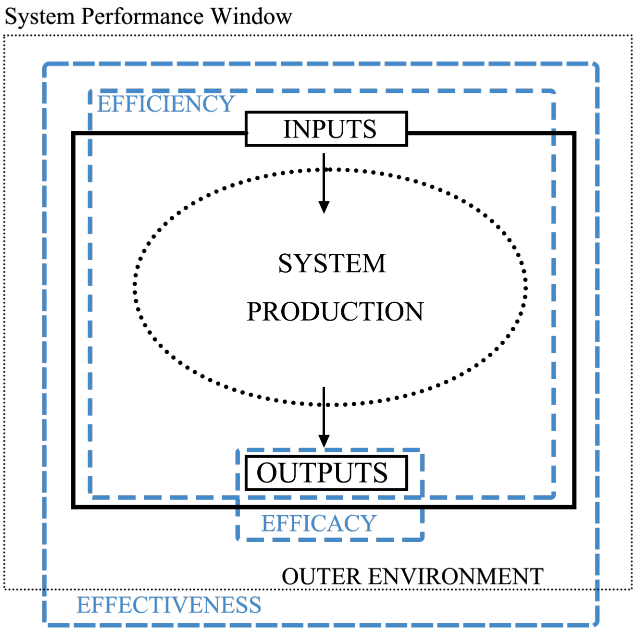


Figure 3.1 Performance Evaluation View to General System in 3E Metrics

Among the 3Es of performance measurements, apparently, efficacy and efficiency maintain within the system boundary of the I-O model. Effectiveness thus links the all system nodes and connections, including and not limited to the supply and use of inputs, the transformation process, and the outputs, with the outer environment beyond the system boundary defined in the I-O system. Thus, determined by the extend to which effectiveness for performance evaluation is concerned, the evaluation window includes everything inside the wider boundary. The enlargement of system boundary for evaluation not only means that some components that were in the outer environment are contained in the evaluated system, but also suggests that these components are attached with certain criteria.

Focusing to sustainability evaluation, the measurements to reflect the system performances of the evaluated subjects in articles from Section 2.5 are categorised according to the 3Es for system performance. To screen the evaluated subject systems as economic-social-environmental systems, the articles using the TBL sustainability framework is selected (33 articles in total).

Listing some for reference, many studies apply SDGs from the UN, including the goals and listed measurements, which can be more easily classified to economic, social, or environmental strategies (Riahi et al., 2017, Bauer et al., 2017, Jin et al., 2006, Amaral et al., 2015, Gonzalez-Garcia et al., 2018). Some tend to bias to one aspect of sustainability, for economic (Wiek et al., 2012, Pelletier and Tyedmers, 2011), social (Eizenberg and Jabareen, 2017, Ozaki, 2011, Stagl, 2006), or environmental (Klein et al., 2005, Hou and Al-Tabbaa, 2014, Holden and Hyer, 2005). Some construct the measurements around the performance of the evaluated subject which can be products or systems (Sheehan et al., 2003, Chen et al., 2008, Deuble and de Dear, 2012, Yellishetty et al., 2011, Pretot et al., 2014). Some develop the measurements based on certain strategies (Langston et al., 2008, Sev, 2009, Duchin, 2008, Kennedy, 2002). Overall, the results are presented in Table 3.1. To understand the measurements in the general sense, contextual contents are excluded and only general terms are presented.

Table 3.13E Classification to Sustainability Evaluation Measurements for Economic-social-environmental Systems

Aspects 3E	Economic	Social	Environmental
Efficacy	Increase product effective time Reduce cost GDP increase Accumulate capitals	Reduce material use Increase production Install energy saving equipment Respect topographical conditions Respect natural conditions Enhance clean technology use Enhance sustainable awareness	Reduce emission and discharge Reduce environmental load Recycle materials and resources Use renewable energy Preserve landscapes and land cover Obey radioactive forcing
Efficiency	Cost effective transformation Increase GDP per capita Reduce payback period	Improve productivity Improve transportation utility Maximise energy efficiency Enhance energy saving Improve transformation efficiency Enhance service mobility Efficient use of natural conditions Enhance sustainable acceptance	Reduce emission and discharge intensity Efficient use of materials and resources Safe use of radioactive matters Enhance material and energy recovery from transformation
Effectiveness	Preserve product potential value Reduce clean energy price Increase investment potential Non-reducing profit	Product security potential Enhance energy and material security Reduce energy demand Reduce the urban heat island effect Protection of stakeholder health and comfort User satisfaction Contribute to policies Enhance sustainable value	Contribute to global warming 2°C target Reduce emissions and discharges to related ecosystems Improve environmental performance Meet potential for trade-offs Decrease environmental risks Improve urban commodity

Although economic-social-environmental systems are widely used for sustainability evaluation as the three pillars demonstrating SD, we notice that, in practice, the measurements form different subsystems of the evaluated subject system and consequently, for instance in the TBL framework, such treatment to the measurements of system performance of the evaluated system would not guarantee the comprehensive analysis for the universal system of the evaluated subject. Apparently from Table 3.1, the measurements over economic, social, and environmental aspects can be clearly categorised to 3Es with some strictly lying in one aspect while some are interactive with more than one aspects. For example, expressed in monetary unit as the energy price, it is believed that better cost-effective management of the production plant and applying social measures, such as technological improvements and institutional incentives, could reduce the energy price at the user end (Stamford and Azapagic, 2014). Stakeholder satisfaction, directly measured through surveys and interviews, is found to be the mutual outcome of acceptance for product prices, the green values acknowledged, and the environmental protection potentials recognised (Taylor and Ampt, 2003). Economic, social, and environmental aspects are not fully independent from each other. Also, empirical studies such as Onat et al. (2014) proxies the valuation for energy produced using gross domestic product (GDP), representing the efficacy of national energy system, and efficiency is measured using GDP per capita which would be the intentional action taken to increase the potential of regional investment for assets and technology. Similarly, Pons and Aguado (2012), focused for social aspects, forms the chain-wise measurement connection that sustainable social value can be enhanced through promoting the acceptance to sustainability attitudes, which is linked with the level of sustainability awareness. Independent concern for system performance over only one aspect is more explicit in the environmental aspects with ecosystem basis. The emission of CO2, often serving as the efficacy of the system, is linked with the emission intensity that is demonstrated by the volume of CO2 emission during transformation for production and, over effectiveness, is regarded to influence global warming due to the physical properties of atmospheric CO2 (Onat et al., 2014, Pons and Aguado, 2012, Gong et al., 2012, Riahi et al., 2017).

Thus, we recognise that in such practices of conducting sustainability evaluation to economic-social-environmental systems, the measurements used are inappropriate for the evaluated subject if the network linkages among the aspects are not recognised and more problematically, the aspects are, in fact, developed into subsystems with independent but strategically linked system performance expectations. To note, the division of the global evaluated subject system into subsystems could have many alternative ways. Different divisions to subsystems for systems on Earth include food webs, waste management systems, cities and technological constructions, energy supply networks (Schwarz-Herion and Omran, 2015). On the one hand, as previously argued, we recognise that all current strategies, objectives, evaluation criteria, and implementations to sustainability are necessary conditions to reaching true sustainability of the planet. Similarly, demonstrating an universal system using economic, social, and environmental aspects would also not be sufficient for sustainability even if the sustainability objectives for different subsystems that may contribute for reaching better state of SD are reached. As the UN suggests, SDGs would alter as the challenges to be faced over the social-environmental interface changes (UNDESA, 2020). Thus, it requires global interpretations for sustainability objectives given to the universal system. On the other hand, revealed by categorising sustainability evaluation measurements into the 3Es for the subsystems, many current sustainability evaluation seem to be arbitrarily dividing the universal evaluated subject system and some important system performance brought by system integrity can be lost. Consequently, since system performance criteria are associated with all components in the system (Lior and Zhang, 2007), we perceive that it is necessary to analyse the 3Es and developing suitable sustainability evaluation measurements for the system performance of the global system.

However, directly using 3E measurements could also be problematic for sustainability evaluation, especially for benchmarking and comparative intentions. As Table 3.1 presented, contextually different subsystems could induce different measurements for 3Es. Within the economic subsystem, measurements frequently include monetary indicators including GDP, cost, revenue, profit. In the social subsystem, demographic, technical, and cultural indicators are used. In the environmental subsystem, measurements of pollution and wastes and of ecosystems are used. Apparently, systems in different industries or producing different outputs would result in deriving different set of performance measurement system using the 3Es. Especially in sustainability evaluation, even the same system with different sustainability criteria defined by the sustainability objectives could form different set of 3E measurements. For instance, for electricity production systems measurements for the CO2, NOx, and SOx emission associate with different sub-processes in the production mix and are measured differently (Commission, 2018*b*). Consequently, sustainability evaluation implementations and suggestions are different for every system evaluated and they could be incomparable since the system construction defined by sustainability criteria that is wilfully contained in the sustainability objectives can be different. In other words, the dimensions of 3Es in evaluation is abstract. In the same time, to note, the sustainability criteria given in the objectives or implied would require that the evaluated subject is a system that is apposite for the given evaluation objectives, which will be explained later.

To this point, we propose an evaluation framework for sustainability with three new dimensions: material and energy, system structure, and value. They together serve as a group of concrete dimensions for the 3Es when applying it for the sustainability evaluation of a system.

3.3.2 A Framework of System Performance Measurements for Sustainability

The key directive that develops the formation of the structure in the social-environmental relations is the collective value associated formed by the values associated with each one of the stakeholders. If the 3Es are directly applied to a system for sustainability evaluation, there are effectiveness attributes that are linked by the non-organic system components which would not associate with the valuation for the sustainability criteria. For example, complex stakeholder connections could demonstrate the influences from local carbon sink to the global carbon sink but would not include the physical trajectory of carbon emission diffusion itself. The diffusion of concentrated CO2 emission driven by atmospheric kinetics would not demonstrate preferences for merits in sustainability evaluation. In other words, while the 3Es are three objective aspects of system performance, to embed subjective objectives contained in evaluation, to the least, value justify the meaningfulness of the system's existence, associating with the preferences of expressed, especially by the DMs and KSs in the evaluation. Especially for sustainability evaluation, value regards it worthwhile to consider the sustainability criteria.

Aside from that, respectively particulate for efficacy and efficiency, the material and energy products and the transformation relations of general systems are considered in sustainability evaluation. As Kondraske (2011) notes, physical mass and energy, and the structure leading to the flow and changes of the mass and energy are the fundamental construction of general systems. We notice, sustainability, for the current planet, is about reducing the accumulation of mass and energy that are already excessive and maintaining certain sustainability criteria for a global system. The performance of sustainability is found to be improper to demonstrate either quantity of inputs and outputs or the transformation pathways. Thus, concluding the basic constitution of general I-O system (Chapter 2), the material and energy, structure, and value dimensions of the MSV metrics, taking the initial letter of each dimension, would also suit for general system, not restricted for system context nor the system components, and enables the consideration to the values held by different types of stakeholders. The three dimensions of MSV metrics together demonstrate sustainability of the system, which under the definition in this thesis, mainly over the sustainability criteria. The conceptual model is exhibited in Figure 3.2.

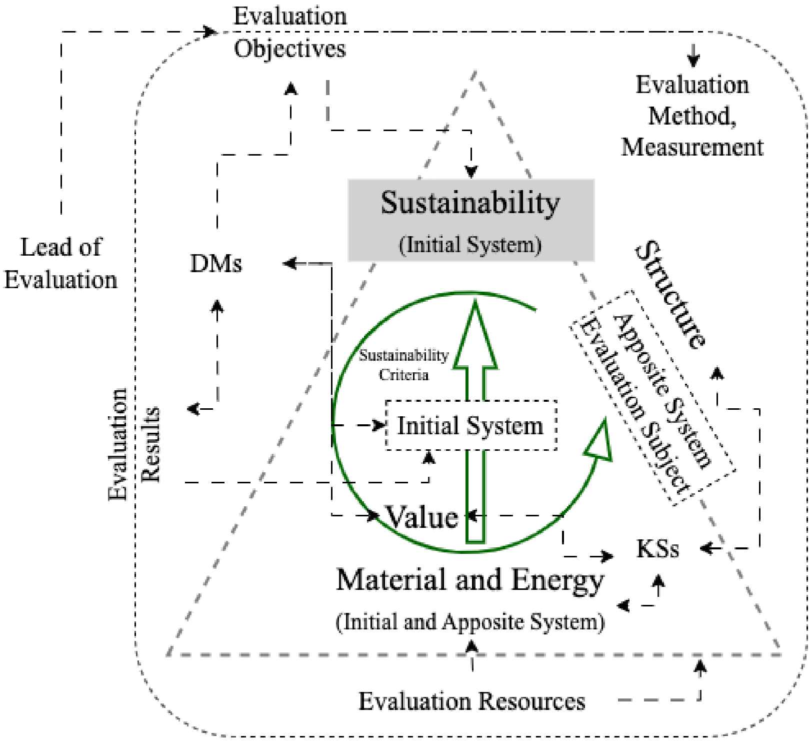


Figure 3.2 Conceptual Model of the MSV Metrics

MSV Metrics

Material and energy demonstrates the physical basis of the system, concluding the system components including the inputs, outputs, and the materials that form the system structures. It mainly links with the efficacy of the system presenting how much materials and energy are accumulated or have flown through. While it has been acknowledged that natural ecosystems require material and energy basis for its subsistence (Odum, 1971), material and/or energy in and out flows are also the basis of industrial ecosystems (Jelinski et al., 1992). For sustainability, the sustainability criteria could be defined for certain material(s), element(s), or type(s) of energy. It is a fundamental aspect of sustainability as the alert for unsustainability mainly comes from the observation that materials also the living beings, or energy could be exhaustible. Eventually, sustainability is about the relations that reach balance for the consumption and reproduction of materials and energy.

Structure demonstrates the transformation relations of the system, that is the construction or the pathways that materials and energy flow or transform. Very often, guided by the system purposes and the values associated with the system, structures are purposefully constructed for producing desired outputs. As material and energy dimension mainly deal with quantity, structure mainly demonstrate the types of sources and the quality of transformation. It mainly associates with the efficiency aspect as the composition mix of the materials and energy can be regarded as a profile including information about the types and respective distributions. On such basis, its role in sustainability can be perceived as the capacity to perform system transformation and the capability to maintain the system transformation relations, the sustainable potential. Currently, substitution to exhaustible sources, the technological improvement to transformation efficiencies, and spatial allocation to the materials and energy are some typical measure of structural arrangements.

Value justifies the existence of the system from both internal and external perspectives, mainly associating with the effectiveness of system performance. It demonstrates the purposes of the system by defining the desirable and undesirable inputs and outputs, and guides the formation of the system structure. Different stakeholders hold different values that associate with power and legitimacy (Mark and Shotland, 1985), and values are currently only able to be implied when the stakeholders are non-human groups. In sustainability relations, colliding and synergetic values among strong and weak stakeholders together form the collective value of the system that the evaluation DMs should follow or respect.

Eventually, as a set of possible concrete metrics of the 3Es, the MSV metrics can be applied to any system to be evaluated for sustainability. It principally demonstrates that sustainability, mainly over the sustainability criteria, is reflected in the material and energy flux, the structural construction, and the value accumulation centring the initial system. Determined by the extent to which the sustainability criteria reaches out to, sustainability evaluation could be done for a wider system so that MSV dimensions are properly measured for a system with sustainable potential. In this way, the uniform concrete metrics that is used for sustainability evaluation results in the producing evaluation feedbacks and implementations for specific sustainable system and could be cross comparable among systems with the same reference system.

3.3.3 Feasible Measurements for MSV Metrics

Sustainability evaluation and performance evaluation could be not mutually exclusive in the division of types of evaluation which means similar measurements could also be used for both evaluations. However, the principle of selecting measures for system performance evaluation and sustainability evaluation are different, which is analysed in this section. It is expected, in this thesis, that sustainability evaluation from the system performance perspective should collectively hold respective features to be feasible measures, especially dealing with the evaluation objectives and the sustainability criteria.

For performance measurement of general systems, generally, as pointed out in Chapter 2, the metrics and measures used in evaluation needs to be measurable, suitable, and approachable as evaluation cannot be done with unmeasurable metrics or measurements (Nielsen and Ejler, 2008, Pawson and Tilley, 1997). Given the expectation to make useful and practical decisions through the evaluation, performance measurement systems are developed following the evaluation objectives and the quality of the measures is often judged over more specific criteria.

There is no fixed standard protocol for developing suitable performance measurement systems the processes are alike. Mainly analysing for different groups of human stakeholders, organisational performance measurement systems are mainly developed following the process of receiving core evaluating objectives, identifying key stakeholders involved with the objectives, determine the suitable explicit objectives, develop performance measures, develop periodic measurement system and provide the needs over resources, timescales, and stakeholder participations for gathering associated data (Hudson et al., 2001). When the system for performance evaluation includes upstream production processes such as the extraction of natural resources, May et al. (2015) concludes the general process for deriving suitable measures as a process of defining reference production system and key functions, identifying system requirements and problematic situations, linking requirements over time, space, and material and energy availability, and then construct measures over the problematic situations and requirements. We recognise that certain explicit criteria are used to direct the development of performance measurement systems.

Such criteria often seem to be given or derived from the evaluation objectives, assisting understanding the evaluation objectives, the system mechanisms, and how the evaluation objectives are realised by the system. Key system performance attributes are found to be guiding the performance measurement systems (Propper, 2003). The suitability of measures can be judged based on the outcomes of how much the implementations behind the measures would improve the current situation or the problematic situation demonstrated by the objectives. Lee et al. (2007) notes that direct performance measures should lead to successful conduction of the evaluation objectives. However, there are many cases that when the evaluation objectives are intentionally given, the evaluated system could be incapable for achieving them. Especially, as Humphreys and Francis (2002) notes, the process of using SSM for performance measures of efficacy, efficiency, and effectiveness reveals that effectiveness is only created linking with external systems through extending mechanisms from the evaluated system. Here, we note this as the suitability of the evaluation objectives for the initial system. Especially in sustainability evaluation where the influences are a rather important aspect of the evaluation objectives, the extended linkage with external systems is critical for the initial system. The measures derived could very significantly whether including the extended systems. As Pun and White (2005) notes, individual objectives and collective objectives need to be evaluated with different measures since direct measures of individual level performance could dilute overall presentations on the system level. Aside from requiring performance measures to be capable of reflecting comprehensive current state, future prospects are also an important aspect of expectations. Facts and data are expected to be indicating the goodness of the current performance and, more importantly, the potential aspects to be improved immediately and in the future (Pun and White, 2005). Hence, based on different future insights, metrics and measures can be highly case-sensitive as the outcomes of stakeholder preferences (Gunasekaran et al., 2004).

Thus, suitable performance measures are expected to hold the following features. They should be directed by objectives, specific defined with explicit purposes and operations, continuously measurable, attainable and easy to use, realistic under limited resources, and provide timely, continuous and accurate evaluation feedbacks (Hudson et al., 2001, Parida and Kumar, 2006). This is a combination of the widely used SMART test and the general characteristics of performance measures. Also, especially when system performance is to be evaluated comprehensively including the outcomes, transformation, and the influences, the system that is evaluated should be an extended system from the initial system. Most importantly but often neglected, when evaluation objectives are not achievable for the initial system, the performance measures need to, at least, follow the root definitions of the objectives (Davis et al., 2015).

For measuring sustainability, we emphasise special issues that are regarded as more feasible measurements in this thesis, the consistency of stakeholders from the evaluation framework used to the measurements, and the requirement for measuring the sustainability criteria.

Although frequently noting the inconsistency of stakeholders in past sustainability evaluation works, from its framework to the selection of measurements, sustainability evaluation could still be done using any frameworks, either focused to human society or to the natural world. Taking human central stakeholder stances would not mean that the sustainability evaluation is fully flawed but indicates that a group of necessary conditions to sustainability are taken under the human benefits. But its limitations are also apparent. For example, social sustainability that sets the objectives as pursuing social well-being would naturally bias towards the values that are more appreciated by human. As more intangible values are included in social well-being such as the aesthetic and cultural values of the nature, the concerns for the weak stakeholders in this thesis are increasing. However, as we notice from the previous chapters, holding human central sustainability values would inevitably miss out some important attributes of the nature, especially the values and nature's services that are not frequently in touch with current human life or are the interactions between weak stakeholders (Yin and Herfel, 2011, Jax et al., 2013, Gretchen C. Daily, 1997). On the one hand, we attribute such limitations in sustainability relations as the limited cognition to stakeholders and their functions on the planet, which induces the unpredictable and the accumulative outcomes until the consequences jeopardise human life. Hence, although sustainability evaluation done lead by human centring frameworks is not fully flawed, on the conceptual level for planet sustainability, induced evaluation implementations could be found to be problematic. On the other hand, we attribute such limitations as the insufficient technical treatment for the evaluated system in sustainability where some necessary measurements are not widely used. For example, according to Vanham (2016) presents, performance evaluation given sustainability goals would always bound with extended impacts from the initial system. Not systemically analysing impacts related to the sustainability goals given for the initial system would result in unsuitable evaluation results over effectiveness metric. Also, evaluating from the thermodynamics point of view using entropy measures, the urban systems are found be unsustainable, which is defined by unstable system constructions. Hence, while we notice that sustainability, defined in evaluations, would always introduce external linkages of the initial system with the external systems and weak stakeholders, after including universal stakeholders in the frameworks, the metrics and measurements alter accordingly. From Chapter 6, the MSV metrics are proposed as a group of feasible metrics, however, the measurements require further development.

Another critical aspect of sustainability measurements is that, without radioactive reactions, sustainability would always hold on the level of chemical elements, such as carbon. However, sustainability does not suggest the preservation of certain chemical elements, but rather the compound products containing the element that could be utilised for transformation in a system. As Baccini and Brunner (2012) points out, any general system can be abstracted into the form of system metabolism with consistent material and energy flows creating relevant values. This means that material stock and energy stock always remain constant over the cosmic level, which, following the First Law, results in the constant non-value lead efficiencies of all systems, $\frac{E_O}{E_I} = 1$(Lior and Zhang, 2007). Hence, from the perspective of chemical elements, reusability, resistance, durability, or any properties linking to the macro-scale stability of a system become meaningless unless radioactive transformation processes occur. The elements would always remain constant in the nature without atomic reactions (Sheu, 2008), and consequently we may be breathing the oxygen our ancestors breathed (Odum, 1971), realising sustainability. Hence, we while we recognise that radiologically stable is an important aspect for the safety of many living organisms (Franks et al., 2011), when it is technologically approachable to measure quantity of compounds of all elements, planet sustainability may be better evaluated.

To be feasible for current sustainability evaluation, more focused to certain compounds of some chemical elements, we appreciate the physical connections of materials and energy that are connected by elements as the criteria demonstrating the fundamental network connections of all living organisms and non-living substances on the planet. Over the macro level, such connections are perhaps the most important linkages to identify the impacts that the initial system has created to the external world. Eventually, it may generate global connections from the initial system with other stakeholders on the planet. Many past sustainability evaluation practices have revealed the effective contribution to producing more suitable sustainability implementations based on part of the elemental connections. Under the guidance of production purposes, the application of LCA to many construction and production processes (Blengini, 2009, Thies et al., 2019). It would also justify sustainability evaluations based on CO2 emission during the life cycle (Gong et al., 2012, Biswas, 2014). Additionally, as Mulia et al. (2016) indicates, the connections among stakeholders associate with values. This means that for certain compound in the nature, for instance CO2, different stakeholders would appreciate it differently. Following the elemental traces of the compounds, the associated values would demonstrate how the quantity of the compound is regulated on the planet.

EEV Measurements

As presented in Figure 3.2, the achievement of sustainability for general systems relates to efforts in three dimensions, material and energy, structure, and value. On top of that, we understand that the material and energy dimension reflects the physical scale of the system, structure presents the organisation of the system for the use of material and energy, and value, especially the collective value of the system, leads the direction of system development. The EEV measurements, also taking the initial letter for each one of the measures, respectively measure the three dimensions using material and emergy, entropy, and value, which includes the intrinsic value and the instrumental value. Taking measurements from different perspectives for evaluating sustainability, EEV measurements integrates system performance perspective with material and thermodynamic perspectives for observing a system. Table. 3.2 presents the outline of the EEV measures. To emphasise, the key reason of proposing the EEV measurements is that, given the context of sustainability on Earth, material and emergy, entropy, and values are general properties that are applicable in any system, not affected by the system scale, the stakeholders, nor the valuation system contained.

Measuring for the MSV metrics, the EEV measurements could also be regarded as a group of concrete measures for sustainability evaluation using the 3Es. It also holds the advantage of MSV metrics that since material and energy

Table 3.2EEV measures and expectations

Framework	Measures	Explanations
Materials and energy	Material Emergy	Would the materials maintain to some range? Does emergy or its change result in good accumulation of energy?
Structure	Entropy	Does entropy or its change result in stabilised structure of the system?
Value	Intrinsic Value Instrumental Value	Are both values accumulating through transformation?

flux, entropy flows, and value changes exist for any system on the macro level, being three relatively independent compound measurements of a system, they are suitable and could be comparable across different systems with universally preferred directions of improvement. Each one of the measurements are explains in subsequent parts.

Materials and Energy Measurements

The material and energy dimension describe what and how much is consumed and produced from the system which should also be measured on both the material and the energy basis. Mass and energy are probably the most frequently seen measurements. However, in sustainability evaluation, especially as we consider for universal stakeholders, the mass and energy flow or transformation relations could be too complicated and hold great variety as the evaluated system changes or as different sustainability criteria is used. To form comprehensive indicators for the MSV metrics, we would expect the material and energy measurement to be feasible for general systems so that, eventually, the compound measurements formed from diverse indicators would still be comparable across sustainability evaluations.

According to the first law, mass and energy, on the macro scope, would remain constant in the universe. However, for sustainability evaluation, which should be done with limited evaluation resources, evaluating using full profile of mass and energy, as previously noted, would be technically infeasible nor would it be necessary. However, given such physical basis of linkages and properties of mass and energy, we suggest treating materials and energy differently for performing sustainability evaluations for systems on Earth. The synergetic treatment for material measurement and energy measurement could be concluded as using the material measurement to describe the mass flow and features of the materials and using emergy measurements to describe the efforts made on the physical mass flows.

Although materials contain energy and its transformation would associate with energy changes, the existence of the materials, physical connections of materials in flows, and, for ecosystem concerns, the capability of diffusion and purification for one material are important features that could be not measured in energy measurements. Here, we point out that sustainability criteria should not be set for certain chemical compounds but rather for certain element(s). As widely recognised, although it is the compounds that would lead to climate issues, the process of forming the compounds through chemical reactions and physical changes need to be traced by element. Although radioactive reactions may alter elements, similar principle would be followed.

Defining for the sustainability criteria, we utilise mass flow of materials as the basis of constructing sustainability relations that constructs the apposite system. As proposed in Chapter 6, in sustainability evaluations, we expect the sustainability criteria, or part of them, to be given in the sustainability evaluation objectives are often associated with one or more material fluxes. For example if the sustainability criteria is set for CO2 emission control, the apposite system would be established on the basis of mass flow of carbon and oxygen leading to the CO2 emission. Traces of carbon containment and carbon emission connect the critical stakeholders which consequently, for the sustainability evaluation, determined the collective values for the sustainability criteria and, more importantly, introduced indicators of carbon containment and carbon emission. However, as analysed in Chapter 4, tracing over one or more elements in the ecosystem could eventually include the whole Earth and perhaps the cosmos as mass and energy exchanges frequently occur among ecosystems and between the Earth and the outer space. Capturing full mass and energy flow for the equilibrium over the sustainability criteria could be infeasible for evaluation sustainability evaluation and thus regional system with enclosing relations could be instead considered. In this way, including new sustainability criteria in the evaluation would suggest the necessity to reconstruct the sustainability relations forming the apposite system based on the mass flow and introducing new indicators in the measurement system.

Another key feature to be treated under the material measurement is for ”pollution”, or in more general terms, over production. Being able to include preferences of weak stakeholders in the sustainability evaluation, it is recognised that ”pollution” becomes a term related to the values of stakeholders for all materials instead of being a criteria that categorises them. As Tomczak Jr (1984) concludes from various philosophical definitions to pollution, when we speak of pollution we are indicating, from the perspective of impact control, the particles or materials which are often wastes or hazardous substances of human industrial activities that are harmful to human, non-human species, and the environment. Jacobsson and Trotz (1986) defines, pollution is defined based on the impact over human health or the living conditions. Also, it is emphasised that a definition of pollution should be clearly stated in time and spatial scale during which the relevant impacts are concerned, else by extending the length of time or wideness of space, the impacts of the ”pollutants” may not be harmful any more (Tomczak Jr, 1984, Tenailleau et al., 2015). They also noted that wastes could not be pollutions at all as they may be supportive or the metabolism of other species. To conclude, pollution, principally and especially considering for a system with universal stakeholders, should be demonstrated as a property of tolerance. As the planet boundary suggested (Chapter 5), for the planet systems, it is only be stepping over a certain boundary where irreversible changes would occur and unsustainable flows and structural changes must occur.

Hence, we propose the use of a tolerance boundary for the materials. For example, for material X in the region during certain length of time, given an ecological threshold or environment capacity of X', when X is not timely distributed to external regions, then given the conceptual definition to pollution, regardless of how human value X, it is always the fact that $(X - X')$ is the undesired quantity of the material for the system. The issue of pollution is described, instead, using the general feature of any material that over-concentration, let it be products, produced wastes, air pollution emissions, or hazardous or toxic substances to living beings, would produce harmful impacts to universal stakeholders. It is recognised that one substance could be harmful to some species but could be useful for others. Such spatio and time differences should be reflected by different X's even for the same material. In this way, whether a material being pollution or not would not bother with philosophical definitions but becomes a characteristics of the material that is influenced by time, space, and other conditions which can be more effective in controlling its production.

Following the treatment to material measurement, we propose using emergy as the energy measurement that also relates with quantity of the materials. As introduced in Chapter 2, emergy, *Em*, of a material or service is all input solar energy accumulated on the unique pathway of transformation using the unit of *solJ* (Washington, 2013, p.6). The emergy for any system outputs is expressed as:

$$Em = \sum_{i=1}^{N} Em_i \tag{3.2}$$

, where N is the number of emergy input sources, which are also all inputs in for the system including transformational inputs, constructional inputs, and information inputs. All materials, energy, services, and information on Earth are regarded to be formed with energy from original sources of solar, geo-potential, and the tides. When a system simultaneously produces more outputs, the emergy flow is divided by the proportion of energy flow at each accumulation process (Herendeen, 2004). Calculating the accumulation of energy, emergy is regarded as a measure of not only energy quantity but also quality following the energy quantity-quality flow (Odum, 1996, p.27). To note, other energy measurements, such as the energy flow of the materials could also be feasible and has been widely used. However, emergy measurement is appreciated for the following reasons.

In sustainability evaluations, it is able to measure the contributions from the primary production of the nature. Originally evaluating for the initial system, the system holds key purposeful transformation processes for which we understand that the purposes and evaluation objectives are determined by the system owners, the evaluation DMs, and some of the KSs. However, following how efficiency is typically defined using ”useful work”, energy measurements are often unable to reflect the cost-free contribution of the nature during primary production processes (Lior and Zhang, 2007). Often in social systems considering capital inputs, the cost-free primary production of the nature is neglected. Unless studies especially focus on the properties of nature's primary production (Woodwell and Whittaker, 1968, Pauly and Christensen, 1995), the sustainability evaluation measurements for efficiency tend to present cost effectiveness. It would not fully consider energy flow associated with sustainability criteria such as carbon. However, as reviewed in Chapter 4, this would neglect the most critical conflict between the nature and excessive human activities where the positive feedbacks caused by human activities have been excessive and are causing degradations of the surrounding environment of human society (Odum, 1971, p.68-75). Thus, emergy measurement, requiring to follow the energy hierarchy from the solar sources, reveals the energy concentration of the evaluated system (Brown and Herendeen, 1996). Especially, the energy accumulation would differ for the same output depending on its pathway of production.

Classic sustainability indicators in emergy analysis classify resources according to current classification of renewable and non-renewable sources, which mainly compares the time duration needed to reproduce the amount of consumed sources with the life span of human production activities (Brown and Ulgiati, 2002, Odum, 2007). Typically, fossil fuels including coal, oil, and natural gas are regarded as non-renewable sources, and wind, solar water for electricity production, and biomass fuels are regarded as renewable sources. Although such sustainability evaluation using environmental accounting methods would still provide implementations for approaching for better sustainability (Ingwersen, 2011), we need to notice that past emergy measurements for sustainability evaluation, taking such treatment for classification, would bias towards human valuation. The nature of renewable sources under the definition of sustainability is that they are bound with cyclic energy hierarchy and would alter the quantity of emergy flow in the system. Considering the massive amount of data needed to fully describe the cyclic system, to simplify the evaluation, the following capable treatment could be used.

To be able to suit valuation of universal stakeholders, we classify material and energy sources in to renewable and non-renewable sources based on the balance between the rate of consumption and rate of production of a region. Genuinely, for any inputs that are the outputs of primary production process from the nature, there are two dynamic properties, the consumption rate and the reproduction rate, where we respectively note as f_h and f_p. Given the time duration of study $\bar{T}$ and quantity of material I, the consumption rate, also naming the harvest rate in primary production processes noting with f_h, follows $f_c = \frac{I}{\bar{T}}$. Similarly, the reproduction rate, f_p, is the quantity naturally produced over time which would be a physical property of the material in the region. Conceptually, the classification for an input source X follows:

$$\begin{aligned} &I \quad is \quad renewable, \quad if \quad f_h \leq f_p \\ &I \quad is \quad non-renewable, \quad if \quad f_h > f_p. \end{aligned}$$

Multiplying the rates with $\bar{T}$, it transforms the comparison between total consumption and total reproduction of the material. To note, as suggested for primary production processes (Odum, 1971, Rockstrm et al., 2009), f_p could be influenced by the accumulation of material, I, and many other conditions. However, it could be simplified by the boundary reproduction rate that could be estimated where when harvesting above the boundary rate, the original ecosystem would degrade or irreversible changes would occur. In this way, by comparing consumption with regeneration, inputs of primary productions could be classified into renewable and non-renewable sources and secondary productions could be produced with renewable and non-renewable components.

For sustainability evaluation, emergy, following Eq. 3.2, could be directly used if all values and stakeholder connections are included. As in sustainability evaluation systems, emergy would continue to accumulate until system output is produced. However, with full consideration of universal stakeholders, more cyclic structure of energy hierarchy would be included by the SA. By considering functions of all stakeholders on the Earth, not only human and animals but also others like plants, germs, and bacteria, the presence of energy hierarchy would alter. By including full universal stakeholders, greater emergy would either indicate increased direct energy input for the system output or increase energy input to support the cycling of the outputs related to the sustainability criteria. Collectively, greater emergy would indicate better planet sustainability. However, this would not be feasible for sustainability values lead by human stances or only considering part of the weak stakeholders.

Following the classification to renewable and non-renewable sources and and to be feasible for flexible system values in sustainability evaluation, we treat the emergy composition of any material as the renewable part, Em_R, and the non-renewable part, Em_N. Thus, for production outputs with N inputs, noting as,

$$Em = \sum_{i=1}^{N} Em_i = Em_R + Em_N \tag{3.3}$$

$$Em_R = \sum Em_{iR}, i \in \{Renewable \quad sources\} \tag{3.4}$$

$$Em_N = \sum Em_{iN}, i \in \{Non-renewable \quad sources\} \tag{3.5}$$

$$i = 1, 2, ...n.$$

With respect to the current sustainability values, the emergy measurement is to measure the non-renewable emergy of system output by $minEm_N$, which suggests less use of non-renewable sources. As emergy notes the accumulation of energy, the quantity of Em_N would be larger for system with same structure but larger scale.

Other measurements or indicators could be developed on such basis, too, including using transformity (Brown and Ulgiati, 2002, Yazdani et al., 2020). As Ingwersen (2011) notes, as emery measures the accumulation of energy inputs, the uncertainty of emergy is an important system attribute linking with the maintenance of the energy flux. Thus, focusing on the renewable proportion, Em_R, renewable transformity would also suggest current sustainability values as, $Tr = \frac{Em_R}{E}$, where E is the energy of the desired system output.

Structure Measure

Reflecting the structure dimension in the MSV metrics, also being feasible for general systems, we propose the use of entropy measurements. As a thermodynamic property of system order, among many forms of entropy, Shannon entropy, as introduced in Eq. 2.2, could be used where for random variable $X = x_1, x_2, ...x_N, N \geq 2$ with corresponding probability of each value $P = p_1, p_2, ...p_N$ and $\sum P_l = 1$, expressing as:

$$S = -\sum_{l=1}^{N} p_l \ln p_l.$$

It quantitatively represents the disorder of the system. As energy passes from high to low, for a system containing internal transformation processes, the internal entropy of the system would spontaneously increase (Washington, 2013, p.6). For more stabilised system organisation, entropy is preferred to be maintained at low levels.

For sustainability evaluation for n countries with the apposite I-O system including m inputs and s outputs, in total N_j variables, for each year, the entropy for each country, noting as the decision-making units (DMU_j) in the year would be,

$$S_j = -\sum_{k=1}^{N_j} \frac{P_{lk}}{P_l} \ln \frac{P_{lk}}{P_l} \tag{3.6}$$

$$s = m+n$$

$$l = 1,2,...,s$$

$$k = 1,2,...,N_j$$

, where P indicates in total $N_j = (m+s)$ variables for the subsystem associated with DMU_j. This has taken similar treatment for calculating entropy with Lin and Xia (2013), however for panel data over spatio difference. Apparently, S_j would indicate better self-organisation of the DMU_j, which suggest that it could be used as an evaluation measure. Then, the overall entropy of a system with all DMUs is measured by:

$$S = \frac{\sum_{j=1}^{n} S_j}{n}.$$

One step further, as the dissipative structure suggests, a macro-scale system would also be able to maintain its self-organisation with sufficient entropy inflow and outflow. The evaluated systems for sustainability evaluation, usually considering the social-environmental relations, are systems far from thermodynamic equilibrium (Purvis et al., 2019). Such initial systems could be demonstrated by dissipative structure whose system organisation could be maintained by sufficient entropy exchanges at the boundary of the open system, compensating for the entropy inflows and the increased internal entropy. As previously reviewed (Chapter 3), the collective value of the system would guide the formation of the sustainability relations in the initial system and would also serve as the "trigger" that determines the direction of entropy flow in the dissipative structure. According to Eq. 2.3, the change of entropy of a dissipative system writes,

$$\frac{dS}{dt} = \frac{d_iS}{dt} + \frac{d_eS}{dt}$$

, where $\frac{d_iS}{dt}$ notes the internal spontaneous increase of entropy which is always greater than 0 and $\frac{d_eS}{dt}$ denotes the exchange of entropy including inflow and outflow. Attaching the planet context to the terms, the first term is associated with the I-O transformation, noting the disorder created by consuming the inputs and creating the outputs, and the efforts to organisation that are needed to maintain the production relations. And the second term explains the purposeful production that has already being brought by the inputs and the released disorder to the external environment. When $\frac{dS}{dt}$ is greater than 0, the organisation of the system presents to be continuously releasing disorder to the external environment, which generally presents as damages to the natural environment. The smaller, the less disorder the system is discharging to to external environment. Thus, as conceptually concluded by Prigogine (1980), the inflow entropy of the inputs is the "good" entropy that enables the system transformation to happen and enables the system to maintain self-organisation, and the outflow entropy would be the "bad" entropy that is released to create disorder in the environment. Here, we regard better preservation to self-organisation of the apposite system for the sustainability criteria as a better state of sustainability on the structural dimension.

Entropy measurements, triggered by certain values, is a measurement of system disorder that would not discriminate any value nor stakeholder stances. Like emergy, it is also a measurement, especially for the structural dimension, that could be feasible for universal stakeholders and general systems. Many studies have confirmed that urbanisation is, in its nature, a massive scaled continuous process that altered the distribution of available materials and energy. Georgescu-Roegen (1986) suggests that entropy indicates the order formed during system transformation, the collective consequence of following or confronting spontaneous energy flows or particle movement. For the Earth, modern cities are concentrations of energetic hot spot supported by surrounding and afar low energy density regions to maintain its orders and functions (Odum, 1971, p.73-76). It is also estimated that urban techno-ecosystems release heat seventy times more than natural wild ecosystems while cities only take up two percent of the Earth surface (Norman, 2019, p.21). Meanwhile, according to Steinborn and Svirezhev (2000), the orders of cities are also associated with concentrated environmental issues and undesirable outputs from the system. Hence, from the entropy perspective to describe the system mechanism in social-environmental relations, the anthroposphere maintains the internal high order by absorbing "good" entropy from the external environment and internally creates "bad" entropy to maintain human-value lead functions of the society and consequently, releases them into the surrounding environment. In this way, anthroposphere is able to be maintained at a relatively low entropy state with intentional orders which can be geographically unadjacent that would not fully follow spontaneous directions of natural occurring.

More importantly, for both value-flexible entropy measurements for sustainability evaluation, there is the need to clearly understand the system boundary which would classify the apposite system being evaluated with its external environment. The system boundary would determine the inputs and outputs, and the roles these variables take in forming the structures of the apposite system. It would also influence the treatments for the material and energy measurements.

The dissipative structure, ΔS meets the general value stakeholders (reflecting the energy measurement 1 suitable for the weak stakeholders). It indicates that smaller the entropy flow, the better self-organisation is achieved for the system. However, when it become less than 0, the system is able to be an entropy source for external environment. This may not be a suitable value for sustainability, especially for plant sustainability as we do not know the suitable direction of value that is sufficient for planet system sustainability.

Value Measurement

Compared with other two dimensions of the MSV metrics, measuring value seems to require much compensation since we have not found a universal measurement valuation system that suits all species, including the strong and weak stakeholders. However, we notice that different values could be partially treated.

As Chapter 3 presents, as a rather robust and philosophical term, the definition and classification of value hold great variety. Considering the association with stakeholder, let it be human or not, the sociology ethical classification categorises value into instructional value and the intrinsic value (Weber et al., 1978). While the instructional value demonstrates the extrinsic value of functional appreciation, the intrinsic value more explains the value contained, such as the cultural value and the aesthetic value. However, as classification to values remain conceptual, there are some treatments, especially embedding weak stakeholders that could be done in sustainability evaluation.

Firstly, capital pricing valuation system of human strong stakeholders would remain to be useful, although it is seemingly that economy a valuation system limited to human species. Such treatment provides a possible way to measure the natural capital, by attaching prices and barriers to the natural materials that used to be totally free. As Kumar (2012) notes, monetary valuation to the goods and services from the natural environment mainly appreciates their biophysical properties and the preferences of humans. McMahon and Mrozek (1997) also detailed down that monetary valuations are also associated with the distribution of materials, the scarcity of the materials, and the biocapacity that can be perceived for the material by humans. From one perspective, some aspects of the intrinsic value of nature might be appreciated. From another perspective, even for the value associated with labour, market pricing only appreciates human labour while labour by other beings, the species and non-living beings, are only reflected as human preferences. As Pascual et al. (2010) states, human preferences attach values to some products or services. Brown and Ulgiati (2004) claims that the core of economic valuation is attaching human utilisation relationship to all beings, that are in this thesis all stakeholders. Thus, the main problem for using monetary valuation measures in sustainability evaluation might be that market pricing is naturally too biased to the acceptability and voices of different human groups so that its pricing may result in exceeded conduction of activities that are apparently unsustainable.

In the meantime, we also recognise that capital accumulation could also contribute to the preservation of other values of the nature. Although economy is a human subsystem, under the anthropocentric view, the increase in wealth could relief social problems of poverty, unemployment, overpopulation, and unjust distribution of social resources (Erickson and Gowdy, 2007, p.4). In association, environmental recoveries are guided under wealthy economic support. Also, capital investment also enabled the conduction of preservation to some wild life habitats and promoted legislation (Bowman et al., 2010). Monetary values seems to be not totally confined to human preferences. In some sense, part of the potentially universal values are contained in monetary pricing and the valuation problem can be regarded as an issue of insufficiently reflecting the values held by weak stakeholders.

However, the presence of the values held by weak stakeholders, mainly non-human, can be massive in sustainability relations. Mingers et al. (2009) suggested that some non-human beings could also hold key performance indicators behind. According to McMahon and Mrozek (1997), we are only able to understand the collective objectives of human economic systems since monetary units are observable and measurable and humans are unable to understand clearly for other beings of how active and massive amount of energy and material exchanges occurred. Raising the clue to look into the universal stakeholders in the system, some clues are exhibited for the values of the weak stakeholders. On the global scale, there are practical and potential values to face ecosystem fluctuations in the origins and maintenance of biodiversity (Roger, 2000). Ct and Darling (2010) further describes it as the capability for different species to face the changing climate and recover from destructive events. Over regional scale, ecosystems are constructed with the dominance of a group of keystone species that thrive during a time through successful competition for resources over space and materials Washington (2013, p.6). Thus, it can be observed in the competition and collaborations among the plants and animals that they implicitly hold the objectives including breeding and fighting for sufficient space for survival (Roger, 2000).

Thus, we understand that it is mainly the instructional value of the weak stakeholders that lack accessible observations, and the intrinsic value, or key part of it about the survival of the weak stakeholders, are observable. For example, electricity production through appreciated technology by human such as wind power is found to cause severe deaths of birds and bats (Sovacool, 2009). The migration routes of birds and the number of deaths of birds and bats are observable and the embedded values for survival of the species are clear. Marine animals are also influenced by concentration of human activities and emissions of waste water (Tomczak Jr, 1984), resulting in unintentional deaths of the species. Hence, for the weak stakeholders, especially non-human species, the required conditions and space could be used as an compensation to fully present intrinsic values held by them.

Also, for primary production by the weak stakeholders also interacting with human, we notice that the intrinsic and instructional value of the product could be recognised, however, cannot be measured properly across species, which may require compensation of the weak stakeholders for the valuation system of the strong stakeholders in the system. For example, honey would be a typical intermediate product that is appreciated by both human and bees. We understand that as an accumulation of labour by bees, the intrinsic value of honey could be valued by the labour of the producers, bees. Its instructional values among bees are acknowledged with much limitation, aside from being food for different individuals of bees in the same hive. Among human, the collection, packaging, transportation, and sales of honey require human labour. Also, in the process the instructional value accumulate by exchange. Consequently, as human and bees do not share the same valuation system, it would be unsuitable to treat the labour of individual of bees as equivalent as individual human. In this scenario, when the sustainability evaluation is only done for bees, the value of goods could be measured by labour of production by bees. However, interacting with human, we may still apply the human capital pricing valuation system for honey, however, compensating the quantity of need for honey to satisfy the survival of bees, the intrinsic value of this group of weak stakeholder. Such value could be contained in the previously established regeneration rate of the product.

Conclusively, if we are unable to fully understand the objectives of the weak stakeholders and we have not currently identified a value system that suits for all, compensation would need to be made for the weak stakeholders during sustainability evaluation. We need to well understand that as Max Weber notes, individual values and collective values are different in rationality (Harald and Rainer, 2020, p.1-3) so as to arrive at suitable sustainability evaluation implementations. There are various types of values and some values may not be able to substitute each other. However, since the lead of sustainability evaluation is inevitably human, there is the limitation that the cognition to system collective values is limited to human insights. Thus, as we are limited in the techniques to construct a valuation system that suits all beings, the current human valuation system would still be used for evaluation but with compensations made in various ways for the weak stakeholders such as standing on the perspective of a metabolism view.

Limitations

As can be recognised from system performance perspective of the three Es, since system output emergy, entropy, and values could also be engaged with different aspects of system performance, the problem that sustainability evaluation objectives may not be suitable for the evaluation subject also remains. Hence, given system objectives for universal stakeholders, the evaluated system for sustainability evaluation using the EEV measures may also require the development for a suitable evaluated system over the objectives. Hence, EEV measures could be, eventually, used for the wider evaluated system revealing how the system with sustainable potential actually consumes source energy, distributes materials, energy, and information, and attempts to accumulate values. SSM remains as a suitable method to understand such connections.

After understanding that the EEV measures could conceptually contain weak stakeholders and could suit general systems, we notice that there are some limitations. For weak stakeholders, as previously noted in Chapter 6, their values cannot be fully collected due to technical limitations and thus compensations should be made, which results in presenting different level of strength of sustainability evaluations. Indeed, full reflection of universal stakeholders would be the most stringent degree of sustainability evaluation, but we are currently only able to perform sustainability evaluations on much weaker level.

Since strong stakeholders are mainly human groups, the value-based measures are also defined with implicit human values. We tend to illustrate in this way that system function could well exist with implied values. Aside from widely evaluated production processes, such implied values are also embedded for wildlife or the ecosystem preservation. For example, as Bowman et al. (2010) concludes from legislations for wildlife, there are aspects such as protecting people's favour to enjoy the wilds, and it is the duty of states and individuals to ensure the capability for such enjoyment. Also when we define ecosystem resilience, a system attribute, it is often applied with the objective to maintain the current level of urban construction (Brand and Jax, 2007). Thus, while all cognitions are based on human stakeholders, the compensation for a suitable valuation system would be necessary, however, may not be so problematic as it sounds conceptually.

3.4 Roadmap for Sustainability Evaluation: a Protocol

Following the above process, we identify a conceptual sustainability evaluation roadmap that is suitable for general systems containing universal stakeholders carrying values. This roadmap includes conducting sustainability evaluation guided by the evaluation objectives to construct an apposite evaluation subject system linked by stakeholder connections. On top of that, from the perspective of possible concrete system performance evaluation, the MSV metrics that are suitable for general systems leading to evaluation results that could be comparable across different evaluation attempts are proposed. Eventually, a protocol is proposed to present the roadmap.

Firstly, rooted on the definition to sustainability, the roadmap targets at the proposal and construction of proper and explicit sustainability evaluation objectives. From this stage, stakeholder participation is found important in sustainability evaluation by giving the sustainability evaluation objectives and having the power to make decisions for the system. We emphasise that sustainability relations in evaluation are, conceptually, built over the **sustainability criteria** that should be clear in evaluation and best, explicitly contained in the evaluation objectives. The sustainability criteria directly reflects the necessary conditions that are followed in the evaluation to reaching sustainability.

Secondly, by analysing the initial system following the sustainability criteria, the apposite system would be an at least self-enclosing system that has the capability to maintain the sustainability criteria, which is often an expanded wider system linked by strong and weak stakeholders contributing over the sustainability criteria. Meanwhile, the development of the wider system should not shift the consistency of stakeholder stances throughout the sustainability evaluation. Especially, when the sustainability evaluation is done for universal stakeholders, the apposite system and the values within the system should be feasible for universal stakeholders, else more assumptions should be attached to the necessary conditions defining sustainability. Thus, the roadmap emphasise to consider for consistent stakeholder connections while constructing the apposite system. The apposite system used for sustainability evaluation should be a global system over the sustainability criteria.

Lastly, the adjustment to the system boundary of the evaluation subject in sustainability evaluation brings associated changes to all evaluation elements. While the evaluation now contains strong and weak stakeholders that could be non-human species, we propose the MSV metrics that could be used for any system including universal stakeholders. Material and energy, structure, and value is a group of concrete measurement of system performance, developed from the 3Es, for sustainability evaluation. Material and energy, and system structure dimensions demonstrate the physical existence of general systems. Value demonstrates the sustainability evaluation objectives and external ideologies that makes the maintained existence of, mainly, the initial system meaningful. Besides, different from human-lead values, values observed from the universal stakeholder stances would require rethinking common concepts used in sustainability evaluations. For example, user satisfaction (Liang et al., 2014) could become an aspect that is limited to human strong stakeholders. In the energy sector, classic definitions to ”clean energy”, ”renewable sources”, ”non-renewable sources”, and ”pollution” are mainly based on human values and could be inconsistent with some values of the weak stakeholders. Thus, using indicators from the measurement system developed from the MSV metrics, the evaluation elements would be eventually explicit and the evaluation would be comparable regardless of the context that the initial system lies in.

3.4.1 Sustainable Level of Sustainability Evaluation

Sustainability evaluation objectives are not necessarily confined to only providing single baseline for necessary conditions of sustainability. The application of multiple baselines determines different sustainability criteria which could be regarded as referencing to different levels of sustainability in sustainability evaluation.

As being argued many times, all current sustainability evaluation are done, both on the conceptual and empirical levels, are using necessary conditions not sufficient conditions of true sustainability. The criticism for sustainability evaluation done using the TBL framework or the SDGs are mainly sceptical over the sustainability implementations given, being too stringent, too impractical, or too ideal. Besides, since sustainability reaches out to wide aspects of the planet, we may be at a state to justify one group of necessary conditions may be more suitable for the initial system over feasibility and practicability, but we are currently unable to judge whether the necessary conditions used would be better another group.

When one sustainability criterium is applied, one criterium could be more stringent than others for the initial system. For example, while the emission of sulphuric compounds could be a heavy issue for coal-fired power generation plants, due to the difference of the system components, sulpher concentration would be much less problematic for wind turbine power generation plants (Zurano-Cervello et al., 2018). Also, the carbon components associate with the whole lifecycle of a building, while energy or water supply mainly associate with the operation phase (Blengini, 2009, Deuble and de Dear, 2012, DOca et al., 2018). The apposite system developed by different criterium could differ significantly in system scale.

When sustainability criteria contain multiple attributes, including more attributes could indicate more comprehensive or stringent levels of sustainability evaluation. It is not expected for an apposite system that has sustainable potential over CO2 to be simultaneously potentially sustainable over SOx. However, when the sustainability evaluation objectives also include the sustainability criteria over SOx emission, the apposite system would be expected to be wider than that only potentially sustainable over CO2 emission. In this case, the strength of sustainability evaluation results are comparable over the strictness of sustainability.

3.4.2 Evaluation Preferences

One issue that remains to be left for evaluators and the DMs of the sustainability evaluation to determine using the MSV metrics is the determination to the evaluation preferences. It is not arbitrarily defined in this proposal that one dimension in the MSV metrics would always be more important then others.

We recognise the TBL framework has not defined that any subsystem would be more important than the others. Also, as Table 3.1 presents, the empirical studies would not clearly determine which sustainability measurement is more heavily weighted without the consideration to the context of the system and the preferences of the DMs. Over the vertical direction of the table, the system performance measurements, 3Es, are also not defined methodological evaluation preferences. As previous analysis notes, the evaluation preferences are mainly determined by the lead of evaluation, the evaluation objectives, and the DMs (Section 3.3.1). There are sustainability evaluations that would only focus on one subsystem in TBL where social sustainability outcomes are more valued than economic or environmental outcomes.

With our expectation that evaluations are eventually done with explicit evaluation elements, to obtain evaluation results, the evaluation preferences must be clearly known. Thus, we could take the treatment that when the preferences are not given in the sustainability evaluation objectives, more communications could be carried out among DMs to form a set of agreeable preferences for the evaluation. To the least, the evaluators could rationally determine possible preferences.

