DEVELOPING AND TESTING A PROTOTYPE NET ZERO COMMUNITY IN THE UK

A thesis submitted in fulfilment of the degree of Doctor of Philosophy

by

Sukanya Ravi

Centre for Architecture and Sustainable Environment

Kent School of Architecture and Planning

University of Kent

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Abstract

Net-zero energy and net-zero carbon are terms that have gained popularity over the past two decades, to such an extent that their usage is being expanded to the scale of communities and cities. Despite the subject's growing momentum there is ambiguity in its understanding and application. Principles for net-zero have been defined for the building scale and energy systems that analyse and rate sustainability of large-scale developments exist. However, there isn't a set of defined benchmarks for testing the authenticity of net zero in large scale developments. This study aims to develop and test a prototype net zero community in the UK which falls under the temperate climate classification. The focus of the project is to investigate if a sustainable community based on user data from surveys on typical British lifestyles can meet a defined net zero benchmark.

This thesis includes three key elements. First, a net zero guide was developed by extrapolating information from current literature and energy rating systems designed to test communities and cities. Second, a prototype community was designed for the temperate climate classification inferred from current and past examples of net zero developments. Third, energy data was gathered for the designed community from an energy modelling software (DesignBuilder) to test if energy demand of the community can be met by renewable energy supply thereby achieving a net zero/positive balance. The community was found to meet net positive energy and net negative carbon emissions. There was an annual 68% surplus energy, of about 535000 kWh/year. The study makes a significant contribution to standardising net zero for easier application of the popularised concept.

"This is a story of our changing planet, and what we can do to help it thrive…"

David Attenborough

Contents

List of Figures

List of Tables

Declaration

I, Sukanya Ravi, declare that the work presented in this thesis is my own. The work presented is original and completed under the supervision of Dr Richard Watkins and Dr Giridharan Renganathan. I have not been awarded a degree by submitting the work included in this thesis for a higher degree at any other institution.

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Chapter 1

Introduction

1.1. Global Sustainability scenario

As a species, humans are known to exploit the environment we inhabit. Our way of living has now led to a global impact threatening the life of the very planet we populate. The detrimental effects of our misuse of resources are evident from the primeval Indus valley civilization and reached their peak, possibly during industrialization in the 19th century. If we were all to live like USA, we would require five earths to support us (Desai, 2010). Today countries world-wide have started to acknowledge that our exploitative lifestyle has led to climate change and there is an imperative requirement to reduce dependency on fossil fuels. Hence, if we continue to function in the way we currently are and have been, especially in the past two decades, the repercussions of climate change could become irreversible.

Several attempts have been made over the past three decades to combat the effects of climate change. One such significant measure initiated in 1992 was the formation of the United Nations Framework Convention on Climate Change (UNFCCC) which has since set the stage for tackling ecological issues at the local, national and global scale (UNFCCC Secretariat, 2012). The ultimate goal of this treaty is to curb greenhouse gas emissions which result in global warming and disrupt natural ecosystems. Globally, nations convene to devise and implement sustainability goals and frameworks. The first agreement was the Kyoto Protocol made in 1997. This was supplanted by the Paris Agreement in 2015 when goals on emissions and curbing global temperature were not met (UNFCCC Secretariat, n.d.). The treaty allows the nations in agreement to define their own climate change diminution goals (Sustainable Development Goals – SDGs) based on their limitations and abilities to tackle them. For example, UK aims to reach a nation-wide net zero carbon target by 2050 while India targets to achieve the same by 2070 (Climate Action Tracker, 2022).

As of 2018, the building and construction sectors contribute 39% of overall global greenhouse gas emissions and 36% of overall global energy use (IEA, 2019). According to UNEP, Buildings are prime consumers of energy typically produced by fossil fuels (UN Environment Programme, n.d.). Curbing harmful emissions implies reducing this energy demand and thereby reliance on fossil fuels. As per both UNEP and World Green Building Council this is more feasible in the building and construction sectors thereby making Sustainable Development Goals more achievable (World Green Building Council, 2019). Initial attempts at a sustainable development were seen in the 70s, spurred by the sudden rise in crude oil price, first in the European subcontinent and later in North America and Canada. Residential buildings were designed as experiments with high energy efficiency standards and typical to the temperate and cold climates. The series of experiments led to the development of low energy buildings which were equipped with renewable energy sources (typically solar panels) to support their low energy demand. The key learnings from these experiments proved to be efficient insulation and air sealing which in 1988 led to the birth of the Passivhaus standard (Passipedia, 2016).

For decades sustainability in the building sector has been implemented by measures to reduce the energy demand and provide local renewable energy supply as opposed to supply from the grid where energy is mostly generated by fossil fuels. These efforts have led to the development of standards and certifications in the past 20-30 years. Almost four decades later, the Passivhaus system is commended to be an efficient system. However, it is limited in terms of regional context. Nevertheless, energy efficient buildings are being designed globally to consume low energy and produce as much renewable energy as feasible on site. This produces an energy equation (supply vs demand) that results in a low value. In highly energy efficient buildings this equation was able to reach near zero thereby tagging these, near zero energy buildings. The advancement in technology along with the drive to achieve excellence in sustainability led to the concept of near zero being tested to its limits as net zero (where, energy supply = energy demand) and net positive (where, energy supply > energy demand). Over the past decade these have been applied to larger developments as well. However, near/net zero is thus far not standardised.