3.4.3 System Scale

The roadmap should be feasible for initial system of any scale and for apposite system of any scale. However, for many initial systems with the associated supply of inputs and distribution of outputs that cannot be demonstrated by internal system transformation relations, the initial system itself could be perceived as a regional subsystem that cannot sustain over the sustainability criteria. Such **regional subsystems** are connected with other regional subsystems that together regulate over the sustainability criteria forming a **global system** that could hold sustainable potential. Perceiving the regional systems and the global system with 3Es, Figure 3.3 presents the composition of an apposite system.

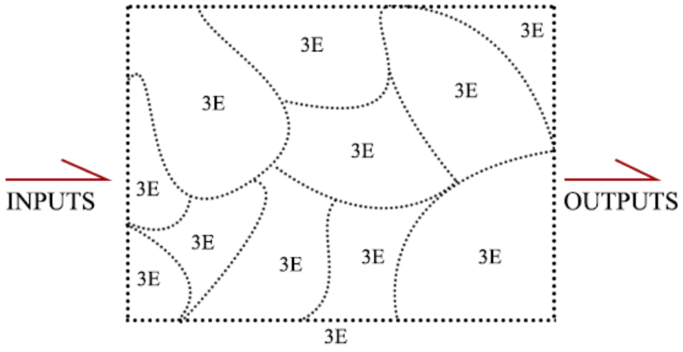


Figure 3.33E Relation of Global System and Subsystems

Apparently, the global system with sustainable potential would not require the regional subsystems to hold sustainable potential. Being sustainable doesn't mean that all unsustainable actions, the actions creating social-environmental problems, are not allowed. The unsustainable actions are allowed with limitation (Smith et al., 2011). Conceptually, when all subsystems are sustainable, the global system must be sustainable, suggesting a strict sufficient condition for planet sustainability. However, in practice, requiring sustainability for regional subsystems, on the one hand, would not be feasible since the negotiation of values among universal stakeholders is currently unapproachable; on the other hand, would be unnecessary since some unsustainable materials or energy we heavily consume now hold certain level of reproducibility. Furthermore, sustainability could be unachievable for regional subsystems. Even using this evaluation framework for sustainability that we propose, we are currently compensating the stakeholder participation with KSs. However, in practice, all beings, living and non-living, are influenced by any actions taken in the initial system. Even by expanding the stakeholders we now concern from human and animals to all living beings, the stakeholder network would be unprecedentedly massive until the whole Earth is included. For example, CO2 emission at a regional is diffused into the carbon cycle on the planet scale which would result in the consequence of causing global climate change (Ramanathan and Feng, 2009). During the process, the stakeholders holding values, the species we know and we don't know are widely interacted through metabolism processes. Hence, while the global system could be attached with sustainable objectives, we accepted that regional subsystems could hold its featuring values that may be unsustainable.

Associated with the scales of systems, apparently, different indicators would be used for evaluation. Harvest rate is only suitable for regional subsystems with primary production processes (Pauly and Christensen, 1995, Woodwell and Whittaker, 1968). On the planet level, the nature's services would be better indicated using biocapacity, biodiversity, and the environmental yield (Kellens et al., 2017, Thrn et al., 2010). Similarly, for human lead values, GDP would be a meaningful indicator for national systems but would be meaningless for cities. Thus, the indicators used for sustainability evaluation also require suitable proxies.

3.4.4 A protocol

Based on the previous understandings to the contributions that different methods could make to more explicitly present the implicit aspects by sustainability objectives and sustainability relations that can be case sensitive, the method begins from understanding the initial system, followed by adapting the initial system to sustainability objectives, identifying and screening stakeholder engagements, which results in forming an explicit system boundary that is suitable for sustainability evaluation with sustainable potential. At the same time, it also requires identification to key stakeholders, key values, and potentially suitable measures for the evaluation. We summarise procedure of preliminary identification of the apposite system for sustainability evaluation into five steps:

1. *Determine the prerequisites* which includes the initial sustainability evaluation objectives (or maybe part of it), the composition of the initial system, and evaluators and the other DMs (or part of them). Clarify the lead and evaluators of the sustainability evaluation and understand the explicit information given in the sustainability evaluation objectives, and the implicit aspects that may require the evaluators to set suitable definitions so that better sustainability evaluation is done. Based on the sustainability evaluation objectives, the attributes and their acceptable ranges defining sustainability should be explicitly defined either by the initial sustainability evaluation objectives or, when the initial objectives mention them implicitly, the evaluators. We name name the defined attributes *the sustainability criteria*. To note, since it is currently incapable to sufficiently define all sustainability criteria, we need to guarantee there is at least one explicit sustainability criteria, forming the necessary condition for sustainability. Also, as the procedure carries on, other aspects may also be identified critical to reach the sustainability objective which would introduce new sustainability criteria. And thus, new groups of DMs may be introduced to the sustainability evaluation. Following that, system boundary of the initial system, where the initial system is expected to be an I-O system holding transformational relations, needs to be confirmed identifying the inputs, the outputs, and the components and transformation relations creating outputs from the inputs.

2. *Identify initial set of KSs and key activities and develop stakeholder network*

over the sustainability criteria. Based on the I-O system and the sustainability criteria in step 1, SA could be done to continuously identify the group of stakeholders involved with the initial system and the key activities performed by them. We identify them following CATOWE stakeholders. Since not all stakeholders can be included in analysis, KSs are screened to those that are essential to the operation of the initial system and the performance of key activities to realise sustainability evaluation objectives. Hence, new DMs for sustainability evaluation may be introduced. The method and criteria for SA are determined by the evaluator, choosing from any applicable ones. For example, we apply SSM. The initial sustainability evaluation objectives (what - P), mainly over the sustainability criteria, are broken down into minor objectives and are linked with why they should be done (R). The KSs for reaching the objectives and the associated activities that should be performed by the KSs are determined (Q). Thus, continuously breaking down the objectives, identifying the KSs and associated sub-activities is the process of expanding the stakeholder network over the sustainability criteria. All activities can be past implementations by KSs or expected implementations by strong KSs. To note, since new components of sustainability criteria may be found critical for the realisation of the sustainability evaluation objectives, this step can be cyclically conducted.

3. *Determine a system boundary from the network of wider KSs and define the system suitable for sustainability evaluation* within which the sustainability potential over the sustainability criteria is explicitly presented. Based on the developed KS network, we identify the regional I-O systems that contain them and support the initial system for its functions or the sustainability criteria. By including all regional I-O systems connected by the KSs, the apposite system with new sets of inputs, outputs, and transformation relations for sustainability evaluation is formed. The system boundary of the apposite system could contain sustainable potential over the sustainability criteria. When we apply SSM to the KS network and the activity models, an indicator system formed by performance indicators of each regional I-O system demonstrating the 3E aspects, the efficacy, efficiency, and effectiveness, is constructed. However, to note, since it cannot be guaranteed that sufficient evaluation resources, especially data, are available for all indicators, it may result in that some indicators from the indicator system is not applicable for this sustainability evaluation.

4. *Identify and determine full evaluation elements*(Table. 2.2) to understand the composition of this practice of sustainability evaluation and the limitations by practical elements mainly including resources, methods, and indi-

cators. The evaluation subject is determined based on the system suitable for sustainability evaluation and other evaluation elements. Identify approachable evaluation measurements from the indicator system. Determine the suitable framework and the measurements that are consistent with the stakeholder stances in this sustainability evaluation. Determine the method that is used, quantitative or qualitative or the combination of both. For system cross-system comparison, MSV metrics and EEV measurements could be used. Often times, the opinions of DMs could also guide some elements and thus, this step would require continuous communication with the DMs.

5. *Conduct evaluation on the method domain and provide decision-making feedback for the DMs*, where through communication with the DMs, the sustainability evaluation objectives, such as the initial system and the sustainability criteria, may be adjusted and a looping routine of evaluation should be done from necessary steps. Based on the limitations identified in step 3 and 4, the evaluation results are expected to reveal sustainability potentials of the system suitable for sustainability evaluation over the sustainability criteria, which are new references as a necessary condition towards sustainability. Also, behavioural implementations can be raised for the initial system. Sustainability evaluation could be a dynamic and continuously developing evaluation as the sustainability evaluation objectives held by the DMs develop.

3.5 Chapter Summary

This chapter mainly proposes a conceptual sustainability evaluation roadmap. Contained is the roadmap is a feasible evaluation framework for sustainability with a group of feasible metrics, the MSV metrics. We propose that sustainability evaluation objectives should be explicitly defined by the DMs or developed by the evaluators. Explicit sustainable criteria would develop for a wider system containing the initial system with the potential to upregulate and down-regulate the sustainability criteria attributes. The global system regulating the sustainability criteria should be evaluated comprehensively. We propose a group of concrete measures of sustainability performance including materials and energy, system structure, and value that could be used to concretely measure system performance for the apposite. This MSV metrics would be suitable for both human and non-human stakeholders. Then, a group of applicable measurements for the MSV metrics is proposed and developed, the EEV measurements. The use of emergy, entropy, and value measurements would be suitable for systems with any context. Evaluating for sustainability evaluation objectives would require additional treatment for the original measures, which are also proposed. It is noticed that the measurements for sustainability evaluation mainly present two forms, being an absolute quantity on their own given sustainability preferences or being a measurement of flow. Conclusively, the EEV measurements demonstrate the use and accumulation of more reproductive energy and material, more stable and organised system structure, and accumulating the values created during the system transformation. However, since there is not yet a known valuation system that is fully suitable for universal stakeholders including the weak stakeholders, there could be the need to apply human valuation system but compensating for the potential values that could be held by the weak stakeholders over their survival. Eventually, we thoroughly present the roadmap with some perceptions for the role of sustainability criteria in sustainability evaluation, the role of stakeholders in determining evaluation preferences, and the influences of system scale to sustainability relations. Eventually, a feasible protocol is proposed.

Chapter 4

Methodology and Methods

4.1 Methodology

Having conceptually constructed a roadmap for sustainability evaluation that enables explicitly developing the evaluation elements, especially for the evaluation objectives and subject, a real-world case should be applied to test its practicability. Also, challenges and limitations of the roadmap in its application require analysis.

Here, considering the maturity of system composition and data availability, empirical studies are done for 28 countries in Europe countries (EU28) considering different structural construction of the electricity systems. An apposite system for EU28 is constructed. To be able to understand the outcomes of the roadmap, country peer ranking is formed using DEA models. This is to understand whether the apposite system and the reference system for sustainability evaluation could be constructed and understand its quality. Then, based on the electricity production system, the suitability of system indicator is analysed using global impact compound indexes. The suitability and implementations of the EEV measurements are analysed.

4.2 Data

For electricity production systems, electricity and energy production, consumption, installation, and CO2 direct emission data are gathered from open databases of Eurostat (also noting as EC), IEA, the World Bank (WB), including years 2005, and from 2015 to 2019. This time range guarantees a complete raw data set. The electricity production technologies include transformation from coal, oil, natural gas (noting as LNG), nuclear, biomass, hydro power, tide, wind, solar PV, and geothermal. Other sources such as combustion of municipal wastes are not considered.

The 2005 data is mainly used for development and verification for the apposite system, constructing the system material and energy inventory following carbon sources leading to direct emissions of all subsystems. Inventory data for electricity power facility construction, installation, and manufacturing and required materials and energy in the process are gathered from previous studies, fact sheets from facility designers, and open reports from related governments, institutions, and organisations. To simplify the network, machinery and facilities for subsystems that are not the initial system are neglected. CO2 emissions are obtained following the values disclosed or the emission factors disclosed, mainly by IPCC and Ecoivent 3.4. When CO2 and other carbon contained green house gas emissions are not directly disclosed, the CO2 emission of the inventory process is estimated by the consumption of carbon contents and fossil fuels. The recycling and import proportions for the EU region mainly bases on import and production data by Eurostat. The non-renewable proportion of materials is being treated as 1 as the upper bound (UB) for NRES and taken a lower bound (LB) as 1E-05 to represent fully renewable materials in one year. The short term carbon sequestration capability of minerals forming carbon sinks are identified from articles or estimated by the main composition of the minerals or raw materials. The physical properties of raw materials are mainly taken the key producers among EU28 or by the fact sheets disclosed by EC. Lastly, emergy values of materials and services are gathered from multiple studies. The quantities, emergy values, material properties, conversion units, and respective sources and estimates are given in Appendix D.4.

Then, to understand the differences caused to ranking results by the indicators suggested in frameworks used for sustainability evaluation, two indicator sets are used, one set for the EEV measurements, applying the entropy and emergy obtained from the previous chapter, and the other following production process. For EEV measurements, since case $V1$ also includes electricity as the output, this is selected for measuring value. Fig. 4.1 presents the relation of transformation.

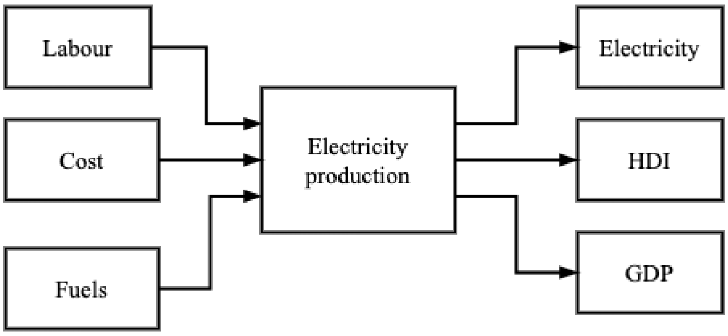


Figure 4.1I-O relations for large scale system indicators.

The chosen variables are CO2 emission for the environmental aspect, human development index (HDI) gathered from UN open database for the social aspect, and GDP for the economic aspect. Table 4.1 presents the data descriptives for the three indexes. The variance among the data set is quite small except for total CO2 emission.

Table 4.1HDI, GDP, total electricity production, CO2 emission output data descriptives.

	Mean	**S.D.**	**Median**	**Min**	**Max**	**Range**
HDI						
2005	0.85	0.04	0.85	0.76	0.91	0.16
2015	0.89	0.04	0.89	0.81	0.94	0.13
2016	0.89	0.04	0.89	0.81	0.94	0.13
2017	0.89	0.04	0.9	0.81	0.94	0.14
2018	0.9	0.04	0.9	0.81	0.94	0.14
2019	0.9	0.04	0.9	0.81	0.95	0.14
GDP						
2005	1.85E+05	4.97E+05	3.85E+04	1.17E+03	2.65E+06	2.65E+06
2015	2.34E+05	6.28E+05	4.61E+04	2.28E+03	3.36E+06	3.36E+06
2016	2.34E+05	6.26E+05	4.73E+04	2.40E+03	3.35E+06	3.35E+06
2017	2.44E+05	6.54E+05	4.97E+04	2.72E+03	3.50E+06	3.50E+06
2018	2.52E+05	6.74E+05	5.09E+04	2.95E+03	3.61E+06	3.61E+06
2019	2.61E+05	7.00E+05	5.23E+04	3.28E+03	3.75E+06	3.75E+06
Electricity						
2005	2.52E+05	6.78E+05	5.70E+04	1.79E+03	3.66E+06	3.65E+06
2015	2.24E+05	6.04E+05	5.24E+04	1.31E+03	3.25E+06	3.25E+06
2016	2.25E+05	6.07E+05	6.03E+04	8.57E+02	3.27E+06	3.27E+06
2017	2.28E+05	6.13E+05	5.94E+04	1.65E+03	3.30E+06	3.30E+06
2018	2.26E+05	6.09E+05	5.96E+04	1.96E+03	3.28E+06	3.28E+06
2019	2.23E+05	6.00E+05	5.32E+04	1.91E+03	3.23E+06	3.23E+06
CO2						
2005	88.85	240.46	1.27	1288.27	1287	
2015	68.64	187.19	0.43	995.21	994.79	
2016	65.82	179.71	0.21	954.32	954.11	
2017	64.97	176.76	0.21	942.07	941.86	
2018	59.85	163.26	0.19	867.84	867.65	
2019	51.47	140.04	0.19	746.29	746.1	

4.3 Method

4.3.1 Apposite System Verification Criteria

Most European countries set sustainability targets for the electricity system over carbon emission levels for the 2005 baseline, which will be introduced in the coming section. The reference system for sustainability evaluation of the electricity production initial system is developed according to the protocol based on transformation data in 2005 and verified for carbon stability using CO2 emission data.

For the initial system, the CO2 emission from the consumption of fuels and the manufacturing and installation of necessary facilities are considered. The system boundary is eliminated at the state when electricity is produced. For the upstream intermediate subsystems until reaching natural carbon sinks, CO2 emission and consumption and key transformational inputs are included and the supportive machinery, building facilities, capital inputs, and labour are excluded from analysis. Capital and prices are regarded as a measurement of value as compensation. For both the initial system and the intermediate systems, the weak stakeholder values are represented by the inclusion of bird, fish, or worker fatalities. In this way, the apposite system is developed following the carbon flow and stakeholder connections.

For regional carbon fluxes, it is understood that there are long-term geographical and demographical carbon sources and sinks. The long term carbon fluxes are considered by estimation to the ocean-air carbon flux, the land-air carbon flux, and the cement carbonation of constructed structures (Grassi et al., 2022, Strapasson et al., 2020). Missing values are estimated interpolating in relation to atmospheric temperature change. Also, a statistical gap is allowed for carbon emission. The value is taken as the historical observation to the increase in ground level carbon contents (Friedlingstein et al., 2022). The long-term carbon balances are regarded as background carbon changes. The short term carbon balances, which could be said to be contained in the long term balances, are independently counted for yearly fluctuations. The main carbon sources are activities of all subsystems in the apposite system. The carbon sinks mainly include the growth of trees and agricultural biomass, and the extra carbon sequestration capability by sources of mines and brines. For excessive carbon emission that cannot be contained in the above long-term and short-term sinks, before considering the atmospheric increase, the necessary area of ocean water bodies in estimated especially for 2005 to serve as the necessary land-use to be expanded and included within the apposite system. Thus, the verification to the carbon levels of the apposite system is done by confirming the final carbon emissions during all key subsystems and identifying the area of land, urban grounds, and ocean that needs to be included to characterise ”Land, water CO2 absorption” in the figures of all apposite systems (Fig. 5.11 - 5.19).

Also, in the measurement of carbon emission by activities and considering the measurement using EEV measures within which NRES emergy needs to be calculated, the following treatment is done for the subsystems treating geographical differences of carbon emission sites. Since the reference system is developed for 2005 of the EU28 countries, not all intermediate goods are manufactured among the countries and external CO2 emission would occur outside the area covered by EU28. Required amount of internal production leading to on-site CO2 emission is estimated by multiplying with the proportion of EU production over the total stock increase. Carbon emission occurring by production activities are estimated by required external land by long-term carbon sinks. The emergy of the intermediate products are released by multiplying the proportion of recycled goods as the emergy could be circularly double counted within the reference system. For primary production from the nature, the carbon non-renewable proportion in emergy input is estimated by the time for form unit of material. The time frequently in relation to one year is used as the f_p for judging RES or NRES instead.

The explicit system boundary of the apposite system, developed following stakeholder connections and their activities contributing to carbon emissions supporting the electricity production systems, is determined following the above criteria for eliminating system boundary or estimation. Eventually, the apposite system would not hold a CO2 emission output as carbon flux could be neutralised within the apposite system. s

4.3.2 EEV Measures

Given the criteria above, the EEV measurements of the apposite system is calculated as following.

For the value measurement, since the values of weak stakeholder over electricity is unknown, value is compensated with human directions. This could be expressed in many forms. Here, we consider two forms, using the price of electricity as one case ($V1$), using the quantity of electricity produced ($V2$) as the second case, and the third case with price times electricity production ($V3$). These are regarded as different value preferences from the perspective of users, industry, and owners.

Emergy measurement, following Chapter 3, is measured by the non-renewable proportion of all emergy inputs, written as Em_{NRES}. Thus, the emergy of electricity from the system output would be $\sum Em_{NRES}$ for all apposite system inputs. Eventually, for all materials, its emergy being measured under the EEV measurement is the NRES proportion over total emergy, noting as f_p. Setting the base year as 1 year, f_p is simplified as following: for primary extracted materials, f_p is estimated by the harvest frequency; for intermediate materials in subsystems, it is approximated by the proportion of material recycling.

Entropy of the apposite system is measured by Shannon Entropy. For all variables in the apposite system, it writes:

$$S = \frac{\sum_{l=1}^{N} -P_l \ln P_l}{N}$$

, where N is the total number of variables in the apposite system, and P_l is the probability of happening for each activity. As the number of subsystems are large and different, we take the average entropy of all subsystems as S, noted as:

$$S = \frac{\sum S_{jq}}{N}, j = 1, 2, ...n \tag{4.1}$$

$$S_j = \frac{\sum S_q}{N_l}, q = 1, 2, ...N_l \tag{4.2}$$

$$\tag{4.3}$$

, in which n is the number of DMUs, and N_l is the number of subsystems associated with the jth DMU. Thus, for a subsystem Sys_{jq}, it contains a series of variables X_{jq} with respective probability of activity calculated as:

$$P_{jq} = \frac{1}{N_{jq}} * \frac{X_l^0}{max(X^0)}$$

, if the variables are positive and taken with minimum for negative variables.

4.3.3 DEA ModelS for Peer Ranking

To form peer rankings among the countries, the DEA method is applied (Charnes et al., 1978). Considering that entropy, emergy, and value are not merely transformational outputs from the inputs that are explicit, by regarding the three aspects as some form of implicit system outputs, an index DEA model without explicit inputs by Liu et al. (2011) is applied, written as:

$$\begin{aligned}
Max \quad & h_0 = \sum_{r=1}^{s} u_r e_{r0} \\
s.t. \quad & \\
& \sum_{r=1}^{s} u_r e_{rj} \leq 1, \quad j = 1, 2, ...n \\
& u_r \geq 0, \quad r = 1, 2, ...s \\
& v_i \geq 0, \quad i = 1, 2, ...m
\end{aligned}$$

, assuming a case of constant return to scale. However, noticing that all index variables should be hold strong disposability and should be desired outputs, not all preferences may suit the original objective function by value judgement to the measurements. Thus for undesirable outputs, they are regarded as undesirable outputs that are weakly disposable (Liu et al., 2010), and the following new output indexes are constructed:

$$e = (\frac{V}{S}, \frac{V}{Em_{NRES}})$$

, within which increase in S and Em_{NRES} are regarded as not wilful. There is also a case, $V1$, when from the consumer's perspective, electricity prices should not be high, and thus, the measures are transformed into its reciprocals.

The above model is also used with treatment to undesirable output as explained for case $V1$. For the I-O data set, the output includes two desirable outputs and one undesirable CO2 emission, the undesirable output is treated alike. The index model (noting Model 1), is also applied to the HDI, GDP, and CO2.

Besides, forming comparison with the I-O transformation relations, and CRS and a VRS model are respectively used, using the basic CRS input oriented DEA model by Charnes et al. (1978), and the VRS model by Banker et al. (1984). Here we use the input-oriented form of Eq. 4.4, written as following, naming Model 2:

$$\begin{aligned}
&Max \quad h_0 = \frac{\textstyle\sum_{r=1}^{s} u_r y_{r0}}{\textstyle\sum_{i=1}^{m} v_i x_{i0}} \\
&s.t. \\
&\quad \frac{\textstyle\sum_{r=1}^{s} u_r y_{rj}}{\textstyle\sum_{i=1}^{m} v_i x_{ij}} \leq 1, \quad j = 1,2,...n \\
&\quad u_r \geq 0, \quad r = 1,2,...s \\
&\quad v_i \geq 0, \quad i = 1,2,...m.
\end{aligned} \tag{4.4}$$

Then by attaching a VRS assumption, Model 3 is in the form of written as Eq. (4.5):

$$\begin{aligned}
&Max \quad h_0 = \frac{\textstyle\sum_{r=1}^{s} u_r y_{r0}}{} \\
&s.t. \\
&\quad \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0, \quad j = 1,2,...n \\
&\quad \sum_{i=1}^{m} v_i x_{i0} = 1 \\
&\quad u_r \geq 0, \quad r = 1,2,...s \\
&\quad v_i \geq 0, \quad i = 1,2,...m.
\end{aligned} \tag{4.5}$$

4.4 Electricity Production System in Europe

Electricity production systems are often distinguished according to national profiles with great difference in the sources of inputs consumed which some require supports from preliminary I-O systems, and necessary technologies installed resulting in varied consequences widely concerned for the sustainable development of the planet. The sources of inputs for electricity generation are popularly classified into renewable (RES) and non-renewable (NRES) sources, based on the length of reproduction duration of the transformational inputs. NRESs include the fossil fuels, including coal, oil, and natural gas (LNG), and nuclear (Nu) that is massive in electricity and heat production but is radioactive and also not reproducible. The fossil fuels are also called the exhaustible energy sources because the current consumption rate of of human activities far exceeds their reproduction rates. Nuclear power is mainly appreciated for its massive volume of production and low-carbon in the transformational sources (IEA, 2019*d*). RESs widely include clean (low pollution and low carbon) and frequently reproductive forms of energy including wind, hydro and tide, solar photovoltaic (SPV or solar PV), and geothermal (Geo) power, and reproductive biomass (Bio), including bio diesel and other forms of biofuels, and the municipal wastes which are reproductive but can be high in carbon emission during electricity production. Sometimes, hydro power plants are not regarded as fully renewable since the life span of a hydro power plant is limited by the mud and river conditions and water kinetic energy may not always recover to the initial state (BP, 2019).

Also, as a consequence of the difference in national accessibility to electricity producing technologies and availability of sources that can be influenced by geographical availability and international energy commercials, the sustainability performance evaluation of electricity production systems should recognise that electricity production systems are open global systems linked with upstream support and downstream influencing systems, and that the variance in national production profiles influence system performance thoroughly and could be serving for sustainability objectives that could be different in countries or regions. This section introduces the status-quo of electricity systems and the associated energy objectives in Europe and further explain the need for proper sustainability evaluation in the electricity sector, focused to the power production system.

4.4.1 Energy and Electricity Overall

Electricity is the energy sector that has gone through the most rapid and advancing changes that successfully substituted primary fossil fuel energy sources with RES or low-carbon sources. It is expected that the demand for electricity would continuously increase as electrification expands to other sectors of energy end-use. Electricity, transportation, and industry are the three main sectors of primary energy source consumption (Commission, 2014). In 2018, infrastructure upgrading for electricity production into RESs has been widely done and is considered the key sector for decarbonisation and transmitting to modern energy (IEA, 2018*b*). As it is globally recognised that the development in electricity production systems has significantly improved energy efficiency, substitution for exhaustible energy sources, and decarbonisation, electrification is expected to be extended for many other energy user-end sectors including transportation, industry, the households, heating and cooling, and digital controls and thus, the demand for electricity is expected for continuous increase (IEA, 2019*d*). For Europe, it is eventually expected to increase the share of RESs for power generation to nearly 80%. In 2021, 23.8% of power production in the European region is from RESs, being the first region in the world with RESs dominating electricity produced by other measures (BP, 2021). Heavily depending on RES, nuclear, and LNG sources, the primary energy consumption in European region present gradual decrease until 2019 and carbon emission of the whole energy sector has decreased by 1.9% compared to that in 2011 (BP, 2022).

Recent crisis resulted in more demanding upgrading for energy efficiency and energy security for electricity systems. European countries in total has replaced 75 gigawatts (GW) of electricity production capacity transforming coal-fired plants into RES or LNG plants during the recovery from economic short fall caused by the COVID-19 pandemic (IEA, 2020*c*). To note, the pandemic also created a global short fall in energy consumption and CO2 emission. Dependency on imported primary energy sources is also regarded one of the key issues in improving energy security (IEA, 2022*a*). Also, having stronger infrastructure base and better flexibility is concerned to be an important objective for electricity production systems and, in association, a delayed recovery expectation that the electricity demand of EU countries would recover by 2023 to the 2019 levels is popularly planned (IEA, 2020*c*). Eventually, we recognise that the support of energy framework is mainly given on the national and policy level by the governments which could be influenced by political issues (Fonseca et al., 2020). Governments hold strong power in decision-making for planning the national electricity production mix.

Developing varieties of electricity production methods is widely recognised as a way to improve energy efficiency and energy security. Aside from high volume of electricity produced, incineration plants also have the advantage that the production is controllable. As McGlade and Ekins (2015) presents, fossil fuels can be extracted, transported, and transformed according to the demand. Meanwhile, in RESs, only hydro power and municipal waste incineration plants are able to have such level of production control. However, no country could guarantee available suitable river sites for constructing hydro power plants. Wind power, solar PV, geothermal, and tides heavily depends on geographical availability of respective natural sources and there is also currently no way to guarantee such power plants to always function at the best possible capacity. Capacity factor is used to demonstrate the attainability of the on-site kinetic or potential energy sources (IEA, 2022*b*). Also, nuclear, being a low-carbon and very cost-effective electricity production approach, is mainly appreciated for its high volume of electricity supply but brings the risks including producing radioactive matters and causing disastrous destruction to the surrounding environment when leakage occurs (Takata et al., 2018). Thus, the instalment of RES electricity production plants could significantly enhance power independency by reducing reliance over primary fuel imports, but requires the consideration to the attainability of the sources from the nature. Similarly, incineration plants often have the advantage that electricity production is controllable, but requires concerning issues for supply and transportation.

Table 4.2 Country Electricity Production Mix (2019 standard)

Country		Coal	Oil	LNG	Nu	Bio	Wind	SPV	Hydro	Geo	Tide	Notes
Austria	AT	1	1	1	0	1	1	1	1	1	0	
Belgium	BE	1	1	1	1	1	1	1	1	0	0	
Bulgaria	BG	1	1	1	1	1	1	1	1	0	0	
Croatia	HR	1	1	1	0	1	1	1	1	1	0	Geo since 2018
Cyprus	CY	0	1	0	0	1	1	1	0	0	0	
Czech Republic	CZ	1	1	1	1	1	1	1	1	0	0	
Denmark	DK	1	1	1	0	1	1	1	1	0	0	
Estonia	EE	1	1	1	0	1	1	1	1	0	0	Solar since 2016
Finland	FI	1	1	1	1	1	1	1	1	0	0	
France	FR	1	1	1	1	1	1	1	1	1	1	
Germany	DE	1	1	1	1	1	1	1	1	1	0	
Greece	EL	1	1	1	0	1	1	1	1	0	0	
Hungary	HU	1	1	1	1	1	1	1	1	1	0	Geo since 2017
Ireland	IR	1	1	1	0	1	1	1	1	0	0	
Italy	IT	1	1	1	0	1	1	1	1	1	0	
Latvia	LV	0	0	1	0	1	1	1	1	0	0	Solar since 2018
Lithuania	LT	1	1	1	0	1	1	0	1	0	0	
Luxembourg	LU	0	0	1	0	1	1	1	1	0	0	
Malta	MT	0	1	1	0	1	0	1	0	0	0	LNG since 2017
Netherlands	NL	1	1	1	1	1	1	1	1	0	0	
Poland	PL	1	1	1	0	1	1	1	1	0	0	
Portugal	PT	1	1	1	0	1	1	0	1	1	0	
Romania	RO	1	1	1	1	1	1	1	1	0	0	
Slovak Republic	SK	1	1	1	1	1	1	1	1	0	0	
Slovenia	SI	1	1	1	1	1	1	1	1	0	0	
Spain	ES	1	1	1	1	1	1	1	1	0	0	
Sweden	SE	1	1	1	1	1	1	1	1	0	0	
United Kingdom	UK	1	1	1	1	1	1	1	1	0	1	No tide in 2016

Table 4.2 exhibits the available (1) and not available (0) main production sources of EU28 countries by 2019. Some RESs that are available but would not take up mass proportion in electricity production is excluded from analysis. By 2019, the installed electricity production mix exhibit clear non-homogeneity.

Among fossil fuels, all countries expect Cyprus have developed power plants consuming LNG. The overall Europe also heavily depends on LNG for electricity production, generating the largest amount of electricity for the countries of the region (BP, 2019). Especially, Malta developed its natural gas power production plants relatively late among EU28 (Commission, 2018*a*). However, the main concern of consuming natural gas is over energy security for supply since it is popularly imported in the pipelines from surrounding countries, especially Russia (IEA, 2020*c*). Besides, the consumption of coal for electricity production is gradually replaced with other technologies. Electricity production by coal has continuously decreased from 63.6 Terra-Watt hour (TWh) to 53.6 TWh in 2019 (BP, 2021, 2018), although it has always taken the least proportion of total electricity production by fossil fuel of less than 4%. Countries including Cyprus, Latvia, Luxembourg, and Malta have eliminated or transformed the coal-fired power plants.

For clean and RES production technologies, the coverage of installation of wind and hydro are high among EU28. Solar PV and geothermal power plants seem to be relatively new technologies for power production with boosting capacities installed during 2015 to 2016. Biofuels and municipal wastes are appreciated RESs from agricultural and urban living although they are not necessarily low-carbon nor less pollutive production sources (Giannetti et al., 2020). Overall, according to the UN, the installation of electricity production capacity of RESs have outpaced the population growth in 2020 in Europe (UNDESA, 2022). Aside from RESs, the key technology believed to contribute to the energy supply security for European countries is nuclear power. The installation for nuclear is influenced by both technological and cultural aspects. Nuclear power plants are mostly installed in countries that require more electricity supply, mainly including France, Germany, and UK. To further improve energy security and reduce dependency for fossil fuels, Belgium plans more construction for nuclear plants (IEA, 2022*a*). Under the current estimation for global supply of uranium fuels, world supply could be met for 65 years from 2009 (Schwarz-Herion and Omran, 2015, p.121-140). However, the case in Lithuania is different. Nuclear power plants have been fully closed down in 2009 and Lithuania became an electricity importing country since then although the proportion of many RESs increased (IEA, 2021*c*).

Figure 4.2 exhibits the electricity production of all European countries. The total electricity supply presents gradual increase from 2016 to 2019. The supply of electricity in overall Europe by RESs is steadily rising, taking up around 36.77% of the total electricity supply by the end of 2019. BP (2019) attributes this increase as the transition from fossil fuel sources to RESs and development in RESs infrastructure of electricity production mix in Europe. Both the BP and IEA explain that the decrease in electricity supply and demand is caused by COVID19 after which many countries are seeking for sustainable pathways to recover back to 2019 level of electricity production.

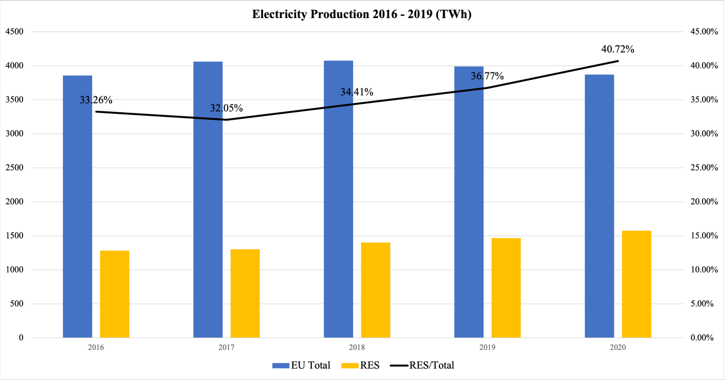


Figure 4.2 Electricity production of Europe from 2016 to 2019

Eventually, we recognise that as the energy sector, especially transportation and the households, develop into modern energy, the dependence on electricity is expected to rise as industries upgrade. In the same time, growing supply of electricity in European countries is supplied by RESs. The efficient and secured operation of the national and cross national grid is the consequence of complex decision-making and planning for the electricity production mix. The sustainable operation of an electricity production system faces challenges from the application of advanced and green technologies, the supply and distribution of fuels and products, the availability of the natural and geographical sources, the treatment to pollutions and wastes, and the social opinions and affairs.

4.4.2 Sustainable Objectives for Electricity

Sustainability objectives of energy and electricity share global consent over sustainability criteria of GHG or carbon emissions and the supply of transformational sources with varied stage-wise objectives in time and space. The focus of this compound group of energy sustainability objectives currently present three key aspects, energy efficiency, energy security, and climate mitigation. Since 2016, the sustainable energy goal, given by the UN, has always been to ”*ensure access to affordable, reliable, sustainable, and modern energy for all*”(UNDESA, 2016). To note, we often relate sustainable and modern energy production measures as cleaner production measures that expect constant introductions of new procedures and technologies into protocols and practices of preventing environmental damages (Giannetti et al., 2020). Cleaner production is also explained as low pollution during the full life cycle for electricity generation from exploitation, transportation, production, and consumption. Most countries attempt to construct or transmit their energy systems for higher energy transformational efficiency, more safe and guaranteed energy supply, and low-carbon and less pollutive production and consumption. Eventually, it is expected for the establishment of worldwide sustainable consumption patterns and lifestyles (Fonseca et al., 2020).

Being one of the main energy sectors, electricity systems are attached with sustainability expectations that present great variety in time and space. Over time, global electricity sustainability objectives continue to develop while adapting to new challenges. In 2017, it mainly targetted for improving electrification in rural area and providing safe electricity for vulnerable groups (UNDESA, 2017). It is recognised that electricity would improve the quality of education and food security. In 2018, the objectives focus on providing electricity from clean sources (mainly non-fossil fuel sources) for heating and cooling, transportation, and cooking and living (UNDESA, 2018). In 2019, while the progress of previous goals remain, as the instalment of RES for electricity production continues to increase, electricity systems focus on improving the energy efficiency and security of electricity production from RES(UNDESA, 2019). This is also the main sustainability objectives for electricity systems that most European countries hold. Apparently influenced by COVID-19, in 2020, many countries attempt to recover economy following more sustainable pathway including containing greater proportion of electricity supply from RES and caring more on healthcare and respiratory illness that can be caused by the consumption of fossil fuels (UNDESA, 2020). Also, the aftermath of the pandemic caused the drop of accessibility to affordable electricity in 2021 and supplying affordable electricity to remove poverty is prioritised in 2022 (UNDESA, 2022). We are alarmed that electricity systems, especially production systems, are long-term open systems that require many years of construction and could operate for long, interacting with wide stakeholders and system components in the time of being.

Over space, in accordance to different levels of electricity system infrastructure instalment, technology development, and different regional affairs, sustainability objectives in Europe mainly target for more efficient production, secured clean production, and relieving global warming potentials. This can be slightly different from the world electricity goals. By the end of 2019, electrification in Europe has reached 100% (UNDESA, 2020). Already achieving the global target of full electrification, countries in Europe, mainly lead by or was lead by the EC, most countries share similar long-term sustainability objectives for electricity systems covering energy efficiency, energy security, and climate mitigations, but with different practical implementations. Given the world objective for dealing with global warming and climate change, in 2012, the EC has emphasised the concern for GHG emission reduction, mainly considering the emission of CO2 or transforming other gases into the amount of CO2 equivalent. The union expected

20% GHG emission reduction by 2020 comparing with that in 1990, 20% of energy from RES, and 20% improvement in energy efficiency (Commission, 2012) . In 2014, the key proxy for climate change is set as CO2 emission. Comprehensive directive SD objectives for electricity include increasing RES proportions, energy efficiency for more affordable prices, enhancing energy supply security, and marching towards low-carbon economy (Commission, 2014). Most union member countries and the United Kingdom (UK) continue using objectives set in 2014 as future sustainable electricity system directives. For most long-term 2050 objectives, most continuously focus on improving energy efficiency, increasing the share of renewable electricity, and developing the instalment of carbon storage and capturing facilities. By 2019, with the significant increase of regional crisis conditions in Europe, developing feasible and more nationally independent electricity production mix, mainly through nuclear power and clean production technologies, are new challenges of electricity security (Commission, 2019*a*).

To achieve such collective regional sustainability objectives, on the one hand, as EC mentioned, as long as the total carbon emission is reduced to the objectives, some member states are allowed for certain level of increase in carbon emission (Commission, 2014). On the other hand, the benchmark level and the actual sustainable electricity objectives held by each country are different. Table 4.3 exhibits the aspects contained in national sustainable electricity objectives for 28 countries in Europe (EU28) reported by the international energy association (IEA) and presents the short-term (2030) and long-term (2050) sustainability electricity production objectives over climate mitigation.

As the table presents, EU28 countries contain different pursuits for energy efficiency and energy security for electricity systems. Energy efficiency objectives can be mainly categorised into two forms, over the technology efficiency of production and over the cost-effective efficiency of input-output transformation. More efficient use of energy sources into increased production of electricity could reduce the demand for primary energy sources of fossil fuels (Fei and Lin, 2016, Guerrini et al., 2017, Pahlavan et al., 2011). Sweden clearly proposed the objective to increase the volume of electricity produced by newer and greener technologies so that energy intensity could be lowered (IEA, 2019*b*). Similarly, Hungary, after reaching the 2020 target over emission reduction, now attempts to reach the 2030 objective mainly by lowering energy intensities. More countries tend to promote the cost-effective efficiency of electricity(Yang and Li, 2017, Wu et al., 2014), that is also the productivity of electricity(Kang and Lee, 2016). While most countries tend to imply the target to increase electricity productivity, Italy clearly noted that it attempts to develop energy efficiency so that the prices of electricity from RES could align with other EU countries (IEA, 2016).

Sustainability objectives for energy security are more diversified, covering security of energy source supply, electricity distribution, and the security of elec-

Table 4.3 Sustainability Objectives of Electricity System for European Countries (28)

Country		Energy Efficiency	Energy Security	Power Independency	Climate Mitigation	2030 Objectives	Long-term Objectives
Austria	AT	Y	Y	Y	Y	100% RES production	Climate neutrality by 2040
Belgium	BE	Y	Y	Y	Y	35% GHG emission reduction*	EC objectives[1]
Croatia	HR	Y	Y	N	Y	EC objectives[1]	
Cyprus	CY	Y	Y	N	Y	EC objectives[1]	
Czech Republic	CZ	Y	Y	N	Y	40% GHG emission reduction**	EC objectives[1]
Denmark	DK	Y	Y	N	Y	50% clean production	100% clean production
Estonia	EE	Y	Y	N	Y	70% GHG emission reduction**	80%GHG emission reduction**
Finland	FI	Y	Y	N	Y	Phase-out coal fired plants	80% GHG emission reduction**
France	FR	Y	Y	N	Y	45%RES production	85%GHG emission reduction**
Germany	DE	Y	Y	N	Y	55%GHG emission reduction	70% GHG emission reduction by 2040 80-95% GHG emission reduction by 2050
Greece	EL	Y	Y	Y	Y	43% GHG emission reduction**	60-70%GHG emission reduction* 85-100% clean production
Hungary	HU	Y	Y	N	Y	16-25%GHG emission reduction by 2025**	EC objectives[1]
Ireland	IE	Y	Y	Y	Y	30% GHG emission reduction*	80-95% GHG emission reduction**
Italy	IT	Y	Y	Y	Y	40% GHG emission reduction**	80-95% GHG emission reduction**
Latvia	LV	Y	Y	N	Y	EC objectives[1]	
Lithuania	LT	Y	Y	N	N	45% RES production	100% clean production
Luxembourg	LU	Y	Y	N	Y	1/3 RES production	Net-zero GHG emissions 100% RES production
Malta	MT	Y	Y	N	Y	EC objectives[1]	
Netherlands	NL	Y	Y	N	Y	EC objectives[1]	
Poland	PL	Y	Y	N	Y	Reduce coal-fired production to 37.5% *	Carbon neutrality
Portugal	PT	Y	Y	Y	Y	80% RES production	100% clean production
Romania	RO	Y	Y	N	Y	EC objectives[1]	
Slovak Republic	SK	Y	Y	N	Y	35 TWh RES production	Energy security for RES EC objectives[1]
Slovenia	SI	Y	Y	N	Y	EC objectives[1]	
Spain	ES	Y	Y	N	Y	74% RES production	100% RES production EC objectives[1]
Sweden	SE	Y	Y	Y	Y	18 TWh clean production	100% clean production by 2040
United Kingdom	UK	Y	Y	Y	Y	50% CO2e emission reduction**	80% GHG emission**

* indicates that the baseline levels are set as 2005.

** indicates that the baseline levels are set as 1990.

[1] EC objectives refer to the sustainability objectives for energy sector, including the electricity systems, proposed by the EC. For 2030 objectives, it targets at reducing at least 30% GHG emissions compared to 2005 baselines, mainly recorded as CO2 emission equivalent. For 2050 objectives, it is set as reaching climate neutrality and officially using the proxy of carbon neutrality by EC. Some country specific objectives are extracted from reports by EC (EC, 2020).

tricity during technology transmission. The concerns are generally shared among nearly all countries, however, each country holds different emphasis for them. France and Greece mainly concern secured production and supply of electricity during the shift from high-carbon electricity productions to cleaner production technologies (IEA, 2021*b*, 2017*b*). Croatia focus on the security of electricity in the distribution process, especially to the rural areas (Commission, 2019*a*). Aside from distribution, Denmark also attempt to improve guaranteed supply of primary electricity sources as the attainability of some RESs are uncontrollable (IEA, 2017*a*). Such concerns for secured sources for electricity has developed into the issue of power independency. Influenced by the current electricity production mix, the global pandemic, and the Russian-Ukraine conflict, some countries, especially those currently holding the capability to develop nuclear power, especially emphasises the contribution of power supply independency to better energy security. Austria, Belgium, Greece, Ireland, Italy, Portugal, Sweden, and UK all contained sustainable electricity objectives of becoming electricity export countries. Belgium and UK specifically state that development in nuclear power is actively planed considering its high volume of electricity production (IEA, 2022*a*, 2019*c*). It is mentioned that for UK, as 50% of the 2017 electricity production mix is low-carbon measures and CO2 emission in the energy sector now falls below the transportation sector, it focus more on the maintenance of the share of clean production in the electricity production mix (IEA, 2019*c*). Sweden attempts develop energy security by lowering energy intensity (IEA, 2019*b*). Differently, Portugal recognises the necessity to better boost domestic electricity production so that the dependency on imported electricity would decrease. Different from most countries, Germany proposed the reduction to domestic electricity demand (IEA, 2020*b*).

Thirdly, the objectives for climate mitigation are mainly given is three forms: reducing GHG emissions, increasing the shares of cleaner production or consumption, and the reduction to the usage of coal. Sustainability objectives for climate change are very often associated with improvement in energy efficiency or energy security. Countries including Austria, Czech Republic, Finland, France, Germany, Latvia, Malta, and Slovenia target for phasing out electricity production from coal, so that coal supply for energy security and carbon emission reduction can be simultaneously improved (IEA, 2020*a*, 2021*a*, 2018*a*, 2021*b*, 2020*b*, Commission, 2019*b*). Among them, Austria target for turning coal-fired plant to natural gas fired power plant instead.

Eventually, for the given sustainable electricity objectives, there are countries that are reported to be unable to reach the proposed short-term objectives. Belgium has failed the previous goals for increasing the installed capacity of RES electricity plants proposed to EC and has adopted new objectives for GHG emission reduction (IEA, 2022*a*). Ireland, as Brexit has significantly influenced its energy price, has fallen short for the 2030 objectives as economy recovery is prioritised (IEA, 2019*a*). Besides, Lithuania, not yet on the track for low-carbon transmission, has not concerned any emission objectives while only considering improving the share of electricity produced from RES mainly for energy efficiency. Thus, by understanding the sustainability objectives of electricity systems for European countries, the EU 28, we collectively comply to the carbon reduction and cost-effective efficiency improvement objectives in this thesis.

4.4.3 Energy Sustainability Evaluation

Sustainability performance evaluations for the energy sector, especially electricity systems have been popularly done for one power plant over its lifecycle(Brown and Ulgiati, 2002, del Ro and Gual, 2004, Cao and parikhani, 2020), the life cycle of the transformational inputs(Zurano-Cervello et al., 2018, Muis et al., 2010, del Ro and Gual, 2004), or, on the national level, the performance of electricity production mix(Zurano-Cervello et al., 2018, Stamford and Azapagic, 2014). Although we may criticise that such attempts could be improper sustainability evaluations considering the issues we reviewed, again regarding them as using certain group of necessary conditions for sustainability, insightful sustainability evaluation results are produced on different focus.

Research for one power plant evaluates system performance from more comprehensive perspective by tracing up and down for the formation and the impacts of the system inputs and outputs. Based on emergy measurement for mass and energy, Brown and Ulgiati (2002) evaluates the sustainability performance, focused on the renew-ability of the sources and the environmental load left to the external systems, of a coal-fired plant tracing upwards to the formation of the transformational fuels and the construction materials and downwards to the production of the electricity. Kabakian et al. (2015) evaluates using LCIA for the life cycle of a solar PV plant, noting that the manufacturing sites for the technology components are distant with associated environmental impacts. Sastre et al. (2016) evaluates a biomass power plant focusing to the CO2 emission for the biofuels and traces the changes of nitrogen to evaluate the impacts of nitrogen fertilizer used. Although determined by the methods used for sustainability evaluation, it is implied in these studies that sustainability of the power plants would be more precisely reflected by considering the upstream orientation of the electricity sources and the downstream impacts after generating electricity. However, the implicit use of sustainability criteria such as CO2 and nitrogen in the evaluations has resulted in the lack of judgement for the feasibility between the evaluation subject and the evaluation objectives.

On the national level, one group of sustainability evaluation focus on the operational phase of power plants, evaluating for the life cycle sustainability performance of transformational fuels and the associated impacts which successfully justified the advantages of using RESs for electricity production. Campos-Guzmn et al. (2019) concludes that for national level sustainability evaluation for electricity systems, LCA is mainly associated with certain projects, technologies, and processes. Muis et al. (2010) evaluates the contribution to CO2 emission reduction for the country electricity production mix by considering overall costs associated with electricity fuels. Boie et al. (2016) further adds the incentives for installation of power plants into the cost terms and still suggested more cost effective performance of RES power plants. However, as stergaard et al. (2020) indicate, the performance over energy efficiency and energy security is influenced by the supply of fossil fuels and the spatio distribution of RESs. RESs are only available to specific sites even though sources including solar radiation, water, wind, and geothermal are not costly. While RESs are more frequent in reproduction, when the sustainability evaluations for electricity production systems focus on the transformation process, the sustainability implementations are more focused to the system performances associated with the transformational sources. The influence from other system components are not evaluated as concrete as the sustainability evaluations for one power plant. As stergaard et al. (2020) suggests, sustainability evaluation for the electricity systems should also consider the wider system impacts associated with the changes in the production technologies.

Another group of sustainability evaluation on the national level evaluate for the performance of the electricity production mix, over the transformation and the environmental and social impacts. Chalvatzis and Hooper (2009) classify electricity production methods into fossil fuel production and RESs production and evaluates sustainability concerns over the proportion of RESs in the installed capacity and energy supply security of fuels imported. Siksnelyte and Zavadskas (2019) perform benchmarking sustainability evaluation for EU28 countries considering economic, environmental, and social outcomes and impacts. Zurano-Cervell et al. (2019), by using DEA, concentrates the sustainability evaluation over the transformation efficiency and the influences of the electricity production process. We notice that on the national level, when the evaluation subject is set to the electricity production mix, these researches associate impacts arbitrarily with national level proxy indicators such as the electricity price, share of RESs, electricity interconnection rate etc. The attempt to understand the formation of the production mix or the cradle-to-crave maintenance of the production mix is not popularly carried out.

Apparently, for more proper sustainability evaluation, the electricity production mix should and could be done with the intention to understand its full process of formation and operation. It is already recognised that the manufacturers of production technology compartments are geographically scattered (Campos-Guzmn et al., 2019). For example, the inverter, batteries, and the crystalline silicon modules of the solar PV power plant evaluated by Kabakian et al. (2015) are respectively supplied by Switzerland, Germany, and China (Wong et al., 2016). Aside from the security of product supply for electricity production systems, in sustainability evaluation, we also perceive the necessity to recognise that associated external impacts, including environmental and social, are created at different sites. As we understand from Chapter 2, relevant contributions to the sustainability criteria should be recognised in the sustainability evaluation. Thus, this chapter performs sustainability evaluation following the MSV framework using the EEV measures to comparatively present the universal sustainability performance of electricity production systems of EU28.

Chapter 5

Results and Findings

5.1 The Apposite System Modelling

We adopt the protocol from 3 for evaluating national electricity production systems of European countries which include non-homogenous production technologies of electricity. To note, as we are aware that each country hold different electricity profiles, the modelling is performed for a full profile of electricity production technologies that are currently applied in Europe. The subsections presents the steps followed.

5.1.1 Initial Settings

Matching the first step in the protocol, we identify the lead of evaluation, the evaluators, the initial system to be evaluated, the sustainability evaluation objectives proposed by the lead of evaluation, and the initial group of DMs. The evaluation is performed for the initial system of national electricity production mix, focusing for EU28. To simplify the process, the specific technological details used for each sub-process is simplified by the dominant technology used for electricity production, being the maximum in production capacity. Also, electricity production process of combusting municipal waste is excluded due to the large variety in the source properties. Other minor production technologies are also excluded in the analysis due to limited structural data.

Lead of Evaluation and Initial Targets

Although we perform the evaluation spontaneously, the lead for sustainable lifestyle and attaching sustainability goals for the electricity production system is mainly the government and relevant organisations such as the EC, IEA, and the OECD. Contained in the energy policies of European countries, Siksnelyte and

Zavadskas (2019) concludes that the development of electricity and the energy sector targets for system modernisation, energy stability, market reinforcement, and action for climate change. The electricity systems of European countries target for increasing energy efficiency, guaranteeing energy security, and decarbonization for climate mitigation. This is perceived as the sustainability objectives that can be used as the evaluation objectives for the initial system. Based on this, we understand that the sustainability evaluation results from this evaluation approach mainly targets for the providing more insightful sustainability recommendations on the macro level for policies.

Evaluators and Initial DMs

The evaluators are apparently us who actually conducts the evaluation. As a third party for the electricity production systems, it is determined that this sustainability evaluation would mainly base on secondary data collected from the lead organisations or the governments. Accordingly, the initial group of DMs for the evaluation would be the evaluators, and the governments and the organisations. Considering the influence to the power plants, we would state that it is more appreciated for the power plant owners to be part of the DMs since more evaluation resources could be introduced. However, for feasibility of the evaluation in general, we could treat them as the KSs in the evaluation.

Explicit Sustainability Evaluation Objectives

As the previous section reveals, sustainability targets in Europe for the electricity production system mainly include higher energy efficiency, better energy security, and better environmental mitigation. For sustainability evaluation of the electricity production system, the evaluation objectives are explicitly deciphered as followed, being clear in what is contained in the objectives, how the objectives are achieved, and the meaningfulness of the objectives.

Based on the national level energy targets set, the sustainability evaluation focus on the national electricity production system (what, also the initial system) that would include primary and secondary production processes (how) for continuous, steady, flexible, supply of electricity by meeting the national demand with the considerations for support from the natural environment, mainly considering carbon emissions (why). Over the evaluation subject, what, national electricity production systems are wide profiles of subsystems electricity production process that vary according to technologies and could be limited by the availability of technologies and resources required for production. For the transformation processes, how, energy transformation efficiency has been widely embedded in the objectives that require consuming less transformational inputs of all types while producing the same or more electricity. The speciality of the electricity production system is that electricity could be the output of primary production or secondary production, during which upstream subsystems differ significantly. Measurements related to efficient electricity production would also be part of the sustainability criteria. However, as energy efficiency of electricity production is highly contained within the initial systems, the system boundary of the evaluated subject system would be feasible enough by containing the initial system. Given the preferred influences, while satisfying the demand for electricity, energy security and climate mitigation are two main objectives that could be mutually influencing. Energy security expect sufficient, continuous, and stable supply of electricity. The main sustainability evaluation criteria concerned could be the balance between the reproduction of the resources and the consumption rate, which often require to investigate into the upstream production systems of the materials and the initial system. Besides, some factors also cause unstable issues in unsecured stakeholder connections such as regional conflicts, global affairs, and the capacity of electricity production infrastructure. Here, we mainly concern the attribute in entropy for structural order. For climate concerns, the comprehensive objectives target for reducing all aspects that are currently recognised as leading to environmental degradation. However, according to Table 4.3, current environmental concern in electricity production focus on carbon emissions that could be associated with transformation or construction. Especially for the decarbonisation of the production process, direct CO2 emission and that equivalent from other emitted particles into the atmosphere is the key compound creating climate challenges. Thus, we identify the sustainability criteria of carbon in this sustainability evaluation that require further analysis for the suitable mechanism of manipulating carbon emission.

The Initial System: Electricity Production Mix

The initial system in this evaluation is the electricity production mix of a country. Assuming a full production mix at this stage of analysis, the I-O relation of the existing initial system is the transformation from energy fuels or other forms of energy through certain technologies into electricity (Energy Information Administration, 2019), during which CO2, also aggregating other GHGs forming CO2 emission equivalent (CO2e), would be directly emitted to the atmosphere and other side-products would be produced. Electricity, after being produced, is either stored or distributed over the grid network but we would not consider electricity consumption in this evaluation. The sources of electricity are proxied as coal for solid fuels, crude oil for liquid fuels, and LNG for gas fuels, kinetic energy for wind, hydro, and tide production, potential heat for nuclear, biofuels, and geothermal production, and solar radiation for solar PV production. Besides the energy transformational inputs, the initial system is also supported by installed infrastructure by many other materials such as the cement, steel and aluminium structures which determines the installed capacity of each power plant, and energy that supports the operation of the installed constructions. It applies to all production pathways that infrastructures for electricity production plants require continuous maintenance and replace of materials. In association with the structure construction, energy, especially in the form of electricity, is consumed to operate the infrastructure. The production structure of the I-O relations are exhibited in Figure 5.1.

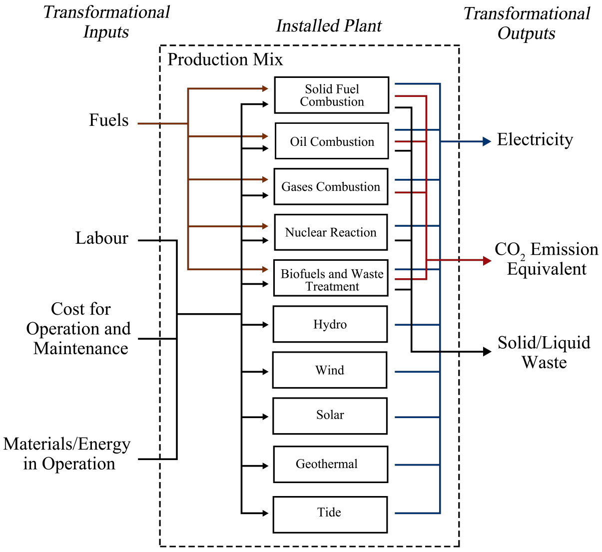


Figure 5.1 Initial system of electricity technology production mix

During the transformation, associated with societal interface, there are also labour and capital consumed, usually required by the owners of the power plants. Such inputs also influence the functionality of the production mix and are associated with CO2 emission during the creation of required labour and capital (Brown and Ulgiati, 2002, Muis et al., 2010). Also to note, there could be capital costs, mainly in the form of exchange value, for fuel transformation inputs. Electricity plants usually need to purchase coal, oil, LNG, Uranium, and some RESs such as biomass and wastes from external upstream suppliers. Meanwhile, some RESs including wind, hydro, geothermal, and solar PV power plants transform capital free energy on the site from the nature which would not involve with the exchange values of the sources. The issues of energy security are different according to the power plant types. One is the structural issue of stability of suppliers and the other is the reproduction and availability property linked with the sources. Thus, here, we also demonstrate the initial system based on the production technology, recognising that different subsystems are contained in the initial system all targetted for producing electricity and associating with impacts over the sustainability criteria, carbon emission. The initial systems are simplified with the most typical technology that is applied for each production method.

Thermo power plant indicates the production technologies that centre the combustion of fuels, including coal-fired, oil-fired, LNG combustion, and biofuels. Depending on the technologies for transformation and the types of fuels used, the production efficiencies and the necessary infrastructures for side product treatment are different where for gas fuels, Claus process usually replaces the flue gas module (Zhang et al., 2021, Spath et al., 1999, Birol, 2010, Yazdani et al., 2020). Presenting various combusting technologies and treatment modules of a typical coal-fired power plant, the process is exhibited in Figure 5.2. The key modules include the insulation module and an associated cooling module, the electricity generation module, and necessary side produce treatment modules. As the figure presents, during electricity production process, the initial system is mainly operated by human stakeholders providing labour and non-human weak stakeholders could be associated by the land taken up by the power plant. The stakeholder involvement would require further analysis when the supply of the input fuels and the construction materials are considered. The raw materials for the construction of the plant would be simplified to concrete, steel, iron, and aluminium. Concrete, steel, and iron mainly serve for the construction of the power plant buildings and offices. As concluded by Brown and Ulgiati (2002) and Zhang et al. (2021), the system components in functional modules include:

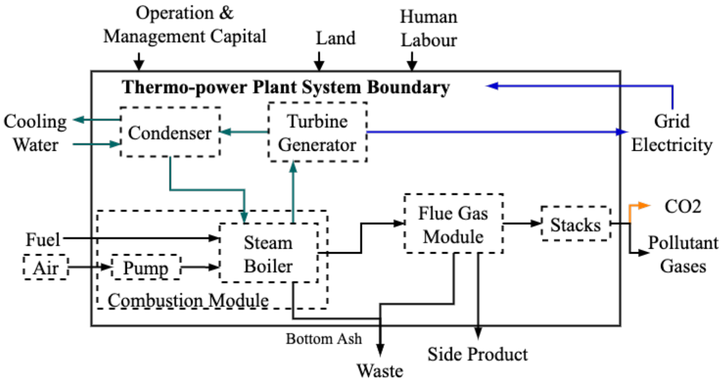


Figure 5.2 Plant Installation Structure and Operation Flow of Thermo-plant

1. Insulation and cooling module: fuel storage tanks (steel), insulating materials, pre-heaters for water and combustion air (steel), pumps and valves(steel), pipes(steel);

2. Generation module: steam turbine generators (steel), electric wires (copper), electrolyse precipitators(steel), electric motors(steel and copper), electric boards and panels(iron), transformers(steel, copper, cooling oil);
3. Emission modules: pipes(steel), storage tanks (steel), lubricants, and paints, chimneys (concrete).

For nuclear power plants, we present a typical initial system structure of pressurised water reactor plant (Figure. 5.3). To note, depending on the types of plant, the radioactive fuels used for reaction could vary, including plutonium 239, uranium-233, and uranium 235 (Sheu, 2008). The main process of nuclear power plants include the reactor, turbine generator, and condensing modules. However, since the heat produced in one unit of nuclear power plant is large, the installation of nuclear power plants is associated with high indirect carbon emission (Sheu, 2008). Also, the radioactive wastes that are inevitably produced from the reactor would require long duration of recovery (Takata et al., 2018). Thus, to note, nuclear power is not a RESs but a cost effective source of electricity. In association with the installation, operation, and disposal of the wastes, stakeholders contributing to indirect carbon emission for the operation of nuclear power plants require analysis.

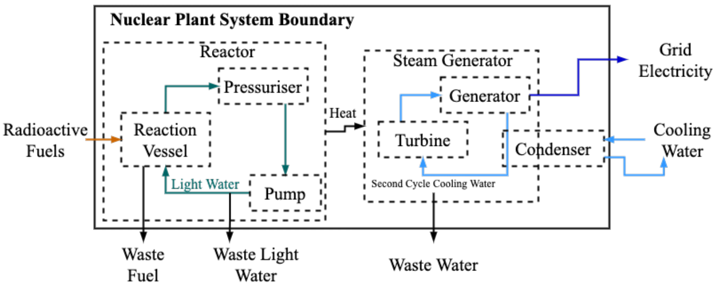


Figure 5.3 Plant installation Structure and Operation Flow of nuclear electricity plant

Then, we present the initial system of solar PV power plants (Figure 5.4). The key transformation process of solar PV is turning solar radiation into usable electricity using the transformation module of silicon panels (Marino et al., 2019, Cao and parikhani, 2020), during which electricity is a form of primary energy. Its amount of electricity produced and the operational efficiency are highly influenced by the strength of direct solar radiation and the coverage and maintenance to the surface of the silicon panels (Mustafa et al., 2020). Very often, considering the attainability of on-site solar radiation and the efficiency of solar PV power plants, electricity storage modules are installed in solar PV power plants. In Figure 5.4, a hydro electricity storage unit is presented. Different power plants could apply different technologies for storage, however, we are only able to consider

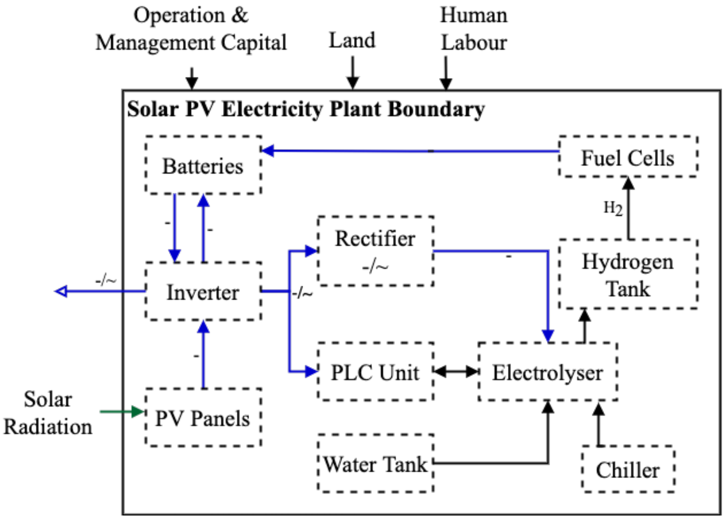


Figure 5.4 Plant Installation Structure and Operation Flow of solar PV electricity plant

part of them that is limited by the available data. Although the operational phase of solar PV consume fully renewable energy, the infrastructure installed for the solar PV power plant to function require continuous maintenance and replacement that could be not fully renewable. The key functional material required by solar PV plants is the high concentration crystalline silicon panels that require different wafer, cells, laminates, and panels for construction (Jungbluth et al., 2008). From the cost effectiveness perspective, the crystalline silicon panel with over nine 9 s purity would require a payback time of usually two to three years (Fthenakis et al., 2011). Other modules contributing to electricity production include buildings and the inverter modules that include the aluminium and steel frames, copper wires, plastic and steel conduits, and steel inverters (Mason et al., 2006). To support the installation of such functional unites, concrete, steel, and aluminium are mainly required materials for office and building construction that are highly concentrated in carbon. As Mason et al. (2006) notes, the inverters are usually estimated for an operational age of 30 years and 10% of other materials need to be replaced every 10 years. We reference to this rate for most constructional materials, especially when the replacing rate is not stated. Also apparently, the strong stakeholders functioning in this initial subsystem is mainly groups of human workers. However, considering the land taken up and the changes to the land covered by the silicon panels, more influences are brought to on-site weak stakeholders. Furthermore, considering the supply of the solar radiation and the materials for infrastructure, more stakeholders that are non-human would be involved, especially featuring for solar PV power plants, in the production of silicon panels.

For electricity production plants of wind, hydro, tide, and geothermal, the key technology for power generation driving turbine generator by the kinetic energy of wind, water, or steam. The initial systems of a typical wind farm unit, hydro turbines for dams and water body reserves, and binary geothermal plants are exhibited.

As Figure 5.5 presents, wind electricity plants are usually constructed as a farm of wind turbine generators. Here, the detail of one wind generator is presented and other components are simplified. As Muljadi and Gevorgian (2011) notes, the core process of the turbine generator is also associated with the suitable transmission line and the outputs to the grid lines as the technology design needs to be able to contain electricity generated by numerous wind turbines. There are also designs of wind farms where gear boxes are unnecessary or when electricity storage modules are installed at site connected to the generation modules (Ming-Shun Lu et al., 2009). Although the core technology of wind power is the wind turbine, the performance of wind power plants highly depends on the local weather conditions, mainly the availability of wind speed and variability (Latiffianti et al., 2022, Slootweg and Kling, 2003). These are also the main causes to the uncertainties of wind farm performances (Dvorkin et al., 2016). Besides, the topology of the converters also influence output grid electricity from wind farms in filtering the direct production from the generator (Peng et al., 2021). The operational phase for wind farms also mainly interact with strong stakeholders that are human. However, as many researches have recognised, the installation of the wind turbines brings danger to the birds and would alter their habits. Further analysis to the weak stakeholders influenced by the installation of wind farms would be required.

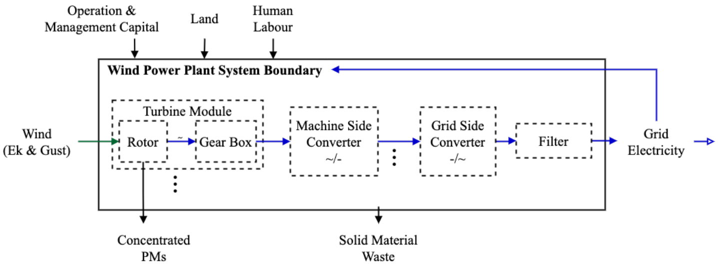


Figure 5.5 Plant Installation Structure and Operation Flow of Multiphase Wind Power Plant

Hydro power is regarded as the most stable source among RESs. We present the initial system of tide power plant together with hydro power plant as the production process is similar and using similar materials. Electricity generated through hydro power plants is also a source of primary energy that is transformed from the kinetic energy of running water. Figure 5.6 exhibits the initial system of a typical hydro power plant installed with dams. As the figure shows, this initial

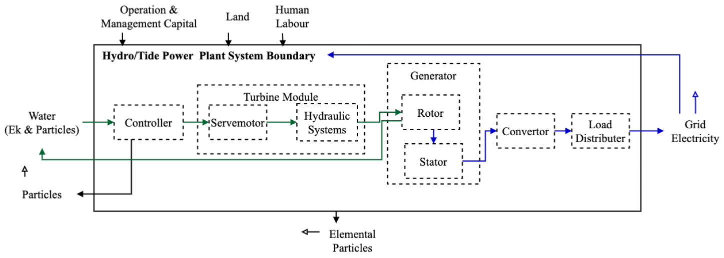


Figure 5.6 Plant Installation Structure and Operation Flow of Reservoir Hydro Power Plant

system mainly contains a controller gate that controls the volume of water that runs through the turbines, a turbine modules that turns kinetic energy of water to mechanical energy and are connected with the generators, and eventually an electricity converting module that filers the produced electricity and distributes electricity to the grid (Singh and Singal, 2017). For hydro power plants installed with a dam, water runs from the reservoir through a tunnel to the turbine gate (Kishor et al., 2007). Similar infrastructure is used for tidal power plants. However, for hydro power plants using pumped storage, the control gate module is replaced with a pump that lifts water from storage to elevated sources so that the gravity of water turns to the kinetic energy to produce electricity under control. The mechanical performance of hydro power plant is therefore influenced by the turbine efficiency and the generator efficiency, and its life span is determined by the dead storage since mud accumulates on the river bed and would bring the hydro power plant to death (Yoo, 2009). Developing technology till now, human workers act the key role in guaranteeing the function of this initial system, digital controls have removed the involvement of many stakeholder groups. However, as the running water contains many living species, and the construction of dams are found to significantly alter the upstream land cover, the weak stakeholders associated with hydro power plants would include human groups and animals associating with the installation of the plant.

Different from wind and hydro power (expect pumped storage), geothermal power plants require both the attainable sites for geothermal sources and a pump for extracting the sources. The types of geothermal sources determine the technologies to be installed for the geothermal electricity plant. Dry steam geothermal power plants direct drive a turbine generator by heat while others pump up the sources to the surface to perform the heat exchange (Brown and Ulgiati, 2002, Buonocore et al., 2015). Among the three types of geothermal plants, single flash, double flash, and binary cycles, binary cycle is most widely applied technology that uses organic matters or ammonia water for the second cycle of heat exchange

(Valdimarsson, 2011). Using a separator, usually a binary cycle plant is developed into a flash-binary geothermal plant (Hijriawan et al., 2019). Here, we present the initial system of a simplified flash-binary geothermal power plant in Figure 5.7. As the figure presents, the main functional modules include the production and reinjection wells, the flash chamber module cycling geothermal sources, the heat exchange module connecting with the second cycle, and the turbine generators producing electricity. These modules together influence the mechanical efficiency of the geothermal power plant in generating electricity. To note, for some plants, there could be a vaporiser installed in in the flash chamber for more efficient energy exchange of heat (Kanoglu, 2002). Just like other power plants, geothermal power plants are also mainly operated by human workers. However, as the installation of the infrastructure would alter the land scape and the surface temperature of soil, the construction and operation of geothermal power plants also influence many weak stakeholders which will be analysed later.

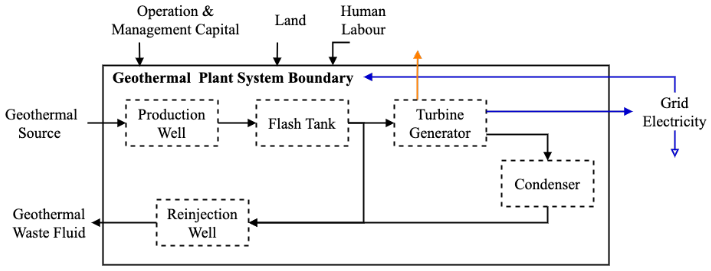


Figure 5.7 Plant Installation Structure and Operation Flow of Binary Geothermal Plant

Among all the subsystems in the initial system of electricity production, the combustion plants, hydro, and geothermal are relatively controllable and steady production technologies. The fuels or primary sources for producing electricity could be controlled. Nuclear plants could also be controlled, however, not as easily since the operation and termination of a nuclear power plant could take much time and associate with much risk. Lastly, solar PV and wind power productions are the most unstable but most reproductive technologies since solar radiation and wind velocity and direction value timely across days (Charfi et al., 2018). Also, as many energy plants are designed to simultaneously produce electricity and heat, the processes for heat productions are neglected in this evaluation to focus on the production of electricity and thus CHP plants are not considered.

5.1.2 Stakeholders and Developing Stakeholder Connections

In this evaluation, as the comparison is made among 28 European countries, the electricity production is analysed for an aggregated production profile of Europe, which is expected to be developed into a wider system that could be applicable for the sustainability evaluation for each one of the countries. As the following process presents the identification of the KSs that are in and should be included in the evaluation focused on the European countries, there are some connected subsystems that may not contain certain technology or upstream systems if none of the European countries apply such technology for production.

Initial Key Stakeholders

Following the protocol, the KSs of the initial system is analysed. Figure 5.8 presents outline of KSs in the initial system that could be further analysed according to each subsystem. As the figure presents, the owners of the initial system mainly include the government and the owners of the electricity production companies. The actors are the employees of associated with the power plants. To note, although we have not classified different roles of employees, there are managers and workers who perform different actions for the electricity plant to function. Among them, the managers could be strong stakeholders who are able to express their opinions to the DMs in the evaluation but the workers could be weak stakeholders whose values may not always be expressed. Besides, since the production of electricity generally interact with combustion, high temperature, or turbines, the actors usually perform the role of controlling, maintaining, or replacing the transformation mechanics. Environment stakeholders are involved with all power plants in the supply of transformation technology. According to country and regional differences, the technologies installed in the production mix of each country would differ. Also, for fossil fuel, nuclear, and biofuel electricity plants, environment stakeholders are involved to supply the fuels, usually including car-

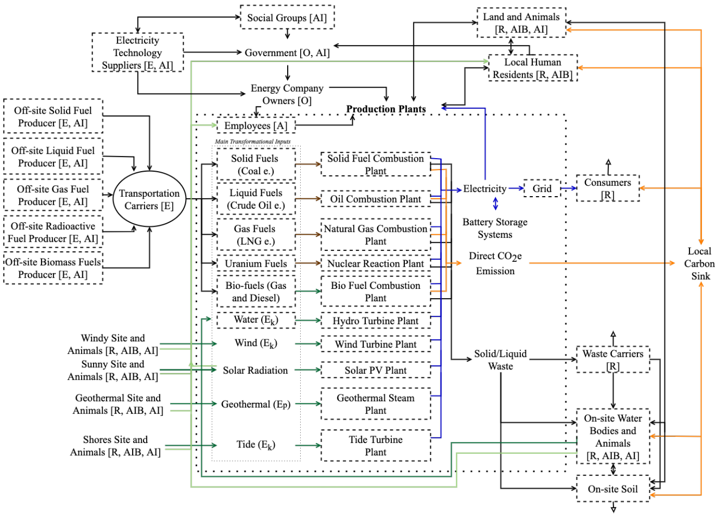


Figure 5.8 Initial KSs in the Electricity Production Mix

riers for transportation. The recipients are more diversified. The direct recipient of electricity produced to the grid are the customers. In this evaluation, we neglect the consumption activities of the customers. Also, the installation and the operation of the power plants would create many recipients. Wind farms influence the survival of many habitual birds due to the wind turbines. The installation of solar PV panels affect the survival of grass land animals that no longer have enough access to sun light. Dams and tidal power plants influence many fish as they warm the surrounding water body and may elevate the water level, influencing on-land species. And, geothermal power plants would also heat the vertical soil layer, creating changes to the surrounding living conditions for both human and animals. The direct emission of CO2, or the GHGs, would influence the weak stakeholders on site, including animals and human residents. The solid and liquid wastes from transformation and maintenance would associate with waste carriers and the on-site water bodies if they are directly released to running water. Eventually, many stakeholders, mainly weak stakeholder are affected, either influencing or being affected by the initial system. Figure 5.1 presents the detail of initial system KSs and the key system components varied by production technologies.

Table 5.1KSs and System Components of a Production Mix

(a) KSs of Initial System

Stakeholder Types	**Categories**	**Stakeholders**
Owner (O)	Ownership	Private electricity plant owners, State owners, Governments
Actor (A)	Transformation and Operation	Electricity plant owners, Managers, Employees
Recipient (R)	Of Electricity	Customers (on and off site)
	Of CO2	On-site employees, Local residents, On-site and local animals
	Of Wastes	On-site employees, Local residents, Disposal site animals, Waste carriers
Environment (E)	For Construction	Technology supplier, Construction material supplier, Government (policy supplier), Owners (capital supplier) Land supplier (government, original residents)
	For Fuels	Fuel suppliers (coal, oil, LNG, Uranium, biomass)
	For Operation	Country (labour supplier)
The Affected Influencing (AI)	Strong Stakeholders	Social groups (opinions), Government (sites), Technology suppliers (availability), Shareholders and creditors (interest), Foreign fuel suppliers, Foreign construction material suppliers, Foreign technology suppliers
	Weak Stakeholders	On-site resident animals
The Affected Influenced By (AIB)	Strong Stakeholders	Local human residents
	Weak Stakeholders	On-site resident animals

(b) Main System Components

Electricity Plant	**Category**	**Components**
Thermo-Plant	Office and Installation	Concrete, Iron and steel, Glass, Paints
	Combustion Module	Concrete, Steel, Copper, Iron, Lubricants, Cooling oil, Insulating materials, Diesel, Turbine (steel, aluminium)
Solar PV Plant	Office and Installation	Concrete, Iron and steel, Glass, Paints
	PV Modules	Concrete, Steel, Aluminium, Copper, Lubricants, Solar Grade Silicon or Crystalline Silicon Panels, Plastics, Batteries, Hydrogen
Nuclear Plant		
Geothermal Plant	Office and Installation	Concrete, Iron and steel, Glass, Paints
	Exchange Module	Concrete, Cement, Steel, Paint, Lubricants, Aluminium, Glass, Copper, Plastic, Iron, Nickel, Molybdenum, Manganese, Turbine (steel, aluminium), Cooling working fluid, Lube oil, Diesel
Wind Plant	Office and Installation	Concrete, Iron and steel, Glass, Paints
	Generation Module	Concrete, Cement, Steel, Paint, Lubricants, Aluminium, Glass, Copper, Plastic, Iron Turbine (steel, aluminium), Diesel
Hydro or Tidal Plant	Office and Installation	Concrete, Iron and steel, Glass, Paints
	Generation Module	Concrete, Cement, Steel, Paint, Lubricants, Aluminium, Glass, Copper, Plastic, Iron, Turbine (steel, aluminium), Diesel

As Table 5.1(a) exhibits, since CATOWE is more of a functional division to different stakeholders, there are stakeholders belonging to different categories performing different purposeful actions. The stakeholders that could be the DMs among the initial KSs would mainly include the owners who, in this evaluation, are mainly human stakeholders holding capitals or authorities. The actors in the initial system conducting actions to enable producing electricity are also mainly human. The inclusion of weak stakeholders mainly include the recipients enduring the outputs such as local human residents who are silent and the animals living in the surrounding environment. Environment stakeholders who provide necessary inputs to the power plants are mostly strong stakeholders of human, but the supply of land for the construction of the power plant would involve human and animals originally living at the site. For the indirectly influencing stakeholders (AI), strong stakeholders are mainly different human groups that influence the stable operation of the electricity plants. Associated weak stakeholders would mainly include animals that would threaten the infrastructure of the power plants or affect normal operation of the transformation modules. The stakeholders indirectly affected by the system of electricity production are mainly the original residents, both human and animal, on the site or on the land influenced by the construction of the power plant. As presented in Table 5.1(b), the system components mainly vary over the electricity production modules. The materials consumed for constructing offices and buildings are simplified to concrete, iron, steel, glass, lubricants, and paints. The detailed use of materials including the plastic pipes for sewage and copper wires for office electricity are neglected. The transformational modules are also simplified by including the key components that supports the production of electricity for each technology.

Developing Stakeholder Connections

Based on such initial group of KSs and the given sustainability evaluation objectives, we apply SSM to perform the stakeholder analysis to develop the wider stakeholder connections over carbon emission. As suggested by Wang et al. (2014), stakeholders, directed by objectives, are associated with purposeful actions that are considered to contribute to the objectives. Thus, the stakeholder connections are constructed by continuously querying what activities should be done by whom to reach the objectives.

First of all, a general activity model for the initial KSs where the details could vary according to the production subsystems is presented (Figure. 5.9). The stakeholder contributions to the sustainability criteria are mainly traced following the physical and value connections of the stakeholders of which the impacts could vary over time and space (Stamford and Azapagic, 2014, Asif et al., 2007). This presents the activities that are expected to be conducted by the stakeholders to realise the objectives. Since this research mainly base on external observations to the initial system, the activities are mainly observed from open reports and the status-quo of current national electricity production mix of European countries. It is noticed that having communications with the DMs in the evaluation would present more practical activity model. The blue lines are used to present traces of electricity, orange for direct CO2 emission.

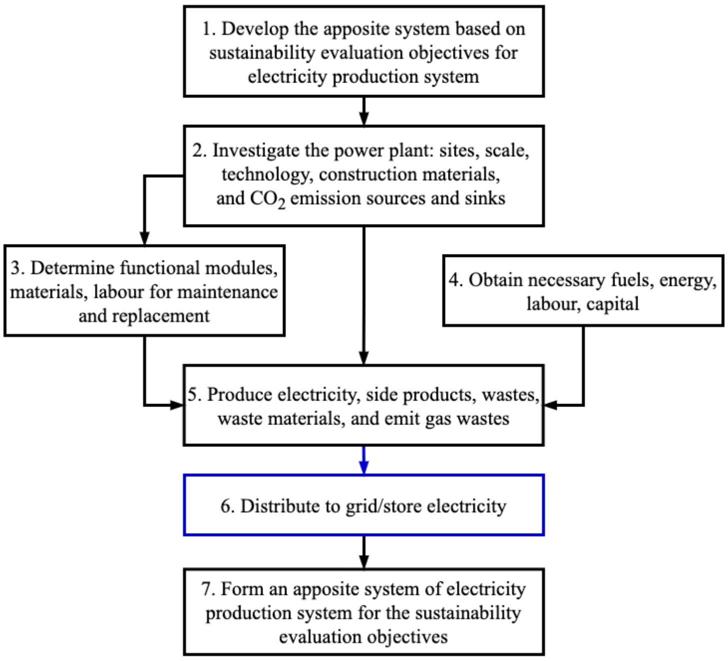


Figure 5.9 General activity model of initial electricity production system

As Figure 5.9 presents, the activity model demonstrates the sources and the emission of CO2 during the process of electricity production. The carbon cycle of electricity production system has two main direct sources from the fuels and the construction materials, and two main indirect sources of producing the construction materials and the manufacturing of the structures and the functional modules. In detail, each one of the production technologies are associated with its own activity model, presented in Appendix D.1.

Here, Figure 5.10 presents the activity of solar PV electricity production system as an example. Different from the general model that also suits for thermo-power plants, it would need to consider the key technological compartment that enables the primary production of electricity. Apparently, thermo-power production subsystems including coal, oil, gas, and biomass electricity production systems heavily produce CO2 emissions from transformational fuels, nuclear power plants rely on complex process of nuclear fuel mining, and other renewable electricity production subsystems hold greater proportion of indirect carbon emission in construction materials. Thus, the stakeholder analysis is done for two key criteria, the direct interaction with CO2 emissions, and the key functional modules of the system, considering that electricity could be primary and secondary energy.

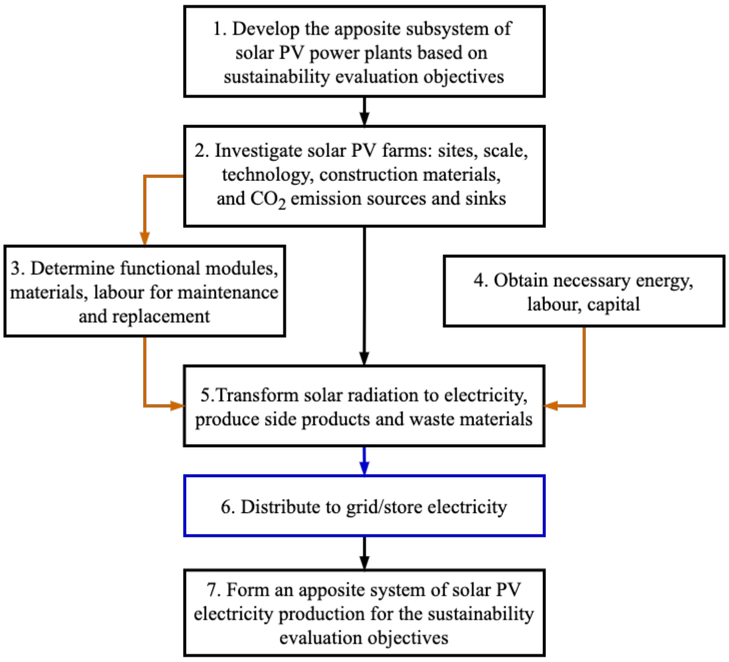


Figure 5.10 Activity model of initial solar PV electricity production system

To complete the top level activities, analysing by SSM, the values and interests of KSs need to be considered and the systems that these KSs play their roles in need to be included in the evaluation. Hence, the following process is to continuously derive the activities to complete the top level activities and the stakeholders associated with the activities. We notice that in the top level activities, it is not explicit that the sustainability criteria, carbon, is fully demonstrated into presenting self-enclosing connections. Both the upper stream origin and the down stream life cycle of CO2 emissions need to be analysed and it is necessary to understand the KSs associated with the cycle that explains the electricity production system and the CO2 emissions within the system.

An example of initial group of KSs using coal-fired power production system is presented. Table 5.2 presents the initial group of KSs who are critical to complete the top level activities for coal-fired electricity production. Activity 1 collects information to understand the sustainability evaluation objectives, explicitly determining the sustainability criteria and preferences in the evaluation. It is key process that requires the evaluators to communicate with accessible primary group of DMs. Activity 2 collects information around the coal-fired electricity production status. It includes the system of land-cover change from other land-types into the current land take-up as coal-fired power plants. Land-cover change would associate with wide ecosystem changes that would directly and indirectly influence wide weak stakeholders, including vegetation and animals in the soil, water, and air (Sleeter et al., 2018). Hence, on the one hand, the weak stakeholders are wide and would vary significantly by case in Europe as past research presents (Tang et al., 2013, Nvoa-Muoz et al., 2008); on the other hand, the differences in the physical properties of the land cover results in different levels of carbon flux with the ocean, land, and the atmosphere (Brando et al., 2013, Cramer et al., 2001, Paustian et al., 2016, Sleeter et al., 2018). Therefore, activity 2, although is a key process of information collection, would interlink with the functional role of land and ocean as two main bodies of atmospheric CO2 absorption sinks (Scholes and Noble, 2001). Activity 3 is the continuous supply of construction materials and transformational modules for coal-fired electricity plants, linking with large groups of up-stream KSs and weak stakeholders are even more diverse geographical sites. Activity 4 is the supply of transformational inputs including coal (fuels), energy, labour, and capital for electricity production. It needs to be understood that each one of the inputs are associated with complex upstream production processes. Activity 5 is the key initial process during which transformation into electricity occurs. In the same time, by-products, wastes, and CO2 are produced and require additional inputs for sell, distribution, and treatment. The emission of atmospheric CO2 would mark and end of the initial system in sustainability evaluation, but not the end for the apposite system. The emitted CO2 is analysed for necessary quantity of carbon sink in the nature. Activity 6 marks the successful production of electricity, which, for the sustainability evaluation for the electricity production systems, would draw a system boundary at the top level activity. Lastly, activity 7 draws the apposite sub-system for coal-fired electricity production system which mainly links with information processing and later steps of evaluation.

Table 5.2 Initial KSs in activity model of coal-fired electricity production system (thermo).

	Key Activities	**Initial System KSs**
1	Develop the apposite subsystem of coal-fired power plants based on sustainability evaluation objectives	O: Coal-fired power plant owners E: Government, Social groups A,R: Managers, Research team, External researchers R: Coal-fired power plant owners, Managers, Research team

	Key Activities	**Initial System KSs**
2	Investigate the power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: Coal-fired power plant owners, Government E: Coal-fired power plant owners, Local residents, Employees working at coal-fired power plants, Animals at coal-fired power plants, Shareholders and creditors of coal-fired power plants, Internal information management teams A, R: Managers, Research team, External researchers
3	Supply functional modules, materials, labour for maintenance and replacement	O: Coal-fired power plant owners E: Technology suppliers (steam boiler manufacturers, turbine generator manufacturers, cooling manufacturers, regenerator manufacturers, flue gas treatment manufacturers), Construction material suppliers (offices, structures), Government (policy), Land supplier, Owners (capital), Material and module carriers, Technicians A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers
4	Obtain fuels from sources, energy, labour, capital	O: Coal-fired power plant owners E: Domestic coal suppliers, Foreign coal suppliers, Domestic energy supplier, Coal-fired power plant owners and Government, Transportation carriers A,R: Managers, Coal-fired power plant employees AI: Country (labour) AIB: Local residents, Animals at and near coal-fired power plants
5	Operate the power plant to produce electricity	O: Coal-fired power plant owners E: Coal-fired power plant owners, Government (quota) A: Employees, Managers, Coal-fired power plant owners R: Coal-fired power plant owners, Managers, Side product customers, Coal-fired power plant employees, Animals at and near coal-fired power plants, Local residents AI: KSs in 2,3,4, Government (quota) AIB: Carbon storage site residents and animals, Waste disposal site residents and animals

	Key Activities	Initial System KSs
6	Distribute to grid/store electricity	O: Coal-fired power plant owners, Government E: Coal-fired power plants, Government A: Coal-fired power plants R: Customers, Coal-fired power plant owners, Managers, Employees AI: Animals at and near coal-fired power plants AIB: Local residents, Animals at and near coal-fired power plants
7	Form an apposite system of coal-fired electricity production for the sustainability evaluation objectives	O: Coal-fired power plant owners E: Information suppliers in 1-6, Coal-fired power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers

The above process is continuously done for all key activities by dividing down levels of activities until the end activities are irrelevant with carbon emission, the sustainability criteria, or no more stakeholders could be identified, reaching merely non-organic end of the world. The stakeholder connections and levels are presented in Appendix D.2 for respective electricity production subsystems including coal-fired, oil-fired, gas-fired, nuclear, biomass, hydro and tide, wind, solar PV, and geothermal electricity production.

The following additional treatment measures are taken to deal with the complex system structures. For weak stakeholders, by understanding its complexity, this work additionally lists birds and bats, and fishes in the near water bodies as many studies indicate they are one of the most jeopardised weak stakeholders during all forms of electricity production subsystems (Sovacool, 2009). It is found that wind turbines are directly detrimental to birds and bats affecting their usual flight and migration. Solar PV farms brings death to birds by creating ”lake effect” that birds would crush onto the panels (Klugmann-Radziemska, 2014). Wind farms would also influence the local residents creating continuous noise. Besides, fossil fuel power plants and hydro power plants create wider accumulative impacts that would affect a large group and wide range of weak stakeholders. Thermo-power plants cause acid rain, mercury and heavy metal accumulation, and underground water pollution; and hydro power plants building dams require displacement of human residents both on-site and downstream, and affect fish species that migrates, including salmon and trout (Klugmann-Radziemska, 2014, Sovacool, 2009). The influence to weak stakeholders could be further developed as influences from climate change and land cover change would easily influence wide varieties of species, especially for wildlife (Ha-Duong et al., 2016). Also, for technological variances, as each country could be applying different methods and technologies to produce electricity, the transformation technology is being simplified and replaced by the dominant technology in Europe across the studied period. If major technology changes occurred, the latest method is used for SA.

Besides, the tracing network construction for materials that are less in quantity or not critically technologically dependent and the machinery and energy in systems afar from the initial system are artificially eliminated. For example, according to Brown et al. (2012), Ingwersen (2011), Ren et al. (2020), the main materials for building and structure construction for thermo-power plants are cement, steel, iron, glass, and paints, and thus other materials are not considered for its upstream production in this thesis. For the functional modules, only the majority materials in quantity and the critical material to enable module functioning are included. Also, the machineries and energy that are needed for the manufacturing of some modules or, in some cases, the treatment of materials are excluded from the analysis as they would not contribute to the carbon emission or carbon concentration for the initial system. For example, to produce paint, the key carbon emission source is the consumption of energy (Saif et al., 2015); also, the mining process of ores mainly emit CO2 mainly sourcing from energy inputs and transportation. Similarly, some process inputs that require complex, variant, and accumulative sources are not considered or simplified in the process. Transformational inputs of electricity, labour, and capital are simplified by using generalised values on the regional level for Europe. Construction materials that, in reality, source from recycled materials are treated as primary productions, including cement, steel and iron, aluminium, and glass (Blengini, 2009, EuLA, 2022). Metallic and non-organic salt materials in Europe have high proportions being produced from recycling plants (Yellishetty et al., 2011). Lastly, non-organic salt inputs and outputs without carbon elements are regarded as an end of apposite system irrelevant to the sustainability criteria. Such materials would, for example, include some solid wastes and by-products by fly ash, mainly heavy metals, and flue gas, mainly sulphur (Yang et al., 2019) and inputs such as silicon sand and salt brine.

From Appendix D.2, the similarities and variances of the subsystems are clear. Thermo-combustion electricity production systems including coal-fired (Appendix D.2.1), oil-fired (Appendix D.2.2), gas-fired (Appendix D.2.3), and biomass combustion (Appendix D.2.5) share many similar KSs for power plant construction and functional module manufacturing. However, biomass electricity production system features in including stakeholders of growing the biomass materials, being a large carbon sink in the system. For nuclear electricity production system (Appendix D.2.4), the building construction is heavy in carbon concentration and the production of uranium fuels, although mainly consuming non-organic inputs without Carbon, require high energy consumption for electricity and heat. Similarly, solar PV electricity production system (Appendix D.2.8) includes long chain of KSs, both domestic and global, for the manufacturing of PV panels. Geothermal electricity production system (Appendix D.2.9), mainly using flash-steam technology in Europe, includes very different group of KSs from the thermal-combustion power plants although it also emits direct CO2 contained in the steam. Lastly, wind (Appendix D.2.7) and (Appendix D.2.6) electricity production systems, although have similar initial system, vary much in the module manufacturers as the technology requirements are largely different. Especially, hydro electricity production system also includes the KSs, both strong and weak, of the water reservoirs.

In this way, the following section concludes the apposite subsystems, which together form a large apposite system, for the sustainability evaluation from the systems owned by and linked to the above KSs.

5.1.3 The Apposite System: Conceptual Models

Based on Appendix D.2, drawing the system boundaries of the KSs, the apposite system for sustainability evaluation of the electricity production system of European countries is a large complex system containing all the subsystems by different electricity production technologies. It is a system that contains the electricity production system of Europe (initial system) for successful electricity production and nearly enclosing system of direct CO2 emissions in the initial system for carbon emission control. The subsystems by electricity production technologies are presented one by one. To note, in all figures, the orange arrows indicating regional CO2 flux links with the land and water absorption process and the natural formation processes would require accumulative time. In common, for all apposite subsystems, it contains subsystems of resource supply, technology supply, production system, and the distribution and influence system (stergaard et al., 2020). However, for this sustainability evaluation, the system boundary is drawn, on the production end side, once electricity is produced.

Figure 5.11 presents the expanded system for coal-fired electricity production. The network construction reveals natural absorption, CO2 condensed reinjection, and soda ash production as three main carbon sinks. While coal combustion create large quantity of CO2 emission, the current treatment method for CO2 absorption in Europe, mainly by condensing gas CO2 into liquid and pumping back into coal mines, enables zero emission of CO2, neglecting the leakage. Also, industrial consumption of CO2 for soda ash production is also widely applied. An industrial cycle for carbon could be formed while influences to more weak stakeholders in different locations need to be recognised. Also, tracing upwards to understand the cyclic network, cement production consume limestone, clay, mudstone, whose natural formation absorb CO2, and fly ashes from coal combustion (Schneider et al., 2011). The strength of stakeholder connections between coal-fired power plant owners and the cement production plant owners would determine the treat-

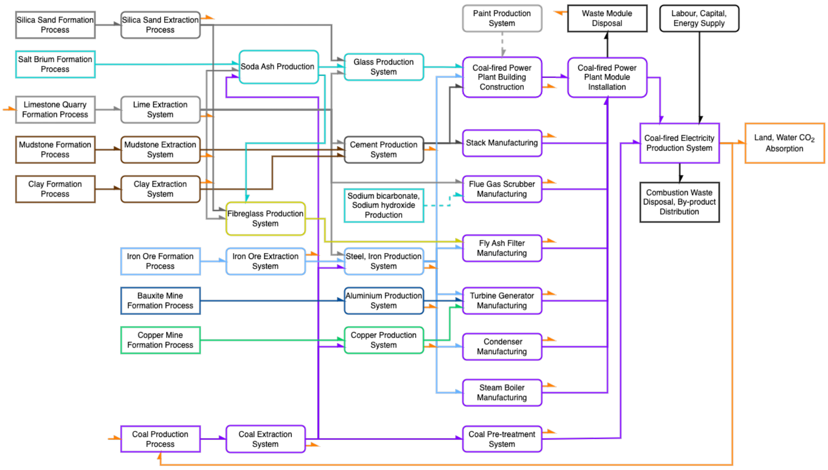


Figure 5.11 Apposite system of coal-fired electricity production system

ment to fly ashes, the non-electricity production of the initial system. Also, it is also clear that the production of some materials, especially metals could be electricity dependent, such as aluminium production, being lower in carbon concentration than fossil-fuel heating dependent metals, such as steel and copper. In this way, the system material and energy basis, structure, and value chain is explicitly presented for coal-fired electricity production.

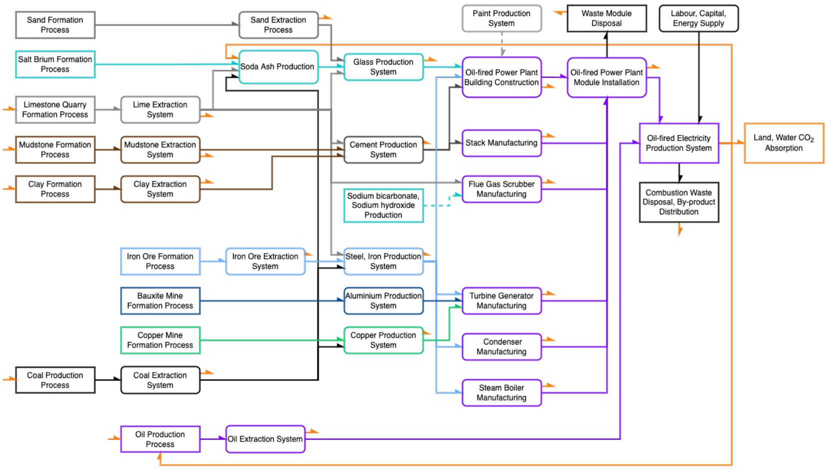


Figure 5.12 Apposite system of oil-fired electricity production system

Figure 5.12 is the expanded system for oil-fired electricity production, in which large varieties of oil products are statistically transformed as crude oil. Carbon sources and sinks are alike coal-fired electricity production system, however, including both sources of coal supply for material production and crude oil supply for electricity production fuel.

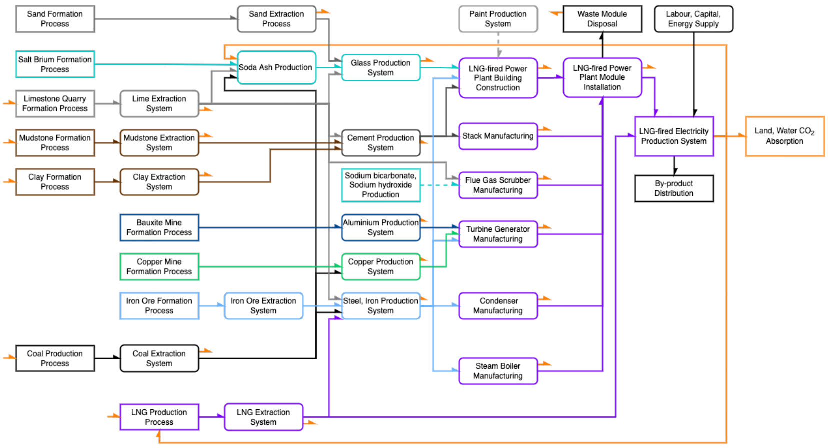


Figure 5.13 Apposite system of gas-fired electricity production system

Figure 5.13 exhibits the developed system for natural gas combustion electricity production. While the carbon sources and sinks are alike coal-fired electricity production, natural gas combustion features in not producing solid nor liquid wastes at the point when it is being burned. In this way, the CO2 produced could be condensed for gas recovery and other gasses could be treated to produce other products. Also, noting the difference with Figure 5.11, as LNG is also used for steel production, it is revealed in this subsystem that LNG production and coal production could be substituted by prioritising the method with lower CO2 emission.

Figure 5.14 is the apposite system for European nuclear electricity production. Due to the complex construction for isolating radioactive cycles and the lack of detailed data, the structure construction and module manufacturing processes are integrated. In this apposite system, olivine formation is being introduced are a new source of fine carbon sink. Aside from the use of carbon intensive materials, the mining and manufacturing of uranium fuels is a process with heavy energy consumption that consume non-carbon products.

Figure 5.15 exhibits the developed system for biomass electricity production. Its initial system a thermo combustion process of biofuels that is alike the processes of fossil fuel electricity production. The linked upstream subsystem for transformational fuels include the production process of biomass and wood fuels, which reproduces biomass and wood fuels much more frequently than fossil fuel sources, being a large carbon sink in the apposite subsystem.

Figure 5.16 is the apposite system of hydro and tide electricity production, mainly presenting the process of large scale processes with water reservoirs such as dams. As running water is required for hydro and tide electricity production,

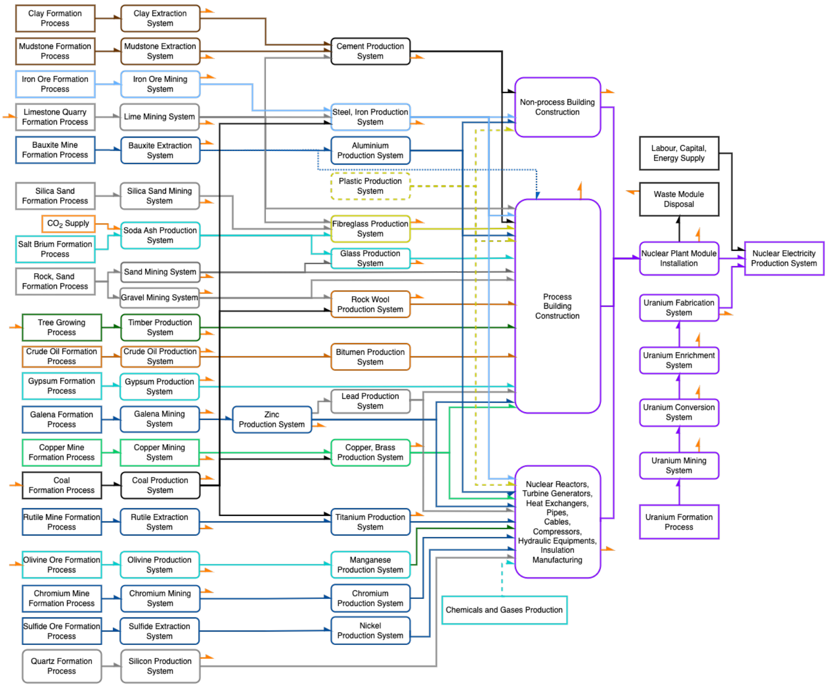


Figure 5.14 Apposite system of nuclear electricity production system

the natural absorption process of CO2 emission that is not presented in the figure would also include wide land use of the water reservoirs.

Figure 5.17 exhibits the developed system for wind electricity production. Similar to hydro, the key subsystems identified are the subsystems for the production of wind turbines. In Europe, wind power mainly include on-shore and off-shore installations for which the main difference are the amount of construction materials used for foundation and the size of the turbines. Generally, off-shore wind has faster wind velocity and electricity is produced with wind turbines with larger blades. Here, the difference in technology is statistically aggregated into on-shore installation.

Figure 5.18 presents the apposite system of solar PV electricity production. Solar PV initial system requires functional structures of PV panels, the mounting system for the panels, and inverters (Ludin et al., 2018). An electrolyser system is widely installed for energy storage, which is eliminated in this evaluation as a downstream production of electricity. As many research have pointed out and analysed (Fouad et al., 2017, Hernndez-Callejo et al., 2019, de Wild-Scholten and Alsema, 2005), different from thermo-combustion electricity production that require complex network for fuel production and supply, solar PV electricity production features in having a complex and high-energy consuming process for the production of solar PV panels, originally made from silicon extracted from quartz

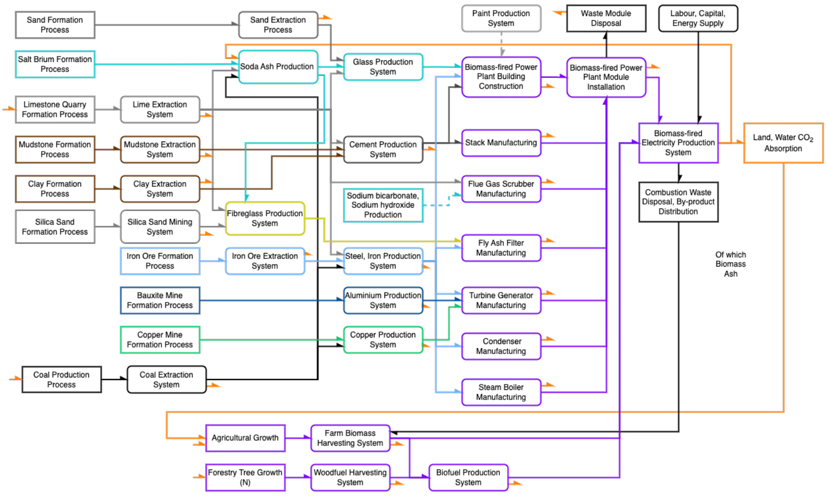


Figure 5.15 Apposite system of biomass electricity production system

mines. To note, for European countries, solar PV panel and wafer demands are fulfilled by trade within the union and imports from China. This has enabled simple and feasible consideration to the influences to weak stakeholders within the upper stream linked subsystems. Consequently, solar PV electricity production system is mainly low-carbon during the operation phase where the subsystems connected by key system functional materials and direct carbon emission are carbon sources in nature and the carbon sinks could be limited in the apposite system.

Lastly, figure 5.19 presents the apposite system for geothermal electricity production. In Europe, the major technology installed for geothermal electricity production is the flash steam cycle where the hot geothermal steam that is used to drive the turbine generator contains gas CO2 and other GHGs. Thus, although being a system of producing electricity as primary energy, unlike other primary production methods, geothermal initial system in Europe is also a source of direct CO2 emission as part of the steam is not condensed and reinjected back underground. Besides, geothermal apposite system concludes great variety of production systems for materials and the installation of geothermal electricity production functional modules, especially wells, would influence weak stakeholders living on site and in the soil, which is not sufficiently presented in the apposite system. Collectively, the primary electricity production technologies including hydro and tide, wind, solar PV, and geothermal require no complex industrial network for fuel supply nor waste distribution.

Noticing that all subsystems share part of the construction materials and feature in the consumption of come materials, the apposite system for sustainability evaluation under the evaluation objectives' scope for European countries would include all apposite systems for all technologies. For any country, the apposite

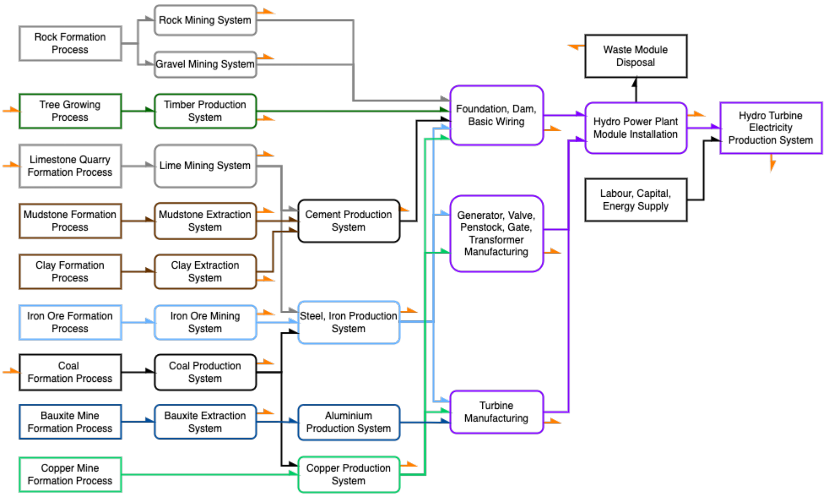


Figure 5.16 Apposite system of hydro and tide electricity production system

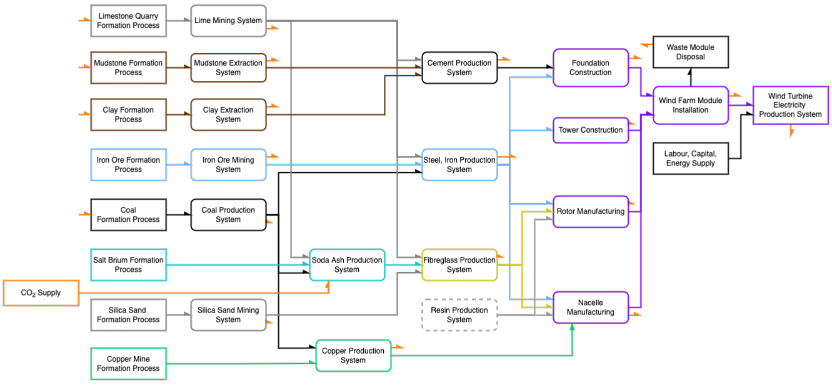


Figure 5.17 Apposite system of wind electricity production system

system could differ according to the electricity production technology profiles as some electricity production technologies could be not available. Also, the other form of energy, heat, is largely neglected in the apposite system as the evaluation objectives focus on the production of electricity. Hence, power plants also producing heat, the CHP power plants (Beccali et al., 2016, Ren et al., 2020), are neglected from the evaluation. Eventually, the large system concluding all apposite subsystems draw the line of the system to be evaluated, the evaluation subject.