According to the Carbon Trust (The Carbon Trust, 2022), net zero entails extensive reduction of emissions which is crucial to achieving the goals set out to diminish the harmful effects of global warming and climate change. Furthermore, their guide on net zero (for businesses) highlights that net zero could curb temperature rise by removing CO_2 from the atmosphere. While terms such as net zero energy (NZE) and net zero carbon (NZC) are yet to be systemised, rating systems that assess the proficiency of sustainable developments include energy efficiency as a primary requirement for certification. Rating systems are excellent tools to measure the efficacy of a development's performance and have been widely used as standards for about two decades. These are particular to the national context they are developed for based on the nation's capabilities and limitations and climate. Some key rating systems include BREEAM (UK), LEED (US, Canada, India, Brazil), Pearl (UAE), Passivhaus (Germany), Green star (Australia, New Zealand, South Africa), GRIHA and IGBC (India), etc. Rating systems have also adapted and developed over the last decade to address carbon emissions and not just building energy consumption. Additionally, rating systems have now expanded from the building scale to as large as cities. This is discussed in detail in 'section 2.2'.

1.2. Need for Net-Zero

Net zero is a relatively new concept that has gained momentum over the past one to two decades. Renewed from near zero energy where a development produces energy to meet its demand but is deficient, net zero developments are able to produce energy that is sufficient to meet their demand. Despite its popularity and several attempts at implementing it, there is often ambiguity in its understanding which has led to a gap in research and practical applicability of the subject. Different countries have varying perceptions of net zero and are endorsing goals based on a system that does not have a clear definition (Sartori, et al., 2010). There is often debate on a development being net zero energy vs net zero carbon. A development that could achieve near or net zero in terms of energy may not necessarily imply near or net zero carbon emissions as emissions entail both operational (energy supply) as well as embodied carbon (materials, LCA). Author of Net Zero Energy Buildings, Attia explains that for the success of this concept in the long run, it is essential to limit emissions related to embodied carbon in building materials (Attia, 2018). Often embodied carbon is overlooked in the process of devising such a system and focus remains on reducing the energy demand and meeting this demand with a renewable energy supply. Neglecting embodied carbon often compromises achieving the overall goal of reduction in carbon emissions (Desai, 2010).

Years of research, experimentation and application of net zero have resulted in some noticeable examples of NZE and NZC buildings. Net zero was first tested in the residential sector and then expanded to the commercial sector. The Solar house in Freiburg (Fig. 1) is a pioneer example for NZE building that was built in the early 90s. During its first three years of occupancy (1992-95) the house remained disconnected from the grid as there was sufficient solar energy that was stored using solar generated hydrogen to run the house through the day. Notable examples of NZE commercial buildings include the office building, Indira Paryavaran Bhavan in New Delhi, India and the NREL office in Colorado, US (Fig. 2,3). Likewise, six offices in MediaCityUK, Manchester, UK (Fig. 4) have been verified to be NZC buildings (pbctoday, 2020).

Figure 1 - Solar house, Freiburg

Figure 2 - NREL, Colorado

Figure 3- Indira Paryavaran Bhawan, New Delhi

Figure 4 - MediaCityUK, Manchester

According to the World Green Building Council, there are about 2000 net zero residential and 500 net zero commercial buildings. This process of identifying key examples is yet again indicative of the distinction between some countries aiming for NZE like US and India and some others such as the UK focusing on NZC. Reducing energy demand and supporting this with clean energy has proved successful and feasible. However, whether these NZE buildings achieve NZC status is questionable. Net zero proves a promising solution to tackle climate change. Hence, it is highly necessary to develop a standard which addresses both energy and emissions (embodied as well as operational) thereby, harmonising the principles of net zero energy and net zero carbon.

The 2000s has seen this scheme being tested globally but mostly being restricted to the scale of single buildings. However, the past one to two decades has seen a shift in the applicability of the scheme to larger scales of developments like communities (BedZED, UK) and even cities (MASDAR, Abu Dhabi and Dongtan, China). According to Kallushi et al, it is beneficial to apply net zero to a large scale of development as it encourages heat sharing, load diversity and diversity in urban densities which facilitate a reduction in energy use as opposed to simply addressing the skin of a building (Kallushi, et al., 2012). A large-scale development also entails opportunities in terms of infrastructure systems such as water, waste and transport that can be energy demanding. Nevertheless, investigating the feasibility and workability of the scheme in large scales of developments is essential and some of these notable communities are discussed in detail in 'section 2.3'.