5.1.4 Full Evaluation Elements

Contingent to previous sections, some elements of the sustainability evaluation, including the objectives, the initial system, the sustainability criteria, the

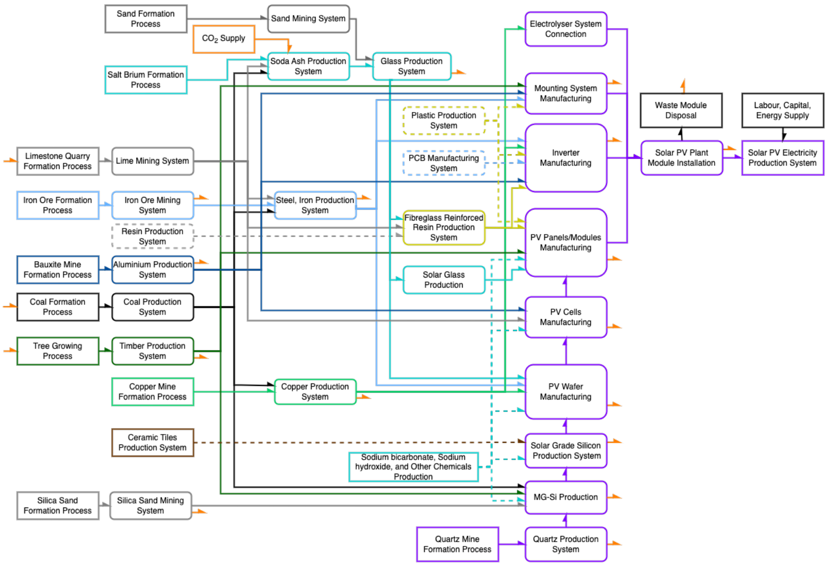


Figure 5.18 Apposite system of solar PV electricity production system

DMs, the KS, and the evaluation subject is explicitly presented. Then input and output data is collected for all subsystems in the apposite system. With the consideration to the evaluation resources, we notice that data availability would eliminate some systems from eventually bing evaluated, especially for most of the weak stakeholders. With the inclusion of weak stakeholders as KSs (Appendix D.2), the rest of the evaluation elements should be able to reflect the stances and interests, compensated by the survival, of the weak stakeholders.

5.2 Apposite System Verification

Following the stakeholder connections and carbon traces of direct CO2 emission, the apposite system formed is a large structure containing ten electricity production pathways and associated production processes for necessary materials and fuels. The categorisations of the subsystems contained include the electricity production system, the initial systems, the manufacturing systems for the construction, transformation, and fuel materials, and the natural formation of the materials and absorption of CO2.

The carbon flow by CO2 emissions is being traced and measured in the apposite system so that it could be verified that this apposite system maintains over the sustainability criteria of carbon, the direct emitted proportion. Table 5.3 presents the carbon fluxes in one year including the yearly emission by power plant operation and the averaged CO2 emission by power plant construction.

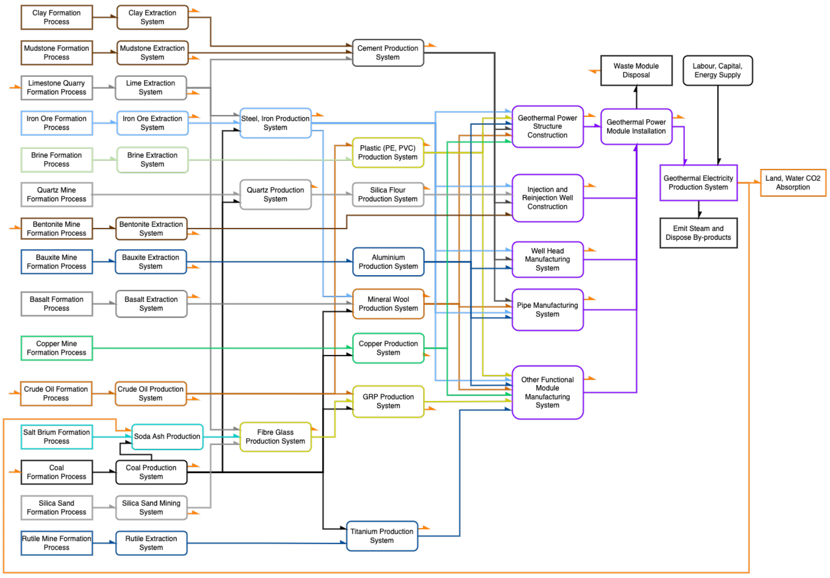


Figure 5.19 Apposite system of geothermal electricity production system

Comparing the carbon sinks formed by land-scape and country land scape, the direct CO2 emitted during electricity production would create increase in atmospheric CO2. The exceeding emission of by energy production activities have massively contributed to the atmospheric increase of CO2 in 2005, taking up 68.8%. This is similar to the proportion in Grassi et al. (2022) and Friedlingstein et al. (2022). It is regarded as a verification to the explanation of the apposite system for the actual electricity production systems. This system is set as the sustainability evaluation reference system. As the carbon emission exceeds the carbon sinks, the developed apposite system should always be wider than the initial system.

Collectively considering the all subsystems in the apposite system, there results a net release of 0.529 PgC of direct CO2 emission into the atmosphere. This proportion of CO2 could only be absorbed for captured from the air. Following the framework, the excessive emission 0.529 PgC of CO2 could be transformed into overall requiring oceanic carbon sink of 5.32E07 km^2, which is capable to be contained by the nearly ocean coverage area in the North hemisphere. This area is distributed to countries requiring the sink, being integrated into entropy S as an input and into Em_{NRES} by subtracting its emergy. For the subsystems in the apposite system, nuclear power production and its related subsystems create the most direct CO2 emissions. Linked subsystems of other production methods also act as carbon source of different levels, relating to the capacity installed, biomass and the linked subsystems presents to be a carbon sink in the apposite system.

Then, we notice during the analysis that there are notable carbon sinks re-

Table 5.3 Carbon flux (in PgC) of 2005 apposite system.

	Carbon Flux (PgC)
Carbon Sinks	
Land Scape Sink	-8.92E-02
Cement Sink	-1.76E-02
Carbon Imbalance	
2005 Atmospheric increase	7.68E-01
Apposite System Release	5.29E-01
Carbon Sources	
Initial System (EU28)	3.52E-01
Apposite Systems	
Coal	2.30E-02
Oil	4.24E-03
LNG	1.94E-02
Nuclear	1.55E+00
Bio	-1.33E+00
Hydro	3.05E-08
Tide	2.69E-09
Wind	2.78E-04
SolarPV	7.52E-03
Geothermal	6.56E-03

vealed in the apposite system. As presented in Table 5.4, in the apposite system, it could be regarded as holding long-term carbon sinks that could be regarded as a background of carbon flux and the short-term carbon sinks serving for more frequent carbon exchanges. Although not considered in the carbon flux balance in Table 5.3, enhancing potential mineral carbon sequestration would significantly contribute towards carbon emission reduction. However, again, when carbon capture and sequestration (CCS) technologies are installed, the subsystems in the apposite system alters and new stakeholder connections and subsystems could be linked.

Overall, it is clarified that the apposite system is a regional system for electricity production of EU28 countries over the sustainability criteria of carbon, in the form of resulting as direct CO2 emission within the region. It requires much wider area serving as carbon sinks in the reference system. This is a necessary condition towards the sustainability of this region, assuming a large carbon sink of surrounding ocean coverage without considering CO2 emissions from activities not related to electricity production.

Table 5.4 Carbon sinks of 2005 apposite system.

Carbon Sinks	PgC
Long - Land Scape	-8.9236E-02
Long - Cement	-1.7636E-02
Long - Ocean (Required)	-5.2868E-01
Short - Biomass growth	-1.3542E+00
Short - Salt Water	-1.5129E-01
Potential - Mineral CCS	
Calcites	-1.0440E+02
Metallic Ores	-1.6914E-03

5.3 Entropy, Emergy Changes

Following the verification to the apposite system, entropy (S), NRES proportion of emergy (Em_{NRES}) input to the apposite system and the value outputs are obtained. Here, it is focused on presenting the entropy and emergy changes, indicating the structural changes and inflow energy properties. Table 5.5 presents the descriptive data for the obtained entropy, the NRES proportion of emergy input to the apposite system.

Table 5.5 Entropy, emergy data descriptives.

	Mean	S.D.	Median	Min	Max	Range
Entropy						
2005	0.19	0.25	0.08	0	1.22	1.22
2015	0.19	0.26	0.12	0	1.32	1.31
2016	0.18	0.24	0.1	0	1.19	1.19
2017	0.19	0.26	0.1	0	1.31	1.31
2018	0.21	0.28	0.14	0	1.44	1.43
2019	0.21	0.28	0.17	0	1.42	1.42
NRES Emergy (seJ)						
2005	3.55E+31	1.31E+32	7.87E+25	1.18E+18	5.15E+32	5.15E+32
2015	4.34E+31	1.55E+32	3.72E+26	5.49E+23	6.29E+32	6.29E+32
2016	4.36E+31	1.55E+32	7.27E+27	1.04E+25	6.32E+32	6.32E+32
2017	3.69E+32	1.02E+33	7.43E+31	2.11E+25	5.35E+33	5.35E+33
2018	4.46E+31	1.57E+32	7.48E+26	1.34E+24	6.46E+32	6.46E+32
2019	4.48E+31	1.58E+32	8.00E+26	1.72E+24	6.50E+32	6.50E+32

Over entropy changes, noting that the entropy in all years are positive, it is confirmed that the overall apposite system is in a state of entropy increase, creating disorder to the external environment. There is a lower level of entropy in 2016, which means more steady production and maintenance of the electricity production system is reached. For the input of NRES emergy inputs, on the one hand, all years are higher than the 2005 level; on the other hand, it suggests that the consumption of NRES materials, not only contained to fossil fuels for electricity production is increasing.

To look into the aspect of structural change and NRES consumption, entropy and emergy gap with the 2005 reference system level is respectively analysed. Fig. 5.20 presents the yearly gap with 2005 system entropy for each country. While many countries including Belgium, Cyprus, Czech Republic, Estonia, Ireland, Lithuania, and Luxembourg, etc. are at a state of maintaining the current system status, some countries have gone through large structural changes in their electricity production systems, including Germany, Netherlands, Spain, and UK. However, having more complex system composition suggests that either the quantity of electricity production has greatly increased, or, since the reference system is developed for all countries, it means that the subsystems, mainly the production lines related to electricity production system have overall become more independent, serving for better energy security.

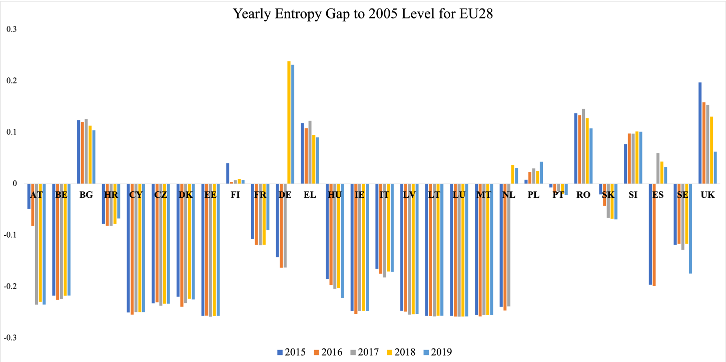


Figure 5.20 Entropy gap with 2005 level from 2015 to 2019 for EU28.

From the perspective of emergy inputs, 2017 is associated with very high emergy input, especially those non-renewable. In association with Fig. 5.20, 2017 is also the year that for many countries, entropy of the system arose. Especially for UK, large emergy input into the apposite system is associated with significant structural changes.

Based on the apposite system in which carbon is sustained for 2005, the sustainability evaluation preferences for the measurements are clear:

Entropy In this sustainability evaluation, entropy should be minimised. When it is lower than the 2005 level, the electricity production system of the country

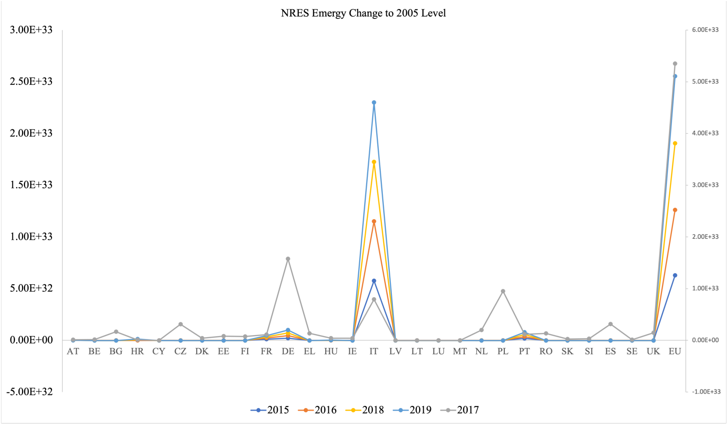


Figure 5.21NRES Emergy gap with 2005 level from 2015 to 2019 for EU28.

could become more stabilised, which means both carbon sources and carbon sinks are clear and guaranteed.

Emergy In this sustainability evaluation, since emergy is measured using the NRES sources, it should be the less the better as it means non-cyclic use of materials and it may hold synergetic influences with entropy.

5.4 Country Peer Performance

Peer performance evaluation is done for EU28 using the DEA model under different objectives. As previously introduced, considering singular measurements and attaching value pursuits from different perspectives would alter the implementations. Table 5.6 presents the rankings of EU28 in 2018 under different measurements.

From overall rankings, Latvia is highly evaluated in all scenarios. Structural changes would highly influence its sustainability. The dependence on singular technology and required materials for electricity production is high. Besides, as noticed previously from the changes in entropy and emergy, without considering value dimension, the countries with large NRESs, being not renewable on the time scale of Earth reproduction, and significant changes in production structures of any subsystems are significantly penalised as being unsustainable for the apposite system. For example, Spain, Italy, Germany, and France. This issue needs to be viewed together with the installed capacity of electricity production technologies (Fig. 5.22).

Spain, Italy, Germany, and France share the similarity that the production profile is quite even, including all technological pathways. However, Spain is ranked

Table 5.6EU28 rankings in 2018

	Entropy	Emergy	V1		V2		V3	
	Ranking	Ranking	Score	Ranking		Ranking		Ranking
Austria	9	22	0.539	8	0.895	9	0.012	24
Belgium	11	18	0.433	9	0.892	10	0.020	17
Bulgaria	25	13	0.046	25	0.886	19	0.024	14
Croatia	16	24	0.018	29	0.886	15	0.000	29
Cyprus	6	5	0.129	19	0.916	8	0.032	12
Czech Republic	8	16	0.792	5	0.100	27	1.000	1
Denmark	10	12	0.213	16	0.127	26	0.187	8
Estonia	2	3	1.000	1	0.982	4	0.274	7
Finland	19	10	0.112	20	0.886	16	0.075	9
France	14	25	1.000	1	0.887	12	0.023	16
Germany	28	27	0.315	10	0.885	23	0.007	26
Greece	23	15	0.045	26	0.886	21	0.015	22
Hungary	12	23	0.135	18	0.048	29	1.000	1
Ireland	7	2	1.000	1	0.918	7	0.677	5
Italy	13	28	0.783	6	0.888	11	0.018	19
Latvia	5	1	1.000	1	1.000	1	1.000	1
Lithuania	3	4	0.231	14	0.966	5	0.034	11
Luxembourg	1	6	0.203	17	1.000	1	0.016	21
Malta	4	7	0.091	22	0.942	6	0.012	25
Netherlands	21	17	0.104	21	0.886	18	0.019	18
Poland	20	9	0.274	12	0.209	25	0.824	4
Portugal	18	26	0.060	23	0.886	17	0.001	27
Romania	26	21	0.041	27	0.886	22	0.001	28
Slovakia	17	11	0.049	24	0.887	14	0.024	15
Slovenia	24	8	0.034	28	0.887	13	0.031	13
Spain	22	19	0.239	13	0.886	20	0.036	10
Sweden	15	14	0.309	11	0.089	28	0.634	6
United Kingdom	27	20	0.217	15	1.000	1	0.018	20
EU28	29	29	0.557	7	0.885	23	0.013	23

higher among the four countries could be mainly because the less proportion of nuclear production compared with France and Germany, and higher proportion of biomass combustion power plants and wind farms than solar PV power farms. Among the apposite system, it is producing electricity with higher proportions that could produce CO2 emissions self-contained within the system. It it noticed that countries with higher proportion of nuclear and solar PV installations, which are complex in production material and fabrication of fuels and machineries, are generally ranked lower.

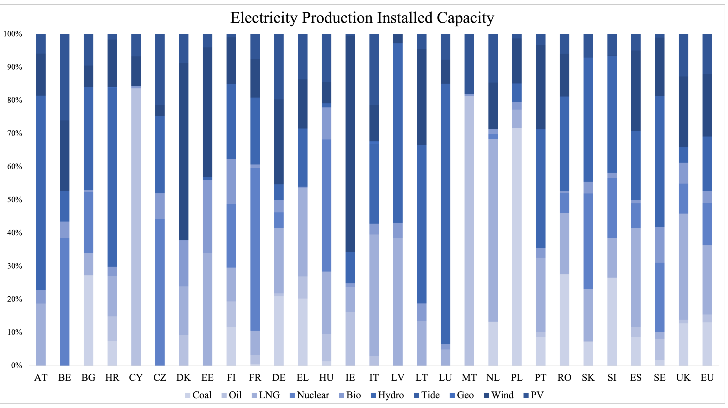


Figure 5.22 Installed electricity production capacity in 2018 for EU28.

Then, observing for different value objectives given, the second case $V2$, ranking Luxembourg, Austria, Estonia higher, presents results similar to many studies (Zurano-Cervello et al., 2018, Lovering et al., 2022). These countries are alike by sharing high proportion of hydroelectricity capacity installed. Referring back to Table 6.1, hydro power production plants is also one of the smallest carbon sources that is widely installed. Again, the preferences of the apposite system is clear, structures and processes that contribute less to the increase of atmospheric CO2. Thus, power production technologies that are highly consuming materials that are not reproducible and require complex materials, such as solar PV power production and geothermal power production is not so sustainable, at least considering direct CO2 emissions.

Lastly, considering different objectives by value, the implementations would be able to suit for different DMs. Case $V1$ could be regarded as an industrial appraisal as producing more electricity. Under such objectives, countries with low non-renewable material consumption, like Latvia and Ireland, steady production structure, like Estonia, and with rather high quantity of electricity production, especially France, is highly appraised. In case $V2$, where lower electricity price is preferred, countries with high electricity prices such as Hungary is ranked significantly lower. In case $V3$, in which it could be regarded as the economic value created by electricity, presents to be compound of both.

5.5 Index Model Comparison

First of all, Model 1 is applied with the indexes. For EEV measurements, entropy and emergy are treated as undesirable inputs that should be reduced. For indexes using HDI, GDP, electricity production, and CO2 emission, CO2 emission is treated as the undesirable output. In general, as some indicators are low in variance, there are countries that are ranked together for the first, which cannot be judged.

More interestingly, the two groups of measurement seem to reveal different aspects of electricity systems. Fig. 5.23 presents a comparison of rankings for the countries in the year of 2018.

The rankings are hardly negotiated except for Czech Republic, Estonia, and Spain. This reveals the unsuitability of applying TBL indicators directly to the initial system. For countries including Austria, Greece, Slovenia, and Sweden, the judgement by two groups of measurements are almost completely opposite. Here, as the ranking by $V1$ is partially obey most judgements for the European countries and their energy objectives (IEA, 2020*c*), it reveals the problem of directly using indicators of TBL pillars without considering the suitability with the evaluation subject. HDI and GDP are very large scaled indicators that cannot be only influenced by the energy system. For example, in 2018, Greece has been penalised by the transformational indicators due to lower performance in economy. However, by EEV index, it reveals that although economic aspects, including the outcomes and influences could be problematic, the energy production system constructed and maintained in the year is appraised. This is the structural aspect that cannot be revealed by other measurements.

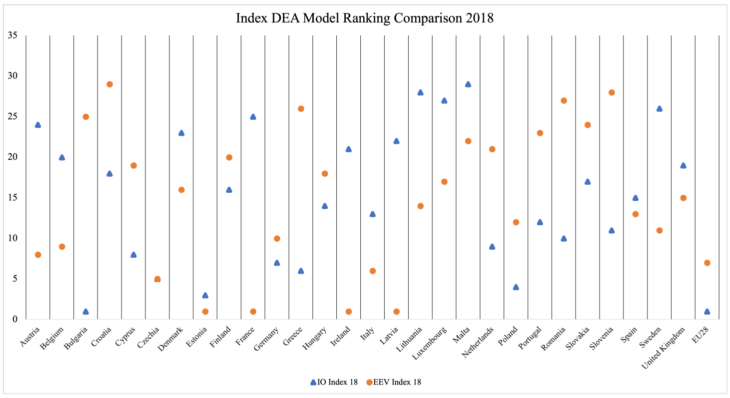


Figure 5.23 Efficiency score comparison by rankings in 2018

5.6 Transformation

To further look in to the relation of EEV measurements with the transformational structure, EEV indicators are regarded possible outcomes of system inputs in Fig. 4.1, and in another scenario, it is regarded as sufficient inputs to produce the larger scale influences. Table 5.7 presents the results of rankings in 2018 of input oriented DEA CRS (Model 2) and VRS (Model 3) models.

Table 5.7 Transformational model (Model 2, 3) comparison in 2018

2018	**I-O Model 2**		**I-O Model 3**		**I-E Model 2**		**I-E Model 3**		**E-O Model 2**		**E-O Model 3**	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
AT	0.43	4	0.48	15	1.00	1	1.00	1	0.13	9	0.15	21
BE	0.33	7	1.00	1	1.00	1	1.00	1	0.10	14	0.60	16
BG	0.02	25	0.02	28	0.62	26	0.80	24	0.06	17	0.07	24
HR	0.22	8	0.22	19	0.60	27	0.69	26	0.15	7	0.16	20
CY	0.53	3	0.55	13	1.00	1	1.00	1	0.00	25	0.72	14
CZ	0.03	20	0.03	24	1.00	1	1.00	1	0.12	10	0.13	22
DK	0.09	14	1.00	1	0.77	20	0.92	22	0.11	12	1.00	1
EE	0.14	10	0.14	21	1.00	1	1.00	1	1.00	1	1.00	1
FI	0.07	18	0.77	12	1.00	1	1.00	1	0.00	25	0.51	17
FR	0.10	12	1.00	1	1.00	1	1.00	1	0.12	11	1.00	1
DE	0.08	16	1.00	1	0.71	23	1.00	1	0.05	19	1.00	1
EL	0.02	24	0.03	26	0.67	25	0.91	23	0.04	21	0.04	26
HU	0.05	19	0.05	23	0.25	29	0.26	28	0.06	18	0.07	25
IE	0.07	17	1.00	1	1.00	1	1.00	1	1.00	1	1.00	1
IT	0.02	27	1.00	1	1.00	1	1.00	1	0.14	8	1.00	1
LV	0.40	5	0.40	17	1.00	1	1.00	1	1.00	1	1.00	1
LT	0.37	6	0.38	18	0.79	19	0.00	29	1.00	1	1.00	1
LU	1.00	1	1.00	1	1.00	1	1.00	1	1.00	1	1.00	1
MT	1.00	1	1.00	1	1.00	1	1.00	1	1.00	1	1.00	1
NL	0.03	22	0.49	14	1.00	1	1.00	1	0.00	25	0.29	19
PL	0.02	23	0.02	27	0.68	24	1.00	1	0.11	13	0.11	23
PT	0.03	21	0.03	25	0.73	22	0.73	25	0.03	23	0.03	27
RO	0.01	29	0.01	29	0.26	28	0.59	27	0.03	24	0.03	28
SK	0.16	9	0.16	20	0.89	16	1.00	1	0.00	25	0.00	29
SI	0.10	13	0.10	22	0.91	15	0.93	21	0.00	25	0.29	18
ES	0.02	26	0.47	16	0.79	17	1.00	1	0.03	22	0.68	15
SE	0.08	15	1.00	1	1.00	1	1.00	1	0.08	16	1.00	1
UK	0.11	11	1.00	1	0.75	21	1.00	1	0.04	20	1.00	1
EU	0.02	28	1.00	1	0.79	18	1.00	1	0.08	15	1.00	1

Collectively, and apparently, VRS models present less variance. However, it covers more countries with less production profile such as Latvia, Lithuania. More importantly, closer linkage with the initial system or the apposite system, the more stabilised DEA rankings could be gained. Again, it notes the importance of suiting the indicators with the evaluation subject. The rankings by I-E and E-O models are alike compared with I-E models. Interestingly, Model 2 of I-E model has already suggested many efficient DMUs. This could be caused by the selection of inputs, where in I-O inputs, fuels are limited to fossil fuel, biomass, and Uranium fuels. For countries such as France, Germany, and Italy, that contain mass variety of electricity production technologies, the installation of technologies that would not require direct fuel inputs, such as solar PV, and wind power would be highly prioritised. Thus, it reveals that to apply EEV measurements, it could be unsuitable for only considering process outputs. It should be applied to at least contain I-O transformation relations, or in other words, the relations that could mutually balance. This trend, as Fig. 5.24 presents, could be observe for all yearly rankings including 2005, and 2015 to 2019.

The above trend, as Fig. 5.24 presents, could be observe for all yearly rankings including 2005, and 2015 to 2019. The clustering of rankings by models are apparent in I-O transformation relations. EEV measures could produce better yearly variances for one DMU.

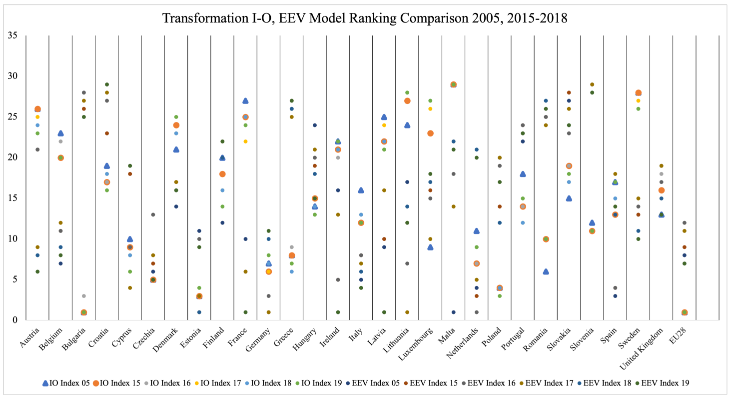


Figure 5.24 Ranking comparison by input output models

Chapter 6

Discussions and Analysis

6.1 Introduction

In this chapter, analysis based on results in Chapter 5 is presented for the indications towards the roadmap. Key discussed issues focus on the practicability of the proposed roadmap for sustainability evaluation. The practice of the evaluation framework for sustainability is reflected as the analysis for MSV metrics and EEV measurements.

6.2 From the Reference System

Section 5.2 presents a carbon-sustainable reference system for electricity production for the 2005 level. This means, this study has assumed that 2005 level status-quo is a sustainable state over carbon criteria. However, noticing that even for the 2005 level, additional area of ocean is required for atmospheric carbon emissions to sustain, it suggests for sustainability evaluations done during 2005 or setting 2005 level as sustainability evaluation objectives for the same subject would not produce systemically carbon sustainable results unless the ocean carbon sink and its related impacts are being fully analysed. It further suggest, even the 2005 scenario for carbon emissions is not reaching sustainability. More importantly, in the selection of sustainability criteria, it suggests to be a cross-systems quantity or a group of related quantities. The boundary of the reference system is mainly drawn by subsystems where CO2 emission are indirect.

6.2.1 Critical Emission Stages by Technology

The collective CO2 emission of series of subsystems could be caused by different aspects. To understand the critical carbon sources in each production technology subsystems, Fig. 6.1 presents the contributions of CO2 emissions by category.

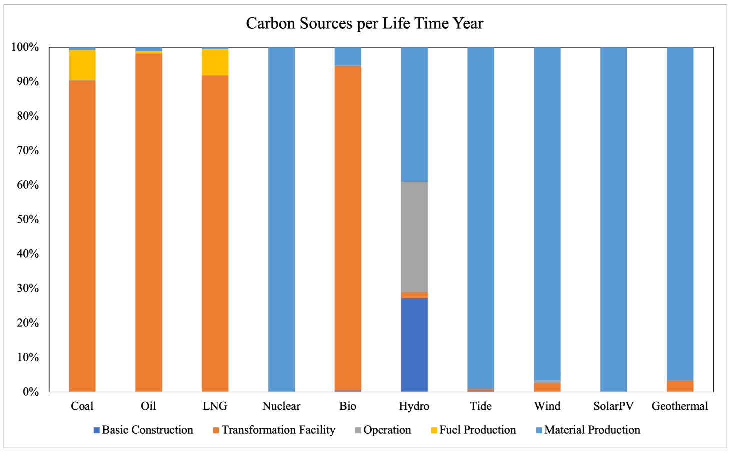


Figure 6.1 Carbon sources in apposite system by proportion per life time.

Basic construction is the construction for structures of the power plants. Transformation facilities include the machineries and technological structures. Fuel production is full process forming the fuel that could be used at plant. They are 0 for renewable energy sources. Material production is the complete inventory for producing necessary materials that compose the structures and machineries of the power plant.

It shows, power plants of combustion technologies heavily emit CO2 during the production of transformation facilities including the turbines and stacks. It suggests that direct CO2 emission, in its quantities and by proportions to other subsystems, is too intensive. Current global trend to substitute thermal electricity production facilities would contribute to sustainability.

Other technologies mainly emit in material production, what is widely called the indirect emissions. However, it explains that for biomass combustion plants, the CO2 absorbed during crop or tree growing would exceed all emission sources, which eventually presents it as a carbon sink. To note, this would only justify biomass as a good material that both absorbs and emits CO2. The challenge for transforming biomass for electricity is the concentration of regional CO2 emission.

Noting that, perhaps due to the great variances and wide installation of power plant scales, hydro power plants, comparing with tidal power plants, are much higher in the proportion of CO2 emission caused by the operation of water turbines. Since the technology profile of hydro power is unified by medium-large facilities with large storage dams, establishment of hydro power in the smaller scale with less concrete consumption would be encouraged.

6.2.2 External Emissions

The reference system is constructed for the EU28 region. However, large amount of materials are imported from other regions and countries. Fig. 6.2 presents the amount of direct CO2 emission outside the apposite system by country and technology differences associating with such production subsystems.

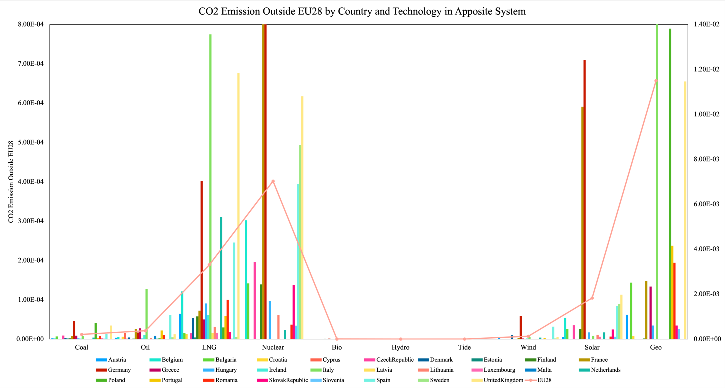


Figure 6.2CO2 emitted externally from EU28 regions.

The emitted marks are respectively, emission in nuclear power production subsystem by France and Germany, up to 3.29E-03 PgC, and 1.06E-03 PgC, and the emission in geothermal power production subsystem by Italy, up to 9.03E-03 PgC.

As presented, natural gas-fired power, nuclear power, solar PV, and geothermal power production technologies depend on heavy imports. When the sustainability evaluation results indicate that these production methods are better others, the regional emission caused far away should be recognised as a limitation of the technology. For products for PV modules, EU28 highly depends on China and Asian pacific countries for production (Frischknecht et al., 2015). External requirements of carbon sinks could be higher. To strictly sourcing the materials, the global supply network might be needed. However, more importantly, it also suggest that in energy security considering the creation of electricity capacity, for EU, LNG, nuclear, solar PV, and geothermal power are relatively low.

6.3 Evaluating System Measurements

Section 5.5 and 5.6 have presented the comparison of indication to electricity consumption end. Although both the I-O measurements and the EEV measurements become lacking capability of explanation, I-O model results are less capable to be explained for its internal structures of leading to the output measurements. Any large number in the output measurements would be exemplified. Here, EEV measurements presented more stable changes in the country rankings. Besides, yearly comparison of EEV measurement rankings indicate better evaluation outcomes for energy security. The countries with significant changes in energy structure transition are revealed.

6.3.1 Preferences of MSV Metrics

To understand the indication quality of the metrics and measurements, Table 6.1 exhibits the country peer rankings in 2018 Section 5.3 and 5.4 with two other sustainability evaluation studies for 2018 for EU28 countries. Tutak et al. (2021) conducted the evaluation using more inputs under TBL framework using entropy weights and complex proportional assessment method. Liu et al. (2021) applied DEA with energy systems data from EIA.

A1 presented higher similarity with rankings by entropy or V1, both considering entropy aspects and using electricity price as the key output index. A2 is more similar to V2, where the quantity of electricity production is included. However, for both Sweden is ranked high, where it is being ranked towards much lower positions by EEV measurements, except V3. As shown in Fig. 5.22, Sweden has relatively large proportion of geothermal installation. We thus understand, according to Fig. 6.2, the past sustainability evaluation has not considered the external emissions of geothermal electricity production subsystem. EEV measurements has penalised Sweden for its distant CO2 emission within the reference system. As for France, both are ranked high by V1 and A1, where looking into its installed capacities and external CO2 emissions, France is rather even in its production profiles. Although it is heavy external emissions caused by nuclear power, its high proportion of wind and biomass has reasonably relieved the emission concentration. Similar explanation can be done for comparing rankings between A2 and V2 for Italy and Hungary. Additionally, the ranking by Siksnelyte and Zavadskas (2019) of multiple year average sustainability evaluation presented similarity with V1.

6.3.2 Explaining Implicit Evaluation Elements

In the practice of the roadmap, the conceptually attained issues in sustainability evaluation became explicit and more explainable. This empirical study finds the advantages of the proposed evaluation framework that:

1. The reference system is specific and thus comparisons made are able to refer back in time and space for the measurements and indicators.

Table 6.1EU28 rankings (with Tutak et al. (2021)(A1) and Liu et al. (2021)(A2)) in 2018

2018	**Entropy**	**Emergy**	**V1**	**V2**	**V3**	**A1**	**A2**
Austria	9	22	8	9	24	4	7
Belgium	11	18	9	10	17	19	9
Bulgaria	25	13	25	19	14	26	12
Croatia	16	24	29	15	29	5	14
Cyprus	6	5	19	8	12	27	
Czechia	8	16	5	27	1	22	
Denmark	10	12	16	26	8	2	11
Estonia	2	3	1	4	7	24	
Finland	19	10	20	16	9	10	10
France	14	25	1	12	16	3	5
Germany	28	27	10	23	26	17	1
Greece	23	15	26	21	22	20	
Hungary	12	23	18	29	1	13	1
Ireland	7	2	1	7	5	15	
Italy	13	28	6	11	19	14	1
Latvia	5	1	1	1	1	11	
Lithuania	3	4	14	5	11	18	
Luxembourg	1	6	17	1	21	21	
Malta	4	7	22	6	25	25	8
Netherlands	21	17	21	18	18	8	
Poland	20	9	12	25	4	23	6
Portugal	18	26	23	17	27	12	
Romania	26	21	27	22	28	6	
Slovakia	17	11	24	14	15	9	
Slovenia	24	8	28	13	13	16	
Spain	22	19	13	20	10	7	
Sweden	15	14	11	28	6	1	1
United Kingdom	27	20	15	1	20		
EU28	29	29	7	23	23		

2. As the 2005 baseline objective for carbon emission is clearly embedded, the evaluation preferences over the sustainability criteria is explicit. In the case of this case study, the preferences are found to be clear for the whole apposite system.

3. As all evaluation elements are developed explicit, the contributions by human stakeholders and structural influences by weak stakeholders are integrated into structural and emergy measurements.

Chapter 7

Conclusions and Future Research

7.1 Research Overview

Overall this thesis constructs an roadmap for sustainability evaluation that could develop explicit and specific fundamental evaluation elements, which is found to induce principle issues in sustainability evaluation. It follows the process of identifying and confirming structural issues from the evaluation perspective and then understanding and attempting the issues from sustainability and sustainability evaluation perspective.

Chapter 2 critically reviewed for evaluation, sustainability, and sustainability evaluation. Definitions for evaluation, sustainability, and performance that is applied in this thesis are formed. A basic group of evaluation elements are used as the proxy of evaluation theories in later chapters. Stakeholder perspectives and sustainability attribute are found critical to developing sustainability evaluation systems. A critical review of 21 articles for sustainability evaluation is reviewed to form an overall idea of analysis done for the evaluation elements in current sustainability studies. It is found that elements such as the evaluation subject and stakeholders are seldom analysed with the sustainability evaluation objectives. This has lead to the use of unsuitable sustainability evaluation objectives for the evaluation subject. This issue is further confirmed by the systemic review to 108 articles of sustainability evaluation empirical studies. Further, it is confirmed that stakeholder stances in sustainability evaluation shifts, and the fact that sustainability, the concept is poorly defined for evaluation, especially being implicit over the sustainability attribute lead to producing unsuitable evaluation results. The idea that the system boundary should be suitable for the evaluation objectives and explicit for only a group of necessary conditions of sustainability of the Earth is presented.

Chapter 3 presents key analysis to constructing the roadmap for sustainability evaluation, based on the evaluation elements. By understanding the sustainability evaluation process using SSM and 3E measurements, we identify that the evaluation subject, its system boundary, could be developed explicit by following certain baseline over the sustainability criteria. Notably, stakeholder connections is identified as one possible baselines to be traced. In this way, we propose a framework and a protocol for developing explicit evaluation elements, disclosing the sustainability potential of the reference system, forming into an apposite system for the sustainability evaluation objectives that could be demonstrated with the MSV metrics. It deals with the issue that current metrics of sustainability, especially the TBL pillars, are clear to be only suitable for global systems. For system metrics, the MSV metric is proposed to consider dimensions of material and energy flux, structure and order, and values. Further, the value changes and stakeholder engagement within the apposite system is included by forming the network of subsystems. Then, suitable measurements for the MSV metrics that could be identified in general systems is proposed as a group of measurements, the EEV measurements. Each matching with one dimension, entropy measures the structure, emergy and material properties together reflect the material and energy flux, and value stands independently as one dimension. It explains that current sustainability evaluation are mainly human central because of the limitation in identifying an universal valuation system that suit for all species.

Chapter 4, Chapter 5, and Chapter6 presents the methodology, methods, data, results, and discussion and analysis for real case studies to practice the proposed evaluation framework for sustainability, and mainly, using the measurements. More practical implementations are produced from the process by understanding that the evaluation framework could develop the conceptual apposite system to be sustainable and the properties of the apposite system meets common sense. Also, explicit evaluation elements are developed, especially forming the clear boundary of the evaluation subject and the preferences for decision-making. In the electricity production systems, it revealed that production technologies of nuclear and solar PV may not be preferably better than fossil fuel combustion transformations. Also, preferable carbon sinks are identified for EU countries for internal development for CCS technologies. However, it is also found that the practice of the framework would associate with vast information crossing multiple disciplines that any improvement for the accuracy of estimation could improve the results.

7.2 Meeting Research Objectives

Overall, this thesis meets the research objectives of constructing a roadmap to sustainability evaluation that by developing other evaluation elements with sustainability evaluation objectives, the sustainable relations and the reference system used for evaluation become explicit.

In detail, evaluation theories are comcluded into a group of fundamental evaluation elements. Then, it is confirmed that some evaluation elements, including the evaluation objectives, the DMs, the KSs, evaluation subject, and resources are often implicit in past sustainability evaluation. As human values guide sustainability evaluation objectives, a roadmap that conceptually enables developing explicit evaluation elements is constructed and proposed as a protocol. Associated with a framework of system sustainability, a group of suitable metrics and associated measurements, testing the roadmap using EU electricity systems has suggested clear advantages and challenges for the roadmap.

7.3 Key Findings

The key findings of this thesis are:

1. The cause, from evaluation perspective, that sustainability evaluation implementations could become unsustainable is mainly containing implicit evaluation elements. The implicit elements are often a demonstration to sustainability definition taken in the evaluation and the restrictions.

2. A reference system that has explicit system boundary and has the potential to reach sustainability evaluation objectives could be developed. It is the reference system that would produce sustainability implementations with regional and time restrictions.

3. Preferences over the sustainability criteria could be developed explicit by the reference system. Strong and weak stakeholders mainly influences sustainability by values and resources.

7.4 Novelty of the Research

The contributions of this thesis follows the research questions, focused on the proposal of a roadmap for sustainability evaluation and verification to the roadmap and the applicable measurements.

Firstly, by conducting thorough reviews respectively for evaluation, an academic article for evaluation elements is in preparation. Based on reviews on sustainability, and sustainability evaluation, an academic article of the systematic review for sustainability evaluation studies in the energy sector is in preparation based on Chapter 2.

Then by concluding the roadmap with an evaluation framework, the proposal of the metrics and construction of the measurements, associated with the testing of the road map and the metrics and measurement, an academic article for the roadmap and the indicators is in preparation, based on Chapter 3, 4,5,6.

7.5 Research Implications

For theoretical aspects, this research has revealed current issues in sustainability evaluation. It explained the unsusainability of some actions taken that are not from the perspective of sustainability, but from evaluation, where the theoretical ground is more solid and issues become more attainable. Most importantly, this research constructs a new roadmap to sustainability evaluation that would eventually create sustainability evaluation results that are more explicit and explainable.

For empirical aspects, an evaluation framework for sustainability is proposed with metrics and measurements. Adopting the measurements with evalaution objectives forms more applicable sustainability evaluation indicators. More critically, the case study has constructed a reference system for EU28 electricity production system that could be applied to other sustainability evalaution with the same subject or amended to suit sustainability objectives not for the 2005 level.

7.6 Research Limitations

The limitations and challenges of the research include:

1. The cognition to stakeholder connections or other baselines to be used to analyse the network of subsystems directly influence the construction of the system. A suitability analysis may be needed to judge the inclusion of subsystems.

2. The selection of sustainability criteria directly influences the reference system construction

3. Recognising the coverage of subsystems, the apposite system and its quantified measurement require accurate measurement or estimation from vast fields of study.

4. As the apposite system would always presented large, massive quantity of information and data is required.

7.7 Future Recommendations

Being an evaluation framework suitable for evaluation purposes, we recognise that sustainability evaluation is done for a group of necessary conditions of sustainability and it is, under current technological development and formation of the valuation system, is very hard to identify the sufficient conditions. Thus, the necessary conditions could be further integrated into environmental management or sustainability management accounts, which could be bridged with performance evaluation outlines with the upper management strategies.

It could be perceived that strategic integration into sustainability could be done under the guide of performance management, although the key challenge lies in the value judgement for management strategies.

The twining of performance evaluation with performance management can be explained that initially understanding the system to evaluate and the formation of the management strategies are the pre-stages to be done(Lebas, 1995). This means that before evaluating, the operation of a system and the purposes of actions taken are already acquainted with some cognition. Very often, this is achieved following some performance management frameworks within an organisation such as the balanced scored card and logic maps. It then forms a structure that the purposes would stand on the apex of object, related actions, and evaluation, where under such construction the aim of evaluation is to know to what extent these purposes have been achieved(Tyler, 1950). Eventually, the system that is measured and what is evaluated are developed on the basis of such cognition (Fig. 7.1).

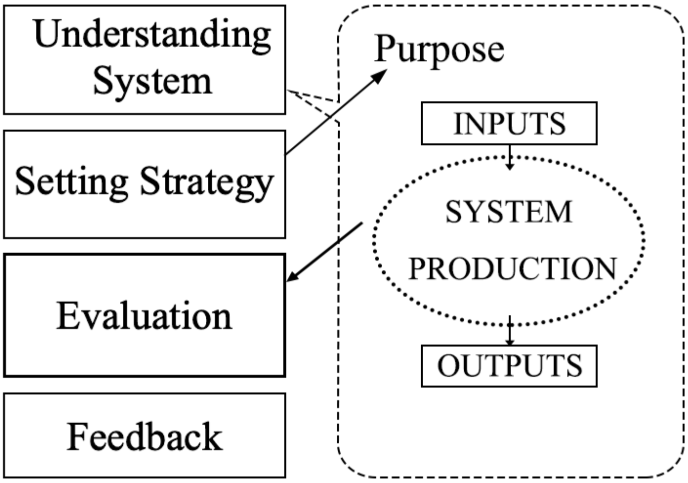


Figure 7.1 Process of performance management and relationship with evaluation. Partly adapted from Lebas (1995), Tyler (1950)

Some features of evaluation attempts can be concluded that(Guba and Lincoln, 1981, p.2): 1) evaluation oriented with the target to standardize and the objective was set with close reference to norms; 2) evaluation never appears individually as it conjoins with measurement; and 3) evaluation paradigm is tied to scientific paradigm of inquiry. As concluded by Elwyn and Miron-Shatz (2010), while performance management often provides purposes of evaluation and the performance measurement system, the selection of the metrics doesn't have much reference to evaluation preferences(Elwyn and Miron-Shatz, 2010), where this preference can be different from that directly derived from management strategies(Chang and Hanna, 2004, Mackenzie, 2005, Rynes et al., 2005, Cherny and Madan, 2008). Such gap became even hard to fulfil as the present performance management frameworks and strategies extends from monitoring to benchmarking domain, suggesting more inclusion of measurements in evaluation for observation purposes(Ermolayev and Matzke, 2007). Brining this gap to sustainability evaluation and environmental management, the trace of stakeholder values could provide explicit reference system not only for the evaluation objectives, but also for the individual values that influences the management strategies. These values may come from strong and weak stakeholders.

Under the performance management perspective, according to Aguinis (2009, p.37-58), the management objectives that guides the performance evaluation is proposed prior to evaluation. Evaluation is the performance assessment phase of performance evaluation that monitors the initial system of the evaluation interest (Sala et al., 2015). Thus, leading the study one step upwards, the origin of the sustainability evaluation objectives could be better studied with strategies to be implied. Eventually, it could form a more compound loop between proposing the objectives and creating the feedbacks (Bititci et al., 1997).

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Appendix A

List of Forms of Evaluation

Table A.1 The List of Comparative Forms of Evaluation

List of Comparative Forms of Evaluation		**Proposed Research**
Explicit	Implicit	Scriven (1996) Gawronski and Bodenhausen (2014)
Formative	Summative	Scriven (1996)
Outcome improvement	Outcome assessment	Chen (1996)
Post event	Operations	Singh (2006)
	Ex-ante	Banks (2000)
Process improvement	Process assessment	Chen (1996)
Qualitative	Quantitative	Scriven (1996) and Patton (2015)
Stakeholder-based	Sponsor-oriented	Mark and Shotland (1985)
	System-resource based	Gregory and Jackson (1992)
Subjective context	Culture-based	Gregory and Jackson (1992)
Target-based	Target-free	Scriven (1996)
Theory-based	Method-based	Stame (2004)
	Result-based	Nielsen and Ejler (2008)
Other	Sustainability	lpez ridaura et al. (2005)
	Program	Chen (1996)

Appendix B

Beings in Sustainability Relations

Table B.1 Beings in Sustainability Relations

Beings	**Explanation**
Human Being	The central player in anthropocentric perspective. It involves the issue of human well-being.
Extended-self	The other players in cosmic aside from human.
Nature Being	The non-organic dynamic environment in the cosmos.

Appendix C

Sustainability Evaluation Articles Reviewed

C.1 List of Articles Reviewed

Table C.1 List of articles included in the review

Authors	Year	Title
Sheehan et al.	2003	Energy and environmental aspects of using corn stover for fuel ethanol
Riahi et al.	2017	The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview
Hertwich	2008	Consumption and the rebound effect: An industrial ecology perspective
Westley et al.	2011	Tipping toward sustainability: Emerging pathways of transformation
Asif et al.	2007	Life cycle assessment: A case study of a dwelling home in Scotland
Blengini	2009	Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy
Klein et al.	2005	Integrating mitigation and adaptation into climate and development policy: Three research questions
Gonzalez-Garcia et al.	2018	Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: Practical case study ‘’ of three houses of low environmental impact
Chen et al.	2008	Sustainable urban form for Chinese compact cities: Challenges of a rapid urbanized economy
Kosareo and Ries	2007	Comparative environmental life cycle assessment of green roofs
Ringler et al.	2013	The nexus across water, energy, land and food (WELF): Potential for improved resource use efficiency?
Wiek et al.	2012	From complex systems analysis to transformational change: A comparative appraisal of sustainability science projects

Continued

Authors	Year	Title
Ozaki	2011	Adopting sustainable innovation: What makes consumers sign up to green electricity?
Berardi	2012	Sustainability Assessment in the Construction Sector: Rating Systems and Rated Buildings
Langston et al.	2008	Strategic assessment of building adaptive reuse opportunities in Hong Kong
Bohdanowicz et al.	2011	International hotel chains and environmental protection: An analysis of Hilton's we care Programme (Europe, 2006-2008)
Becken and Patterson	2006	Measuring national carbon dioxide emissions from tourism as a key step towards achieving sustainable tourism
Brown and Ulgiati	2004	Emergy evaluation of the biosphere and natural capital
Noppers et al.	2014	The adoption of sustainable innovations: Driven by symbolic and environmental motives
van Vuuren et al.	2017	Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm
Bailis et al.	2015	The carbon footprint of traditional wood fuels
Sev	2009	How can the construction industry contribute to sustainable development? A conceptual framework
Deuble and de Dear	2012	Green occupants for green buildings: The missing link?
Chavalparit et al.	2006	Options for environmental sustainability of the crude palm oil industry in Thailand through enhancement of industrial ecosystems
Sandstrom	2002	Green infrastructure planning in urban Sweden
Sheu	2008	Green supply chain management, reverse logistics and nuclear power generation
Franks et al.	2011	Sustainable development principles for the disposal of mining and mineral processing wastes
Duchin	2008	Sustainable consumption of food: A framework for analyzing scenarios about changes in diets
Stagl	2006	Multicriteria evaluation and public participation: The case of UK energy policy
Altomonte and Schiavon	2013	Occupant satisfaction in LEED and non-LEED certified buildings
Hou and Al-Tabbaa	2014	Sustainability: A new imperative in contaminated land remediation
Gssling and Peeters	2015	Assessing tourism's global environmental impact 19002050
Yellishetty et al.	2011	Environmental life-cycle comparisons of steel production and recycling: Sustainability issues, problems and prospects
Gerilla et al.	2007	An environmental assessment of wood and steel reinforced concrete housing construction
Woodwell and Whittaker	1968	Primary production in terrestrial ecosystems
Lundy and Wade	2011	Integrating sciences to sustain urban ecosystem services

Continued

Authors	Year	Title
Wolsink	2010	Contested environmental policy infrastructure: Socio-political acceptance of renewable energy, water, and waste facilities
Pauliuk and Mller	2014	The role of in-use stocks in the social metabolism and in climate change mitigation
Berges et al.	2010	Enhancing electricity audits in residential buildings with nonintrusive load monitoring
Koroneos and Dompros	2007	Environmental assessment of brick production in Greece
Giampietro and Mayumi	2000	Multiple-scale integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales
Kriegler et al.	2017	Fossil-fuelled development (SSP5): An energy and resource intensive scenario for the 21st century
Liang et al.	2014	Satisfaction of occupants toward indoor environment quality of certified green office buildings in Taiwan
van Ruijven et al.	2008	Modelling Energy and Development: An Evaluation of Models and Concepts
engl et al.	2008	Toward sustainable nano-products: An overview of nano-manufacturing methods
Doan et al.	2017	A critical comparison of green building rating systems
Hiremath et al.	2013	Indicator-based urban sustainability-A review
Kennedy	2002	A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area
Masera et al.	2005	From cookstoves to cooking systems: the integrated program on sustainable household energy use in Mexico
Jim and Tsang	2011	Biophysical properties and thermal performance of an intensive green roof
Azhar and Brown	2009	BIM for sustainability analysis
Werner et al.	2010	National and global greenhouse gas dynamics of different forest management and wood use scenarios: a model-based assessment
Li and Mak	2007	The assessment of the performance of a windcatcher system using computational fluid dynamics
Stamford and Azapagic	2014	Life cycle sustainability assessment of UK electricity scenarios to 2070
Konis	2013	Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office building in San Francisco, California
Tabares-Velasco and Srebric	2012	A heat transfer model for assessment of plant based roofing systems in summer conditions
Huang et al.	2009	A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation
Giljum et al.	2008	Modelling scenarios towards a sustainable use of natural resources in Europe

Continued

Authors	Year	Title
Spiertz and Ewert	2009	Crop production and resource use to meet the growing demand for food, feed and fuel: Opportunities and constraints
Batidzirai et al.	2006	Biomass and bioenergy supply from Mozambique
Bauer et al.	2017	Shared Socio-Economic Pathways of the Energy Sector Quantifying the Narratives
Pelletier and Tyedmers	2011	An ecological economic critique of the use of market information in life cycle assessment research
Uiterkamp and Vlek	2007	Practice and outcomes of multidisciplinary research for environmental sustainability
Jin et al.	2006	Exposure to indoor air pollution from household energy use in rural China: The interactions of technology, behaviour, and knowledge in health risk management
Xu et al.	2000	The calculation and analysis of ecological footprints of Gansu Province
Basiago	1995	Methods of defining 'sustainability'
Ramaswami et al.	2012	A Social-Ecological-Infrastructural Systems Framework for Interdisciplinary Study of Sustainable City Systems: An Integrative Curriculum Across Seven Major Disciplines
Eizenberg and Jabareen	2017	Social sustainability: A new conceptual framework
Gonzlez et al.	2013	A decision-support system for sustainable urban metabolism in Europe
Taylor and Ampt	2003	Travelling smarter down under: Policies for voluntary travel behaviour change in Australia
Pretot et al.	2014	Life cycle assessment of a hemp concrete wall: Impact of thickness and coating
Deng and Wu	2014	Economic returns to residential green building investment: The developers' perspective
Tatari and Kucukvar	2011	Cost premium prediction of certified green buildings: A neural network approach
Si et al.	2016	Assessment of building-integrated green technologies: A review and case study on applications of Multi-Criteria decision-making (MCDM) method
Lotteau et al.	2015	Critical review of life cycle assessment (LCA) for the built environment at the neighbourhood scale
Stazi et al.	2012	Life cycle assessment approach for the optimization of sustainable building envelopes: An application on solar wall systems
Krause	2012	An assessment of the impact that participation in local climate networks has on cities' implementation of climate, energy, and transportation policies
Onat et al.	2014	Towards life cycle sustainability assessment of alternative passenger vehicles
Pons and Aguado	2012	Integrated value model for sustainable assessment applied to technologies used to build schools in Catalonia, Spain

Continued

Authors	Year	Title
Welz et al.	2011	Environmental impacts of lighting technologies - Life cycle assessment and sensitivity analysis
Girardin and Bockstaller	2000	Assessment of potential impacts of agricultural practices on the environment: The AGRO*ECO method
Gong et al.	2012	Life cycle energy consumption and carbon dioxide emission of residential building designs in Beijing: A comparative study
Holden and Hyer	2005	The ecological footprints of fuels
Gagliano et al.	2015	A multi-criteria methodology for comparing the energy and environmental behaviour of cool, green and traditional roofs
Keirstead and Leach	2008	Bridging the gaps between theory and practice: A service niche approach to urban sustainability indicators
Gervsio et al.	2014	A macro-component approach for the assessment of building sustainability in early stages of design
Pushkar et al.	2005	A methodology for design of environmentally optimal buildings by variable grouping
Che et al.	2002	Strategic Environmental Assessment and its development in China
Asdrubali et al.	2015	A comparison between environmental sustainability rating systems LEED and ITACA for residential buildings
De Sousa et al.	2012	Using Life Cycle Assessment to Evaluate Green and Grey Combined Sewer Overflow Control Strategies
Gawel and Ludwig	2011	The iLUC dilemma: How to deal with indirect land use changes when governing energy crops?
Frey et al.	2008	Ecological footprint analysis applied to mobile phones
Ingwersen	2011	Emergy as a Life Cycle Impact Assessment Indicator: A Gold Mining Case Study
Sassi et al.	2010	IMACLIM-R: A modelling framework to simulate sustainable development pathways
Abeysundara et al.	2009	A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka
Wu et al.	2016	Measuring energy and environmental efficiency of transportation systems in China based on a parallel DEA approach
Vanham	2016	Does the water footprint concept provide relevant information to address the water-food-energy-ecosystem nexus?
Bjrn and Hauschild	2013	Absolute versus Relative Environmental Sustainability: What can the Cradle-to-Cradle and Eco-efficiency Concepts Learn from Each Other? Bjrn and Hauschild Cradle to Cradle versus Eco-efficiency
De Meester et al.	2009	Exergetic life-cycle assessment (ELCA) for resource consumption evaluation in the built environment

Continued

Authors	**Year**	**Title**
Lowe and Lorenzoni	2007	Danger is all around: Eliciting expert perceptions for managing climate change through a mental models approach
del Ro and Gual	2004	The promotion of green electricity in Europe: Present and future
Wood and Lenzen	2003	An application of a modified ecological footprint method and structural path analysis in a comparative institutional study
Nijkamp and Pepping	1998	A meta-analytical evaluation of sustainable city initiatives
Park and Boo	2010	An assessment of convention tourism's potential contribution to environmentally sustainable growth
Zellner et al.	2008	A new framework for urban sustainability assessments: Linking complexity, information and policy
Amaral et al.	2015	Quest for a sustainable university: A review
Gober	2010	Desert urbanization and the challenges of water sustainability
Thrn et al.	2010	Global biomass potentials - Resources, drivers and scenario results
Zvolinschi et al.	2007	Exergy sustainability indicators as a tool in industrial ecology: Application to two gas-fired combined-cycle power plants

C.2 Articles Counts for Evaluation Framework

Framework	**Cnt.**	Attached Sustainability Objectives (cnt.)	System Derived Sustainability Objectives (cnt.)
Resource Management	18	11	7
TBL [1]	52	37	15
Urban Ecology [2]	26	9	17
Environmental Accounting	4	1	3
Planet Boundary[3]	8	1	7
Sum	108		

[1] TBL includes frameworks of general TBL, TBL with special measurements, and TBL using only two dimensions.

[2] Urban ecology includes the framework of urban ecology and industrial ecology. They are not separated since similar sustainability evaluation objectives are applied.

[3] Planet boundary includes framework of planet boundary and ecosystem succession. They are not separated since similar sustainability evaluation objectives are applied.

Appendix D

Supplementary Analysis and Data for Chapter 8

D.1 Activity Models by Technology

We demonstrate thermo-plants for electricity production plants consuming fossil fuels, biofuels, and renewable wastes which all produce electricity through the combustion process of the input sources. In Figure D.1, activity 7 mainly suits

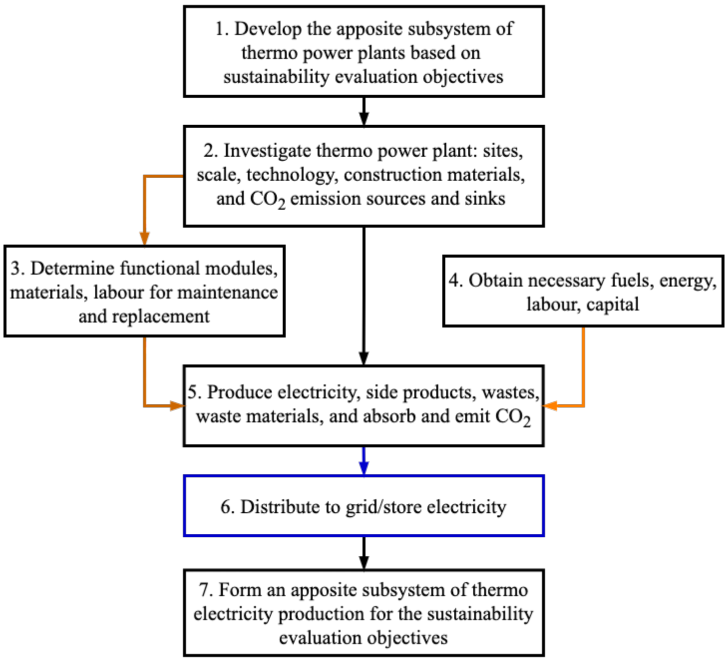

Figure D.1 Activity model of thermo electricity production initial system.

for coal-fired, oil-fired, biofuel, and municipal waste power plants. For power plants consuming natural gas, activity 7 could be detailed as a flue bag that produces side products from gases or merely absorbs them.

Similarly, consuming different fuels, the activity model of nuclear production is presented in Figure D.2. There are no direct CO2 emission in nuclear electricity production but it is associated with indirect carbon inputs.

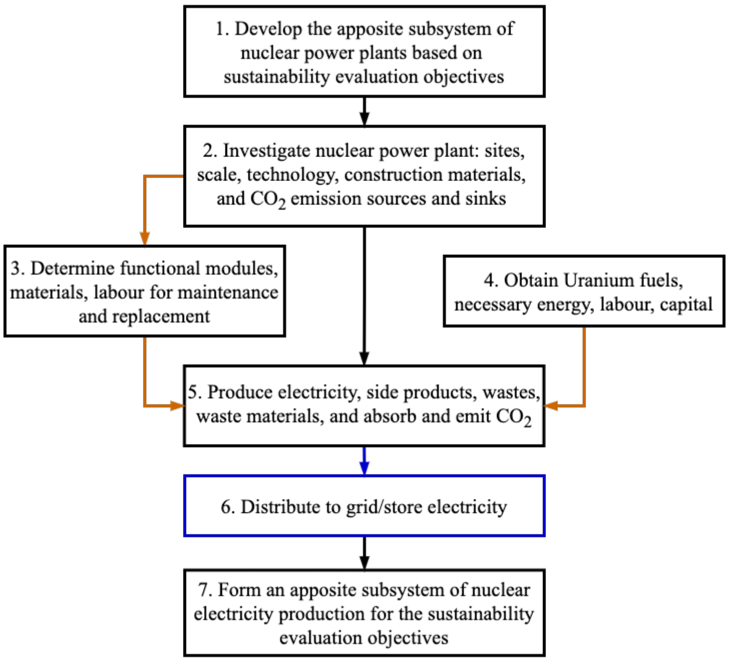

Figure D.2 Activity model of Nuclear electricity production initial system.

Following solar PV power plants, the activity model of initial systems for geothermal, wind, hydro and tide power production systems are presented.

Geothermal power plants also mainly associate with the carbon traces in the installed infrastructures and the working fluid. Similarly, mainly depending on turbine generators, wind power, and hydro and tidal power plants also contain heavy carbon traces in the infrastructures.

To note, as presented in the activity model of wind power plants, availability of windy sites require additional investigation. Similarly, for the development or installation of hydro and tidal power plants, the availability of suitable river or lakes and sea shore sites needs to be investigated.

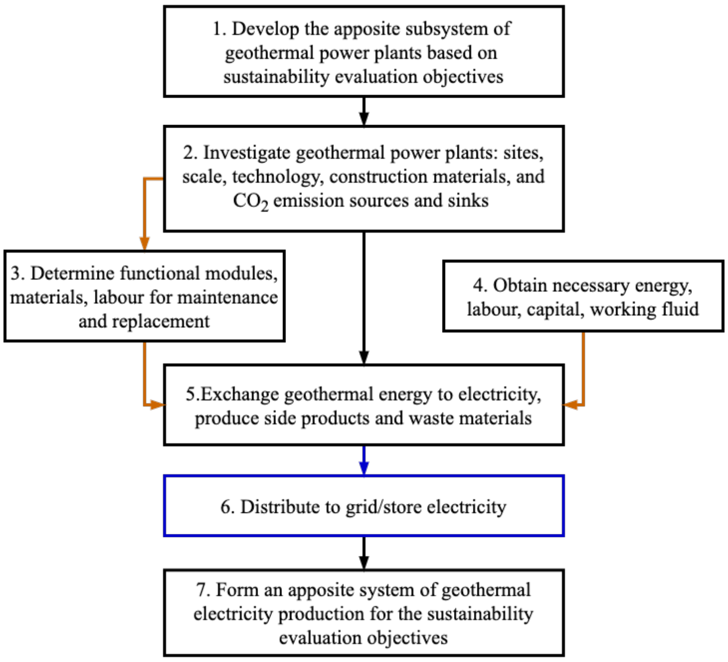

Figure D.3 Activity model of geothermal electricity production initial system

D.2 Table of Wider KSs by Technology

Here, the connections of KSs are developed according to types of technologies until enclosing physical flow of carbon cycle contributing to CO2 emission is captured among the stakeholders. Due to different sources of materials and fuels consumed by power production technologies, the necessary rounds of KS expansion could be different. The activities that are terminated by not linking with direct CO2 emission or by the scope of the research is coloured by yellow in the tables. The brackets following activities are the upstream activities.

D.2.1 Wider KSs of Coal-fired Power Production

The table presents the complete expanded stakeholder analysis for coal-fired power production system.

Level	Activity	Key Stakeholders	End
Top	**1.** Develop the apposite subsystem of coal-fired power plants based on sustainability evaluation objectives	O: Coal-fired power plant owners E: Government, Social groups A,R: Managers, Research team, External researchers R: Coal-fired power plant owners, Managers, Research team	

Level	Activity	Key Stakeholders	End
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objectives	O: Government, Coal-fired power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
1	1.2 Identify lead of sustainability evaluation objectives relating to coal-fired electricity and the sustainability criteria: governments, and organisations joined by the country	O: Government, Coal-fired power plant owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	
1	1.3 Determine the the system boundary of coal-fired electricity production system, the initial system, and the time scope of evaluation	O: Government, Coal-fired power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.**Investigate the power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: Coal-fired power plant owners, Government E: Coal-fired power plant owners, Local residents, Employees working at coal-fired power plants, Animals at coal-fired power plants, Shareholders and creditors of coal-fired power plants, Internal information management teams A, R: Managers, Research team, External researchers	
2	2.1 Determine the power plants to be included in evaluation	O: Government, Coal-fired power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, Coal-fired power plant owners E: Government A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
2	2.3 Determine used area, technologies, and materials	O: Government, Coal-fired power plant owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI:Social groups (Eurocoal, EC, IEA, European parliament, European Economic and Social Committee, IEA, World Coal Association), Railway carriers for coal AIB: Original residents at coal-fired power plant sites, Coal-fired power plant employees, Original on-ground and underground animals at coal-fired power plants, Migration birds passing the coal-fired power plants	
2	2.4 Investigate carbon containment and emission of the materials and modules	O: Coal-fired power plant owners E: Material suppliers, Module suppliers A,R: Managers, Research team, External researchers	
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of coal-fired power plants	O: Coal-fired power plant owners E, A, R: Managers, Research team, External researchers	
Top	**3.**Supply functional modules, materials, labour for maintenance and replacement	O: Coal-fired power plant owners E: Technology suppliers (steam boiler manufacturers, turbine generator manufacturers, cooling manufacturers, regenerator manufacturers, flue gas treatment manufacturers), Construction material suppliers (offices, structures), Government (policy), Land supplier, Owners (capital), Material and module carriers, Technicians A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or more efficient substitutes (2.5)	O: Coal-fired power plant owners E: Coal-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
3	3.2 Supply materials for building construction (3.1)	O:Coal-fired power plant owners E: Government, Material suppliers, Coal-fired power plant owners A,R: Managers, Research team, External researchers, Construction team, Office repairing workers AI: Government (construction, technology policy), Foreign material suppliers AIB: On-site and on-route human and animals for material production and transportation, On-site underground and water animals	
3.2	3.2.1 Supply capital for purchasing construction materials: cement, steel, glass, paint	O: Coal-fired power plant owners E: Government (policy), Coal-fired power plant owners A,R: Coal-fired power plant managers R: O of 3.2.2-5 AI: Shareholders of coal-fired power plants	
3.2	3.2.2 Produce cement	O: Cement plant owners E: Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companies A,R: Cement plant employees AI: Cement plant shareholders AIB: Cement plant engineers, Birds and fish at the cement plants	
3.2.2	3.2.2.1 Supply capital for purchasing cement (limestone, mudstone, clay)	O: Cement plant owners E: Government (policy), Cement plant owners A: Cement plant managers R: O of 3.2.2.2-4 AI: Cement plant shareholders	
3.2.2	3.2.2.2 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Government (policy), Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.2.2.N Natural formation of lime mines
3.2.2	3.2.2.3 Extract mudstone	O: Mudstone plant owners E: Machinery manufacturers, Energy companies A,R: Mudstone plant employees AI: Government (policy), Mudstone plant shareholders AIB: Mudstone miners, Birds and fish at mudstone mines	3.2.2.3.N Natural formation of mudstone mines
3.2.2	3.2.2.4 Extract clay	O: Clay plant owners E: Machinery manufacturers, Energy companies A,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.2.4.N Natural formation of clay

Level	**Activity**	**Key Stakeholders**	**End**
3.2.2	3.2.2.5 Transport materials and produce concrete (3.2.2.2-4)	O: Cement plant owners E: Government (transportation), Cement plant owners, O of 3.2.2.2-4, Transportation companies A: Cement plant employees, Transportation carriers R: Cement plants, Birds and fish at cement plant sites AI: Foreign O of 3.2.2.2-5 AIB: Birds on transportation routes	
3.2	3.2.3 Produce steel	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.3	3.2.3.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.3.2-5 AI: Steel plant shareholders	
3.2.3	3.2.3.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.3.2.N Natural formation of iron ores
3.2.3	3.2.3.3 Extract limestone		Continue to 3.2.2.2
3.2.3	3.2.3.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.3	3.2.3.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery manufacturers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.3.5.N Natural formation of coal or LNG
3.2.3	3.2.3.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.3.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.3.2-5 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.2	3.2.4 Produce glass	O: Glass plants E: Sand plants, Soda ash plants, Limestone plants, Machinery suppliers, Energy companies A: Glass plant employees AI: Glass plant shareholders AIB: Glass plant engineers, Birds and fish at the glass plants	
3.2.4	3.2.4.1 Supply capital for purchasing glass (limestone, sand, soda ash)	O: Glass plant owners E: Government (policy), Glass plant owners A,R: Glass plant employees, Manufacturers in 3.2.4.2-4	
3.2.4	3.2.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4	3.2.4.3 Extract sand	O: Sand mine owners E: Machinery suppliers, Energy companies A,R: Sand mine employees AI: Sand mine shareholders AIB: Sand miners, Birds and fish at the sand mines	3.2.4.3.N Natural formation of sand
3.2.4	3.2.4.4 Produce soda ash [C-]	O: Soda ash plants E: Limestone plants, CO2 suppliers, Salt brine mines, Machinery suppliers, Energy companies A,R: Soda ash plant employees AI: Government (transportation), Soda ash plant shareholders AIB: Soda ash plant engineers, Fish in water bodies at the soda ash plants	
3.2.4.4	3.2.4.4.1 Supply capital for purchasing soda ash	O: Soda ash plant owners E: Government (policy), Soda ash plant owners A,R: Soda ash plant employees, Manufacturers in 3.2.4.4.2-4	
3.2.4.4	3.2.4.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4.4	3.2.4.4.3 Extract salt brines	O: Salt brine mine owners E: Machinery suppliers, Energy companies A,R: Salt brine mine employees AI: Salt brine mine shareholders AIB: Salt brine miners, Birds and fish at the salt brine mines	3.2.4.4.3.N Natural formation of salt brines
3.2.4.4	3.2.4.4.4 Supply CO2	O: CO2 suppliers (fossil fuel-fired power plants) E: Machinery suppliers, Energy companies A,R: CO2 supplier employees AI: Government (transportation), CO2 supplier shareholders AIB: CO2 supplier engineers, Fish in water bodies at the CO2 supplier sites	3.2.4.4.4 Supply of industrial CO2

Level	Activity	Key Stakeholders	End
3.2.4.4	3.2.4.4.5 Transport raw materials and produce soda ash (3.2.4.4.2-4)	O: Soda ash plant owners E: O of 3.2.4.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Soda ash plant employees R: Soda ash plants, Birds and fish at soda ash plant sites AI: Foreign O of 3.2.4.4.2-4 AIB: Birds on transportation routes	
3.2.4	3.2.4.5 Transport raw materials and produce glass (3.2.4.2-4)	O: Glass plant owners E: O of 3.2.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Glass plant employees R: Glass plants, Birds and fish at glass plant sites AI: Foreign O of 3.2.4.2-4 AIB: Birds on transportation routes	
3.2	3.2.5 Produce paint	O: Paint plants E: Chemical suppliers, Machinery suppliers, Energy companies A: Paint plant employees AI: Paint plant shareholders AIB: Paint plant engineers, Birds and fish at the paint plants	
3.2	3.2.6 Transport materials and construct buildings (3.2.2-5)	O: Coal-fired power plant owners E: O of 3.2.2-5, Transportation companies, Coal-fired power plant owners, Construction companies A: Transportation carriers, Construction team R: Coal-fired power plants, Bird and fish at the coal-fired power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.2.2-5 AIB: Birds and fish at the coal-fired power plants, Birds on transportation routes	
3	3.3 Supply functional modules installed and carbon intensities (3.1)	O:Coal-fired power plant owners E: Government, Coal-fired power plant owners, Module suppliers (coal-pretreatment grinder and separator, steam boiler, condenser, turbine generator, regenerator, flue gas treatment) A,R: Managers, Research team, External researchers, Construction team, Installation and repairing engineers AI: Government (construction, technology policy), Foreign technology suppliers AIB: On-site and on-route human and animals for module production and transportation	

Level	Activity	Key Stakeholders	End
3.3	3.3.1 Supply capital for purchasing modules (coal pretreatment, steam boiler, condenser and pumps, turbine generator, fly ash filter, flue gas scrubber)	O: Coal-fired power plant owners E: Government (policy), Coal-fired power plant owners A,R: Coal-fired power plant managers R: O of 3.3.2-7 AI: Shareholders of coal-fired power plants	
3.3	3.3.2 Manufacture coal grinder (steel)	O: Coal grinder manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Coal grinder manufacturing plant employees AI: Coal grinder manufacturing plant shareholders AIB: Coal grinder manufacturing plant engineers, Birds and fish at the coal grinder manufacturing plants	Continue to 3.2.3
3.3	3.3.3 Manufacture steam boiler (steel)	O: Steam boiler manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Steam boiler manufacturing plant employees AI: Steam boiler manufacturing plant shareholders AIB: Steam boiler manufacturing plant engineers, Birds and fish at the steam boiler manufacturing plants	Continue to 3.2.3
3.3	3.3.4 Manufacture condensing compartments (steel)	O: Condensing system manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Condensing system manufacturing plant employees AI: Condensing system manufacturing plant shareholders AIB: Condensing system manufacturing plant engineers, Birds and fish at the condensing system manufacturing plants	Continue to 3.2.3
3.3	3.3.5 Manufacture turbine and generator (steel and iron, aluminium, copper)	O: Turbine generator manufacturing plant owners E: Steel plants, Aluminium plants, Copper plants, Machinery suppliers, Energy companies A,R: Turbine generator manufacturing plant employees AI: Turbine generator manufacturing plant shareholders AIB: Turbine generator manufacturing plant engineers, Birds and fish at the turbine generator manufacturing plants	

Level	Activity	Key Stakeholders	End
3.3.5	3.3.5.1 Supply capital for purchasing turbine generators	O: Turbine generator manufacturing plant owners E: Government (policy), Turbine generator manufacturing plant owners A,R: Turbine generator manufacturing plant managers R: O of 3.3.5.2-4 AI: Shareholders of turbine generator manufacturing plants	
3.3.5	3.3.5.2 Produce steel		Continue to 3.2.3
3.3.5	3.3.5.3 Produce copper products	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	
3.3.5.3	3.3.5.3.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.3.5.3.2 AI: Copper plant shareholders	
3.3.5.3	3.3.5.3.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.3.5.3.2.N Natural formation of copper ores
3.3.5.3	3.3.5.3.3 Transport and produce copper products	O: Copper plant owners E: O of 3.3.5.3.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.3.5.3.2 AIB: Birds on transportation routes	
3.3.5	3.3.5.4 Produce aluminium products	O: Aluminium plant owners E: Bauxite mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	
3.3.5.4	3.3.5.4.1 Supply capital for purchasing aluminium	O: Aluminium plant owners E: Government (policy), Aluminium plant owners A,R: Aluminium plant employees, O of 3.3.5.4.2 AI: Aluminium plant shareholders	

Level	Activity	Key Stakeholders	End
3.3.5.4	3.3.5.4.2 Extract and process bauxite or process recycled aluminium products	O: Bauxite mine owners E: Machinery suppliers, Energy companies A,R: Bauxite mine employees AI: Government (transportation), Bauxite mine shareholders AIB: Bauxite miners, Birds and fish at bauxite mines	3.3.5.4.2.N Natural formation of bauxite mines
3.3.5.4	3.3.5.4.3 Transport and produce aluminium products	O: Aluminium plant owners E: O of 3.3.5.4.2, Government (transportation), Transportation carriers A: Transportation carriers, Aluminium plant employees R: Aluminium plants, Birds and fish at aluminium plant sites AI: Foreign O of 3.3.5.4.2 AIB: Birds on transportation routes	
3.3.5	3.3.5.5 Transport materials and manufacture turbine generators	O: Turbine generator manufacturing plant owners E: O of 3.3.5.2-4, Transportation companies, Turbine generator manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Turbine generator manufacturing plant employees, Birds and fish at the turbine generator manufacturing plants AI: Social groups, Nearby residents, Government (policy) AIB: Birds on transportation routes	
3.3	3.3.6 Manufacture fly ash filters (steel)	O: Fly ash filter manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Fly ash filter manufacturing plant employees AI: Fly ash filter manufacturing plant shareholders AIB:Fly ash filter manufacturing plant engineers, Birds and fish at the fly ash filter manufacturing plants	Continue to 3.2.3
3.3	3.3.7 Manufacture flue gas scrubber (NaHCO3, NaOH, stacks)	O: Flue gas scrubber manufacturing plant owners E: Cement plants, Sodium hydroxide plants, Soda carbonate plants, Machinery suppliers, Energy companies A,R: Condensing system manufacturing plant employees AI: Condensing system manufacturing plant shareholders AIB: Condensing system manufacturing plant engineers, Birds and fish at the condensing system manufacturing plants	Continue to 3.2.2

Level	Activity	Key Stakeholders	End
3.3	3.3.8 Transport and install or construct the modules (3.3.2-7)	O: Coal-fired power plant owners E: O of 3.3.2-7, Transportation companies, Coal-fired power plant owners, Construction companies A: Transportation carriers, Construction team R: Coal-fired power plants, Birds and fish at the coal-fired power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2-7 AIB: Birds and fish at the coal-fired power plants, Birds on transportation routes	
3	3.4 Compile national coal-fired power plant profile: installed capacity, coal consumption rate, CO2 intensity profile in time and space, replacement rate of materials and modules (3.2, 3.3)	O: Coal-fired power plant owners E, A, R: Managers, Research team, External researchers	
Top	**4.**Obtain fuels from sources, energy, labour, capital	O: Coal-fired power plant owners E: Domestic coal suppliers, Foreign coal suppliers, Domestic energy supplier, Coal-fired power plant owners and Government, Transportation carriers A,R: Managers, Coal-fired power plant employees AI: Country (labour) AIB: Local residents, Animals at and near coal-fired power plants	
4	4.1 Investigate sources of coal, electricity, and labour	O: Coal-fired power plant owners E: Coal-fired power plant owners, Country (labour), Energy companies, Geographic observatories A, R: Managers, Research team, External researchers	
4	4.2 Supply coal, electricity, labour, and capital	O: Coal-fired power plant owners E: Coal-fired power plant owners, E of 4.1 A,R: Managers, Employees, Engineers AI: Foreign E of 4.1, Government (policy) AIB: Original residents near coal-fired power plants, Birds and fish at coal-fired power plant	
4.2	4.2.1 Prepare electricity, engineers, and capital	O: Coal-fired power plant owners E: Coal-fired power plant owners, Electricity companies, Country (labour) A: Managers, Coal-fired power plant owners R: Coal-fired power plant employees AI: Coal-fired power plant shareholders, Government (policy)	

Level	Activity	Key Stakeholders	End
4.2	4.2.2 Produce coal	O: Coal-fired power plant owners, Coal storage plants E: Coal mines, Machinery suppliers, Energy companies A,R: Coal plants AI: Government (policy), Coal plant shareholders AIB: Coal plant engineers, Birds and bats and fish at the coal plant sites	
4.2.2	4.2.2.1 Supply capital for purchasing primary coal	O: Coal plant owners E: Government (policy), Coal plant owners A,R: Coal plant employees, O of 4.2.2.2 AI: Coal plant shareholders	
4.2.2	4.2.2.2 Extract and process primary coal	O: Coal mine owners E: Machinery suppliers, Energy companies A,R: Coal mine employees AI: Government (transportation), Coal mine shareholders AIB: Coal miners, Birds and fish at coal mines	4.2.2.2.N Natural formation of coal
4.2.2	4.2.2.3 Transport and produce rough coal	O: Coal plant owners E: O of 4.2.2.2, Government (transportation), Transportation carriers A: Transportation carriers, Coal plant employees R: Coal plants, Birds and fish at coal plant sites AI: Foreign O of 4.2.2.2 AIB: Birds on transportation routes	
4.2	4.2.3 Transport and store coal	O: Coal-fired power plant owners E: O of 4.2.2, Government (transportation), Railway companies A: Storehouse employees, Transportation carriers R: Coal-fired power plants, Storehouse workers, Birds and fish at coal plant sites AI: Foreign O of 4.2.2 AIB: Birds on transportation routes	
4	4.3 Compile consumption profile of transformational inputs for coal-fired electricity production	O: Coal-fired power plant owners E, A, R: Managers, Research team, External researchers	
Top	**5.**Operate the power plant to produce electricity	O: Coal-fired power plant owners E: Coal-fired power plant owners, Government (quota) A: Employees, Managers, Coal-fired power plant owners R: Coal-fired power plant owners, Managers, Side product customers, Coal-fired power plant employees, Animals at and near coal-fired power plants, Local residents AI: KSs in 2,3,4, Government (quota) AIB: Carbon storage site residents and animals, Waste disposal site residents and animals	

Level	Activity	Key Stakeholders	End
5	5.1 Repair and replace structural and functional parts (3.4)	O: Coal-fired power plant owners E: Coal-fired power plant owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of power plant storehouse, Compartment Carriers, Carriers for waste compartments	
5.1	5.1.1 Investigate low-carbon or energy saving construction materials (3.2.6)	O: Coal-fired power plant owners E: Coal-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Government (foreign suppliers)	
5.1	5.1.2 Investigate low-carbon or more efficient modules (3.3.8)	O: Coal-fired power plant owners E: Coal-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Government (foreign suppliers)	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: Coal-fired power plant owners E: Coal-fired power plant owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: Coal-fired power plant owners, Recycling companies, Steel plants E: Coal-fired power plant owners A,R: Recycling plants, Waste landfill plants AI: Government (transportation, policy), Social groups (policy), Residents at each plant sites AIB: Birds and Fish at each plant	
5	5.2 Operate and produce (4.3; 5.1)	O: Coal-fired power plant owners E: E of 3.4 and 4.3, Electricity company A: Engineers, Managers, Coal-fired power plant owners R: Customers (electricity), Employees of coal-fired power plants, Birds and fish at coal-fired power plant sites	
5	5.3 Distribute by-products, coal combustion waste, and emit CO2 (5.2)	O: Coal-fired power plant owners E: Government (transportation), Carbon storage site owners (CO2) A: Coal-fired power plant employees R: Bottom ash carriers, Customers (by product), By-product carriers, Coal-fired power plant employees, Carbon storage site owners, Birds and Fishes at the power plants and storage sites AI:Government (CO2 budget), Customers (demand), Local residents and social groups AIB: Local residents, Birds and fish at coal-fired power plant sites	

Level	Activity	Key Stakeholders	End
5.3	5.3.1 Store by-products (5.2)	O: Coal-fired power plant owners E: Coal-fired power plant owners A: Managers, Storehouse workers R: Storehouse workers, A of 5.3.2 AIB: Fish at coal-fired power plant sites	
5.3	5.3.2 Identify demand and sell by-products (5.3.1)	O: Coal-fired power plant owners E: Coal-fired power plant owners A: Managers, Storehouse workers, Sales manager, Sales R: Customers (by-product) AI: Government (policy)	
5.3	5.3.3 Identify bottom ash recycling plants, landfill plants, and CO2 storage mining sites	O: Government, Coal-fired power plant owners E: Government A: Managers, Research team, External researchers R: Customers (Bottom ash recycling plants, Landfill plants, CO2 storage mines, By-product customers)	
5.3	5.3.4 Supply capital for waste treatment (bottom ash etc.) and CO2 storage (5.3.3)	O: Coal-fired power plant owners E: Coal-fired power plant owners A,R: Managers, Research team, External researchers	
5.3	5.3.5 Distribute combustion wastes, wastes from by-product production, and CO2 (5.3.4)	O: R of 5.3.3 E: Coal-fired power plant owners A: Waste carriers R: O of 5.3.5	
5.3	5.3.6 Emit CO2 (diffused) (5.2, 5.3.2, 5.3.5)	O, E, A: Coal-fired power plant owners R: Wide weak stakeholders on land and water bodies	5.3.6.N Natural diffusion and absorption of CO2
5.3	5.3.7 Compile waste treatment and emission profile (5.3.6)	O: Coal-fired power plant owners E,A,R: Managers, Research team, External researchers	
Top	**6.** Distribute to grid/store electricity	O: Coal-fired power plant owners, Government E: Coal-fired power plants, Government A: Coal-fired power plants R: Customers, Coal-fired power plant owners, Managers, Employees AI: Animals at and near coal-fired power plants AIB: Local residents, Animals at and near coal-fired power plants	
Top	**7.** Form an apposite system of coal-fired electricity production for the sustainability evaluation objectives	O: Coal-fired power plant owners E: Information suppliers in 1-6, Coal-fired power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

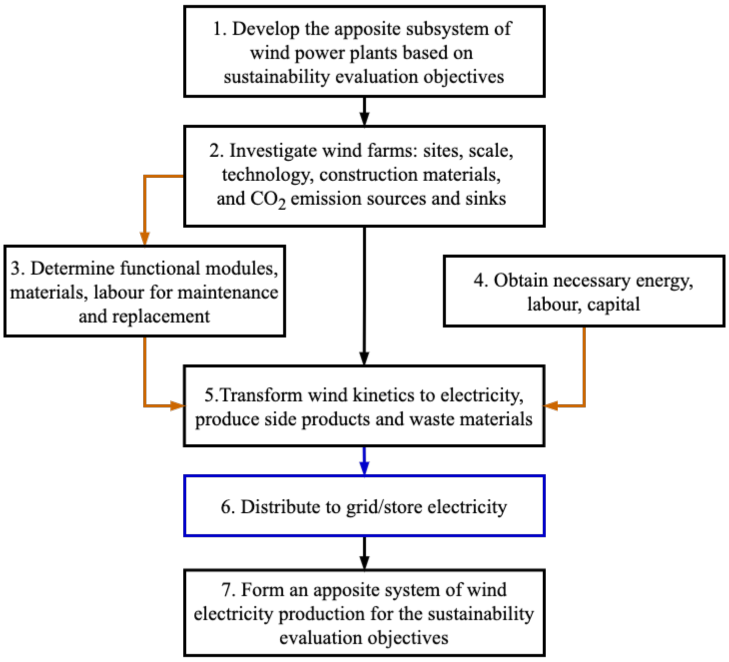

Figure D.4 Activity model of wind electricity production initial system

D.2.2 Wider KSs of Oil-fired Power Production

The table presents the complete expanded stakeholder analysis for oil-fired power production system.

Level	Activity	Key Stakeholders	End
Top	**1.** Develop the apposite subsystem of oil-fired power plants based on sustainability evaluation objectives	O: Oil-fired power plant owners E: Government, Social groups (EC, UN, IEA, OECD) A,R: Managers, Research team, External researchers R: Oil-fired power plant owners, Managers, Research team	
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objectives	O: Government, Oil-fired power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
1	1.2 Identify lead of sustainability evaluation objectives relating to oil-fired electricity and the sustainability criteria: governments, and organisations joined by the country	O: Government, Oil-fired power plant owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	
1	1.3 Determine the the system boundary of oil-fired electricity production system, the initial system, and the time scope of evaluation	O: Government, Oil-fired power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.** Investigate the power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: Oil-fired power plant owners, Government E: Oil-fired power plant owners, Local residents, Employees working at oil-fired power plants, Animals at oil-fired power plants, Shareholders and creditors of oil-fired power plants, Internal information management teams A,R: Managers, Research team, External researcher	
2	2.1 Determine the power plants to be included in evaluation	O: Government, Oil-fired power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, Oil-fired power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.3 Determine used area, technologies, and materials	O: Government, Oil-fired power plant owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI: Social groups (EC, IEA, European parliament, European Economic and Social Committee, IEA), Transportation and pipeline carriers AIB: Original residents at oil-fired power plant sites, Oil-fired power plant employees, Original on-ground and underground animals at oil-fired power plants, Migration birds passing the oil-fired power plants	

Level	Activity	Key Stakeholders	End
2	2.4 Investigate carbon containment and emission of the materials and modules	O: Oil-fired power plant owners E: Material suppliers, Module suppliers A,R: Managers, Research team, External researchers	
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of oil-fired plants	O: Oil-fired power plant owners E, A, R: Managers, Research team, External researchers	
Top	**3.** Supply functional modules, materials, labour for maintenance and replacement	O: Oil-fired power plant owners E: Technology suppliers (steam boiler manufacturers, turbine generator manufacturers, cooling manufacturers, flue gas treatment manufacturers), Construction material suppliers (offices, structures), Government (policy), Land supplier, Owners (capital), Material and modules carriers, Technicians A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or more efficient substitutes	O: Oil-fired power plant owners E: Oil-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers	
3	3.2 Supply materials for building construction (3.1)	O: Oil-fired power plant owners E: Government, Material suppliers, Oil-fired power plant owners A,R: Managers, Research team, External researchers, Construction team, Office repairing workers AI: Government (construction, technology policy), Foreign material suppliers AIB: On-site and on-route human and animals for material production and transportation, On-site underground and water animals	
3.2	3.2.1 Supply capital for purchasing construction materials: cement, steel, glass, paint	O: Oil-fired power plant owners E: Government (policy), Oil-fired power plant owners A,R: Oil-fired power plant managers R: O of 3.2.2-5 AI: Shareholders of oil-fired power plants	

Level	Activity	Key Stakeholders	End
3.2	3.2.2 Produce cement	O: Cement plant owners E: Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companiesA,R: Cement plant employees AI: Cement plant shareholders AIB: Cement plant engineers, Birds and fish at the cement plants	
3.2.2	3.2.2.1 Supply capital for purchasing cement (limestone, mudstone, clay)	O: Cement plant owners E: Government (policy), Cement plant owners A: Cement plant managers R: O of 3.2.2.2-4 AI: Cement plant shareholders	
3.2.2	3.2.2.2 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Government (policy), Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.2.2.N Natural formation of lime mines
3.2.2	3.2.2.3 Extract mudstone	3.2.2.3 O: Mudstone plant owners E: Machinery manufacturers, Energy companies A,R: Mudstone plant employees AI: Government (policy), Mudstone plant shareholders AIB: Mudstone miners, Birds and fish at mudstone mines	3.2.2.3.N Natural formation of mudstone mines
3.2.2	3.2.2.4 Extract clay	O: Clay plant owners E: Machinery manufacturers, Energy companiesA,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.2.4.N Natural formation of clay
3.2.2	3.2.2.5 Transport materials and produce concrete (3.2.2.2-4)	O: Cement plant owners E: Government (transportation), Cement plant owners, O of 3.2.2.2-4, Transportation companies A: Cement plant employees, Transportation carriers R: Cement plants, Birds and fish at cement plant sites AI: Foreign O of 3.2.2.2-5 AIB: Birds on transportation routes	
3.2	3.2.3 Produce steel	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.3	3.2.3.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.3.2-5 AI: Steel plant shareholders	

Level	Activity	Key Stakeholders	End
3.2.3	3.2.3.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.3.2.N Natural formation of iron ores
3.2.3	3.2.3.3 Extract limestone		Continue to 3.2.2.2
3.2.3	3.2.3.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.3	3.2.3.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery suppliers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.3.5.N Natural formation of coal or LNG
3.2.3	3.2.3.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.3.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.3.2-5 AIB: Birds on transportation routes	
3.2	3.2.4 Produce glass	O: Glass plants E: Sand plants, Soda ash plants, Limestone plants, Machinery suppliers, Energy companies A: Glass plant employees AI: Glass plant shareholders AIB: Glass plant engineers, Birds and fish at the glass plants	
3.2.4	3.2.4.1 Supply capital for purchasing glass (limestone, sand, soda ash)	O: Glass plant owners E: Government (policy), Glass plant owners A,R: Glass plant employees, Manufacturers in 3.2.4.2-4	
3.2.4	3.2.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4	3.2.4.3 Extract sand	O: Sand mine owners E: Machinery suppliers, Energy companies A,R: Sand mine employees AI: Sand mine shareholders AIB: Sand miners, Birds and fish at the sand mines	3.2.4.3.N Natural formation of sand

Level	**Activity**	**Key Stakeholders**	**End**
3.2.4	3.2.4.4 Produce soda ash [C-]	O: Soda ash plants E: Limestone plants, CO2 suppliers, Salt brine mines, Machinery suppliers, Energy companies A,R: Soda ash plant employees AI: Government (transportation), Soda ash plant shareholders AIB: Soda ash plant engineers, Fish in water bodies at the soda ash plants	
3.2.4.4	3.2.4.4.1 Supply capital for purchasing soda ash	O: Soda ash plant owners E: Government (policy), Soda ash plant owners A,R: Soda ash plant employees, Manufacturers in 3.2.4.4.2-4	
3.2.4.4	3.2.4.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4.4	3.2.4.4.3 Extract salt brines	O: Salt brine mine owners E: Machinery suppliers, Energy companies A,R: Salt brine mine employees AI: Salt brine mine shareholders AIB: Salt brine miners, Birds and fish at the salt brine mines	3.2.4.4.3.N Natural formation of salt brines
3.2.4.4	3.2.4.4.4 Supply CO2	O: CO2 suppliers (fossil fuel-fired power plants) E: Machinery suppliers, Energy companies A,R: CO2 supplier employees AI: Government (transportation), CO2 supplier shareholders AIB: CO2 supplier engineers, Fish in water bodies at the CO2 supplier sites	3.2.4.4.4 Supply of industrial CO2
3.2.4.4	3.2.4.4.5 Transport raw materials and produce soda ash (3.2.4.4.2-4)	O: Soda ash plant owners E: O of 3.2.4.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Soda ash plant employees R: Soda ash plants, Birds and fish at soda ash plant sites AI: Foreign O of 3.2.4.4.2-4 AIB: Birds on transportation routes	
3.2.4	3.2.4.5 Transport raw materials and produce glass (3.2.4.2-4)	O: Glass plant owners E: O of 3.2.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Glass plant employees R: Glass plants, Birds and fish at glass plant sites AI: Foreign O of 3.2.4.2-4 AIB: Birds on transportation routes	
3.2	3.2.5 Produce paint	O: Paint plants E: Chemical suppliers, Machinery suppliers, Energy companies A: Paint plant employees AI: Paint plant shareholders AIB: Paint plant engineers, Birds and fish at the paint plants	

Level	Activity	Key Stakeholders	End
3.2	3.2.6 Transport materials and construct buildings (3.1.1-5)	O: Oil-fired power plant owners E: O of 3.2.2-5, Transportation companies, Oil-fired power plant owners, Construction companies A: Transportation carriers, Construction team R: Oil-fired power plants, Bird and fish at the oil-fired power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.2.2-5 AIB: Birds and fish at the oil-fired power plants, Birds on transportation routes	
3	3.3 Supply functional modules installed and carbon intensities (3.1)	O: Oil-fired power plant owners E: Government, Oil-fired power plant owners, Module suppliers (steam boiler, condenser, turbine generator, flue gas treatment) A,R: Managers, Research team, External researchers, Construction team, Installation and repairing engineers AI: Government (construction, technology policy), Foreign technology suppliers AIB: On-site and on-route human and animals for module production and transportation	
3.3	3.3.1 Supply capital for purchasing modules (steam boiler, condenser and pumps, turbine generator, flue gas scrubber)	O: Oil-fired power plant owners E: Government (policy), Oil-fired power plant owners A,R: Oil-fired power plant managers R: O of 3.3.2-5 AI: Shareholders of oil-fired power plants	
3.3	3.3.2 Manufacture steam boiler (steel)	O: Steam boiler manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Steam boiler manufacturing plant employees AI: Steam boiler manufacturing plant shareholders AIB: Steam boiler manufacturing plant engineers, Birds and fish at the steam boiler manufacturing plants	Continue to 3.2.3
3.3	3.3.3 Manufacture condensing compartments (steel)	O: Condensing system manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Condensing system manufacturing plant employees AI: Condensing system manufacturing plant shareholders AIB: Condensing system manufacturing plant engineers, Birds and fish at the condensing system manufacturing plants	Continue to 3.2.3

Level	Activity	Key Stakeholders	End
3.3	3.3.4 Manufacture turbine and generator (steel and iron, aluminium, copper)	O: Turbine generator manufacturing plant owners E: Steel plants, Aluminium plants, Copper plants, Machinery suppliers, Energy companies A,R: Turbine generator manufacturing plant employees AI: Turbine generator manufacturing plant shareholders AIB: Turbine generator manufacturing plant engineers, Birds and fish at the turbine generator manufacturing plants	
3.3.4	3.3.4.1 Supply capital for purchasing turbine generators	O: Turbine generator manufacturing plant owners E: Government (policy), Turbine generator manufacturing plant owners A,R: Turbine generator manufacturing plant managers R: O of 3.3.4.2-4 AI: Shareholders of turbine generator manufacturing plants	
3.3.4	3.3.4.2 Produce steel		Continue to 3.2.3
3.3.4	3.3.4.3 Produce copper products	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	
3.3.4.3	3.3.4.3.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.3.4.3.2 AI: Copper plant shareholders	
3.3.4.3	3.3.4.3.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.3.4.3.2.N Natural formation of copper ores
3.3.4.3	3.3.4.3.3 Transport and produce copper products	O: Copper plant owners E: O of 3.3.4.3.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.3.4.3.2 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.3.4	3.3.4.4 Produce aluminium products	O: Aluminium plant owners E: Bauxite mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	
3.3.4.4	3.3.4.4.1 Supply capital for purchasing aluminium	O: Aluminium plant owners E: Government (policy), Aluminium plant owners A,R: Aluminium plant employees, O of 3.3.4.4.2 AI: Aluminium plant shareholders	
3.3.4.4	3.3.4.4.2 Extract and process bauxite or process recycled aluminium products	O: Bauxite mine owners E: Machinery suppliers, Energy companies A,R: Bauxite mine employees AI: Government (transportation), Bauxite mine shareholders AIB: Bauxite miners, Birds and fish at bauxite mines	3.3.4.4.2.N Natural formation of bauxite mines
3.3.4.4	3.3.4.4.3 Transport and produce aluminium products	O: Aluminium plant owners E: O of 3.3.4.4.2, Government (transportation), Transportation carriers A: Transportation carriers, Aluminium plant employees R: Aluminium plants, Birds and fish at aluminium plant sites AI: Foreign O of 3.3.4.4.2 AIB: Birds on transportation routes	
3.3.4	3.3.4.5 Transport materials and manufacture turbine generators	O: Turbine generator manufacturing plant owners E: O of 3.3.4.2-4, Transportation companies, Turbine generator manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Turbine generator manufacturing plant employees, Birds and fish at the turbine generator manufacturing plants AI: Social groups, Nearby residents, Government (policy) AIB: Birds on transportation route	
3.3	3.3.5 Manufacture flue gas scrubber (NaHCO3, NaOH, stacks)	O: Flue gas scrubber manufacturing plant owners E: Cement plants, Sodium hydroxide plants, Soda carbonate plants, Machinery suppliers, Energy companies A,R: Condensing system manufacturing plant employees AI: Condensing system manufacturing plant shareholders AIB: Condensing system manufacturing plant engineers, Birds and fish at the condensing system manufacturing plants	Continue to 3.2.2

Level	**Activity**	**Key Stakeholders**	**End**
3.3	3.3.6 Transport and install or construct the modules (3.3.2-5)	O: Oil-fired power plant owners E: O of 3.3.2-5, Transportation companies, Oil-fired power plant owners, Construction companies A: Transportation carriers, Construction team R: Oil-fired power plants, Birds and fish at the oil-fired power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2-5 AIB: Birds and fish at the oil-fired power plants, Birds on transportation routes	
3	3.4 Compile national oil-fired plant profile: installed capacity, oil consumption, CO2 intensity profile in time and space, replacement rate of materials and modules (3.2, 3.3)	O: Oil-fired power plant owners E, A, R: Managers, Research team, External researchers	
Top	**4.** Obtain fuels from sources, energy, labour, capital	O: Oil-fired power plant owners E: Domestic oil suppliers, Foreign oil suppliers, Domestic energy supplier, Oil-fired power plant owners and Government, Transportation carriers A,R: Managers, Employees AI: Country (labour) AIB: Local residents, Animals at and near oil-fired power plants	
4	4.1 Investigate sources of oil, electricity, and labour	O: Oil-fired power plant owners E: Oil-fired power plant owners, Oil extraction plants, Country (labour), Energy companies, Geographic observatories A, R: Managers, Research team, External researchers	
4	4.2 Supply oil, electricity, labour, and capital	O: Oil-fired power plant owners E: Oil-fired power plant owners, E of 4.1 A, R: Managers, Employees, Engineers AI: Foreign oil suppliers, Government (transportation) AIB: Original residents at extraction site, On-ground and underground animals on-site and at the extraction site, Migration birds, Fishes in on-site water bodies	

Level	Activity	Key Stakeholders	End
4.2	4.2.1 Prepare electricity, engineers, and capital	O: Oil-fired power plant owners E: Oil-fired power plant owners, Electricity companies, Country (labour) A: Managers, Oil-fired power plant owners R: All employees in the power plant AI: Shareholders, Government (policy)	
4.2	4.2.2 Produce oil	O: Oil plants, Oil storage plants E: Oil wells, Machinery suppliers, Energy companies A,R: Oil plants AI: Government (policy), Oil plant shareholders AIB: Oil plant engineers, Birds and bats and fish at the oil plant sites	
4.2.2	4.2.2.1 Supply capital for purchasing raw oil fuels	O: Oil plant owners E: Government (policy), Oil plant owners A,R: Oil plant employees, O of 4.2.2.2 AI: Oil plant shareholders	
4.2.2	4.2.2.2 Extract oil fuels	O: Oil well owners E: Machinery suppliers, Energy companies A,R: Oil well employees AI: Government (transportation), Oil well shareholders AIB: Oil well miners, Birds and fish at oil wells	4.2.2.2.N Natural formation of oil
4.2.2	4.2.2.3 Transport and process oil fuels	O: Oil plant owners E: O of 4.2.2.2, Government (transportation), Transportation carriers A: Transportation carriers, Oil plant employees R: Oil plants, Birds and fish at oil plant sites AI: Foreign O of 4.2.2.2 AIB: Birds on transportation routes	
4.2	4.2.3 Transport and store oil	O: Oil-fired power plant owners E: O of 4.2.2, Government (transportation), Pipeline owners A: Storehouse employees, Transportation carriers R: Oil-fired power plants, Storehouse workers, Birds and fish at oil plant sites AI: Foreign O of 4.2.2 AIB: Birds and fish on transportation routes	
4	4.3 Compile consumption profile of transformational inputs for oil-fired electricity production	O: Oil-fired power plant owners E, A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
Top	**5.** Operate the power plant to produce electricity	O: Oil-fired power plant owners E: Oil-fired power plant owners, Government (quota) A: Employees, Managers, Oil-fired power plant owners R: Oil-fired power plant owners, Managers, Employees, Side product customers, Oil-fired power plant employees, Animals at and near oil-fired power plants, Local residents AI: KSs in 2,3,4, Government (quota) AIB: Carbon storage site residents and animals, Waste disposal site residents and animals	
5	5.1 Repair and replace structural and functional parts (3.4)	O: Oil-fired power plant owners E: Oil-fired power plant owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of power plant storehouse, Compartment Carriers, Carriers for waste compartments	
5.1	5.1.1 Investigate low-carbon or energy saving construction materials (3.2.6)	O: Oil-fired power plant owners E: Oil-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Government (foreign suppliers)	
5.1	5.1.2 Investigate low-carbon or more efficient modules (3.3.8)	O: Oil-fired power plant owners E: Oil-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Government (foreign suppliers)	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: Oil-fired power plant owners E: Oil-fired power plant owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: Oil-fired power plant owners, Recycling companies, Steel plants E: Oil-fired power plant owners A,R: Recycling plants, Waste landfill plants AI: Government (transportation, policy), Social groups (policy), Residents at each plant site AIB: Birds and Fish at each plant	
5	5.2 Operate and produce (4.3; 5.1)	O: Oil-fired power plant owners E: E of 3.4 and 4.3, Electricity company A: Engineers, Managers, Oil-fired power plant owners R: Customers (electricity), Employees of oil-fired power plants, Birds and fish at oil-fired power plant sites	

Level	Activity	Key Stakeholders	End
5	5.3 Distribute by-products, Liquid combustion waste, and emit CO2 (5.2)	O: Oil-fired power plant owners E: Government (transportation), Carbon storage site owners (CO2) A: Oil-fired power plant employees R: Liquid waste carriers, Customers (by product), By-product carriers, Birds and Fishes at the power plants and storage sites AI: Oil-fired power plant employees, Carbon storage site owners AI: Government (CO2 budget), Customers (demand), Local residents and social groups AIB: Local residents, Birds and fish at oil-fired power plant sites	
5.3	5.3.1 Store by-products (5.2)	O: Oil-fired power plant owners E: Oil-fired power plant owners A: Managers, Storehouse workers R: Storehouse workers, A of 5.3.2 AIB: Fish at oil-fired power plants	
5.3	5.3.2 Identify demand and sell by-products (5.3.1)	O: Oil-fired power plant owners E: Oil-fired power plant owners A: Managers, Storehouse workers, Sales manager, Sales R: Customers (by-product) AI: Government (policy)	
5.3	5.3.3 Identify combustion waste recycling plants, landfill plants, and CO2 storage mining sites	O: Government, Oil-fired power plant owners E: Government A: Managers, Research team, External researchers R: Customers (Combustion waste recycling plants, Landfill plants, CO2 storage mines, By-product customers)	
5.3	5.3.4 Supply capital for waste treatment (bottom ash etc) and CO2 storage (5.3.3)	O: Oil-fired power plant owners E: Oil-fired power plant owners A,R: Managers, Research team, External researchers	
5.3	5.3.5 Distribute combustion wastes, wastes from by-product production, and CO2 (5.3.4)	O: R of 5.3.3 E: Oil-fired power plant owners A: Waste carriers R: O of 5.3.5	
5.3	5.3.6 Emit CO2 (diffused) (5.2, 5.3.2, 5.3.5)	O, E, A: Oil-fired power plant owners R: Wide weak stakeholders on land and water bodies	5.3.6.N Natural diffusion and absorption of CO2
5.3	5.3.7 Compile waste treatment and emission profile (5.3.6)	O: Oil-fired power plant owners E,A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
Top	6. Distribute to grid/store electricity	O: Oil-fired power plant owners, Government E: Oil-fired power plants, Government A: Oil-fired power plants R: Customers, Oil-fired power plant owners, Managers, Employees AI: Animals at and near oil-fired power plants AIB: Local residents, Animals at and near oil-fired power plants	
Top	7. Form an apposite system of oil-fired electricity production for the sustainability evaluation objectives	O: Oil-fired power plant owners E: Information suppliers in 1-6, Oil-fired power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

D.2.3 Wider KSs of Gas-fired Power Production

The table presents the complete expanded stakeholder analysis for gas-fired power production system.

Level	Activity	Key Stakeholders	End
Top	**1.** Develop the apposite subsystem of gas-fired power plants based on sustainability evaluation objectives	O: LNG-fired power plant owners E: Government, Social groups (EC, UN, IEA, OECD) A,R: Managers, Research team, External researchers R: LNG-fired power plant owners, Managers, Research team	
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objectives	O: Government, LNG-fired power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
1	1.2 Identify lead of sustainability evaluation objectives relating to LNG-fired electricity and the sustainability criteria: governments, and organisations joined by the country	O: Government, LNG-fired power plant owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	

Level	**Activity**	**Key Stakeholders**	**End**
1	1.3 Determine the the system boundary of LNG-fired electricity production system, the initial system, and the time scope of evaluation	O: Government, LNG-fired power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.** Investigate the power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: LNG-fired power plant owners, Government E: LNG-fired power plant owners, Local residents, Employees working at LNG-fired power plants, Animals at LNG-fired power plants, Shareholders and creditors of LNG-fired power plants, Internal information management teams A,R: Managers, Research team, External researchers	
2	2.1 Determine the power plants to be included in evaluation	O: Government, LNG-fired power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, LNG-fired power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.3 Determine used area, technologies, and materials	O: Government, LNG-fired power plant owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI: Social groups (EC, IEA, European parliament, European Economic and Social Committee, IEA), Transportation and pipeline carriers AIB: Original residents at LNG-fired power plant sites, LNG-fired power plant employees, Original on-ground and underground animals at LNG-fired power plants, Migration birds passing the LNG-fired power plants	
2	2.4 Investigate carbon containment and emission of the materials and modules	O: LNG-fired power plant owners E: Material suppliers, Module suppliers A,R: Managers, Research team, External researchers	
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of LNG-fired plants	O: LNG-fired power plant owners E, A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
Top	**3.** Supply functional modules, materials, labour for maintenance and replacement	O: LNG-fired power plant owners E: Technology suppliers (steam boiler manufacturers, turbine generator manufacturers, cooling manufacturers, flue gas treatment manufacturers), Construction material suppliers (offices, structures), Government (policy), Land supplier, Owners (capital), Material and modules carriers, Technicians A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or more efficient substitutes	O: LNG-fired power plant owners E: LNG-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers	
3	3.2 Supply materials for building construction (3.1)	O: LNG-fired power plant owners E: Government, Material suppliers, LNG-fired power plant owners A,R: Managers, Research team, External researchers, Construction team, Office repairing workers AI: Government (construction, technology policy), Foreign material suppliers AIB: On-site and on-route human and animals for material production and transportation, On-site underground and water animals	
3.2	3.2.1 Supply capital for purchasing construction materials: cement, steel, glass, paint	O: LNG-fired power plant owners E: Government (policy), LNG-fired power plant owners A,R: LNG-fired power plant managers R: O of 3.2.2-5 AI: Shareholders of LNG-fired power plants	
3.2	3.2.2 Produce cement	O: Cement plant owners E: Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companiesA,R: Cement plant employees AI: Cement plant shareholders AIB: Cement plant engineers, Birds and fish at the cement plants	
3.2.2	3.2.2.1 Supply capital for purchasing cement (limestone, mudstone, clay)	O: Cement plant owners E: Government (policy), Cement plant owners A: Cement plant managers R: O of 3.2.2.2-4 AI: Cement plant shareholders	

Level	Activity	Key Stakeholders	End
3.2.2	3.2.2.2 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Government (policy), Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.2.2.N Natural formation of lime mines
3.2.2	3.2.2.3 Extract mudstone	O: Mudstone plant owners E: Machinery manufacturers, Energy companies A,R: Mudstone plant employees AI: Government (policy), Mudstone plant shareholders AIB: Mudstone miners, Birds and fish at mudstone mines	3.2.2.3.N Natural formation of mudstone mines
3.2.2	3.2.2.4 Extract clay	O: Clay plant owners E: Machinery manufacturers, Energy companies A,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.2.4.N Natural formation of clay
3.2.2	3.2.2.5 Transport materials and produce concrete (3.2.2.2-4)	O: Cement plant owners E: Government (transportation), Cement plant owners, O of 3.2.2.2-4, Transportation companies A: Cement plant employees, Transportation carriers R: Cement plants, Birds and fish at cement plant sites AI: Foreign O of 3.2.2.2-5 AIB: Birds on transportation routes	
3.2	3.2.3 Produce steel	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.3	3.2.3.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.3.2-5 AI: Steel plant shareholders	
3.2.3	3.2.3.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.3.2.N Natural formation of iron ores
3.2.3	3.2.3.3 Extract limestone		Continue to 3.2.2.2

Level	**Activity**	**Key Stakeholders**	**End**
3.2.3	3.2.3.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.3	3.2.3.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery manufacturers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.3.5.N Natural formation of coal or LNG
3.2.3	3.2.3.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.3.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.3.2-5 AIB: Birds on transportation routes	
3.2	3.2.4 Produce glass	O: Glass plants E: Sand plants, Soda ash plants, Limestone plants, Machinery suppliers, Energy companies A: Glass plant employees AI: Glass plant shareholders AIB: Glass plant engineers, Birds and fish at the glass plants	
3.2.4	3.2.4.1 Supply capital for purchasing glass (limestone, sand, soda ash)	O: Glass plant owners E: Government (policy), Glass plant owners A,R: Glass plant employees, Manufacturers in 3.2.4.2-4	
3.2.4	3.2.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4	3.2.4.3 Extract sand	O: Sand mine owners E: Machinery suppliers, Energy companies A,R: Sand mine employees AI: Sand mine shareholders AIB: Sand miners, Birds and fish at the sand mines	3.2.4.3.N Natural formation of sand
3.2.4	3.2.4.4 Produce soda ash [C-]	O: Soda ash plants E: Limestone plants, CO2 suppliers, Salt brine mines, Machinery suppliers, Energy companies A,R: Soda ash plant employees AI: Government (transportation), Soda ash plant shareholders AIB: Soda ash plant engineers, Fish in water bodies at the soda ash plants	
3.2.4.4	3.2.4.4.1 Supply capital for purchasing soda ash	O: Soda ash plant owners E: Government (policy), Soda ash plant owners A,R: Soda ash plant employees, Manufacturers in 3.2.4.4.2-4	

Level	Activity	Key Stakeholders	End
3.2.4.4	3.2.4.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4.4	3.2.4.4.3 Extract salt brines	O: Salt brine mine owners E: Machinery suppliers, Energy companies A,R: Salt brine mine employees AI: Salt brine mine shareholders AIB: Salt brine miners, Birds and fish at the salt brine mines	3.2.4.4.3.N Natural formation of salt brines
3.2.4.4	3.2.4.4.4 Supply CO2	O: CO2 suppliers (fossil fuel-fired power plants) E: Machinery suppliers, Energy companies A,R: CO2 supplier employees AI: Government (transportation), CO2 supplier shareholders AIB: CO2 supplier engineers, Fish in water bodies at the CO2 supplier sites	3.2.4.4.4 Supply of industrial CO2
3.2.4.4	3.2.4.4.5 Transport raw materials and produce soda ash (3.2.4.4.2-4)	O: Soda ash plant owners E: O of 3.2.4.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Soda ash plant employees R: Soda ash plants, Birds and fish at soda ash plant sites AI: Foreign O of 3.2.4.4.2-4 AIB: Birds on transportation routes	
3.2.4	3.2.4.5 Transport raw materials and produce glass (3.2.4.2-4)	O: Glass plant owners E: O of 3.2.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Glass plant employees R: Glass plants, Birds and fish at glass plant sites AI: Foreign O of 3.2.4.2-4 AIB: Birds on transportation routes	
3.2	3.2.5 Produce paint	O: Paint plants E: Chemical suppliers, Machinery suppliers, Energy companies A: Paint plant employees AI: Paint plant shareholders AIB: Paint plant engineers, Birds and fish at the paint plants	
3.2	3.2.6 Transport materials and construct buildings (3.1.1-5)	O: LNG-fired power plant owners E: O of 3.2.2-5, Transportation companies, LNG-fired power plant owners, Construction companies A: Transportation carriers, Construction team R: LNG-fired power plants, Bird and fish at the LNG-fired power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.2.2-5 AIB: Birds and fish at the LNG-fired power plants, Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3	3.3 Supply functional modules installed and carbon intensities (3.1)	O: LNG-fired power plant owners E: Government, LNG-fired power plant owners, Module suppliers (steam boiler, condenser, turbine generator, flue gas treatment) A,R: Managers, Research team, External researchers, Construction team, Installation and repairing engineers AI: Government (construction, technology policy), Foreign technology suppliers AIB: On-site and on-route human and animals for module production and transportation	
3.3	3.3.1 Supply capital for purchasing modules (steam boiler, condenser and pumps, turbine generator, flue gas scrubber)	O: LNG-fired power plant owners E: Government (policy), LNG-fired power plant owners A,R: LNG-fired power plant managers R: O of 3.3.2-5 AI: Shareholders of LNG-fired power plants	
3.3	3.3.2 Manufacture steam boiler (steel)	O: Steam boiler manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Steam boiler manufacturing plant employees AI: Steam boiler manufacturing plant shareholders AIB: Steam boiler manufacturing plant engineers, Birds and fish at the steam boiler manufacturing plants	Continue to 3.2.3
3.3	3.3.3 Manufacture condensing compartments (steel)	O: Condensing system manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Condensing system manufacturing plant employees AI: Condensing system manufacturing plant shareholders AIB: Condensing system manufacturing plant engineers, Birds and fish at the condensing system manufacturing plants	Continue to 3.2.3
3.3	3.3.4 Manufacture turbine and generator (steel and iron, aluminium, copper)	O: Turbine generator manufacturing plant owners E: Steel plants, Aluminium plants, Copper plants, Machinery suppliers, Energy companies A,R: Turbine generator manufacturing plant employees AI: Turbine generator manufacturing plant shareholders AIB: Turbine generator manufacturing plant engineers, Birds and fish at the turbine generator manufacturing plants	

Level	Activity	Key Stakeholders	End
3.3.4	3.3.4.1 Supply capital for purchasing turbine generators	O: Turbine generator manufacturing plant owners E: Government (policy), Turbine generator manufacturing plant owners A,R: Turbine generator manufacturing plant managers R: O of 3.3.4.2-4 AI: Shareholders of turbine generator manufacturing plants	
3.3.4	3.3.4.2 Produce steel	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plant	Continue to 3.2.3
3.3.4	3.3.4.3 Produce copper products	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	
3.3.4.3	3.3.4.3.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.3.4.3.2 AI: Copper plant shareholders	
3.3.4.3	3.3.4.3.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.3.4.3.2.N Natural formation of copper ores
3.3.4.3	3.3.4.3.3 Transport and produce copper products	O: Copper plant owners E: O of 3.3.4.3.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.3.4.3.2 AIB: Birds on transportation routes	
3.3.4	3.3.4.4 Produce aluminium products	O: Aluminium plant owners E: Bauxite mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	

Level	Activity	Key Stakeholders	End
3.3.4	3.3.4.4.1 Supply capital for purchasing Aluminium	O: Aluminium plant owners E: Government (policy), Aluminium plant owners A,R: Aluminium plant employees, O of 3.3.4.4.2 AI: Aluminium plant shareholders	
3.3.4	3.3.4.4.2 Extract and process bauxite or process recycled aluminium products	O: Bauxite mine owners E: Machinery suppliers, Energy companies A,R: Bauxite mine employees AI: Government (transportation), Bauxite mine shareholders AIB: Bauxite miners, Birds and fish at bauxite mines	3.3.4.4.2.N Natural formation of bauxite mines
3.3.4	3.3.4.4.3 Transport and produce aluminium products	O: Aluminium plant owners E: O of 3.3.4.4.2, Government (transportation), Transportation carriers A: Transportation carriers, Aluminium plant employees R: Aluminium plants, Birds and fish at aluminium plant sites AI: Foreign O of 3.3.4.4.2 AIB: Birds on transportation routes	
3.3.4	3.3.4.5 Transport materials and manufacture turbine generators	O: Turbine generator manufacturing plant owners E: O of 3.3.4.2-4, Transportation companies, Turbine generator manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Turbine generator manufacturing plant employees, Birds and fish at the turbine generator manufacturing plants AI: Social groups, Nearby residents, Government (policy) AIB: Birds on transportation routes	
3.3	3.3.5 Manufacture flue gas scrubber ($NaHCO3$, $NaOH$, stacks)	O: Flue gas scrubber manufacturing plant owners E: Cement plants, Sodium hydroxide plants, Soda carbonate plants, Machinery suppliers, Energy companies A,R: Condensing system manufacturing plant employees AI: Condensing system manufacturing plant shareholders AIB: Condensing system manufacturing plant engineers, Birds and fish at the condensing system manufacturing plants	Continue to 3.2.2

Level	Activity	Key Stakeholders	End
3.3	3.3.6 Transport and install or construct the modules (3.3.2-5)	O: LNG-fired power plant owners E: O of 3.3.2-5, Transportation companies, LNG-fied power plant owners, Construction companies A: Transportation carriers, Construction team R: LNG-fired power plants, Birds and fish at the LNG-fired power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2-5 AIB: Birds and fish at the LNG-fired power plants, Birds on transportation routes	
3	3.4 Compile national LNG-fired plant profile: installed capacity, LNG consumption, CO2 intensity profile in time and space, replacement rate of materials and modules (3.2, 3.3)	O: LNG-fired power plant owners E, A, R: Managers, Research team, External researchers	
Top	**4.** Obtain fuels from sources, energy, labour, capital	O: LNG-fired power plant owners E: Domestic LNG suppliers, Foreign LNG suppliers, Domestic energy supplier, LNG-fired power plant owners and Government, Transportation carriers A,R: Managers, Employees AI: Country (labour) AIB: Local residents, Animals at and near LNG-fired power plants	
4	4.1 Investigate sources of LNG, electricity, and labour	O: LNG-fired power plant owners E: LNG-fired power plant owners, LNG extraction plants, Country (labour), Energy companies, Geographic observatories A, R: Managers, Research team, External researchers	
4	4.2 Supply LNG, electricity, labour, and capital	O: LNG-fired power plant owners E: LNG-fired power plant owners, E of 4.1 A, R: Managers, Employees, Engineers AI: Foreign LNG suppliers, Government (transportation) AIB: Original residents at extraction site, Onground and underground animals on-site and at the extraction site, Migration birds, Fishes in on-site water bodies	

Level	Activity	Key Stakeholders	End
4.2	4.2.1 Prepare electricity, engineers, and capital	O: LNG-fired power plant owners E: LNG-fired power plant owners, Electricity companies, Country (labour) A: Managers, LNG-fired power plant owners R: All employees in the power plant AI: Shareholders, Government (policy)	
4.2	4.2.2 Produce LNG	O: LNG plants, LNG storage plants E: LNG wells, Machinery suppliers, Energy companies A,R: LNG plants AI: Government (policy), LNG plant shareholders AIB: LNG plant engineers, Birds and bats and fish at the LNG plant sites	
4.2.2	4.2.2.1 Supply capital for purchasing raw LNG fuels	O: LNG plant owners E: Government (policy), LNG plant owners A,R: LNG plant employees, O of 4.2.2.2 AI: LNG plant shareholders	
4.2.2	4.2.2.2 Extract LNG fuels	O: LNG well owners E: Machinery suppliers, Energy companies A,R: LNG well employees AI: Government (transportation), LNG well shareholders AIB: LNG well miners, Birds and fish at LNG wells	4.2.2.2.N Natural formation of LNG
4.2.2	4.2.2.3 Transport and process LNG fuels	O: LNG plant owners E: O of 4.2.2.2, Government (transportation), Transportation carriers A: Transportation carriers, LNG plant employees R: LNG plants, Birds and fish at LNG plant sites AI: Foreign O of 4.2.2.2 AIB: Birds on transportation routes	
4.2	4.2.3 Transport and store LNG	O: LNG-fired power plant owners E: O of 4.2.2, Government (transportation), Pipeline owners A: Storehouse employees, Transportation carriers R: LNG-fired power plants, Storehouse workers, Birds and fish at LNG plant sites AI: Foreign O of 4.2.2 AIB: Birds and fish on transportation routes	
4	4.3 Compile consumption profile of transformational inputs for LNG-fired electricity production	O: LNG-fired power plant owners E, A, R: Managers, Research team, External researchers	

Level	**Activity**	**Key Stakeholders**	**End**
Top	**5.** Operate the power plant to produce electricity	O: LNG-fired power plant owners E: LNG-fired power plant owners, Government (quota) A: Employees, Managers, LNG-fired power plant owners R: LNG-fired power plant owners, Managers, Employees, Side product customers, LNG-fired power plant employees, Animals at and near LNG-fired power plants, Local residents AI: KSs in 2,3,4, Government (quota) AIB: Carbon storage site residents and animals, Waste disposal site residents and animals	
5	5.1 Repair and replace structural and functional parts (3.4)	O: LNG-fired power plant owners E: LNG-fired power plant owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of power plant storehouse, Compartment Carriers, Carriers for waste compartments	
5.1	5.1.1 Investigate low-carbon or energy saving construction materials (3.2.6)	O: LNG-fired power plant owners E: LNG-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Government (foreign suppliers)	
5.1	5.1.2 Investigate low-carbon or more efficient modules (3.3.8)	O: LNG-fired power plant owners E: LNG-fired power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Government (foreign suppliers)	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: LNG-fired power plant owners E: LNG-fired power plant owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: LNG-fired power plant owners, Recycling companies, Steel plants E: LNG-fired power plant owners A,R: Recycling plants, Waste landfill plants AI: Government (transportation, policy), Social groups (policy), Residents at each plant site AIB: Birds and Fish at each plant	
5	5.2 Operate and produce (4.3; 5.1)	O: LNG-fired power plant owners E: E of 3.4 and 4.3, Electricity company A: Engineers, Managers, LNG-fired power plant owners R: Customers (electricity), Employees of LNG-fired power plants, Birds and fish at LNG-fired power plant sites	

Level	Activity	Key Stakeholders	End
5	5.3 Distribute by-products, emit other aerosols and CO2 (5.2)	O: LNG-fired power plant owners E: Government (transportation), Carbon storage site owners (CO2) A: LNG-fired power plant employees R: Customers (by product), By-product carriers, Birds and Fishes at the power plants and storage sites AI: LNG-fired power plant employees, Carbon storage site owners AI: Government (CO2 budget), Customers (demand), Local residents and social groups AIB: Local residents, Birds and fish at LNG-fired power plant sites	
5.3	5.3.1 Store by-products (5.2)	O: LNG-fired power plant owners E: LNG-fired power plant owners A: Managers, Storehouse workers R: Storehouse workers, A of 5.3.2 AIB: Fish at LNG-fired power plants	
5.3	5.3.2 Identify demand and sell by-products (5.3.1)	O: LNG-fired power plant owners E: LNG-fired power plant owners A: Managers, Storehouse workers, Sales manager, Sales R: Customers (by-product) AI: Government (policy)	
5.3	5.3.3 Identify combustion waste recycling plants, landfill plants, and CO2 storage mining sites	O: Government, LNG-fired power plant owners E: Government A: Managers, Research team, External researchers R: Customers (landfill plants, CO2 storage mines, by-product customers)	
5.3	5.3.4 Supply capital for waste treatment (bottom ash etc) and CO2 storage (5.3.3)	O: LNG-fired power plant owners E: LNG-fired power plant owners A,R: Managers, Research team, External researchers	
5.3	5.3.5 Distribute combustion wastes, wastes from by-product production, and CO2 (5.3.4)	O: R of 5.3.3 E: LNG-fired power plant owners A: Waste carriers R: O of 5.3.5	
5.3	5.3.6 Emit CO2 (diffused) (5.2, 5.3.2, 5.3.5)	O, E, A: LNG-fired power plant owners R: Wide weak stakeholders on land and water bodies	5.3.6.N Natural diffusion and absorption of CO2
5.3	5.3.7 Compile waste treatment and emission profile (5.3.6)	O: LNG-fired power plant owners E,A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
Top	6. Distribute to grid/store electricity	O: LNG-fired power plant owners, Government E: LNG-fired power plants, Government A: LNG-fired power plants R: Customers, LNG-fired power plant owners, Managers, Employees AI: Animals at and near LNG-fired power plants AIB: Local residents, Animals at and near LNG-fired power plants	
Top	7. Form an apposite system of LNG-fired electricity production for the sustainability evaluation objectives	O: LNG-fired power plant owners E: Information suppliers in 1-6, LNG-fired power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

D.2.4 Wider KSs of Nuclear Power Production

The table presents the complete expanded stakeholder analysis for nuclear power production system.

Level	Activity	Key Stakeholders	End
Top	**1.** Develop the apposite subsystem of nuclear power plants based on sustainability evaluation objectives	O: Nuclear power plant owners E: Government, Social groups (EC, UN, IEA, OECD) A,R: Managers, Research team, External researchers R: Nuclear power plant owners, Managers, Research team	
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objectives	O: Government, Nuclear power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
1	1.2 Identify lead of sustainability evaluation objectives relating to nuclear electricity and the sustainability criteria: governments, and organisations joined by the country	O: Government, Nuclear power plant owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
1	1.3 Determine the the system boundary of nuclear electricity production system, the initial system, and the time scope of evaluation	O: Government, Nuclear power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.** Investigate nuclear power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: Nuclear power plant owners, Government E: Nuclear power plant owners, Local residents, Employees working at nuclear power plant sites, Animals at and near nuclear power plants, Shareholders and creditors, Internal information management teams A,R: Managers, Research team, External researchers	
2	2.1 Determine the power plants to be included in evaluation	O: Government, Nuclear power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, Nuclear power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.3 Determine used area, technologies, and materials	O: Government, Nuclear power plant owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI:Social groups (EC, IEA, European parliament, European Economic and Social Committee, IEA, European Nuclear Energy Council, World Nuclear Association, European Nuclear Society) AIB: Original residents at nuclear power plants, Local residents, Nuclear power plant employees, Original animals at nuclear power plants, Migration birds	
2	2.4 Investigate carbon containment and emission of the materials and modules	O: Nuclear power plant owners E: Material suppliers A,R: Managers, Research team, External researchers	
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of nuclear plants.	Nuclear power plant owners E, A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
Top	**3.** Supply functional modules, materials, labour for maintenance and replacement	O: Nuclear power plant owners E: Technology suppliers (buildings, nuclear reactor, turbine generator, heat exchangers, pipes, cables, compressors, hydraulic equipment, thermal electric insulation), Construction material suppliers (offices, structures), Government (policy), Land supplier, Nuclear power plant owners (capital), Material and modules carriers, Engineers A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or technical efficient substitutes	O: Nuclear power plant owners E: Nuclear power plant owners, Available suppliers A, R: Managers, Research team, External researchers	
3	3.2 Construct structures and buildings, install functional modules (buildings, nuclear reactor, turbine generator, heat exchangers, pipes, cables, compressors, hydraulic equipment, thermal electric insulation)	O: Nuclear power plant owners E: Government (land), Material suppliers, Nuclear power plant owners, Construction companies A,R: Managers, Construction and maintenance team AI: Government (policy), Foreign material suppliers AIB: Local residents of nuclear power plants, Birds and migration birds resting near Nuclear power plant sites, Fish in water bodies at nuclear power plant sites	
3.2	3.2.1 Supply capital for purchasing materials (construction, modules)	O: Nuclear power plant owners E: Government (policy), Nuclear power plant owners A,R: Nuclear power plant managers R: O of 3.2.2-20 AI: Shareholders of nuclear power plant	
3.2	3.2.2 Produce aluminium	O: Aluminium plant owners E: Bauxite mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	
3.2.2	3.2.2.1 Supply capital for purchasing Aluminium	O: Aluminium plant owners E: Government (policy), Aluminium plant owners A,R: Aluminium plant employees, O of 3.2.2.2 AI: Aluminium plant shareholders	

Level	Activity	Key Stakeholders	End
3.2.2	3.2.2.2 Extract and process bauxite or process recycled aluminium products	O: Bauxite mine owners E: Machinery suppliers, Energy companies A,R: Bauxite mine employees AI: Government (transportation), Bauxite mine shareholders AIB: Bauxite miners, Birds and fish at bauxite mines	3.2.2.2.N Natural formation of bauxite mines
3.2.2	3.2.2.3 Transport and produce aluminium products	O: Aluminium plant owners E: O of 3.3.4.4.2, Government (transportation), Transportation carriers A: Transportation carriers, Aluminium plant employees R: Aluminium plants, Birds and fish at aluminium plant sites AI: Foreign O of 3.2.2.2 AIB: Birds on transportation routes	
3.2	3.2.3 Produce clay, bentonite	O: Clay plant owners E: Machinery manufacturers, Energy companies A,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.3.N Natural formation of clay
3.2	3.2.4 Produce basalt	O: Basalt plant owners E: Machinery manufacturers, Energy companies A,R: Basalt plant employees AI: Basalt shareholders AIB: Basalt miners, Birds and fish at basalt mines	3.2.4.N Natural formation of basalt rocks
3.2	3.2.5 Produce chromium	3.2.5 O: Chromium plant owners E: Chromium ore mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	
3.2.5	3.2.5.1 Supply capital for purchasing chromium ores	O: Chromium plant owners E: Government (policy), chromium plant owners A,R: Chromium plant employees, O of 3.2.5.2 AI: Chromium plant shareholders	
3.2.5	3.2.5.2 Extract and process chromium ores or recycle chromium materials	O: Chromium mine owners E: Machinery suppliers, Energy companies A,R: Chromium mine employees AI: Government (transportation), Chromium mine shareholders AIB: Chromium ore miners, Birds and fish at chromium mines	3.2.5.2.N Natural formation of chromium mines

Level	Activity	Key Stakeholders	End
3.2.5	3.2.5.3 Transport and produce chromium products	O: Aluminium plant owners E: O of 3.2.5.2, Government (transportation), Transportation carriers A: Transportation carriers, Chromium plant employees R: Chromium plants, Birds and fish at chromium plant sites AI: Foreign O of 3.2.5.2 AIB: Birds on transportation routes	
3.2	3.2.6 Produce copper	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	
3.2.6	3.2.6.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.2.6.2 AI: Copper plant shareholders	
3.2.6	3.2.6.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.2.6.2.N Natural formation of copper ores
3.2.6	3.2.6.3 Transport and produce copper products	O: Copper plant owners E: O of 3.2.6.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.2.6.2 AIB: Birds on transportation routes	
3.2	3.2.7 Produce fluorspar	O: Fluorspar plant owners E: Fluorite mines, Machinery suppliers, Energy companies A,R: Fluorspar plant employees AI: Fluorspar plant shareholders AIB: Fluorspar plant engineers, Birds and fish at the fluorspar plant	
3.2.7	3.2.7.1 Supply capital for purchasing fluorspar	O: Fluorite plant owners E: Government (policy), Fluorite plant owners A,R: Fluorite plant employees, O of 3.2.7.2 AI: Fluorite plant shareholders	
3.2.7	3.2.7.2 Extract fluorite ores or process recycled materials	O: Fluorite ore mine owners E: Machinery suppliers, Energy companies A,R: Fluorite ore mine employees AI: Government (transportation), Fluorite ore mine shareholders AIB: Fluorite ore miners, Birds and fish at fluorite ore mines	3.2.7.2.N Natural formation of fluorite ores

Level	Activity	Key Stakeholders	End
3.2.7	3.2.7.3 Transport and produce fluorspar	O: Fluorite plant owners E: O of 3.2.7.2, Government (transportation), Transportation carriers A: Transportation carriers, Fluorite plant employees R: Fluorite plants, Birds and fish at fluorite plant sites AI: Foreign O of 3.2.7.2 AIB: Birds on transportation routes	
3.2	3.2.8 Produce gravel	O: Gravel mine owners E: Machinery suppliers, Energy companies A,R: Gravel mine employees AI: Gravel mine shareholders AIB: Gravel miners, Birds and fish at the gravel mines	3.2.8.N Natural formation of gravel
3.2	3.2.9 Extract sand	O: Sand mine owners E: Machinery suppliers, Energy companies A,R: Sand mine employees AI: Sand mine shareholders AIB: Sand miners, Birds and fish at the sand mines	3.2.9.N Natural formation of sand
3.2	3.2.10 Produce gypsum	O: Gypsum mine owners E: Machinery suppliers, Energy companies A,R: Gypsum mine employees AI: Gypsum mine shareholders AIB: Gypsum miners, Birds and fish at the gypsum mines	3.2.10.N Natural formation of gypsum mines
3.2	3.2.11 Produce iron	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.11	3.2.11.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.11.2-5 AI: Steel plant shareholders	
3.2.11	3.2.11.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.11.2.N Natural formation of iron ores
3.2.11	3.2.11.3 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.3.3.N Natural formation of lime mines

Level	Activity	Key Stakeholders	End
3.2.11	3.2.11.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.11	3.2.11.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery manufacturers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.11.5.N Natural formation of coal or LNG
3.2.11	3.2.11.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.11.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.11.2-5 AIB: Birds on transportation routes	
3.2	3.2.12 Produce lead	3.2.12 O: Lead plant (also zinc plant) owners E: Galena mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Lead plant employees AI: Lead plant shareholders AIB: Lead plant engineers, Birds and fish at the lead plant	
3.2.12	3.2.12.1 Supply capital for purchasing galena ores	O: Lead plant owners E: Government (policy), Lead plant owners A,R: Lead plant employees, O of 3.2.12.2 AI: Lead plant shareholders	
3.2.12	3.2.12.2 Extract galena ores	O: Galena ore mine owners E: Machinery suppliers, Energy companies A,R: Galena mine employees AI: Government (transportation), Galena mine shareholders AIB: Galena ore miners, Birds and fish at galena mines	3.2.12.2.N Natural formation of galena
3.2.12	3.2.12.3 Transport and produce lead products	O: Lead plant owners E: O of 3.2.12.2, Government (transportation), Transportation carriers A: Transportation carriers, Lead plant employees R: Lead plants, Birds and fish at lead plant sites AI: Foreign O of 3.2.12.2 AIB: Birds on transportation routes	

Level	**Activity**	**Key Stakeholders**	**End**
3.2	3.2.13 Produce calcite	O: Calcite plant owners E:Limestone mines, CO2 suppliers, Machinery suppliers, Energy companies A,R: Lead plant employees AI: Lead plant shareholders AIB: Lead plant engineers, Birds and fish at the lead plant	
3.2.13	3.2.13.1 Supply capital for purchasing limestone		
3.2.13	3.2.13.2 Extract limestone		Continue to 3.2.11.3
3.2.13	3.2.13.3 Supply CO2 [C-]	O,E,A,R: Up-stream CO2 production plants	3.2.7.3 - CO2 production from industrial sources
3.2.13	3.2.13.4 Transport materials and produce calcite	O: Calcite plant owners E: Government (transportation), Calcite plant owners, O of 3.2.13.2-3, Transportation companies A: Calcite plant employees, Transportation carriers R: Calcite plants, Birds and fish at calcite plant sites AI: Foreign O of 3.2.13.2-3 AIB: Birds on transportation routes	
3.2	3.2.14 Produce manganese	O: Manganese plant owners E: Manganese ore mines, Machinery suppliers, Recycled manganese product owners, Energy companies A,R: Manganese plant employees AI: Manganese plant shareholders AIB: Manganese plant engineers, Birds and fish at the manganese plant	
3.2.14	3.2.14.1 Supply capital for purchasing manganese ores	O: Manganese plant owners E: Government (policy), Manganese plant owners A,R: Manganese plant employees, O of 3.2.14.2 AI: Manganese plant shareholders	
3.2.14	3.2.14.2 Extract manganese ores (also olivine in EU)	O: Manganese mine owners E: Machinery suppliers, Energy companies A,R: Manganese mine employees AI: Government (transportation), Manganese mine shareholders AIB: Manganese ore miners, Birds and fish at manganese mines	3.2.14.2.N Natural formation of manganese mines

Level	Activity	Key Stakeholders	End
3.2.14	3.2.14.3 Transport and produce manganese	O: Manganese plant owners E: O of 3.2.14.2, Government (transportation), Transportation carriers A: Transportation carriers, Manganese plant employees R: Manganese plants, Birds and fish at manganese mine sites AI: Foreign O of 3.2.14.2 AIB: Birds on transportation routes	
3.2	3.2.15 Produce Nickel	O: Nickel plant owners E: Nickel sulphide ore mines, Machinery suppliers, Recycled nickel product owners, Energy companies A,R: Nickel plant employees AI: Nickel plant shareholders AIB: Nickel plant engineers, Birds and fish at the nickel plant	
3.2.15	3.2.15.1 Supply capital for purchasing sulphide ores	: Nickel plant owners E: Government (policy), Nickel plant owners A,R: Nickel plant employees, O of 3.2.15.2 AI: Nickel plant shareholders	
3.2.15	3.2.15.2 Extract sulphide ores	O: Sulphide mine owners E: Machinery suppliers, Energy companies A,R: Sulphide mine employees AI: Government (transportation), Sulphide mine shareholders AIB: Sulphide ore miners, Birds and fish at sulphide mines	3.2.15.2.N Natural formation of sulphide mines
3.2.15	3.2.15.3 Transport and produce nickel	O: Nickel plant owners E: O of 3.2.15.2, Government (transportation), Transportation carriers A: Transportation carriers, Nickel plant employees R: Sulphide mine employees, Birds and fish at sulphide mine sites AI: Foreign O of 3.2.15.2 AIB: Birds on transportation routes	
3.2	3.2.16 Produce olivine	O: Olivine plant owners E: Olivine ore mines, Machinery suppliers, Energy companies A,R: Olivine plant employees AI: Olivine plant shareholders AIB: Manganese plant engineers, Birds and fish at the olivine plant	
3.2.16	3.2.16.1 Supply capital for purchasing olivine ores	O: Olivine plant owners E: Government (policy), Manganese plant owners A,R: Olivine plant employees, O of 3.2.16.2 AI: Olivine plant shareholders	
3.2.16	3.2.16.2 Extract olivine ores	O: Olivine mine owners E: Machinery suppliers, Energy companies A,R: Olivine mine employees AI: Government (transportation), Olivine mine shareholders AIB: Olivine miners, Birds and fish at olivine mines	3.2.16.2.N Natural formation of olivine

Level	Activity	Key Stakeholders	End
3.2.16	3.2.16.3 Transport and produce olivine	O: Olivine plant owners E: O of 3.2.16.2, Government (transportation), Transportation carriers A: Transportation carriers, Olivine plant employees R: Olivine plants, Birds and fish at olivine mine sites AI: Foreign O of 3.2.16.2 AIB: Birds on transportation routes	
3.2	3.2.17 Produce sodium chloride	O: Salt plants E: Brine wells, Machinery suppliers, Energy companies A: Managers, Research team, External researchers, Salt plants AI: Salt plant owners AIB: Fish in water bodies at the salt plants	3.2.17.N Natural formation of brine (salt water)
3.2	3.2.18 Extract soil	O: Loam plants E: Sand plants, Clay plants, Machinery suppliers, Energy companies A: Managers, Research team, External researchers, Loam plants AI: Loam plant owners AIB: Fish in water bodies at the loam plants	3.2.18.N Natural formation of soil, sand, clay
3.2	3.2.19 Produce Titanium	O: Titanium plant owners E: Rutile mines, Coal plants (coke), Machinery suppliers, Energy companies A,R: Titanium plant employees AI: Titanium plant owners AIB: Birds and fish at titanium plants	
3.2.19	3.2.19.1 Supply capital for purchasing titanium	O: Titanium plant owners E: Government (policy), Titanium plant owners A: Titanium plant managers R: O of 3.2.19.2-3 AI: Titanium plant shareholders	
3.2.19	3.2.19.2 Extract rutile	O: Rutile mine owners E: Machinery manufacturers, Energy companies A,R: Rutile mine employees AI: Government (policy), Rutile mine shareholders AIB: Rutile miners, Birds and fish at rutile mines	3.2.19.2.N Natural formation of rutile
3.2.19	3.2.19.3 Produce coke		Continue to 3.2.11.5
3.2.19	3.2.19.4 Transport materials and produce titanium products	O: Titanium plant owners E: Government (transportation), Titanium plant owners, O of 3.2.19.2-3, Transportation companies A: Titanium plant employees, Transportation carriers R: Titanium plant employees, Birds and fish at Titanium plants AI: Foreign O of 3.2.19.2-3 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.2	3.2.20 Produce Zinc	O: Zinc plant owners E: Galena mines, Machinery suppliers, Waste zinc product owners, Energy companies A,R: Zinc plant employees AI: Zinc plant shareholders AIB: Zinc plant engineers, Birds and fish at the zinc plant	Continue to 3.2.12.2
3.2	3.2.21 Transport materials and construct buildings and modules (3.2.2-20)	O: Nuclear power plant owners E: O of 3.2.2-20, Transportation companies, Nuclear power plant owners, Construction companies A: Transportation carriers, Construction team R: Nuclear power plants, Bird and fish at the Nuclear power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.2.2-20 AIB: Birds and fish at the Nuclear power plants, Birds on transportation routes	
3	3.3 Compile national nuclear plant profile: installed capacity, CO2 intensity profile in time and space, replacement rate of materials and modules	O: Nuclear power plant owners E, A, R: Managers, Research team, External researchers	
Top	**4.** Obtain necessary Uranium fuels, energy, labour, capital	O: Nuclear power plant owners E: Domestic energy supplier, Nuclear power plant owners, Government, Uranium fuel suppliers A,R: Managers, Employees AI: Country (labour), Foreign Uranium fuel suppliers AIB: Local residents, Animals at nuclear power plants	
4	4.1 Investigate sources of Uranium fuel suppliers, electricity, and labour	O: Nuclear power plant owners E: Nuclear power plant owners, Country (labour), Energy companies, Meteorology institutions, Geographic observatories A, R: Managers, Research team, External researchers	
4	4.2 Supply Uranium nuclear fuel, electricity, labour, capital	O: Nuclear power plant owners E: Nuclear power plant owners, Determined E of 4.1, Uranium fabrication plants A: Managers, Engineers R: Managers, Employees, Engineers AI: Foreign Es, Government (transportation) AIB: Original residents near nuclear power plant site, On-ground and underground animals vertically near the drills, Birds and fish at nuclear power plant sites	

Level	Activity	Key Stakeholders	End
4.2	4.2.1 Supply capital for UF6 fabrication	O: Uranium fabrication plant owners E: Government (policy), Uranium fabrication plant owners A,R: Uranium fabrication plant employees, O of 4.2.2 AI: Uranium fabrication plant shareholders	
4.2	4.2.2 Supply UF6 solid	O: Uranium enrichment plant owners E: Uranium enrichment plants, Machinery suppliers, Energy companies A,R: Uranium enrichment plant employees AI: Government (transportation), Uranium enrichment plant shareholders AIB: Uranium enrichment plant employees, Birds and fish at Uranium enrichment plant	
4.2.2	4.2.2.1 Supply capital for UF6 enrichment	O: Uranium enrichment plant owners E: Government (policy), Uranium enrichment plant owners A,R: Uranium enrichment plant employees, O of 4.2.2.2 AI: Uranium enrichment plant shareholders	
4.2.2	4.2.2.2 Supply UF6 gas	O: Uranium conversion plant owners E: Uranium conversion plants, Machinery suppliers, Energy companies A,R: Uranium conversion plant employees AI: Government (transportation), Uranium conversion plant shareholders AIB: Uranium conversion plant employees, Birds and fish at Uranium conversion plant	
4.2.2.2	4.2.2.2.1 Supply capital for Urania conversion	O: Uranium conversion plant owners E: Government (policy), Uranium conversion plant owners A,R: Uranium conversion plant employees, O of 4.2.2.2.2 AI: Uranium conversion plant shareholders	
4.2.2.2	4.2.2.2.2 Supply Urania	O: Uranium mine owners E: Uranium mines, Machinery suppliers, Energy companies A,R: Uranium mine employees AI: Government (transportation), Uranium mine shareholders AIB: Uranium mine employees, Birds and fish at Uranium mines	4.2.2.2.2.N Natural formation of Uranium mines
4.2.2.2	4.2.2.2.3 Supply and form UF6 gas	O: Uranium conversion plant owners E: O of 4.2.2.2.2, Government (transportation), Transportation carriers A: Transportation carriers, Uranium conversion plant employees R: Uranium mine employees, Birds and fish at Uranium conversion sites AI: Foreign O of 4.2.2.2.2 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
4.2.2	4.2.2.3 Supply and form UF6 solid	O: Uranium enrichment plant owners E: O of 4.2.2.2, Government (transportation), Transportation carriers A: Transportation carriers, Uranium enrichment plant employees R: Uranium fabrication plants, Birds and fish at Uranium enrichment sites AI: Foreign O of 4.2.2.2 AIB: Birds on transportation routes	
4.2	4.2.3 Supply and form UO2 fabricated uranium fuel	O: Uranium fabrication plant owners E: O of 4.2.2, Government (transportation), Transportation carriers A: Transportation carriers, Uranium fabrication plant employees R: Uranium fabrication plants, Birds and fish at Uranium fabrication sites AI: Foreign O of 4.2.2 AIB: Birds on transportation routes	
4	4.3Compile consumption profile of transformational inputs for nuclear electricity production	O: Nuclear power plant owners E, A, R: Managers, Research team, External researchers	
Top	**5.** Operate the power plant to produce electricity	O: Nuclear power plant owners E: Nuclear power plant owners, Government (quota) A: Employees, Managers, Nuclear power plant owners R: Nuclear power plant owners, Managers, Employees, Nuclear power plant employees, Local residents, Animals at and near nuclear power plants AI: KSs in 2,3,4, Government (quota) AIB: Waste disposal site residents and animals	
5	5.1 Repair and replace structural and functional parts (3.4)	O: Nuclear power plant owners E: Nuclear power plant owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of storehouse, Compartment Carriers, Carriers for displaced compartments	
5.1	5.1.1 Investigate low-carbon or energy saving construction materials	O: Nuclear power plant owners E: Nuclear power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.2 Investigate low-carbon or more efficient modules	O: Nuclear power plant owners E: Nuclear power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: Nuclear power plant owners E: Nuclear power plant owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	

Level	Activity	Key Stakeholders	End
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: Nuclear power plant owners, Recycling companies E: Nuclear power plant owners A,R: Transportation carriers, Recycling plants, Landfill companies AI: Government (transportation, policy), Social groups (policy), Residents at each plant site AIB: Birds and fish at each plant	
5	5.2 Operate and produce electricity (4.3; 5.1)	O: Nuclear power plant owners E: E of 3, 4, Energy companies A: Engineers, Managers, Nuclear power plant owners R: Customers (electricity), Employees of nuclear power plants, Birds and fish at nuclear power plant sites	
5	5.3 Dispose radioactive wastes(5.2)	O: Nuclear power plant owners E: Government (transportation) A: Engineers, Managers R: Birds and fish at Nuclear power plant sites, Nuclear power plant employees AI: Government (policy), Nuclear power plant shareholder, Social groups AIB: Local residents	
Top	**6.** Distribute to grid/store electricity	O: Nuclear power plant owners, Government E: Nuclear power plant, Government A: Nuclear power plant R: Customers, Nuclear power plant owners, Managers, Employees AI: Animals at and near nuclear power plants AIB: Local residents, Animals at and near nuclear power plants	
Top	**7.** Form an apposite system of nuclear electricity production for the sustainability evaluation objectives	O: Nuclear power plant owners E: Information suppliers in 1-6, Nuclear power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

D.2.5 Wider KSs of Biomass Power Production

The table presents the complete expanded stakeholder analysis for biomass power production system.

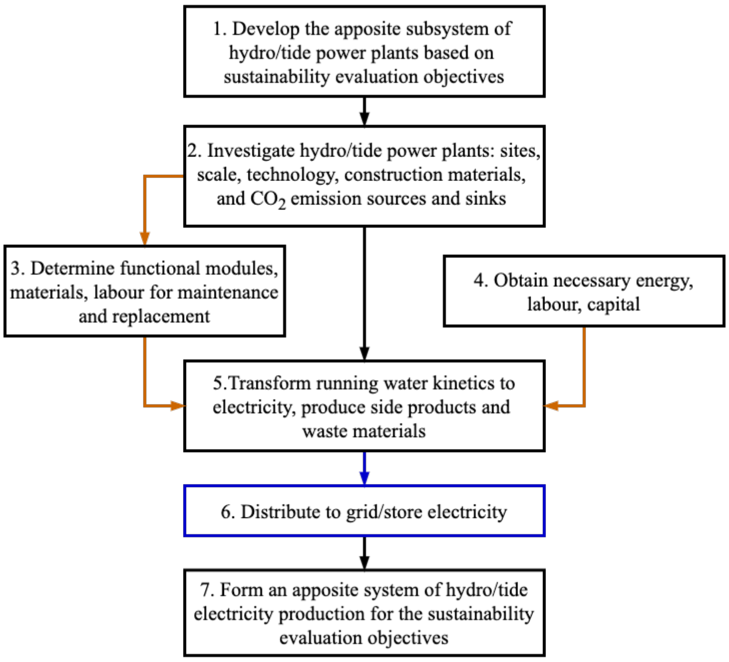

Figure D.5 Activity model of hydro and tidal electricity production initial system

Level	Activity	Key Stakeholders	End
Top	**1.** Develop the apposite subsystem of biomass combustion power plants based on sustainability evaluation objectives	O: Biomass combustion power plant owners E: Government, Social groups (EC, UN, IEA, OECD) A,R: Managers, Research team, External researchers R: Biomass combustion power plant owners, Managers, Research team	
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objectives	O: Government, Biomass combustion power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
1	1.2 Identify lead of sustainability evaluation objectives relating to biomass combustion electricity and the sustainability criteria: governments, and organisations joined by the country	O: Government, Biomass combustion power plant owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
1	1.3 Determine the the system boundary of biomass combustion electricity production system, the initial system, and the time scope of evaluation	O: Government, Biomass combustion power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.** Investigate the power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: Biomass combustion power plant owners, Government E: Biomass combustion power plant owners, Local residents, Employees working at biomass combustion power plants, Animals at biomass combustion power plants, Shareholders and creditors of biomass combustion power plants, Internal information management teams A,R: Managers, Research team, External researchers	
2	2.1 Determine the power plants to be included in evaluation	O: Government, Biomass combustion power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, Biomass combustion power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.3 Determine used area, technologies, and materials	O: Government, Biomass combustion power plant owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI:Social groups (EC, IEA, European parliament, European Economic and Social Committee, IEA), Carriers for biomass, Pipeline owners AIB: Original residents at biomass combustion power plant sites, Biomass combustion power plant employees, Original on-ground and underground animals at biomass combustion power plants, Migration birds passing the biomass combustion power plants	
2	2.4 Investigate carbon containment and emission of the materials and modules	O: Biomass combustion power plant owners E: Material suppliers, Module suppliers A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of biomass power plants.	O: Biomass combustion power plant owners E, A, R: Managers, Research team, External researchers	
Top	**3.** Supply functional modules, materials, labour for maintenance and replacement	O: Biomass combustion power plant owners E: Technology suppliers (steam boiler manufacturers, turbine generator manufacturers, cooling manufacturers, regenerator manufacturers, flue gas treatment manufacturers), Construction material suppliers (offices, structures), Government (policy), Land supplier, Owners (capital), Material and module carriers, Technicians A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or more efficient substitutes (2.5)	O: Biomass combustion power plant owners E: Biomass combustion power plant owners, Available suppliers A, R: Managers, Research team, External researchers	
3	3.2 Supply materials for building construction (3.1)	O: Biomass combustion power plant owners E: Government, Material suppliers, Biomass combustion power plant owners A,R: Managers, Research team, External researchers, Construction team, Office repairing workers AI: Government (construction, technology policy), Foreign material suppliers AIB: On-site and on-route human and animals for material production and transportation, On-site underground and water animals	
3.2	3.2.1 Supply capital for purchasing construction materials: cement, steel, glass, paint	O: Biomass combustion power plant owners E: Government (policy), Biomass combustion power plant owners A,R: Biomass combustion power plant managers R: O in 3.2.2-5 AI: Shareholders of biomass combustion power plants	

Level	Activity	Key Stakeholders	End
3.2	3.2.2 Produce cement	O: Cement plant owners E: Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companies A,R: Cement plant employees AI: Cement plant shareholders AIB: Cement plant engineers, Birds and fish at the cement plants	
3.2.2	3.2.2.1 Supply capital for purchasing cement (limestone, mudstone, clay)	O: Cement plant owners E: Government (policy), Cement plant owners A: Cement plant managers R: O of 3.2.2.2-4 AI: Cement plant shareholders	
3.2.2	3.2.2.2 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Government (policy), Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.2.2.N Natural formation of lime mines
3.2.2	3.2.2.3 Extract mudstone	O: Mudstone plant owners E: Machinery manufacturers, Energy companies A,R: Mudstone plant employees AI: Government (policy), Mudstone plant shareholders AIB: Mudstone miners, Birds and fish at mudstone mines	3.2.2.3.N Natural formation of mudstone mines
3.2.2	3.2.2.4 Extract clay	O: Clay plant owners E: Machinery manufacturers, Energy companies A,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.2.4.N Natural formation of clay
3.2.2	3.2.2.5 Transport materials and produce cement (3.2.2.2-4)	O: Cement plant owners E: Government (transportation), Cement plant owners, O of 3.2.2.2-4, Transportation companies A: Cement plant employees, Transportation carriers R: Cement plants, Birds and fish at cement plant sites AI: Foreign O of 3.2.2.2-5 AIB: Birds on transportation routes	
3.2	3.2.3 Produce steel	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.3	3.2.3.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.3.2-5 AI: Steel plant shareholders	

Level	Activity	Key Stakeholders	End
3.2.3	3.2.3.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.3.2.N Natural formation of iron ores
3.2.3	3.2.3.3 Extract limestone		Continue to 3.2.2.2
3.2.3	3.2.3.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.3	3.2.3.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery manufacturers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.3.5.N Natural formation of coal or LNG
3.2.3	3.2.3.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.3.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.3.2-5 AIB: Birds on transportation routes	
3.2	3.2.4 Produce glass	O: Glass plants E: Sand plants, Soda ash plants, Limestone plants, Machinery suppliers, Energy companies A: Glass plant employees AI: Glass plant shareholders AIB: Glass plant engineers, Birds and fish at the glass plants	
3.2.4	3.2.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4	3.2.4.3 Extract sand	O: Sand mine owners E: Machinery suppliers, Energy companies A,R: Sand mine employees AI: Sand mine shareholders AIB: Sand miners, Birds and fish at the sand mines	3.2.4.3.N Natural formation of sand
3.2.4	3.2.4.4 Produce soda ash [C-]	O: Soda ash plants E: Limestone plants, CO2 suppliers, Salt brine mines, Machinery suppliers, Energy companies A,R: Soda ash plant employees AI: Government (transportation), Soda ash plant shareholders AIB: Soda ash plant engineers, Fish in water bodies at the soda ash plants	

Level	Activity	Key Stakeholders	End
3.2.4.4	3.2.4.4.1 Supply capital for purchasing soda ash	O: Soda ash plant owners E: Government (policy), Soda ash plant owners A,R: Soda ash plant employees, Manufacturers in 3.2.4.4.2-4	
3.2.4.4	3.2.4.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4.4	3.2.4.4.3 Extract salt brines	O: Salt brine mine owners E: Machinery suppliers, Energy companies A,R: Salt brine mine employees AI: Salt brine mine shareholders AIB: Salt brine miners, Birds and fish at the salt brine mines	3.2.4.4.3.N Natural formation of salt brines
3.2.4.4	3.2.4.4.4 Supply CO2	O: CO2 suppliers (fossil fuel-fired power plants) E: Machinery suppliers, Energy companies A,R: CO2 supplier employees AI: Government (transportation), CO2 supplier shareholders AIB: CO2 supplier engineers, Fish in water bodies at the CO2 supplier sites	3.2.4.4.4 Supply of industrial CO2
3.2.4.4	3.2.4.4.5 Transport raw materials and produce soda ash (3.2.4.4.2-4)	O: Soda ash plant owners E: O of 3.2.4.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Soda ash plant employees R: Soda ash plants, Birds and fish at soda ash plant sites AI: Foreign O of 3.2.4.4.2-4 AIB: Birds on transportation routes	
3.2.4	3.2.4.5 Transport raw materials and produce glass (3.2.4.2-4)	O: Glass plant owners E: O of 3.2.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Glass plant employees R: Glass plants, Birds and fish at glass plant sites AI: Foreign O of 3.2.4.2-4 AIB: Birds on transportation routes	
3.2	3.2.5 Produce paint	O: Paint plants E: Chemical suppliers, Machinery suppliers, Energy companies A: Paint plant employees AI: Paint plant shareholders AIB: Paint plant engineers, Birds and fish at the paint plants	

Level	Activity	Key Stakeholders	End
3.2	3.2.6 Transport materials and construct buildings (3.1.1-5)	O: Biomass combustion power plant owners E: O of 3.2.2-5, Transportation companies, Biomass combustion power plant owners, Construction companies A: Transportation carriers, Construction team R: Biomass combustion power plants, Bird and fish at the biomass combustion power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.2.2-5 AIB: Birds and fish at the biomass combustion power plants, Birds on transportation routes	
3	3.3 Supply functional modules installed and carbon intensities (3.1)	O: Biomass combustion power plant owners E: Government, Biomass combustion power plant owners, Module suppliers (steam boiler, condenser, turbine generator, regenerator, flue gas treatment) A,R: Managers, Research team, External researchers, Construction team, Installation and repairing engineers AI: Government (construction, technology policy), Foreign technology suppliers AIB: On-site and on-route human and animals for module production and transportation	
3.3	3.3.1 Supply capital for purchasing modules (steam boiler, condenser and pumps, turbine generator, fly ash filter, flue gas scrubber)	O: Biomass combustion power plant owners E: Government (policy), Biomass combustion power plant owners A,R: Biomass combustion power plant managers R: O in 3.3.2-6 AI: Shareholders of biomass combustion power plants	
3.3	3.3.2 Manufacture steam boiler (steel)	O: Steam boiler manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Steam boiler manufacturing plant employees AI: Steam boiler manufacturing plant shareholders AIB: Steam boiler manufacturing plant engineers, Birds and fish at the steam boiler manufacturing plants	Continue to 3.2.3

Level	Activity	Key Stakeholders	End
3.3	3.3.3 Manufacture condensing compartments (steel)	O: Condensing system manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Condensing system manufacturing plant employees AI: Condensing system manufacturing plant shareholders AIB: Condensing system manufacturing plant engineers, Birds and fish at the condensing system manufacturing plants	Continue to 3.2.3
3.3	3.3.4 Manufacture turbine and generator (steel and iron, aluminium, copper)	O: Turbine generator manufacturing plant owners E: Steel plants, Aluminium plants, Copper plants, Machinery suppliers, Energy companies A,R: Turbine generator manufacturing plant employees AI: Turbine generator manufacturing plant shareholders AIB: Turbine generator manufacturing plant engineers, Birds and fish at the turbine generator manufacturing plants	
3.3.4	3.3.4.1 Supply capital for purchasing turbine generators	O: Turbine generator manufacturing plant owners E: Government (policy), Turbine generator manufacturing plant owners A,R: Turbine generator manufacturing plant managers R: O of 3.3.4.2-4 AI: Shareholders of turbine generator manufacturing plants	
3.3.4	3.3.4.2 Produce steel		Continue to 3.2.3
3.3.4	3.3.4.3 Produce copper products	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	
3.3.4.3	3.3.4.3.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.3.4.3.2 AI: Copper plant shareholders	
3.3.4.3	3.3.4.3.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.3.4.3.2.N Natural formation of copper ores

Level	Activity	Key Stakeholders	End
3.3.4.3	3.3.4.3.3 Transport and produce copper products	O: Copper plant owners E: O of 3.3.4.3.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.3.4.3.2 AIB: Birds on transportation routes	
3.3.4	3.3.4.4 Produce aluminium products	O: Aluminium plant owners E: Bauxite mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	
3.3.4.4	3.3.4.4.1 Supply capital for purchasing aluminium	O: Aluminium plant owners E: Government (policy), Aluminium plant owners A,R: Aluminium plant employees, O of 3.3.4.4.2 AI: Aluminium plant shareholders	
3.3.4.4	3.3.4.4.2 Extract and process bauxite or process recycled aluminium products	O: Bauxite mine owners E: Machinery suppliers, Energy companies A,R: Bauxite mine employees AI: Government (transportation), Bauxite mine shareholders AIB: Bauxite miners, Birds and fish at bauxite mines	3.3.4.4.2.N Natural formation of bauxite mines
3.3.4.4	3.3.4.4.3 Transport and produce aluminium products	O: Aluminium plant owners E: O of 3.3.4.4.2, Government (transportation), Transportation carriers A: Transportation carriers, Aluminium plant employees R: Aluminium plants, Birds and fish at aluminium plant sites AI: Foreign O of 3.3.4.4.2 AIB: Birds on transportation routes	
3.3.4	3.3.4.5 Transport materials and manufacture turbine generators	O: Turbine generator manufacturing plant owners E: O of 3.3.4.2-4, Transportation companies, Turbine generator manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Turbine generator manufacturing plant employees, Birds and fish at the turbine generator manufacturing plants AI: Social groups, Nearby residents, Government (policy) AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.3	3.3.5 Manufacture fly ash filters (steel)	O: Fly ash filter manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Fly ash filter manufacturing plant employees AI: Fly ash filter manufacturing plant shareholders AIB:Fly ash filter manufacturing plant engineers, Birds and fish at the fly ash filter manufacturing plants	Continue to 3.2.3
3.3	3.3.6 Manufacture flue gas scrubber (NaHCO3, NaOH, stacks)	O: Flue gas scrubber manufacturing plant owners E: Cement plants, Sodium hydroxide plants, Soda carbonate plants, Machinery suppliers, Energy companies A,R: Condensing system manufacturing plant employees AI: Condensing system manufacturing plant shareholders AIB: Condensing system manufacturing plant engineers, Birds and fish at the condensing system manufacturing plants	Continue to 3.2.2
3.3	3.3.7 Transport and install or construct the modules (3.3.2-6)	O: Biomass combustion power plant owners E: O of 3.3.2-6, Transportation companies, Biomass combustion power plant owners, Construction companies A: Transportation carriers, Construction team R: Biomass combustion power plants, Birds and fish at the biomass combustion power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2-6 AIB: Birds and fish at the biomass combustion power plants, Birds on transportation routes	
3	3.4 Compile national biomass combustion plant profile: installed capacity, coal consumption rate, CO2 intensity profile in time and space, replacement rate of materials and modules (3.2, 3.3)	O: Biomass combustion power plant owners E, A, R: Managers, Research team, External researchers	
Top	**4.** Obtain fuels from sources, energy, labour, capital	O: Biomass combustion power plant owners E: Domestic biomass suppliers, Foreign biomass suppliers, Domestic energy supplier, Plant owners and Government, Carrier drivers A,R: Managers, Employees AI: Country (labour) AIB: Local residents, Animals at and near biomass combustion power plants	

Level	Activity	Key Stakeholders	End
4	4.1 Investigate sources of biomass, biofuels, electricity, labour, capital	O: Biomass combustion power plant owners E: Biomass combustion power plant owners, Farms, Biofuel plants, Country (labour), Energy companies A, R: Managers, Research team, External researchers	
4	4.2 Supply biomass, biofuels, electricity, labour, capital	O: Biomass combustion power plant owners E: E of 4.1 A,R: Managers, Employees, Engineers AI: Foreign E of 4.1 AIB: Original residents near biomass combustion power plants, Birds and fish at biomass combustion power plants	
4.2	4.2.1 Prepare electricity, engineers and employees, and capital	O: Biomass combustion power plant owners E: Biomass combustion power plant owners, Electricity companies, Country (labour) A: Biomass combustion power plant managers R: Biomass combustion power plant employees AI: Biomass combustion power plant shareholders, Government (policy)	
4.2	4.2.2 Produce biomass(4.2.1)	O: Farms, Wood-fuel plants E: Machinery suppliers, Energy companies A, R: Farms, Wood-fuel plants AI: Government (policy, transportation), Farm shareholders, Wood-fuel plant shareholders AIB: Farm and wood-fuel plant engineers, Birds and bats and fish at the farms and wood-fuel plants	4.2.2.N Natural growth of trees; Agricultural natural growth of biomass
4.2	4.2.3 Produce biofuel (4.2.2)	O: Biofuel plants E: Farms, Wood-fuel plants, Enzyme suppliers, Machinery suppliers, Energy companies A, R: Biofuel plants AI: Government (policy, transportation), Biofuel plant shareholders AIB: Biofuel plant engineers, Birds and bats and fish at biofuel plants	Continue to 4.2.2
4.2	4.2.4 Transport and store biomass and biofuel (4.2.2-3)	O: Biomass combustion power plant owners E: O of 4.2.2-3, Government (transportation) A: Storehouse employees, Transportation carriers R: Biomass combustion power plants, Storehouse workers, Birds and fish at biomass combustion power planr sites AI: Foreign O of 4.2.2-3 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
4	4.3 Compile consumption profile of transformational inputs for biomass electricity production (4.2-3)	O: Biomass combustion power plant owners E, A, R: Managers, Research team, External researchers	
Top	**5.** Operate the power plant to produce electricity	O: Biomass combustion power plant owners E: Biomass combustion power plant owners, Government (quota) A: Employees, Managers, Biomass combustion power plant owners R: Biomass combustion power plant owners, Managers, Employees, Side product customers, Biomass combustion power plant employees, Animals at and near biomass combustion power plants, Local residents AI: KSs in 2,3,4, Government (quota) AIB: Carbon storage site residents and animals, Waste disposal site residents and animals	
5	5.1 Repair and replace structural and functional parts (3.4)	O: Biomass combustion power plant owners E: Biomass combustion power plant owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of power plant storehouse, Compartment Carriers, Carriers for waste compartments	
5.1	5.1.1 Investigate low-carbon or energy saving construction materials (3.2.6)	O: Biomass combustion power plant owners E: Biomass combustion power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Government (foreign suppliers)	
5.1	5.1.2 Investigate low-carbon or more efficient modules (3.3.8)	O: Biomass combustion power plant owners E: Biomass combustion power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Government (foreign suppliers)	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: Biomass combustion power plant owners E: Biomass combustion power plant owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	

Level	Activity	Key Stakeholders	End
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: Biomass combustion power plant owners, Recycling companies, Steel plants E: Biomass combustion power plant owners A,R: Recycling plants, Waste landfill plants AI: Government (transportation, policy), Social groups (policy), Residents at each plant sites AIB: Birds and Fish at each plant	
5	5.2 Operate and produce (4.3; 5.1)	O: Biomass combustion power plant owners E: E of 3.4 and 4.3, Electricity company A: Engineers, Managers, Biomass combustion power plant owners R: Customers (electricity), Employees of biomass combustion power plants, Birds and fish at biomass combustion power plant sites	
5	5.3 Distribute by-products, biomass ash, wastes, and emit CO2 (5.2)	O: Biomass combustion power plant owners E: Government (transportation), Carbon storage site owners (CO2) A: Biomass combustion power plant employees R:Biomass ash carriers, Farms, Customers (by product), By-product carriers, Biomass combustion power plant employees, Carbon storage site owners, Birds and Fishes at the power plants and storage sites AI:Government (CO2 budget), Customers (demand), Local residents and social groups AIB: Local residents, Birds and fish at biomass combustion power plant sites	
5.3	5.3.1 Store by-products (5.2)	O: Biomass combustion power plant owners E: Biomass combustion power plant owners A: Managers, Storehouse workers R: Storehouse workers, A of 5.3.2 AIB: Fish at Biomass combustion power plant sites	
5.3	5.3.2 Identify demand and sell by-products (5.3.1)	O: Biomass combustion power plant owners E: Biomass combustion power plant owners A: Managers, Storehouse workers, Sales manager, Sales R: Customers (by-product) AI: Government (policy)	
5.3	5.3.3 Identify biomass ash recycling plants, biomass ash buyers, landfill plants, and CO2 storage mining sites	O: Government, Biomass combustion power plant owners E: Government A: Managers, Research team, External researchers R: Customers (Biomass ash recycling plants, Farms, Landfill plants, CO2 storage mines, By-product customers)	

Level	Activity	Key Stakeholders	End
5.3	5.3.4 Supply capital for waste treatment (bottom ash etc) and CO2 storage (5.3.3)	O: Biomass combustion power plant owners E: Biomass combustion power plant owners A,R: Managers, Research team, External researchers	
5.3	5.3.5 Distribute combustion wastes, wastes from by-product production, and CO2 (5.3.4)	O: R of 5.3.3 E: Biomass combustion power plant owners A: Waste carriers R: O of 5.3.5	
5.3	5.3.6 Emit CO2 (diffused) (5.2, 5.3.2, 5.3.5)	O, E, A: Biomass combustion power plant owners R: Wide weak stakeholders on land and water bodies	5.3.6.N Natural diffusion and absorption of CO2
5.3	5.3.7 Compile waste treatment and emission profile (5.3.6)	Biomass combustion power plant owners E,A,R: Managers, Research team, External researchers	
Top	**6.** Distribute to grid/store electricity	O: Biomass combustion power plant owners, Government E: Biomass combustion power plants, Government A: Biomass combustion power plants R: Customers, Biomass combustion power plant owners, Managers, Employees AI: Animals at and near biomass combustion power plants AIB: Local residents, Animals at and near biomass combustion power plants	
Top	**7.** Form an apposite system of biomass combustion electricity production for the sustainability evaluation objectives	O: Biomass combustion power plant owners E: Information suppliers in 1-6, Biomass combustion power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

D.2.6 Wider KSs of Hydro/Tide Power Production

The table presents the complete expanded stakeholder analysis for hydro or tide power production system.

Level	**Activity**	**Key Stakeholders**	**End**
Top	**1.** Develop the apposite subsystem of hydro power plants based on sustainability evaluation objectives	O: Hydro power plant owners E: Government, Social groups (EC, UN, IEA, OECD) A,R: Managers, Research team, External researchers R: Hydro power plant owners, Managers, Research team	
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objectives	O: Government, Hydro power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
1	1.2 Identify lead of sustainability evaluation objectives relating to hydro electricity and the sustainability criteria: governments, and organisations joined by the country	O: Government, Hydro power plant owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	
1	1.3 Determine the the system boundary of hydro power electricity production system, the initial system, and the time scope of evaluation	O: Government, Hydro power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.** Investigate hydro and tide power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: Hydro power plant owners, Government E: Hydro power plant owners, Local residents, Hydro power plant employees, Animals at and near hydro power plants, Shareholders and creditors of hydro power plants, Internal information management teams A,R: Managers, Research team, External researchers	
2	2.1 Determine the power plants to be included in evaluation	O: Government, Hydro power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, Hydro power plant owners E: Government A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
2	2.3 Determine used area, technologies, and materials	O: Government, Hydro power plant owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI:Social groups (EC, IEA, European parliament, European Economic and Social Committee, IEA, IRENA, Hydropower Europe, International Hydropower Association), Government (natural reserves) AIB: Original residents on-site, Hydro power plant employees, Original on-ground and underground animals at hydro power plant sites, Migration birds, Fish in water bodies at hydro power plant sites	
2	2.4 Investigate carbon containment and emission of the materials and modules	O: Hydro power plant owners E: Construction material suppliers, Module suppliers A,R: Managers, Research team, External researchers	
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of hydro power plants	O: Hydro power plant owners E, A, R: Managers, Research team, External researchers	
Top	**3.** Supply functional modules, materials, labour for maintenance and replacement	O: Hydro power plant owners E: Technology suppliers (gates, penstocks, inlet valves, pumps, turbine generators), Construction material suppliers (structures), Government (policy), Land supplier, Hydro power plant owners (capital), Material and modules carriers, Technicians A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or more efficient substitutes (2.5)	O: Hydro power plant owners E: Hydro power plant owners, Available suppliers A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
3	3.2 Construct foundation and dams (3.1)	O:Hydro power plant owners E: Government (land), Construction material suppliers, Hydro power plant owners, Construction companies A,R: Managers, Construction and maintenance team AI: Government (policy), Foreign material suppliers AIB: Local residents of hydro power plants, Displaced residents, Birds and migration birds resting near dams, Fish in water bodies at dams	
3.2	3.2.1 Supply capital for purchasing construction materials: cement, rocks, steel, timber, gravel	O: Hydro power plant owners E: Government (policy), Hydro power plant owners A,R: Hydro power plant managers R: O in 3.2.2-7 AI: Shareholders of hydro power plant	
3.2	3.2.2 Produce cement	O: Cement plant owners E: Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companies A,R: Cement plant employees AI: Cement plant shareholders AIB: Cement plant engineers, Birds and fish at the cement plants	
3.2.2	3.2.2.1 Supply capital for purchasing cement (limestone, mudstone, clay)	O: Cement plant owners E: Government (policy), Cement plant owners A: Cement plant managers R: O of 3.2.2.2-4 AI: Cement plant shareholders	
3.2.2	3.2.2.2 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Government (policy), Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.2.2.N Natural formation of lime mines
3.2.2	3.2.2.3 Extract mudstone	O: Mudstone plant owners E: Machinery manufacturers, Energy companies A,R: Mudstone plant employees AI: Government (policy), Mudstone plant shareholders AIB: Mudstone miners, Birds and fish at mudstone mines	3.2.2.3.N Natural formation of mudstone mines
3.2.2	3.2.2.4 Extract clay	O: Clay plant owners E: Machinery manufacturers, Energy companies A,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.2.4.N Natural formation of clay

Level	Activity	Key Stakeholders	End
3.2.2	3.2.2.5 Transport materials and produce cement (3.2.2.2-4)	O: Cement plant owners E: Government (transportation), Cement plant owners, O of 3.2.2.2-4, Transportation companies A: Cement plant employees, Transportation carriers R: Cement plants, Birds and fish at cement plant sites AI: Foreign O of 3.2.2.2-5 AIB: Birds on transportation routes	
3.2	3.2.3 Produce rocks	O: Rock mine owners E: Machinery suppliers, Energy companies A,R: Rock mine employees AI: Rock mine shareholders AIB: Rock miners, BIrds and fish at the rock mines	3.2.3.N Natural weathering of rocks
3.2	3.2.4 Produce steel	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.4	3.2.4.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.4.2-5 AI: Steel plant shareholders	
3.2.4	3.2.4.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.4.2.N Natural formation of iron ores
3.2.4	3.2.4.3 Extract limestone		Continue to 3.2.2.2
3.2.4	3.2.4.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.4	3.2.4.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery manufacturers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.4.5.N Natural formation of coal or LNG

Level	Activity	Key Stakeholders	End
3.2.4	3.2.4.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.4.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.4.2-5 AIB: Birds on transportation routes	
3.2	3.2.5 Produce timber	O: Timber manufacturing company owners E: Machinery suppliers, Energy companies A,R: Timber manufacturing company employees AI: Timber manufacturing company shareholders AIB: Timber manufacturing company engineers, Birds and fish at harvesting forests and manufacturing sites	3.2.5.N Natural or agricultural growth of trees for timber [C-]
3.2	3.2.6 Produce gravel	O: Gravel mine owners E: Machinery suppliers, Energy companies A,R: Gravel mine employees AI: Gravel mine shareholders AIB: Gravel miners, Birds and fish at the gravel mines	3.2.6.N Natural formation of gravel
3.2	3.2.7 Transport materials and construct structures and buildings (3.2.2-6)	O: Hydro power plant owners E: O in 3.2.2-6, Transportation companies, Hydro power plant owners, Construction companies A: Transportation carriers, Construction team R: Hydro power plants, Birds and fish at the hydro power plants AI: Social groups, Nearby residents, Government (policy) AIB: Birds and fish near dams, Birds on transportation routes	
3	3.3 Install functional modules (gates, penstocks, inlet valves, pumps, turbine generators) (3.1)	O:Hydro power plant owners E: Government (land), Hydro power plant owners, Module suppliers A,R: Managers, Construction and maintenance team AI: Government (policy), Foreign module suppliers AIB: Local residents of hydro power plants, Birds and migration birds resting near hydro power plant sites, Fish in water bodies at hydro power plant sites	
3.3	3.3.1 Supply capital for purchase of functional modules: penstocks, valves, gates, turbines, generators	O: Hydro power plant owners E: Government (policy), Hydro power plant owners A,R: Hydro power plant managers R: O of 3.3.2-6 AI: Shareholders of hydro power plant	

Level	Activity	Key Stakeholders	End
3.3	3.3.2 Produce materials for penstocks (steel, cement)	O: Steel plant owners, Cement plant owners E: Iron ore mines, Waste steel product owners, Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companies A,R: Steel plant employees, Cement plant employees AI: Steel plant shareholders, Cement plant shareholders AIB: Steel engineers, Cement plant engineers, Birds and fish at the steel plants and cement plants	Continue to 3.2.2 and 3.2.4
3.3	3.3.3 Manufacture gates (cement, steel)	O: Gate manufacturing plant owners E: Steel plants, Cement plants, Machinery suppliers, Energy companies A,R: Gate manufacturing plant employees AI: Gate manufacturing plant shareholders AIB: Gate manufacturing plant engineers, BIrds and fish at the gate manufacturing sites	
3.3.3	3.3.3.1 Supply capital for purchasing steel, cement	O: Gate manufacturing plant owners E: Government (policy), Gate manufacturing plant owners A,R: Gate manufacturing plant managers R: O of 3.3.3.2-3 AI: Shareholders of gate manufacturing plants	
3.3.3	3.3.3.2 Produce steel		Continue to 3.2.4
3.3.3	3.3.3.3 Produce cement		Continue to 3.2.2
3.3.3	3.3.3.4 Transport materials and manufacture inlet, outlet gates	O: Gate manufacturing plant owners E: O in 3.3.3.2-3, Transportation companies, Gate manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Gate manufacturing plant employees, Birds and fish at the gate manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.3.2-3 AIB: Birds on transportation routes	
3.3	3.3.4 Manufacture valves (steel)	O: Valve manufacturing plant owners E: Steel plants, Machinery suppliers, Waste steel product owners, Energy companies A,R: Valve manufacturing plant employees AI: Valve manufacturing plant shareholders AIB: Valve manufacturing plant engineers, Birds and fish at valve manufacturing plants	Continue to 3.2.4

Level	Activity	Key Stakeholders	End
3.3	3.3.5 Manufacture turbines (steel, copper, aluminium, iron)	O: Turbine manufacturing plant owners E: Steel plants, Copper plants, Aluminium plants, Machinery suppliers, Energy companies A,R: Turbine manufacturing plant employees AI: Turbine manufacturing plant shareholders AIB: Turbine manufacturing plant engineers, Birds and fish at turbine manufacturing plants	
3.3.5	3.3.5.1 Supply capital for purchasing steel, copper, aluminium products	O: Turbine manufacturing plant owners E: Government (policy), Turbine manufacturing plant owners A,R: Turbine manufacturing plant managers R: O in 3.3.5.2-4 AI: Shareholders of turbine manufacturing plants	
3.3.5	3.3.5.2 Produce steel		Continue to 3.2.4
3.3.5	3.3.5.3 Produce copper products	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	
3.3.5.3	3.3.5.3.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.3.5.3.2 AI: Copper plant shareholders	
3.3.5.3	3.3.5.3.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.3.5.3.2.N Natural formation of copper ores
3.3.5.3	3.3.5.3.3 Transport and produce copper products	O: Copper plant owners E: O of 3.3.5.3.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.3.5.3.2 AIB: Birds on transportation routes	
3.3.5	3.3.5.4 Produce aluminium products	O: Aluminium plant owners E: Bauxite mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	

Level	Activity	Key Stakeholders	End
3.3.5.4	3.3.5.4.1 Supply capital for purchasing aluminium	O: Aluminium plant owners E: Government (policy), Aluminium plant owners A,R: Aluminium plant employees, O of 3.3.5.4.2 AI: Aluminium plant shareholders	
3.3.5.4	3.3.5.4.2 Extract and process bauxite or process recycled aluminium products	O: Bauxite mine owners E: Machinery suppliers, Energy companies A,R: Bauxite mine employees AI: Government (transportation), Bauxite mine shareholders AIB: Bauxite miners, Birds and fish at bauxite mines	3.3.5.4.2.N Natural formation of bauxite mines
3.3.5.4	3.3.5.4.3 Transport and produce aluminium products	O: Aluminium plant owners E: O of 3.3.5.4.2, Government (transportation), Transportation carriers A: Transportation carriers, Aluminium plant employees R: Aluminium plants, Birds and fish at aluminium plant sites AI: Foreign O of 3.3.5.4.2 AIB: Birds on transportation routes	
3.3.5	3.3.5.5 Transport materials and manufacture hydro kinetic turbines	O: Turbine manufacturing plant owners E: O in 3.3.5.2-4, Transportation companies, Turbine manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Turbine manufacturing plant employees, Birds and fish at the turbine manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.5.2-4 AIB: Birds on transportation routes	
3.3	3.3.6 Manufacture generator and transformers (steel, copper)	O: Generator manufacturing plant owners E: Steel plants, Copper plants, Machinery suppliers, Energy companies A,R: Generator manufacturing plant employees AI: Generator manufacturing plant shareholders AIB: Generator manufacturing plant engineers, Birds and fish at generator manufacturing plant	
3.3.6	3.3.6.1 Supply capital for purchasing steel, copper products	O: Generator manufacturing plant owners E: Government (policy), Generator manufacturing plant owners A,R: Generator manufacturing plant managers R: O in 3.3.5.2-3 AI: Shareholders of generator manufacturing plants	
3.3.6	3.3.6.2 Produce steel		Continue to 3.2.4
3.3.6	3.3.6.3 Produce copper products		Continue to 3.3.5.3

Level	Activity	Key Stakeholders	End
3.3.6	3.3.6.4 Transport materials and manufacture generator and electrical compartments	O: Generator manufacturing plant owners E: O in 3.3.6.2-3, Transportation companies, Generator manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Generator manufacturing plant employees, Birds and fish at the generator manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.6.2-3 AIB: Birds on transportation routes	
3.3	3.3.7 Transport materials and modules and install at the geothermal power plant site (3.3.2-6)	O: Hydro power plant owners E: O of 3.3.2-6, Transportation companies, Hydro power plant owners, Construction companies A: Transportation carriers, Construction team R: Hydro power plants, Birds and fish at the hydro power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2-6 AIB: Birds and fish near dams, Birds on transportation routes	
3	3.4 Compile national hydro power plant profile: installed capacity, CO2 intensity profile in time and space, replacement rate of materials and modules (3.2, 3.3)	O: Hydro power plant owners E, A, R: Managers, Research team, External researchers	
Top	**4.** Obtain necessary energy, labour, capital	O: Hydro power plant owners E: Domestic energy supplier, Hydro power plant owners, Government A,R: Managers, Employees AI: Country (labour) AIB: Local residents, Animals at and near hydro power plants	
4	4.1 Investigate sources of running water, electricity, and labour	O: Hydro power plant owners E: Hydro power plant owners, Country (labour), Energy companies, Meterology institutions, Geographic observatories A, R: Managers, Research team, External researchers	
4	4.2 Supply electricity, labour, and capital	O: Hydro power plant owners E: Hydro power plant owners, E of 4.1 A,R: Managers, Employees, Engineers AI: Foreign E of 4.1, Government (policy) AIB: Original residents near hydro power plants, Upstream residents of dams, Birds and fish at hydro power plant dams	

Level	Activity	Key Stakeholders	End
4	4.3 Compile consumption profile of transformational inputs for hydro power production	O: Hydro power plant owners E, A, R: Managers, Research team, External researchers	
Top	**5.** Operate the power plant to produce electricity	O: Hydro power plant owners E: Hydro power plant owners, Government (quota) A: Employees, Managers, Hydro power plant owners R: Hydro power plant owners, Managers, Hydro power plant employees, Local residents, Animals at and near hydro power plants AI: KSs in 2,3,4, Government (quota) AIB: Waste disposal site residents and animals	
5	5.1 Repair and replace structural and functional parts (3.4)	O: Hydro power plant owners E: Hydro power plant owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of storehouse, Compartment Carriers, Carriers for displaced compartments	
5.1	5.1.1 Investigate low-carbon or energy saving construction materials	O: Hydro power plant owners E: Hydro power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.2 Investigate low-carbon or more efficient modules	O: Hydro power plant owners E: Hydro power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: Hydro power plant owners E: Hydro power plant owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: Hydro power plant owners, Recycling companies E: Hydro power plant owners A,R: Transportation carriers, Recycling plants, Landfill companies AI: Government (transportation, policy), Social groups (policy), Residents at each plant site AIB: Birds and fish at each plant	
5	5.2 Operate and produce (4.3; 5.1)	O: Hydro power plant owners E: Suppliers from 3 and 4, Energy companies A: Engineers, Managers, Hydro power plant owners R: Customers (electricity), Employees of hydro power plants, Birds and fish at hydro power plant sites and dams	

Level	Activity	Key Stakeholders	End
5	5.3 Emit CO2 (5.2)	O: Hydro power plant owners E: Government (transportation) A: Engineers, Managers R: Birds and fish at hydro power plant sites, Hydro power plant employees working on-site AI: Government (policy), Hydro power plant shareholder, Social groups AIB: Local residents	5.3.N Natural diffusion and absorption of CO2
Top	**6.** Distribute to grid/store electricity	O: Hydro power plant owners, Government E: Hydro power plants, Government A: Hydro power plant R: Customers, Hydro power plant owners, Managers, Employees AI: Animals at and near hydro power plants AIB: Local residents, Animals at and near hydro power plants	
Top	**7.** Form an apposite system of hydro electricity production for the sustainability evaluation objectives	O: Hydro power plant owners E: Information suppliers in 1-6, Hydro power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

D.2.7 Wider KSs of Wind Power Production

The table presents the complete expanded stakeholder analysis for wind power production system.

Level	Activity	Key Stakeholders	End
Top	**1.** Develop the apposite subsystem of wind power plants based on sustainability evaluation objectives	O: Wind farm owners E: Government, Social groups (EC, UN, IEA, OECD) A,R: Managers, Research team, External researchers R: Wind farm owners, Managers, Research team	
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objectives	O: Government, Wind farm owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
1	1.2 Identify lead of sustainability evaluation objectives relating to wind primary electricity and the sustainability criteria: governments, and organisations joined by the country	O: Government, Wind farm owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	
1	1.3 Determine the the system boundary of wind power electricity production system, the initial system, and the time scope of evaluation	O: Government, Wind farm owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.** Investigate the power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: Wind farm owners, Government E: Wind farm owners, Local residents, Wind farm employees, Animals at and near wind farms, Shareholders and creditors of wind farms, Internal information management teams A,R: Managers, Research team, External researchers	
2	2.1 Determine the power plants to be included in evaluation	O: Government, Wind farm owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, Wind farm owners E: Government A,R: Managers, Research team, External researchers	
2	2.3 Determine used area, technologies, and materials	O: Government, Wind farm owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI:Social groups (EC, IEA, European parliament, European Economic and Social Committee, IEA, IRENA) AI: Government (natural reserves) AIB: Original residents on-site, Current employees working on-site, original on-ground and underground animals on-site, migration birds	
2	2.4 Investigate carbon containment and emission of the materials and modules	O: Wind farm owners E: Construction material suppliers, Module suppliers A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of wind farms	O: Wind farm owners E, A, R: Managers, Research team, External researchers	
Top	**3.** Supply functional modules, materials, labour for maintenance and replacement	O: Wind farm owners E: Technology suppliers (wind turbines, ground structures, transformation subsystem compartments), Construction material suppliers (structures), Government (policy), Land supplier, Owners (capital), Material and modules carriers, Technicians A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or more efficient substitutes (2.5)	O: Wind farm owners E: Wind farm owners, Available suppliers A, R: Managers, Research team, External researchers	
3	3.2 Construct foundation (3.1)	O:Wind farm owners E: Government, Material suppliers, Wind farm owners A,R: Managers, Research team, External researchers, Construction and repairing team AI: Government (construction, technology policy), Foreign material suppliers AIB: Local residents of wind farms, Displaced residents, Birds and migration birds at wind farms	
3.2	3.2.1 Supply capital for purchasing construction materials: iron, steel, concrete	O: Wind farm owners E: Government (policy), Wind farm owners A,R: Wind farm managers R: O in 3.2.2-3 AI: Shareholders of wind farms	
3.2	3.2.2 Produce cement	O: Cement plant owners E: Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companies A,R: Cement plant employees AI: Cement plant shareholders AIB: Cement plant engineers, Birds and fish at the cement plants	
3.2.2	3.2.2.1 Supply capital for purchasing cement (limestone, mudstone, clay)	O: Cement plant owners E: Government (policy), Cement plant owners A: Cement plant managers R: O of 3.2.2.2-4 AI: Cement plant shareholders	

Level	Activity	Key Stakeholders	End
3.2.2	3.2.2.2 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Government (policy), Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.2.2.N Natural formation of lime mines
3.2.2	3.2.2.3 Extract mudstone	O: Mudstone plant owners E: Machinery manufacturers, Energy companies A,R: Mudstone plant employees AI: Government (policy), Mudstone plant shareholders AIB: Mudstone miners, Birds and fish at mudstone mines	3.2.2.3.N Natural formation of mudstone mines
3.2.2	3.2.2.4 Extract clay	O: Clay plant owners E: Machinery manufacturers, Energy companies A,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.2.4.N Natural formation of clay
3.2.2	3.2.2.5 Transport materials and produce cement (3.2.2.2-4)	O: Cement plant owners E: Government (transportation), Cement plant owners, O of 3.2.2.2-4, Transportation companies A: Cement plant employees, Transportation carriers R: Cement plants, Birds and fish at cement plant sites AI: Foreign O of 3.2.2.2-5 AIB: Birds on transportation routes	
3.2	3.2.3 Produce steel and iron	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.3	3.2.3.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.3.2-5 AI: Steel plant shareholders	
3.2.3	3.2.3.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.3.2.N Natural formation of iron ores
3.2.3	3.2.3.3 Extract limestone		Continue to 3.2.2.2

Level	Activity	Key Stakeholders	End
3.2.3	3.2.3.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.3	3.2.3.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery manufacturers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.3.5.N Natural formation of coal or LNG
3.2.3	3.2.3.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.3.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.3.2-5 AIB: Birds on transportation routes	
3.2	3.2.4 Transport materials and construct foundation (3.2.2-3)	O: Wind farm owners E: O in 3.2.2-3, Transportation companies, Wind farm owners, Construction companies A: Transportation carriers, Construction team R: Wind farm plants, Birds and fish at the wind farms AI: Social groups, Nearby residents, Government (policy) AIB: Birds and fish near wind farms, Birds on transportation routes	
3	3.3 Install functional modules (3.1)	O:Wind farm owners E: Government, Wind farm owners, Module suppliers (wind turbines, ground structures, transformation subsystem compartments) A,R: Managers, Research team, External researchers, Construction team, Installation and repairing engineers AI: Government (construction, technology policy), Foreign module suppliers AIB: Animals at and near the wind farms, Residents near the wind farms	
3.3	3.3.1 Supply capital for purchasing modules: tower (steel), rotor, nacelle	O: Wind farm owners E: Government (policy), Wind farm owners A,R: Wind farm managers R: O of 3.3.2-4 AI: Shareholders of wind farms	

Level	Activity	Key Stakeholders	End
3.3	3.3.2 Produce rotors (cast iron, glass fibre, resin)	O: Rotor manufacturers E: Steel plants, glass fibre plants, Resin plants (mix), Machinery suppliers, Energy companies A,R: Rotor manufacturing plant employees AI: Rotor manufacturing plant shareholders AIB: Rotor manufacturing plant engineers, Birds and fish at rotor manufacturing plants	
3.3.2	3.3.2.1 Supply capital for purchasing materials: iron, glass fibre, resin	O: Rotor manufacturing plant owners E: Government (policy), Rotor manufacturing plant owners A,R: Rotor manufacturing plant managers R: O of 3.3.2.2-4 AI: Shareholders of gate manufacturing plants	
3.3.2	3.3.2.2 Produce iron		Continue to 3.2.3
3.3.2	3.3.2.3 Produce fibreglass (silica sand, limestone, soda ash)	O: Fibreglass plants E: Silica sand suppliers, Limestone plants, Soda ash plants, Machinery suppliers, Energy companies A,R: Fibreglass plant employees AI: Fibreglass plant shareholders AIB: Fibreglass plant engineers, Birds and fish at the fibreglass plant	
3.3.2.3	3.3.2.3.1 Supply capital for purchasing materials: silica sand, limestone, soda ash	O: Glass fibre manufacturing plant owners E: Government (policy), Glass fibre manufacturing plant owners A,R: Glass fibre manufacturing plant managers R: O of 3.3.2.3.2-4 AI: Shareholders of glass fibre manufacturing plants	
3.3.2.3	3.3.2.3.2 Extract silica sand	O: Silica sand mine owners E: Machinery suppliers, Energy companies A,R: Silica sand mine employees AI: Silica sand mine shareholders AIB: Silica sand mine engineers, Birds and fish at silica sand mines	3.3.2.3.2.N Natural formation of silica mines
3.3.2.3	3.3.2.3.3 Extract limestones		Continue to 3.2.2.2
3.3.2.3	3.3.2.3.4 Produce soda ash [C-]	O: Soda ash plants E: Limestone plants, CO2 suppliers, Salt brine mines, Machinery suppliers, Energy companies A,R: Soda ash plant employees AI: Government (transportation), Soda ash plant shareholders AIB: Soda ash plant engineers, Fish in water bodies at the soda ash plants	
3.3.2.3.4	3.3.2.3.4.1 Supply capital for purchasing soda ash	O: Soda ash plant owners E: Government (policy), Soda ash plant owners A,R: Soda ash plant employees, Manufacturers in 3.3.2.3.4.2-4	

Level	Activity	Key Stakeholders	End
3.3.2.3.4	3.3.2.3.4.2 Extract limestone		Continue to 3.2.2.2
3.3.2.3.4	3.3.2.3.4.3 Extract salt brines	O: Salt brine mine owners E: Machinery suppliers, Energy companies A,R: Salt brine mine employees AI: Salt brine mine shareholders AIB: Salt brine miners, Birds and fish at the salt brine mines	3.3.2.3.4.3.N Natural formation of salt brines
3.3.2.3.4	3.3.2.3.4.4 Supply CO2	O: CO2 suppliers (fossil fuel-fired power plants) E: Machinery suppliers, Energy companies A,R: CO2 supplier employees AI: Government (transportation), CO2 supplier shareholders AIB: CO2 supplier engineers, Fish in water bodies at the CO2 supplier sites	3.3.2.3.4.4 Supply of industrial CO2
3.3.2.3.4	3.3.2.3.4.5 Transport raw materials and produce soda ash (3.3.2.3.4.2-4)	O: Soda ash plant owners E: O in 3.3.2.3.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Soda ash plant employees R: Soda ash plants, Birds and fish at soda ash plant sites AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2.3.4.2-4 AIB: Birds on transportation routes	
3.3.2.3	3.3.2.3.5 Transport materials and produce glass fibre	O: Glass fibre manufacturing plant owners E: Government (transportation), O in 3.3.2.3.2-4, Transportation companies A: Transportation carriers, Glass fibre manufacturing plants R: Glass fibre manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign suppliers 3.3.2.3.2-4 AIB: Birds on transportation routes	
3.3.2	3.3.2.4 Extract resin	O: Plastic plants E: Coal suppliers, Crude oil suppliers, Machinery suppliers, Energy companies A,R: Plastic plant employees AI: Plastic plant shareholders AIB: Plastic plant engineers, Birds and fish at the plastic plant	

Level	Activity	Key Stakeholders	End
3.3.2	3.3.2.5 Transport and produce rotors (3.3.2-4)	O: Rotor manufacturing plant owners E: O in 3.3.2.2-3, Transportation companies, Rotor manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Rotor manufacturing plant employees, Birds and fish at the rotor manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign suppliers 3.3.2.2-4 AIB: Birds on transportation routes	
3.3	3.3.3 Produce raw materials for tower (iron, steel)	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plant	Continue to 3.2.3
3.3	3.3.4 Produce nacelle: frame and cover (iron, steel, glass fibre, resin), transformer(steel, copper), generator (copper, steel), gearbox (steel, iron)	O: Nacelle manufacturers E: Steel plants, Glass fibre plants, Resin plants (mix), Copper plants, Machinery suppliers, Energy companies A,R: Nacelle manufacturing plant employees AI: Nacelle manufacturing plant shareholders AIB: Nacelle manufacturing plant engineers, Birds and fish at nacelle manufacturing plants	
3.3.4	3.3.4.1 Supply capital for purchasing materials: steel, iron, fibreglass, resin, copper	O: Nacelle manufacturing plant owners E: Government (policy), Nacelle manufacturing plant owners A,R: Nacelle manufacturing plant managers R: O of 3.3.4.2-5 AI: Shareholders of nacelle manufacturing plants	
3.3.4	3.3.4.2 Produce iron		Continue to 3.2.3
3.3.4	3.3.4.3 Produce fibreglass		Continue to 3.3.2.3
3.3.4	3.3.4.4 Produce resin		Continue to 3.3.2.4
3.3.4	3.3.4.5 Produce copper	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	

Level	Activity	Key Stakeholders	End
3.3.4.5	3.3.4.5.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.3.4.5.2 AI: Copper plant shareholders	
3.3.4.5	3.3.4.5.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.3.4.5.2.N Natural formation of copper ores
3.3.4.5	3.3.4.5.3 Transport and produce copper products	O: Copper plant owners E: O of 3.3.4.5.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.3.4.5.2 AIB: Birds on transportation routes	
3.3.4	3.3.4.6 Transport and produce nacelle (3.3.2-5)	O: Nacelle manufacturing plant owners E: O of 3.3.4.2-5, Transportation companies, Nacelle manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: Nacelle manufacturing plant employees, Birds and fish at the nacelle manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign suppliers 3.3.4.2-5 AIB: Birds on transportation routes	
3.3	3.3.5 Transport and install or construct the modules (3.3.2-4)	O: Wind farm owners E: O of 3.3.2-5, Transportation companies, Wind farm owners, Construction companies A: Transportation carriers, Construction team R: Wind farm employees, Birds and fish at wind farms AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2-5 AIB: Birds and fish near wind farms, Birds on transportation routes	
3	3.4 Compile national wind farm profile: installed capacity, CO2 intensity profile in time and space, replacement rate of materials and modules (3.2, 3.3)	O: Wind farm owners E, A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
Top	**4.** Obtain necessary energy, labour, capital	O: Wind farm owners E: Domestic energy supplier, Wind farm owners and Government A,R: Managers, Wind farm employees AI: Country (labour) AIB: Local residents, Animals at and near wind farms	
4	4.1 Investigate suitable wind spots, electricity, and labour	O: Wind farm owners E: Wind farm owners, Country (labour), Energy companies, Meteorology institutions A, R: Managers, Research team, External researchers	
4	4.2 Supply electricity, labour, and capital	O: Wind farm owners E: Wind farm owners, E of 4.1 A,R: Managers, Employees, Engineers AI: Foreign E of 4.1, Government (policy)	
4	4.3 Compile consumption profile of transformational inputs for wind power production	O: Wind farm owners E, A, R: Managers, Research team, External researchers	
Top	**5.** Operate the power plant to produce electricity	O: Wind farm owners E: Wind farm owners, Government (quota) A: Employees, Managers, Coal-fired power plant owners R: Wind farm owners, Managers, Wind farm employees, Animals at and near wind farms, Local residents AI: KSs in 2,3,4, Government (quota) AIB: Waste disposal site residents and animals	
5	5.1 Repair and replace structural and functional parts (3.4)	O: Wind farm owners E: Wind farm owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of storehouse, Compartment Carriers, Carriers for waste compartments	
5.1	5.1.1 Investigate low-carbon or energy saving construction materials	O: Wind farm owners E: Wind farm owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.2 Investigate low-carbon or more efficient modules	O: Wind farm owners E: Wind farm owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: Wind farm owners E: Wind farm owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	

Level	Activity	Key Stakeholders	End
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: Wind farm owners, Recycling companies E: Wind farm owners A,R: Transportation carriers, Recycling plants, Landfill companies AI: Government (transportation, policy), Social groups (policy), Residents at each plant site AIB: Birds and fish at each plant	
5	5.2 Operate and produce (4.3; 5.1)	O: Wind farm owners E: Suppliers from 3.4 and 4.3, Energy companies A: Engineers, Managers, Wind farm owners R: Customers (electricity), Employees of wind farms, Birds and fish at wind farms	
5	5.3 Emit CO2 (5.2)	O: Wind farm owners E: Government (transportation) A: Engineers, Managers R: Birds and fish at wind farms, Wind farm employees working on-site AI: Government (policy), Wind farm shareholder, Social groups AIB: Local residents	5.3.N Natural diffusion and absorption of CO2
Top	**6.** Distribute to grid/store electricity	O:Wind farm owners, Government E: Wind farms, Government A: Wind farms R: Customers, Wind farm owners, Managers, Employees AI: Animals at and near wind farms AIB: Local residents, Animals at and near wind farms	
Top	**7.** Form an apposite system of wind electricity production for the sustainability evaluation objectives	O: Wind farm owners E: Information providers in 1-6, Wind farm owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

D.2.8 Wider KSs of Solar PV Power Production

The table presents the complete expanded stakeholder analysis for solar PVpower production system.

Level	Activity	Key Stakeholders	End
Top	**1.** Develop the apposite subsystem of solar PV power plants based on sustainability evaluation objectives	O: Solar PV power plant E: Government, Social groups (EC, UN, IEA, OECD), Plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers R: Solar PV power plant owners, Managers, Research team	

Level	Activity	Key Stakeholders	End
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objective	O: Government, Solar PV power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
1	1.2 Identify lead of sustainability evaluation objectives relating to solar power and the sustainability criteria: governments, and organisations joined by the country	O: Government, Solar PV power plant owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	
1	1.3 Determine the the system boundary of solar PV electricity production system, the initial system, and the time scope of evaluation	O: Government, Solar PV power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.** Investigate solar PV farms: sites, scale, technology, construction materials, and CO2 emission sources and sinks	O: Solar PV power plant owners, Government E: Solar PV power plant owners, Local residents, Solar PV power plant employees, Animals at and near solar PV power plants, Shareholders and creditors of solar PV power plants, Internal information management teams A,R: Managers, Research team, External researchers	
2	2.1 Determine the power plants to be included in evaluation	O: Government, Solar PV power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, Solar PV power plant owners E: Government A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
2	2.3 Determine used area, technologies, and materials	O: Government, Solar PV power plant owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI: Social groups (EC, IEA, European parliament, European Economic and Social Committee, IEA, World Bank, Solar Power Europe, International Solar Alliance) AIB: Original residents at Solar PV power plant sites, Solar PV power plant employees, Original on-ground and underground animals at Solar PV power plants, Migration birds passing the Solar PV power plants	
2	2.4 Investigate carbon containment and emission of the materials and modules	O: Solar PV power plant owners E: Material suppliers (Cement, Steel and Aluminium, Glass, PV panels) A,R: Managers, Research team, External researchers	
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of solar PV farms	O: Solar PV power plant owners E, A, R: Managers, Research team, External researchers	
Top	**3.** Supply functional modules, materials, labour for maintenance and replacement	O: Solar PV power plant owners E: Technology suppliers (PV module, mounting system, inverter), Construction material suppliers (offices, structures), Government (policy), Land supplier, Owners (capital), Material and modules carriers, Technicians A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or more efficient substitutes (2.5)	O: Solar PV power plant owners E: Solar PV power plant owners, Available suppliers A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
3	3.2 Supply materials for structure construction (3.1)	O: Solar PV power plant owners E: Government, Material suppliers, Solar PV power plant owners A,R: Managers, Research team, External researchers, Construction team, Office repairing workers AI: Government (construction, technology policy), Foreign material suppliers AIB: On-site and on-route human and animals for material production and transportation, on-site underground and water animals	
3.2	3.2.1 Supply capital for purchasing construction materials: cement, steel, glass, paint	O: Solar PV power plant owners E: Government (policy), Solar PV power plant owners A,R: Solar PV power plant managers R: O in 3.2.2-4 AI: Shareholders of Solar PV power plants	
3.2	3.2.2 Produce cement	O: Cement plant owners E: Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companies A,R: Cement plant employees AI: Cement plant shareholders AIB: Cement plant engineers, Birds and fish at the cement plants	
3.2.2	3.2.2.1 Supply capital for purchasing cement (limestone, mudstone, clay)	O: Cement plant owners E: Government (policy), Cement plant owners A: Cement plant managers R: O of 3.2.2.2-4 AI: Cement plant shareholders	
3.2.2	3.2.2.2 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Government (policy), Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.2.2.N Natural formation of lime mines
3.2.2	3.2.2.3 Extract mudstone	O: Mudstone plant owners E: Machinery manufacturers, Energy companies A,R: Mudstone plant employees AI: Government (policy), Mudstone plant shareholders AIB: Mudstone miners, Birds and fish at mudstone mines	3.2.2.3.N Natural formation of mudstone mines
3.2.2	3.2.2.4 Extract clay	O: Clay plant owners E: Machinery manufacturers, Energy companies A,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.2.4.N Natural formation of clay

Level	Activity	Key Stakeholders	End
3.2.2	3.2.2.5 Transport materials and produce cement (3.2.2.2-4)	O: Cement plant owners E: Government (transportation), Cement plant owners, O of 3.2.2.2-4, Transportation companies A: Cement plant employees, Transportation carriers R: Cement plants, Birds and fish at cement plant sites AI: Foreign O of 3.2.2.2-5 AIB: Birds on transportation routes	
3.2	3.2.3 Produce steel	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.3	3.2.3.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.3.2-5 AI: Steel plant shareholders	
3.2.3	3.2.3.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.3.2.N Natural formation of iron ores
3.2.3	3.2.3.3 Extract limestone		Continue to 3.2.2.2
3.2.3	3.2.3.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.3	3.2.3.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery manufacturers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.3.5.N Natural formation of coal or LNG
3.2.3	3.2.3.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.3.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.3.2-5 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.2	3.2.4 Produce glass	O: Glass plants E: Sand plants, Soda ash plants, Limestone plants, Machinery suppliers, Energy companies A: Glass plant employees AI: Glass plant shareholders AIB: Glass plant engineers, Birds and fish at the glass plants	
3.2.4	3.2.4.1 Supply capital for purchasing glass (limestone, sand, soda ash)	O: Glass plant owners E: Government (policy), Glass plant owners A,R: Glass plant employees, Manufacturers in 3.2.4.2-4	
3.2.4	3.2.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4	3.2.4.3 Extract sand	O: Sand mine owners E: Machinery suppliers, Energy companies A,R: Sand mine employees AI: Sand mine shareholders AIB: Sand miners, Birds and fish at the sand mines	3.2.4.3.N Natural formation of sand
3.2.4	3.2.4.4 Produce soda ash [C-]	O: Soda ash plants E: Limestone plants, CO2 suppliers, Salt brine mines, Machinery suppliers, Energy companies A,R: Soda ash plant employees AI: Government (transportation), Soda ash plant shareholders AIB: Soda ash plant engineers, Fish in water bodies at the soda ash plants	
3.2.4.4	3.2.4.4.1 Supply capital for purchasing soda ash	O: Soda ash plant owners E: Government (policy), Soda ash plant owners A,R: Soda ash plant employees, Manufacturers in 3.2.4.4.2-4	
3.2.4.4	3.2.4.4.2 Extract limestone		Continue to 3.2.2.2
3.2.4.4	3.2.4.4.3 Extract salt brines	O: Salt brine mine owners E: Machinery suppliers, Energy companies A,R: Salt brine mine employees AI: Salt brine mine shareholders AIB: Salt brine miners, Birds and fish at the salt brine mines	3.2.4.4.3.N Natural formation of salt brines
3.2.4.4	3.2.4.4.4 Supply CO2	O: CO2 suppliers (fossil fuel-fired power plants) E: Machinery suppliers, Energy companies A,R: CO2 supplier employees AI: Government (transportation), CO2 supplier shareholders AIB: CO2 supplier engineers, Fish in water bodies at the CO2 supplier sites	3.2.4.4.4 Supply of industrial CO2

Level	Activity	Key Stakeholders	End
3.2.4.4	3.2.4.4.5 Transport raw materials and produce soda ash (3.2.4.4.2-4)	O: Soda ash plant owners E: O of 3.2.4.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Soda ash plant employees R: Soda ash plants, Birds and fish at soda ash plant sites AI: Foreign O of 3.2.4.4.2-4 AIB: Birds on transportation routes	
3.2.4	3.2.4.5 Transport raw materials and produce glass (3.2.4.2-4)	O: Glass plant owners E: O of 3.2.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Glass plant employees R: Glass plants, Birds and fish at glass plant sites AI: Foreign O of 3.2.4.2-4 AIB: Birds on transportation routes	
3.2	3.2.5 Transport materials and construct buildings (3.2.2-4)	O: Solar PV power plant owners E: O of 3.2.2-5, Transportation companies, Solar PV power plant owners, Construction companies A: Transportation carriers, Construction team R: Solar PV power plants, Bird and fish at the Solar PV power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.2.2-5 AIB: Birds and fish at the Solar PV power plants, Birds on transportation route	
3	3.3 Supply functional modules installed and carbon intensities (3.1)	O: Solar PV power plant owners E: Government, Solar PV power plant owners, Module suppliers (PV module, mounting system, inverter) A,R: Managers, Research team, External researchers, Construction team, Installation and repairing engineers AI: Government (construction, technology policy), Panel manufacturers (China 0.3) AIB: On-site and on-route human and animals for module production and transportation	
3.3	3.3.1 Supply capital for purchasing modules (PV module, mounting system, inverter, electrolyser)	O: Solar PV power plant owners E: Government (policy), Solar PV power plant owners A,R: Solar PV power plant managers R: O of 3.3.2-4 AI: Shareholders of Solar PV power plants	

Level	Activity	Key Stakeholders	End
3.3	3.3.2 Manufacture PV panels/modules (multi-crystalline)	O: PV panel manufacturing plant owners E: PV cell manufacturing plant plants, Machinery suppliers, Energy companies A,R: PV panel manufacturing plant employees AI: PV panel manufacturing plant shareholders AIB: PV panel manufacturing plant engineers, Birds and fish at the PV panel manufacturing plants	
3.3.2	3.3.2.1 Supply capital for purchasing materials: PV cells (multi-Si), frame (aluminium)	O: PV panel manufacturing plant owners E: Government (policy), PV panel manufacturing plant owners A,R: PV panel manufacturing plant managers R: O of 3.3.2.2-3 AI: Shareholders of PV panel manufacturing plants	
3.3.2	3.3.2.2 Manufacture PV laminates (PV wafer multi-Si, Solar glass, Copper, Aluminium, Ethylvinylacetate)	O: PV cell manufacturing plant owners E: PV wafer manufacturing plants (0.8 EU, 0.2 China), Solar glass manufacturers, Copper plants, Aluminium plants, Ethylvinylacetate plants, Machinery suppliers, Energy companies A,R: PV cell manufacturing plant employees AI: PV cell manufacturing plant shareholders AIB: PV cell manufacturing plant engineers, Birds and fish at the PV cell manufacturing plants	
3.3.2.2	3.3.2.2.1 Supply capital for purchasing materials: PV wafers (multi-Si), solar glass, copper, aluminium, ethylvinylacetate	O: PV cell manufacturing plant owners E: Government (policy), PV cell manufacturing plant owners A,R: PV cell manufacturing plant managers R: O of 3.3.2.2.2-5 AI: Shareholders of PV cell manufacturing plants	
3.3.2.2	3.3.2.2.2 Manufacture PV wafers (Multi-Si)	O: PV wafer manufacturing plant owners E: Poly-Si plants, Machinery suppliers, Energy companies A,R: PV wafer manufacturing plant employees AI: PV wafer manufacturing plant shareholders AIB: PV wafer manufacturing plant engineers, Birds and fish at the PV wafer manufacturing plants	
3.3.2.2.2	3.3.2.2.2.1 Supply capital for purchasing materials: ingot [poly-Si], auxiliaries	O: PV wafer manufacturing plant owners E: Government (policy), PV wafer manufacturing plant owners A,R: PV wafer manufacturing plant managers R: O of 3.3.2.2.2.2 AI: Shareholders of PV wafer manufacturing plants	

Level	Activity	Key Stakeholders	End
3.3.2.2.2	3.3.2.2.2.2 Produce poly-Si ingot (all EU)	O: Poly-Si plant owners E: MG-silicon plants, Machinery suppliers, Electricity companies A,R: Poly-Si plant employees AI: Poly-Si plant shareholders AIB: Poly-Si plant engineers, Birds and fish at the Poly-Si plant	
3.3.2.2.2.2	3.3.2.2.2.2.1 Supply capital for purchasing materials: MG-silicon, auxiliaries	O: Poly-Si plant owners E: Government (policy), Poly-Si plant owners A,R:Poly-Si plant managers R: O of 3.3.2.2.2.2.2 AI: Shareholders of Poly-Si plants	
3.3.2.2.2.2	3.3.2.2.2.2.2 Produce MG-silicon	O: MG-Si plants E: Quartz mines, Machinery suppliers, Electricity companies A,R: MG-silicon plants AIB: Birds and fish at MG-silicon plants	
3.3.2.2.2.2.2	3.3.2.2.2.2.2.1 Supply capital for quartz and auxiliaries	O: MG-Si plant owners E: Government (policy), MG-Si plant owners A,R: MG-Si plant managers R: O of 3.3.2.2.2.2.2.2-3 AI: Shareholders of MG-Si plants	
3.3.2.2.2.2.2	3.3.2.2.2.2.2.2 Supply carbon (coal)		Continue to 3.2.3.5
3.3.2.2.2.2.2	3.3.2.2.2.2.2.3 Mine and produce quartz	O: Quartz mine owners E: Machinery suppliers, Energy companies A,R: Quartz mine employees AI: Government (transportation), Quartz mine shareholders AIB: Quartz miners, Birds and fish at quartz mines	3.3.2.2.2.2.2.3 Natural formation of quartz
3.3.2.2.2.2.2	3.3.2.2.2.2.2.4 Transport materials and produce MG-silicon	O: MG-Si plant owners E: O of 3.3.2.2.2.2.2.2-3, Transportation companies, MG-Si plant owners, Construction companies A: Transportation carriers, Construction team R: MG-Si plant employees, Birds and fish at the MG-Si plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2.2.2.2.2.2-3 AIB: Birds on transportation routes	
3.3.2.2.2.2	3.3.2.2.2.2.3 Transport materials and produce poly-Si ingots	O: Poly-Si plant owners E: O of 3.3.2.2.2.2.2, Transportation companies, Poly-Si plant owners, Construction companies A: Transportation carriers, Construction team R: Poly-Si plant employees, Birds and fish at the Poly-Si plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2.2.2.2.2 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.3.2.2.2	3.3.2.2.2.3 Transport materials and produce PV wafers	O: PV wafer manufacturing plant owners E: O of 3.3.2.2.2.2, Transportation companies, PV wafer manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: PV wafer manufacturing plant employees, Birds and fish at the PV wafer manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2.2.2.2 AIB: Birds on transportation routes	
3.3.2.2	3.3.2.2.3 Manufacture Solar glass	O: Solar glass plant owners E: Float glass plants, Machinery suppliers, Electricity plants A,R: Solar glass plant employees AI: Solar glass plant shareholders AIB: Solar glass plant engineers, Birds and fish at solar glass plants	
3.3.2.2.3	3.3.2.2.3.1 Supply capital for purchasing float glass	O: Solar glass plant owners E: Government (policy), Solar glass plant owners A,R: Solar glass plant managers R: O of 3.3.2.2.3.2 AI: Shareholders of solar glass plants	
3.3.2.2.3	3.3.2.2.3.2 Produce ad supply float glass	O: Float glass plants E: Glass plants, Machinery suppliers, Energy companies A,R: Float glass plant employees AI: Float glass plant shareholders AIB: Float glass plant engineers, Birds and fish at the float glass plant	Continue as 3.2.4
3.3.2.2.3	3.3.2.2.3.3 Transport materials and produce solar glass	O: Solar glass plant owners E: O of 3.3.2.2.3.2, Transportation companies, Solar glass plant owners, Construction companies A: Transportation carriers, Construction team R: Solar glass plant employees, Birds and fish at the solar glass plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2.2.3.2 AIB: Birds on transportation routes	
3.3.2.2	3.3.2.2.4 Manufacture copper products	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	

Level	Activity	Key Stakeholders	End
3.3.2.2.4	3.3.2.2.4.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.3.2.2.4.2 AI: Copper plant shareholders	
3.3.2.2.4	3.3.2.2.4.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.3.2.2.4.2.N Natural formation of copper ores
3.3.2.2.4	3.3.2.2.4.3 Transport and produce copper products	O: Copper plant owners E: O of 3.3.2.2.4.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.3.2.2.4.2 AIB: Birds on transportation routes	
3.3.2.2	3.3.2.2.5 Manufacture framing materials (aluminium, Ethylvinylacetate)	O: Aluminium plant owners, EVA plant owners E: Bauxite mines, Ethylene suppliers, VAM suppliers, Machinery suppliers, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	
3.3.2.2.5	3.3.2.2.5.1 Supply capital for purchasing Aluminium	O: Aluminium plant owners E: Government (policy), Aluminium plant owners A,R: Aluminium plant employees, O of 3.3.2.2.5.2 AI: Aluminium plant shareholders	
3.3.2.2.5	3.3.2.2.5.2 Extract and process bauxite or process recycled aluminium products	O: Bauxite mine owners E: Machinery suppliers, Energy companies A,R: Bauxite mine employees AI: Government (transportation), Bauxite mine shareholders AIB: Bauxite miners, Birds and fish at bauxite mines	3.3.2.2.5.2.N Natural formation of bauxite mines
3.3.2.2.5	3.3.2.2.5.3 Transport and produce aluminium products	O: Aluminium plant owners E: O of 3.3.2.2.5.2, Government (transportation), Transportation carriers A: Transportation carriers, Aluminium plant employees R: Aluminium plants, Birds and fish at aluminium plant sites AI: Foreign O of 3.3.2.2.5.2 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.3.2.2	3.3.2.2.6 Transport materials and produce PV cells	O: PV cell manufacturing plant owners E: O of 3.3.2.2.2-5, Transportation companies, PV cell manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: PV cell manufacturing plant employees, Birds and fish at the PV cell manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2.2.2-5 AIB: Birds on transportation routes	
3.3.2	3.3.2.3 Manufacture frame (aluminium)	O: Aluminium plant owners E: Bauxite mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at Aluminium plants	Continue to 3.3.2.2.5.2
3.3.2	3.3.2.4 Transport materials and produce PV panels	O: PV panel manufacturing plant owners E: O in 3.3.2.2-3, Transportation companies, PV panel manufacturing plant owners, Construction companies A: Transportation carriers, Construction team R: PV panel manufacturing plant employees, Birds and fish at the PV panel manufacturing plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2.2-3 AIB: Birds on transportation routes	
3.3	3.3.3 Produce materials for mounting system (stainless steel)	O: Mounting system manufacturing plant owners E: Steel plants, Machinery suppliers, Energy companies A,R: Mounting system manufacturing plant employees AI: Mounting system manufacturing plant shareholders AIB: Mounting system manufacturing plant engineers, Birds and fish at the mounting system manufacturing plants	Continue to 3.2.3
3.3	3.3.4 Manufacture inverters (steel, copper, aluminium)	O: Solar inverter manufacturing plant owners E: Steel plants, Aluminium plants, Copper plants, Machinery suppliers, Energy companies A,R: Solar inverter manufacturing plant employees AI: Solar inverter manufacturing plant shareholders AIB: Solar inverter manufacturing plant engineers, Birds and fish at the solar inverter manufacturing plants	Continue to 3.2.3, 3.3.2.4, 3.3.2.2.5.2

Level	Activity	Key Stakeholders	End
3.3	3.3.5 Transport and install or construct the modules (3.3.2-5)	O: Solar PV power plant owners E: O of 3.3.2-4, Transportation companies, Solar PV power plant owners, Construction companies A: Transportation carriers, Construction team R: Solar PV power plants, Birds and fish at the Solar PV power plants AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2-4 AIB: Birds and fish at the Solar PV power plants, Birds on transportation routes	
3	3.4 Compile national solar PV farms profile: installed capacity, CO2 intensity profile in time and space, replacement rate of materials and modules (3.2, 3.3)	O: Solar PV power plant owners E, A, R: Managers, Research team, External researchers	
Top	**4.** Obtain necessary energy, labour, capital	O: Solar PV power plant owners E: Domestic energy supplier, Solar PV power plant owners, Government A,R: Managers, Employees AI: Country (labour) AIB: Local residents, Animals at and near solar PV power plants	
4	4.1 Investigate sources of electricity, labour and quantity of solar radiation	O: Solar PV power plant owners E: Solar PV power plant owners, Country (labour), Energy companies, Meteorology organisations A, R: Managers, Research team, External researchers	
4	4.2 Supply electricity, labour, and capital	O: Solar PV power plant owners E: Solar PV power plant owners, E of 4.1 A, R: Managers, Employees AI: Foreign E of 4.1, Government (policy) AIB: Original residents near solar PV power plants, Birds and fish at solar PV power plant dams	
4	4.3 Compile consumption profile of transformational inputs for solar PV production	O: Solar PV power plant owners E, A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
Top	**5.** Operate the power plant to produce electricity	O: Solar PV power plant owners E: Solar PV power plant owners, Government (quota) A: Employees, Managers, Solar PV power plant owners R: Solar PV power plant owners, Managers, Solar PV power plant employees, Local residents, Animals at and near solar PV power plants AI: KSs in 2,3,4, Government (Quota) AIB: Waste disposal site residents and animals	
5	5.1 Repair and replace structural and functional parts (3.4)	O: Solar PV power plant owners E: Solar PV power plant owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of power plant storehouse, Compartment Carriers, Carriers for waste compartments	
5.1	5.1.1 Investigate low-carbon or energy saving construction materials	O: Solar PV power plant owners E: Solar PV power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.2 Investigate low-carbon or more efficient modules	O: Solar PV power plant owners E: Solar PV power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: Solar PV power plant owners E: Solar PV power plant owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: Solar PV power plant owners, Recycling companies E: Solar PV power plant owners A,R: Transportation carriers, Recycling plants, Landfill companies AI: Government (transportation, policy), Social groups (policy), Residents at each plant site AIB: Birds and fish at each plant	
5	5.2 Operate and produce (4.3; 5.1)	O: Solar PV power plant owners E: E of 3.4 and 4.3, Electricity company A: Engineers, Managers, Solar PV power plant owners R: Customers (electricity), Employees of solar PV power plants, Birds and fish at solar PV power plant sites	

Level	Activity	Key Stakeholders	End
5	5.3 Emit CO2 (5.2)	O: Solar PV power plant owners E: Government (transportation) A: Solar PV power plant employees R: Solar PV power plant employees, Birds and Fishes at the power plants AI: Government (CO2 budget), Customers (demand), Local residents and social groups AIB: Local residents, Birds and fish at solar PV power plant sites	5.3.N Natural diffusion and absorption of CO2
Top	**6.** Distribute to grid/store electricity	O: Solar PV power plant owners, Government E: Solar PV power plants, Government A: Solar PV power plant R: Customers, Solar PV power plant owners, Managers, Employees AI: Animals at and near solar PV power plants AIB: Local residents, Animals at and near solar PV power plants	
Top	**7.** Form an apposite system of solar PV electricity production for the sustainability evaluation objectives	O: Solar PV power plant owners E: Information suppliers in 1-6, Solar PV power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

D.2.9 Wider KSs of Geothermal Power Production

The table presents the complete expanded stakeholder analysis for geothermal power production system.

Level	Activity	Key Stakeholders	End
Top	**1.** Develop the apposite subsystem of geothermal power plants based on sustainability evaluation objectives	O: Geothermal power plant owners E: Government, Social groups (EC, UN, IEA, OECD) A,R: Managers, Research team, External researchers R: Geothermal power plant owners, Managers, Research team	
1	1.1 Identify the sustainability criteria for evaluation based on the sustainability evaluation objectives	O: Government, Geothermal power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
1	1.2 Identify lead of sustainability evaluation objectives relating to geothermal electricity and the sustainability criteria: governments, and organisations joined by the country	O: Government, Geothermal power plant owners E: O, Other DMs, Research team, Social groups A,R: Managers, Research team, External researchers	
1	1.3 Determine the the system boundary of geothermal electricity production system, the initial system, and the time scope of evaluation	O: Government, Geothermal power plant owners E: O, Other DMs, Research team A,R: Managers, Research team, External researchers	
Top	**2.** Investigate geothermal power plant: scale, technology used, construction materials, and CO2 emission sources and sinks	O: Geothermal power plant owners, Government E: Geothermal power plant owners, Local residents, Geothermal power plant employees, Animals at and near geothermal power plants, Shareholders and creditors of geothermal power plants, Internal information management teams A,R: Managers, Research team, External researchers	
2	2.1 Determine the power plants to be included in evaluation	O: Government, Geothermal power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.2 Identify sources of information	O: Government, Geothermal power plant owners E: Government A,R: Managers, Research team, External researchers	
2	2.3 Determine used area, technologies, and materials	O: Government, Geothermal power plant owners E: Government, Managers, Research team, Data platforms A,R: Managers, Research team, External researchers AI:Social groups (EC, IEA, European parliament, European Economic and Social Committee, IEA, European Geothermal Energy Council) AIB: Original residents on-site, Current employees working on-site, Original on-ground and underground animals on-site, Migration birds	
2	2.4 Investigate carbon containment and emission of the materials and modules	O: Geothermal power plant owners E: Material suppliers A,R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
2	2.5 Compile national planning, technology mix, and carbon sources and sinks about construction of geothermal plants	O: Geothermal power plant owners E, A, R: Managers, Research team, External researchers	
Top	**3.** Supply functional modules, materials, labour for maintenance and replacement	O: Geothermal power plant owners E: Technology suppliers (well construction companies, well head manufacturers, flash separator manufacturers, moisture remover manufacturers, turbine generator manufacturers, condenser manufacturers, cooling tower construction companies, pipe manufacturers), Construction material suppliers (offices, structures), Government (policy), Land supplier, Geothermal power plant owners (capital), Material and modules carriers, Engineers A,R: Managers, Employees AI: Foreign construction material suppliers, Foreign technology suppliers, Country (labour) AIB: Potential technology suppliers, Potential carriers, Potential material suppliers	
3	3.1 Investigate low carbon or more efficient substitutes (2.5)	O: Geothermal power plant owners E: Geothermal power plant owners, Available suppliers A, R: Managers, Research team, External researchers	
3	3.2 Construct structures and buildings (3.1)	O:Geothermal power plant owners E: Government (land), Construction material suppliers, Geothermal power plant owners, Construction companies A,R: Managers, Construction and maintenance team AI: Government (policy), Foreign material suppliers AIB: Local residents of geothermal power plants, Birds and migration birds resting near geothermal power plant sites, Fish in water bodies at geothermal power plant sites	
3.2	3.2.1 Supply capital for purchasing construction materials (steel, plastic, aluminium, mineral wool, copper, concrete)	O: Geothermal power plant owners E: Government (policy), Geothermal power plant owners A,R: Geothermal power plant managers R: O of 3.2.2-7 AI: Shareholders of geothermal power plant	

Level	**Activity**	**Key Stakeholders**	**End**
3.2	3.2.2 Produce steel	O: Steel plant owners E: Iron ore mines, Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Steel plant shareholders AIB: Steel plant engineers, Birds and fish at the steel plants	
3.2.2	3.2.2.1 Supply capital for purchasing steel	O: Steel plant owners E: Government (policy), Steel plant owners A,R: Steel plant employees, O of 3.2.2.2-5 AI: Steel plant shareholders	
3.2.2	3.2.2.2 Extract iron ores	O: Iron mine owners E: Machinery suppliers, Energy companies A,R: Iron mine employees AI: Government (transportation), Iron mine shareholders AIB: Iron ore miners, Birds and fish at iron mines	3.2.2.2.N Natural formation of iron ores
3.2.2	3.2.2.3 Extract limestone	O: Limestone plant owners E: Machinery manufacturers, Energy companies A,R: Limestone plant employees AI: Government (policy), Limestone shareholders AIB: Limestone miners, Birds and fish at limestone mines	3.2.2.3.N Natural formation of lime mines
3.2.2	3.2.2.4 Process recycled steel	O: Steel plant owners E: Machinery suppliers, Waste steel product owners, Energy companies A,R: Steel plant employees AI: Government (transportation), Steel plant shareholders AIB: Birds and fish at steel plants	
3.2.2	3.2.2.5 Produce coal or natural gas	O: Coal plant owners, LNG plant owners E: Machinery manufacturers, Energy companies A,R: Coal plant employees, LNG plant employees AI: Government (policy), Coal plants or LNG plants shareholders AIB: Coal plant engineers, Birds and fish at coal mines or LNG mines	3.2.2.5.N Natural formation of coal or LNG
3.2.2	3.2.2.6 Transport raw materials and produce steel	O: Steel plant owners E: O of 3.2.2.2-5, Government (transportation), Transportation carriers A: Transportation carriers, Steel plant employees R: Steel plants, Birds and fish at steel plant sites AI: Foreign O of 3.2.2.2-5 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.2	3.2.3 Produce plastic (PE, PVC)	O: Plastic company owners E: Crude oil suppliers, Brine supplier, Machinery suppliers, Energy companies A,R: Plastic company employees AI: Plastic company shareholders AIB: Plastic plant engineers, Birds and fish at plastic companies	
3.2.3	3.2.3.1 Supply capital for plastic purchase	O: Plastic company owners E: Government (policy), Plastic company owners A,R: Plastic company employees, O of 3.2.3.2-3 AI: Plastic company shareholders	
3.2.3	3.2.3.2 Extract ethylene (crude oil)	O: Oil plant owners E: Machinery suppliers, Energy companies A,R: Oil plant employees AI: Government (transportation), Oil plant shareholders AIB: Oil plant engineers, Birds and fish at oil plants	3.2.3.2.N Natural formation of crude oil
3.2.3	3.2.3.3 Extract brine	O: Brine plant owners E: Machinery manufacturers, Energy companies A,R: Brine plant employees AI: Government (policy, transportation), Brine plant shareholders AIB: Brine extraction engineers, Birds and fish at the brine lake sites	3.2.3.3.N Natural formation of brine (salt water)
3.2.3	3.2.3.4 Transport materials and produce plastics	O: Plastic plant owners E: O of 3.2.3.2-3, Government (transportation), Transportation carriers A: Transportation carriers, Plastic plant employees R: Plastic plant employees, Birds and fish at plastic plant sites AI: Foreign O of 3.2.3.2-3 AIB: Birds on transportation routes	
3.2	3.2.4 Produce aluminium products	O: Aluminium plant owners E: Bauxite mines, Machinery suppliers, Waste aluminium product owners, Electricity plants A,R: Aluminium plant employees AI: Aluminium plant shareholders AIB: Aluminium plant engineers, Birds and fish at aluminium plants	
3.2.4	3.2.4.1 Supply capital for purchasing aluminium	O: Aluminium plant owners E: Government (policy), Aluminium plant owners A,R: Aluminium plant employees, O of 3.2.4.2 AI: Aluminium plant shareholders	

Level	Activity	Key Stakeholders	End
3.2.4	3.2.4.2 Extract and process bauxite or process recycled aluminium products	O: Bauxite mine owners E: Machinery suppliers, Energy companies A,R: Bauxite mine employees AI: Government (transportation), Bauxite mine shareholders AIB: Bauxite miners, Birds and fish at bauxite mines	3.2.4.2.N Natural formation of bauxite mines
3.2.4	3.2.4.3 Transport and produce aluminium products	O: Aluminium plant owners E: O of 3.2.4.2, Government (transportation), Transportation carriers A: Transportation carriers, Aluminium plant employees R: Aluminium plants, Birds and fish at aluminium plant sites AI: Foreign O of 3.2.4.2 AIB: Birds on transportation routes	
3.2	3.2.5 Produce mineral wool	O: Mineral wool insulation plant owners E: Coke (Coal) suppliers, Slag suppliers, Rock suppliers, Machinery suppliers, Energy companies A,R: Mineral wool insulation plant employees AI: Mineral wool insulation plant shareholders AIB: Mineral wool insulation plant engineers, Birds and fish at mineral wool insulation plants	
3.2.5	3.2.5.1 Supply capital for purchasing mineral wool	O: Mineral wool insulation plant owners E: Government (policy), Mineral wool insulation plant owners A,R: Mineral wool insulation plant employees, O of 3.2.5.2-4 AI: Mineral wool insulation plant shareholders	
3.2.5	3.2.5.2 Produce slag		Continue to 3.2.2
3.2.5	3.2.5.3 Extract rocks (basalt)	O: Basalt plant owners E: Machinery manufacturers, Energy companies A,R: Basalt plant employees AI: Basalt shareholders AIB: Basalt miners, Birds and fish at basalt mines	
3.2.5	3.2.5.4 Produce coke (coal)		Continue to 3.2.2.5
3.2.5	3.2.5.5 Transport and produce mineral wool	O: Mineral wool insulation plant owners E: O of 3.2.5.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Mineral wool insulation plant employees R: Mineral wool insulation plants, Birds and fish at mineral wool insulation plant sites AI: Foreign O of 3.2.5.2-4 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.2	3.2.6 Produce copper products	O: Copper plant owners E: Copper mines, Machinery suppliers, Waste copper product owners, Energy companies A,R: Copper plant employees AI: Copper plant shareholders AIB: Copper plant engineers, Birds and fish at the copper plant	
3.2.6	3.2.6.1 Supply capital for purchasing copper	O: Copper plant owners E: Government (policy), Copper plant owners A,R: Copper plant employees, O of 3.2.6.2 AI: Copper plant shareholders	
3.2.6	3.2.6.2 Extract copper ores or process recycled copper	O: Copper ore mine owners E: Machinery suppliers, Energy companies A,R: Copper ore mine employees AI: Government (transportation), Copper ore mine shareholders AIB: Copper ore miners, Birds and fish at copper ore mines	3.2.6.2.N Natural formation of copper ores
3.2.6	3.2.6.3 Transport and produce copper products	O: Copper plant owners E: O of 3.2.6.2, Government (transportation), Transportation carriers A: Transportation carriers, Copper plant employees R: Copper plants, Birds and fish at copper plant sites AI: Foreign O of 3.2.6.2 AIB: Birds on transportation routes	
3.2	3.2.7 Produce concrete (cement)	O: Cement plant owners E: Limestone plants, Mudstone plants, Clay plants, Machinery suppliers, Energy companies A,R: Cement plant employees AI: Cement plant shareholders AIB: Cement plant engineers, Birds and fish at the cement plants	
3.2.7	3.2.7.1 Supply capital for purchasing cement: limestone, mudstone, clay	O: Cement plant owners E: Government (policy), Cement plant owners A: Cement plant managers R: O of 3.2.7.2-4 AI: Cement plant shareholders	
3.2.7	3.2.7.2 Extract limestone		Continue to 3.2.2.3
3.2.7	3.2.7.3 Extract mudstone	O: Mudstone plant owners E: Machinery manufacturers, Energy companies A,R: Mudstone plant employees AI: Government (policy), Mudstone plant shareholders AIB: Mudstone miners, Birds and fish at mudstone mines	3.2.7.3.N Natural formation of mudstone mines

Level	Activity	Key Stakeholders	End
3.2.7	3.2.7.4 Extract clay	O: Clay plant owners E: Machinery manufacturers, Energy companies A,R: Clay plant employees AI: Government (policy), Clay plant shareholders AIB: Clay miners, Birds and fish at clay mines	3.2.7.4.N Natural formation of clay
3.2.7	3.2.7.5 Transport materials and produce concrete (3.2.7.2-4)	O: Cement plant owners E: Government (transportation), Cement plant owners, O of 3.2.7.2-4, Transportation companies A: Cement plant employees, Transportation carriers R: Cement plants, Birds and fish at cement plant sites AI: Foreign O of 3.2.7.2-5 AIB: Birds on transportation routes	
3.2	3.2.8 Transport materials and construct structures and buildings (3.2.1-7)	O: Geothermal power plant owners E: O of 3.2.2-7, Transportation companies, Geothermal power plant owners, Construction companies A: Transportation carriers, Construction team R: Geothermal power plants AI: Social groups, Nearby residents, Government (policy) AIB: Birds and fish near geothermal power plant site, Birds on transportation routes	
3	3.3 Install functional modules (3.1)	O:Geothermal power plant owners E: Government (land), Geothermal power plant owners, Module suppliers (well construction companies, well head manufacturers, flash separator manufacturers, moisture remover manufacturers, turbine generator manufacturers, condenser manufacturers, cooling tower construction companies, pipe manufacturers) A,R: Managers, Construction and maintenance team AI: Government (policy), Foreign module suppliers AIB: Local residents of geothermal power plants, Birds and migration birds resting near geothermal power plant sites, Fish in water bodies at geothermal power plant sites	

Level	Activity	Key Stakeholders	End
3.3	3.3.1 Supply capital for purchase of functional modules: wells, well heads, pipes, aggregated other modules for high presser and lower pressures (flash separator, moisture remover, turbine generator, condenser, cooling tower)	O: Geothermal power plant owners E: Government (policy), Geothermal power plant owners A,R: Geothermal power plant managers R: O of 3.3.2-5 AI: Shareholders of geothermal power plant	
3.3	3.3.2 Produce materials for wells: cement, steel, silica flour, bentonite	O: Steel plant owners, Cement plant owners, Silicon plant owners, Bentonite plant owners E: Iron ore mines, Limestone plants, Limestone plants, Mudstone plants, Quartz mines, Bentonite mines, Energy companies, Machinery suppliers A,R: Steel plants, Cement plants, Silicon plants, Bentonite plants AI: Shareholders of O AIB: Engineers of A, Birds and fish at steel plants, cement plants, silicon plants, bentonite plants	
3.3.2	3.3.2.1 Supply capital for purchasing raw materials of wells (cement, steel, silica flour, bentonite)		
3.3.2	3.3.2.2 Produce cement		Continue to 3.2.7
3.3.2	3.3.2.3 Produce steel		Continue to 3.2.2
3.3.2	3.3.2.4 Produce silica flour	O: Silicon plant owners E: Quartz mines, Coal plants, Machinery suppliers, Energy companies A,R: Silicon plant employees AI: Silicon plant shareholders AIB: Silicon plant engineers, Birds and fish at the silicon plant	
3.3.2.4	3.3.2.4.1 Supply capital for purchasing raw material for silicon (quartz, coal)		
3.3.2.4	3.3.2.4.2 Extract quartz	2 O: Quartz mine owners E: Machinery manufacturers, Energy companies A,R: Quartz mine employees AI: Government (policy), Quartz mine shareholders AIB: Birds and fish at Quartz mines	3.3.2.4.2.N Natural formation of quartz mines
3.3.2.4	3.3.2.4.3 Produce coal		Continue to 3.2.2.5

Level	Activity	Key Stakeholders	End
3.3.2.4	3.3.2.4.4 Transport materials and produce silicon flour		
3.3.2	3.3.2.5 Extract bentonite	O: Bentonite plant owners E: Machinery manufacturers, Energy companies A,R: Bentonite plant employees AI: Government (policy), Bentonite plant shareholders AIB: Bentonite miners, Birds and fish at bentonite mines	3.3.2.5.N Natural formation of bentonite mines
3.3.2	3.3.2.6 Supply and store raw materials	O: Well manufacturing company owners E: Government (transportation), Well manufacturing company owners, O of 3.3.2.2-5, Transportation companies A: Well manufacturing company employees, Transportation carriers R: Well manufacturing companies, Birds and fish at geothermal power plants AI: Foreign O of 3.3.2.2-5 AIB: Birds on transportation routes	
3.3	3.3.3 Manufacture well heads (steel, aluminium)	O: Well head manufacturers E: Steel plants, Aluminium plants, Energy companies, Machinery suppliers A,R: Well head manufacturers AI: Well head manufacturer shareholders AIB: Well head manufacturing engineers, Birds and fish at well head manufacturing plants	Continue to 3.2.2, 3.2.4
3.3	3.3.4 Manufacture pipes (steel, mineral wool, aluminium, concrete)	O: Steel plant owners, Mineral wool insulation plant owners, Aluminium plant owners, Cement plant owners E: Iron ore mines, Steel recycling plants, Limestone plants, Mudstone plants, Coke (Coal) suppliers, Slag suppliers, Rock suppliers, Bauxite mines, Energy companies, Machinery suppliers A,R: Steel plants, Mineral wool insulation plants, Aluminium plants, Cement plants AI: Shareholders of A AIB: Engineers of A, Birds and fish at sites around A	Continue to 3.2.2, 3.2.5, 3.2.4, 3.2.7

Level	Activity	Key Stakeholders	End
3.3	3.3.5 Manufacture other modules [aggregated] (steel, glass fibre reinforced plastic, titanium, copper, aluminium, mineral wool, plastic)	O: Steel plant owners, Plastic plant owners, Titanium plant owners, Copper plant owners, Aluminium plant owners, Mineral wool insulation plant owners E: Iron ore mines, Steel recycling plants, Glass fibre plants, Resin plants, Crude oil suppliers, Brine supplier, Rutile mines, Copper mines, Bauxite mines, Coke (Coal) suppliers, Slag suppliers, Rock suppliers, Energy companies, Machinery suppliers A,R: Steel plants, Plastic plants, Titanium plants, Copper plants, Aluminium plants, Mineral wool insulation plants AI: Shareholders of O AIB: Module manufacturing engineers, Birds and fish at the manufacturing plants	
3.3.5	3.3.5.1 Supply capital for purchasing raw materials for functional modules (steel, glassfibre plastic, plastic, titanium, copper, aluminium, mineral wool)	O: Owners of module manufacturing plants (Flash separator, Moisture remover, Turbine generator, Condenser, Cooling tower) E: Government (policy), Os A,R: Managers of module manufacturing plants R: O of 3.3.5.2-8 AI: Shareholders of module manufacturing plants	
3.3.5	3.3.5.2 Produce steel		Continue to 3.2.2
3.3.5	3.3.5.3 Produce glassfibre reinforced plastic	O: Plastic company owners E: Fibre glass plants, Coal plants, Crude oil plants, Machinery suppliers, Energy companies A,R: Plastic company employees AI: Plastic company owners AIB: Birds and fish at plastic companies	
3.3.5.3	3.3.5.3.1 Supply capital for purchasing materials for GRP	O: Plastic company owners E: Government (policy), Plastic company owners A: Plastic company managers R: O of 3.3.5.3.2-3 AI: Plastic company shareholders	
3.3.5.3	3.3.5.3.2 Produce fibreglass	O: Fibreglass plant owners E: Silica sand suppliers, Limestone plants, Soda ash plants, Machinery manufacturers, Energy companies A,R: Fibreglass plants AI: Fibreglass plant owners AIB: Birds and fish at the fibreglass plants	
3.3.5.3.2	3.3.5.3.2.1 Supply capital for purchasing materials for fibreglass (silica sand, limestone, soda ash)	O: Fibreglass plant owners E: Government (policy), Fibreglass plant owners A: Fibreglass plant managers R: O of 3.3.5.3.2.2-4 AI: Fibreglass plant shareholders	

Level	Activity	Key Stakeholders	End
3.3.5.3.2	3.3.5.3.2.2 Extract silica sand	O: Silica sand mine owners E: Machinery manufacturers, Energy companies A,R: Silica sand mine employees AI: Government (policy), Silica sand mine shareholders AIB: Silica sand miners, Birds and fish at silica sand mines	3.3.5.3.2.2.N Natural formation of silica sand
3.3.5.3.2	3.3.5.3.2.3 Extract limestone		Continue to 3.2.2.3
3.3.5.3.2	3.3.5.3.2.4 Produce soda ash	O: Soda ash plants E: Limestone plants, CO2 suppliers, Salt brine mines, Machinery suppliers, Energy companies A,R: Soda ash plant employees AI: Government (transportation), Soda ash plant shareholders AIB: Soda ash plant engineers, Fish in water bodies at the soda ash plants	
3.3.5.3.2.4	3.3.5.3.2.4.1 Supply capital for purchasing soda ash	O: Soda ash plant owners E: Government (policy), Soda ash plant owners A,R: Soda ash plant employees, Manufacturers in 3.3.5.3.2.4.2-4	
3.3.5.3.2.4	3.3.5.3.2.4.2 Extract limestone		Continue to 3.2.2.3
3.3.5.3.2.4	3.3.5.3.2.4.3 Extract salt brines	O: Salt brine mine owners E: Machinery suppliers, Energy companies A,R: Salt brine mine employees AI: Salt brine mine shareholders AIB: Salt brine miners, Birds and fish at the salt brine mines	3.3.5.3.2.4.3.N Natural formation of salt brines
3.3.5.3.2.4	3.3.5.3.2.4.4 Supply CO2	O: CO2 suppliers (fossil fuel-fired power plants) E: Machinery suppliers, Energy companies A,R: CO2 supplier employees AI: Government (transportation), CO2 supplier shareholders AIB: CO2 supplier engineers, Fish in water bodies at the CO2 supplier sites	3.3.5.3.2.4.4 Supply of industrial CO2
3.3.5.3.2.4	3.3.5.3.2.4.5 Transport raw materials and produce soda ash (3.3.5.3.2.4.2-4)	O: Soda ash plant owners E: O of 3.3.5.3.2.4.2-4, Government (transportation), Transportation carriers A: Transportation carriers, Soda ash plant employees R: Soda ash plants, Birds and fish at soda ash plant sites AI: Foreign O of 3.3.5.3.2.4.2-4 AIB: Birds on transportation routes	

Level	Activity	Key Stakeholders	End
3.3.5.3.2	3.3.5.3.2.5 Transport materials and produce fibreglass	O: Fibreglass plant owners E: Government (transportation), Fibreglass plant owners, O of 3.3.5.3.2.2-4, Transportation companies A: Fibreglass plant employees, Transportation carriers R: Fibreglass plant employees, Birds and fish at fibreglass plant AI: Foreign O of 3.3.5.3.2.2-4 AIB: Birds on transportation routes	
3.3.5.3	3.3.5.3.3 Extract resin (coal, crude oil)		Continue to 3.2.2.5, 3.2.3.2
3.3.5.3	3.3.5.3.4 Transport materials and produce GRP	O: Plastic company owners E: Government (transportation), Plastic company owners, O of 3.3.5.3.2-3, Transportation companies A: Plastic company employees, Transportation carriers R: Plastic company employees, Birds and fish at plastic company AI: Foreign O of 3.3.5.3.2-3 AIB: Birds on transportation routes	
3.3.5	3.3.5.4 Produce plastic (PE, PVC)		Continue to 3.2.3
3.3.5	3.3.5.5 Produce titanium products	O: Titanium plant owners E: Rutile mines, Coal plants (coke), Machinery suppliers, Energy companies A,R: Titanium plant employees AI: Titanium plant owners AIB: Birds and fish at titanium plants	
3.3.5.5	3.3.5.5.1 Supply capital for purchasing titanium	O: Titanium plant owners E: Government (policy), Titanium plant owners A: Titanium plant managers R: O of 3.3.5.5.2-3 AI: Titanium plant shareholders	
3.3.5.5	3.3.5.5.2 Extract rutile	O: Rutile mine owners E: Machinery manufacturers, Energy companies A,R: Rutile mine employees AI: Government (policy), Rutile mine shareholders AIB: Rutile miners, Birds and fish at rutile mines	3.3.5.5.2.N Natural formation of rutile mines
3.3.5.5	3.3.5.5.3 Produce coke		Continue to 3.2.2.5

Level	Activity	Key Stakeholders	End
3.3.5.5	3.3.5.5.4 Transport materials and produce titanium products	O: Titanium plant owners E: Government (transportation), Titanium plant owners, O of 3.3.5.5.2-3, Transportation companies A: Titanium plant employees, Transportation carriers R: Titanium plant employees, Birds and fish at Titanium plants AI: Foreign O of 3.3.5.5.2-3 AIB: Birds on transportation routes	
3.3.5	3.3.5.6 Produce copper products		Continue to 3.2.6
3.3.5	3.3.5.7 Produce aluminium products		Continue to 3.2.4
3.3.5	3.3.5.8 Produce mineral wool		Continue to 3.2.5
3.3.5	3.3.5.9 Transport materials and manufacture modules (flash separator, moisture remover, turbine generator, condenser, cooling tower)	O: Owners of module manufacturing plants E: O of 3.3.5.2-8, Transportation companies, Owners of module manufacturing plants A: Transportation carriers, Construction team R: Module manufacturing plant employees, Birds and fish at manufacturing plants AI: Foreign O of 3.3.5.2-8 AIB: Birds on transportation routes	
3.3	3.3.6 Transport materials and modules and install at the geothermal power plant site (3.3.2-6)	O: Geothermal power plant owners E: O of 3.3.2-5, Transportation companies, Geothermal power plant owners, Construction companies A:Transportation carriers, Construction team, Engineering team R: Geothermal power plants, Birds and fish near geothermal power plant site AI: Social groups, Nearby residents, Government (policy), Foreign O of 3.3.2-5 AIB: Birds on transportation routes	
3	3.4 Compile national geothermal plant profile: installed capacity, CO2 intensity profile in time and space, replacement rate of materials and modules (3.2, 3.3)	O: Geothermal power plant owners E, A, R: Managers, Research team, External researchers	

Level	Activity	Key Stakeholders	End
Top	**4.** Obtain necessary energy, labour, capital	O: Geothermal power plant owners E: Domestic energy supplier, Geothermal power plant owners, Government A,R: Managers, Employees AI: Country (labour) AIB: Local residents, Animals at and near geothermal power plants	
4	4.1 Investigate sources of geothermal sites, electricity, and labour	O: Geothermal power plant owners E: Geothermal power plant owners, Country (labour), Energy companies, Meteorology institutions, Geographic observatories A, R: Managers, Research team, External researchers	
4	4.2 Supply electricity, labour, capital	O: Geothermal power plant owners E: Geothermal power plant owners, Determined E in 4.1 A: Managers, Engineers R: Managers, Employees, Engineers AI: Foreign Es, Government (transportation) AIB: Original residents near geothermal power plant site, On-ground and underground animals vertically near the drills, Birds and fish at geothermal power plant sites	
4	4.3 Compile consumption profile of transformational inputs for geothermal electricity production	O: Geothermal power plant owners E, A, R: Managers, Research team, External researchers	
Top	**5.** Operate the power plant to produce electricity	O: Geothermal power plant owners E: Geothermal power plant owners, Government (quota) A: Employees, Managers, Geothermal power plant owners R: Geothermal power plant owners, Managers, Geothermal power plant employees, Local residents, Animals at and near geothermal power plants I: KSs in 2,3,4, Government (quota) AIB: Waste disposal site residents and animals	
5	5.1 Repair and replace structural and functional parts (3.4)	O: Geothermal power plant owners E: Geothermal power plant owners, E of 3.4 A: Engineers, Repairing teams, Managers R: Managers of storehouse, Compartment Carriers, Carriers for displaced compartments	

Level	**Activity**	**Key Stakeholders**	**End**
5.1	5.1.1 Investigate low-carbon or energy saving construction materials	O: Geothermal power plant owners E: Geothermal power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.2 Investigate low-carbon or more efficient modules	O: Geothermal power plant owners E: Geothermal power plant owners, Available suppliers A, R: Managers, Research team, External researchers AI: Foreign suppliers	
5.1	5.1.3 Repair or replace compartments (5.1.1-2)	O: Geothermal power plant owners E: Geothermal power plant owners, Managers A: Engineers, Managers R: Storehouse manager, A of 5.1.4	
5.1	5.1.4 Dispose replaced materials or wastes (5.1.3)	O: Geothermal power plant owners, Recycling companies E: Geothermal power plant owners A,R: Transportation carriers, Recycling plants, Landfill companies AI: Government (transportation, policy), Social groups (policy), Residents at each plant site AIB: Birds and fish at each plant	
5	5.2 Operate and produce electricity (4.3; 5.1)	O: Geothermal power plant owners E: E of 3, 4, Energy companies A: Engineers, Managers, Geothermal power plant owners R: Customers (electricity), Employees of geothermal power plants, Birds and fish at geothermal power plant sites	
5	5.3 Reinject and emit CO2 (5.2)	O: Geothermal power plant owners E: Government (transportation) A: Engineers, Managers R: Birds and fish at geothermal power plant sites, Geothermal power plant employees working on-site AI: Government (policy), geothermal power plant shareholder, Social groups AIB: Local residents	5.3.N Natural diffusion and absorption of CO2; Natural cycle of cooled geothermal flows
Top	**6.** Distribute to grid/store electricity	O: Geothermal power plant owners, Government E: Geothermal power plant, Government A: Geothermal power plant R: Customers, Geothermal power plant owners, Managers, Employees AI: Animals at and near geothermal power plants AIB: Local residents, Animals at and near geothermal power plants	

Level	**Activity**	**Key Stakeholders**	**End**
Top	**7.** Form an apposite system of geothermal electricity production for the sustainability evaluation objectives	O: Geothermal power plant owners E: Information suppliers in 1-6, Geothermal power plant owners, Other DMs, Research team A,R: Managers, Research team, External researchers AI: DMs, Data providers	

D.3 Estimation for Solar Radiation

Solar power input for PV electricity production is gained estimated by global horizontal irradiation (GHI), data sourcing from the World Bank. Fig. D.6 presents the distribution of GHI, covering all European countries included.

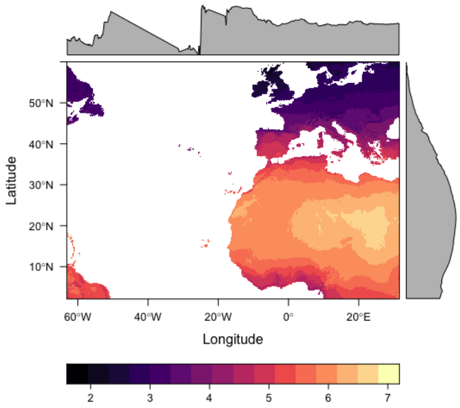

Figure D.6 Global horizontal irradiation in EU28 country region.

D.4 Data Table and Conversion Units

D.4.1 List of Emergy Value References

	Unit	Transformity (seJ/J)	Source
Coal	J	6.71E+04	Yanchun and Lingmei (2010)
Hard coal	g	8.84E+04	Corcelli et al. (2017)
Crude oil	J	9.06E+04	Brown and Ulgiati (2004)
Diesel	J	1.13E+05	Pulselli et al. (2007)
Petroleum fuel	J	1.11E+05	Campbell et al. (2005)
Gasoline	g	2.92E+09	Yang and Chen (2016)
	J	2.30E+05	Ciobanu et al. (2022)
LNG			
head	J	6.28E+04	Ren et al. (2020)
production	J	8.05E+04	Brown and Ulgiati (2004), Campbell et al. (2005)
Uranium ore	g	2.96E+09	Campbell et al. (2005)
Biomass			
forest biomass	J	4.82E+04	Campbell et al. (2005)
Wood biomass		1.84E+04	Brown and Ulgiati (2004)
Hydro	J	1.70E+04	Brown et al. (2012)
Tide	J	7.39E+04	Brown and Ulgiati (2010)
Wind (Ek)	J	1.06E+03	Campbell et al. (2005)
Solar	J	1.00E+00	Brown and Ulgiati (2004), Pulselli et al. (2007), Brown et al. (2012)
Geo heat	J	1.02E+04	Brown and Ulgiati (2004)
Water			
ground water	J	2.72E+05	Campbell et al. (2005)
	g	3.17E+04	Chen and Liu (2022)
for cooling	g	1.10E+04	Brown et al. (2012)
Air	g	6.75E+07	Ren et al. (2020)
Labour and Services	person*yr	2.19E+16	Corcelli et al. (2017)
Metals	g	6.97E+09	Pulselli et al. (2007)
Metals (Al, Fe, Zn, Cu, Pb)	g	1.68E+09	Brown and Ulgiati (2004)
Metal rod	g	6.31E+09	Ren et al. (2020)
Aluminium	g	2.10E+10	Campbell et al. (2005)
Ammonia, NH3	g	4.81E+09	Nimmanterdwong (2017)
Ammonium soap	g	2.82E+08	Corcelli et al. (2017)
Asphalt	g	4.60E+09	Ciobanu et al. (2022)
Basalt rock	g	3.35E+10	Brown et al. (2012)
Bauxite, Aluminium ore	g	2.52E+07	Campbell et al. (2005)
Bentonite	g	3.35E+09	in this study
Bitumen	g	4.60E+09	in this study
Brick	g	3.68E+09	Pulselli et al. (2007)

	Unit	**Transformity (seJ/J)**	**Source**
Brass	g	1.04E+11	in this study
Brine	J	2.72E+05	in this study
Calcite	g	1.68E+09	in this study
Cement	m3	3.96E+08	Ren et al. (2020)
Ceramic tiles	g	4.80E+09	Pulselli et al. (2007)
Chemicals	g	6.37E+08	Brown and Ulgiati (2004)
Chlorine	g	2.82E+08	Corcelli et al. (2017)
Ferric chloride	g	6.42E+09	Ciobanu et al. (2022)
Helium	g	2.82E+08	in this study
Hydrochloric acid	g	2.82E+08	Corcelli et al. (2017)
Hydrogen	J	2.10E+04	Nimmanterdwong et al. (2022)
Oxygen	g	8.65E+07	Ciobanu et al. (2022), Yazdani et al. (2020), Brown and Ulgiati (2004)
Polyacrylamide	g	4.45E+09	Chen and Liu (2022)
Poly Aluminium Chloride	g	4.45E+09	Chen and Liu (2022)
Polyelectrolyte	g	5.95E+09	Ciobanu et al. (2022)
Polyvinyl Alcohol	g	2.82E+08	Corcelli et al. (2017)
Sodium chloride	g	2.82E+08	Corcelli et al. (2017)
Sodium hydroxide, NaOH	g	4.37E+09	Corcelli et al. (2017)
Sulphuric acid, H2SO4	g	8.97E+09	Corcelli et al. (2017)
Nitrogen	g	2.82E+08	Corcelli et al. (2017)
Chromium	g	1.68E+09	Buonocore et al. (2015)
Clay	g	3.35E+09	Campbell et al. (2005)
CO2	g	6.75E+07	in this study
industrial use from CCS	g	1.09E+08	Nimmanterdwong et al. (2022)
Coal bed gas	g	8.05E+04	Yanchun and Lingmei (2010)
Coal gauge	g	6.88E+09	Yanchun and Lingmei (2010)
Concrete	g	1.81E+09	Pulselli et al. (2007)
	m3	4.23E+08	Ren et al. (2020)
Copper	g	1.04E+11	Pulselli et al. (2007)
Copper ore	g	2.52E+07	in this study
Corn	J	3.56E+04	Wang et al. (2019)
Diesel	g	8.65E+07	Ciobanu et al. (2022), Yazdani et al. (2020), Brown and Ulgiati (2004)
fuel	g	1.84E+09	Ren et al. (2020)
for machinery	J	1.89E+05	Buonocore et al. (2015)
Fibre glass	g	5.04E+09	Yang and Chen (2016)
Fluorspar, fluorite	g	1.68E+09	in this study
Fly ash	g	1.39E+09	Yanchun and Lingmei (2010)
Glass	g	3.62E+09	Buonocore et al. (2015)
flat glass	g	1.41E+09	Pulselli et al. (2007)
solar glass	g	8.00E+09	Brown et al. (2012)

	Unit	Transformity (seJ/J)	Source
Glass-fibre reinforced plastic	g	9.84E+09	Buonocore et al. (2015)
Gravel	g	1.87E+09	Ciobanu et al. (2022)
Gypsum	g	3.29E+03	in this study
Lead	g	1.04E+11	in this study
Limestone, Lime	g	1.68E+09	Campbell et al. (2005), Nimmanterdwong (2017)
Loam	g	3.31E+09	in this study
Lubricants	g	2.03E+09	Ren et al. (2020)
	J	4.83E+04	in this study
Olivine	g	2.24E+09	in this study
Paint	g	2.55E+10	Pulselli et al. (2007)
Paper, paperboard	g	2.39E+05	Campbell et al. (2005)
Perlite	g	6.97E+09	in this study
Plaster	g	3.29E+03	Pulselli et al. (2007)
Plastic and rubber	g	4.63E+09	Campbell et al. (2005)
Electricity insulating material	g	9.84E+09	Buonocore et al. (2015)
PVC	g	9.86E+09	Pulselli et al. (2007)
plastic sheeting	g	2.68E+09	Wang et al. (2019)
Rubber	g	7.22E+09	Pulselli et al. (2007)
PS, HDPE	g	8.85E+09	Pulselli et al. (2007)
PE, Polyester	g	6.22E+09	Yang and Chen (2016)
Phosphate rock	g	6.54E+09	Brown and Ulgiati (2004)
Manganese	g	1.14E+11	Buonocore et al. (2015)
Molybdenum	g	1.04E+11	in this study
Mudstone	g	3.31E+09	Pulselli et al. (2007)
Nickel	g	1.68E+09	Buonocore et al. (2015)
Resin	g	6.22E+09	Yang and Chen (2016)
Rutile	g	2.24E+09	in this study
Sand	g	2.24E+09	Campbell et al. (2005)
Sandstone	g	1.68E+09	Campbell et al. (2005)
Silica sand	g	2.06E+06	Corcelli et al. (2017)
Silicon			
MG Silicon	g	1.83E+10	Corcelli et al. (2017)
silica flour	g	1.83E+10	in this study
Silicon	g	1.68E+09	Yang and Chen (2016)
Slag	g	1.68E+09	Yanchun and Lingmei (2010)
Soda ash (natural)	g	2.72E+05	in this study
Steel, Iron			
for building and machinery	g	6.97E+09	Pulselli et al. (2007)
Iron	g	2.50E+09	Buonocore et al. (2015)
Iron Ore	g	1.04E+08	Campbell et al. (2005)
Stone	g	2.44E+09	Pulselli et al. (2007)
Thermal insulating materials	g	3.35E+10	Brown et al. (2012)

	Unit	**Transformity (seJ/J)**	**Source**
Timber			
net timber growth	J	3.57E+04	Campbell et al. (2005)
products	g	2.40E+09	Pulselli et al. (2007)
Tin	g	1.04E+11	in this study
Titanium	g	1.04E+11	in this study
Vanadium	g	1.68E+09	in this study
Zinc	g	1.04E+11	Pulselli et al. (2007)
Electricity Production	J	2.91E+05	Campbell et al. (2005)
	kWh	1.05E+12	Ciobanu et al. (2022)

D.4.2 Life Time of Power Plants

Table D.11 Power plant life time

	Time (yrs)
Thermo	30
Nuclear	60
Hydro	150
Wind	25
SolarPV	35
Geothermal	30

D.4.3 Conversion Estimates

Table D.12 Cement composition est.

Concrete composition by Flury and Frischknecht (2012)				
Concrete	1	m3	2.40E+06	g
cement	0.8	m3	2.00E+06	g
gravel	0.127	m3	1.27E+05	g
water	0.073	m3	2.30E+05	g

Table D.13 Building material composition estimates.

Building composition		Pulselli et al. (2007)	
for 1m3 of building	mass/quantity	unit	mass ratio to concrete
Concrete	263,665	kg	
Steel	7898	kg	
Glass	201	kg	0.000762331
Diesel	2.17E+09	J	8.23E+03

Nuclear Conduit by EMWG (2007)						
	Price for nuclear plant		Overall		Proportion	Length
Steel conduit	43.84	USD	36.5	USD	0.677362637	206934.2857
Non-metallic conduit	21.09	USD	305500	m	0.322637363	98565.71429

Table D.14PVC pipe composition est.

Conduit, Tray, Pipes		(Koltun et al., 2011), EMWG (2007)					
				Property in detail			
		g/m	lbs/ft	Size in.	Inner diameter in.	Outer diameter in.	Wall thickness in.
Large-bore pipe (PVC)	PVC	14896.4816	10.01	12	11.938	12.75	0.406
Small-bore pipe (PVC)	PVC	1011.9488	0.68	2	2.067	2.375	0.154
		g/m	kg/m	Width mm	Thickness mm		
Cable tray	Aluminium	850	0.85	400	30		
		g/m	kg/100 ft	diameter mm			
Conduit	steel	8835.301837	269.3	50			
		g/m	lbs/ft				
	non-metallic	3440.62592	2.312	100			

Table D.15 Biomass fuel conversion est.

Biomass Fuel	Proportion	Dry		Yield	Bio-oil			
Corn stover, Agricultural	0.6	10.73	MJ/kg	225 litre/ton	as Ethanol	27.4	MJ/kg	Sheehan et al. (2003)
Fuelwood	0.4	2.03E+01	MJ/kg	0.64 t/t	as oil	22.7	MJ/kg	Bjrnsson et al. (2021)
	by EC	Osman et al. (2021)						

Table D.16 Fuel consumption in turbines est.

Consumption of fossil fuel in turbines			
	Consumption		Source
Thermo	1.38E-03		as geothermal
Nuclear	8.44E-05	MJ/kWh Lubricant	UNECE (2021)
	1.48E-03	MJ/kWh Diesel	
Hydro/Tide	1.36E-06	MJ/kWh Lubricant	Flury and Frischknecht (2012)
Wind	1.42E-03	MJ/kWh Diesel	Yang and Chen (2016)
Geothermal	1.38E-03	MJ/kWh Diesel	Karlsdttir et al. (2015)

Table D.17 Geothermal steam composition est.

Geothermal Steam Composition and Estimate			Karlsdttir et al. (2015)
Input, from ground and other			
Geothermal fluid	12.45	kg	
Brine	6.474	kg	
Steam	5.976	kg	
Geothermal energy	2.11E+04	kJ	
Electricity	0.040032	kWh	
Output, to plant and air			
CO2, in steam	1.75E-02	kg	
H2S, in steam	4.50E-03	kg	
Heat, reinjected	1596	kJ	
Electricity	1	kWh	

Table D.18 Heavy machine diesel consumption est.

General Machinery	Estimates		
Heavy machinery	8	gallon/h	Diesel consumption
Water inlet pumps (not for electricity)	12	m^3 liquid/h	
Chemical production	As ammonium		

Table D.19GRP composition est.

Fibreglass reinforced fabric	Composition Est.
Fibreglass	0.3
Fabric	0.7

Table D.20 Bird and fish and human fatality composition est

Avian or Fish deaths per year			
birdfatality windturbine	0.269	no/GWh	
	0.806569343	no/MW	
birdfatality coalmine	0.02	no/GWh	
birdfatality thermoOM	0.07	no/GWh	
birdfatality acidrain	0.05	no/GWh	
birdfatality Mercury	0.06	no/GWh	
birdfatality climatechange	4.98	no/GWh	
fishbird waterfatality mine	0.006	no/GWh	Uranium mining
birdfatality Uranium	4.76247745	no/t U	Uranium milling
birdfatality nulcearOM	0.188	no/GWh	
birdfatality solar	10.7	no/MW	
fishfatality hydro	0.009299021	no/MW	
birdfatality non-open mining	3.33333E-05	no/kg	Est.
birdfatality open mining	1.03E-07	no/kg	Est.
birdfatality building	0.07444818	no/kg	Est.
fish	3.08E-08	no/kg	Est.

Table D.21 Fuel consumption and CO2 emission in general machining est

General Manufacturing		Brown and Ulgiati (2002)	Campbell et al. (2005)
1 unit product	CO2 emission		Proportion consumption
Diesel for machines	9.12E-01	kg CO2/kg	8.18E-01
Lubricants	2.03E-01	kg CO2/kg	1.82E-01
Machining	1.115800	kg CO2/kg	Su et al. (2012)
	Estimated quantity		
Diesel for machines	9.43E-02	MJ/kg	
Lubricants	4.15E-01	MJ/kg product	

Table D.22 Biomass properties est

Harvesting					
Diesel	6.2	l/ha	Ecoinvent 3.4		
density, diesel	0.85	kg/l			
	0.000527	kg/m2			
Corn Harvest	1.05	kg/m2	Shinners et al. (2007)		
Wood Harvest					
Area	1.05E+10	m2			Arets et al. (2011)
Fuel wood	2927000	m3			
Harvest	1.32E-01	kg/m2	Soft	528,000	m3
			Hard	2,399,000	m3
Timber	198,916,000	m3	40in. Diameter, 68ft, in 50 yrs		Est.
Harvest	1.32E-01	kg/m2	Soft	528,000	m3
			Hard	2,399,000	m3
Density					
Softwood	300	kg/m3	Est.	472.1182098	
Hardwood	510	kg/m3	As pine		

Table D.23 Short-term carbon sequestration composition est

Short term Carbon sinks			
Annual			
Biomass Growth		kg CO2/unit	
Crop	2.78E-05	kg	Est.
Tree	1.11E-06	kg	Est.
Basalt Rock	2.04E-01	kg	Sanna et al. (2014)
Brine	7.00E-01	kg	Sanna et al. (2014)
fresh water	1.45E-01	kg	CO2 dissolution rate
Magnesite	5.50E+00	kg	Sanna et al. (2014)
Iron ore	2.80E+00	kg	Sanna et al. (2014)
Feldspar	4.40E+00	kg	Sanna et al. (2014)
Calcite	2.80E+00	kg	Est. by Sanna et al. (2014)