1.3. Need for research on net zero

Net zero has been in trial for years and is continuously being tested and updated to cater for the ever-changing climate change initiatives. However, the achievability of this concept and its feasibility in *large scale* developments require thorough investigation before its application. Even at the building scale, net zero is challenging to achieve for buildings such as airports, hospitals and towers (Attia, 2018). Regardless of its inadequate standardisation and shortcomings in its understanding, nations around the world have developed their own systems and definitions to join the energy efficiency movement. The past decade has seen the growth of net zero communities and cities. Despite its wide application this research indicated insufficiency in thorough documentation of these tailored systems and successful examples across the globe.

The current trend in net zero is the 'Race to Zero' campaign launched at the UN Climate Action Summit in 2019. This initiative encourages the 120 countries in agreement to push for zero carbon emissions by 2050 (UNFCCC, 2019). While this is a commendable initiative alongside the many other policies and standards that have been devised to tackle climate change, the lack of resources and the gap in literature to apply and assess net zero should not become an endless race to zero. Hence, it is essential to develop a system to understand the application and evaluation of net zero. This encourages further research on the achievability and workability of net zero as a subject irrespective of scale. The Passivhaus standard is a commendable system. However, a system like net zero addresses sustainability holistically and focuses on energy and emissions which are key to challenge global ecological issues.

1.3.1. Aims and objectives of the thesis

This thesis aims to develop an efficient standard and guide for net zero communities. The project entails formulating a rating system and then putting this to the test using a designed hypothetical community. It is essential for this guide to suit climate and location and for this purpose, the community will be a prototype situated in the UK which falls under the temperate climate classification. The prototype can be replicated in other locations with similar climate conditions if successful. The community will be designed holistically, considering sustainability in terms of energy demand, clean energy supply, thermal comfort, water, waste, food and most importantly occupants' lifestyles. Surveys conducted to identify typical British lifestyles will be used to create household patterns in terms of occupancy, heating, lighting and equipment use. The survey data is crucial to the study as these will be used to extract data to run energy simulations on 'EnergyPlus'. This thesis aims to develop a thorough guide for net zero and to test the achievability of NZE for a prototype community while attempting significant reductions in carbon emissions.

1.4. Structure of the thesis

Chapter 1: Introduction

This chapter introduces the thesis, outlining the current global scenario, need for net zero and gap in research in the subject. The chapter discusses the aims and objectives of this thesis.

Chapter 2: Literature review

This chapter introduces the different definitions of net zero for the building and community scale. It reviews existing benchmarks, principles and standards to identify an evaluation method for net zero. The chapter aims to review literature and existing research on net zero to standardise it so as to design and test a prototype community in the UK.

Chapter 3: Methods of evaluating a net zero development

The chapter presents a net zero guide that has been developed from globally recognised energy rating systems. Five noted energy rating systems that test sustainability of large-scale developments have been analysed in detail and compared to develop a standard for net zero.

Chapter 4: A review of large-scale net zero case studies

The chapter entails detailed analysis case studies on sustainable communities from history and investigation of present-day net zero developments to understand the achievability of net zero.

Chapter 5: Survey on typical British lifestyles

This chapter discusses the survey conducted on typical British lifestyles and the data collected from this. The survey gathered data on house type and size, household sizes, occupancy, heating, hot water and equipment usage. This information is used to design and model houses on an energy simulation software to obtain the energy consumption of the various British households modelled from the survey.

Chapter 6: Designing a prototype net zero community

The chapter presents elaborate building and urban design of the net zero community. Design development is informed from literature (Chapter 2), derived net zero rating system (Chapter 3) and survey data (Chapter 5).

Chapter 7: Energy Modelling and Simulations

This chapter discusses modelling and performing energy simulations on Designbuilder (energy modelling software) to obtain the energy consumption of the prototype community. The chapter validates the prototype model used for this project. Additionally, this chapter presents the results for building energy demand, urban energy demand for the survey sample and renewable energy supply.

Chapter 8: Discussions

This chapter tests if energy supply from renewable sources meets energy demand for the prototype community designed using data from the literature and surveys. Sensitivity analysis on lifestyles such as frugal, typical and profligate is performed to discover variations in energy demand. The chapter also calibrates the model community to the developed net zero rating system (from Chapter 3).

Chapter 9: Conclusions

The chapter summarises objectives of this thesis and findings from this study and highlights challenges and future research and considerations for this subject.

1.5. Methodological framework and research methods

The thesis entails, designing and testing a prototype net zero community for the UK. A detailed methodological framework was established for this. The overall methodology involved six stages as shown in Fig. 5 – Identifying location and studying climate, climate appropriate building design, climate appropriate urban design of community, modelling and simulating the development, deducing energy demand for the community and calculating energy supply from renewables based on location and climate. The prototype community will aim to incorporate real-time lifestyles of typical Britons. This will be informed from location and be used to input appropriate model data for energy modelling and simulation. The thesis aims to identify if energy demand can be met by energy supply thereby producing a net-zero energy equation. The overall data collection process is qualitative as well as quantitative in nature.

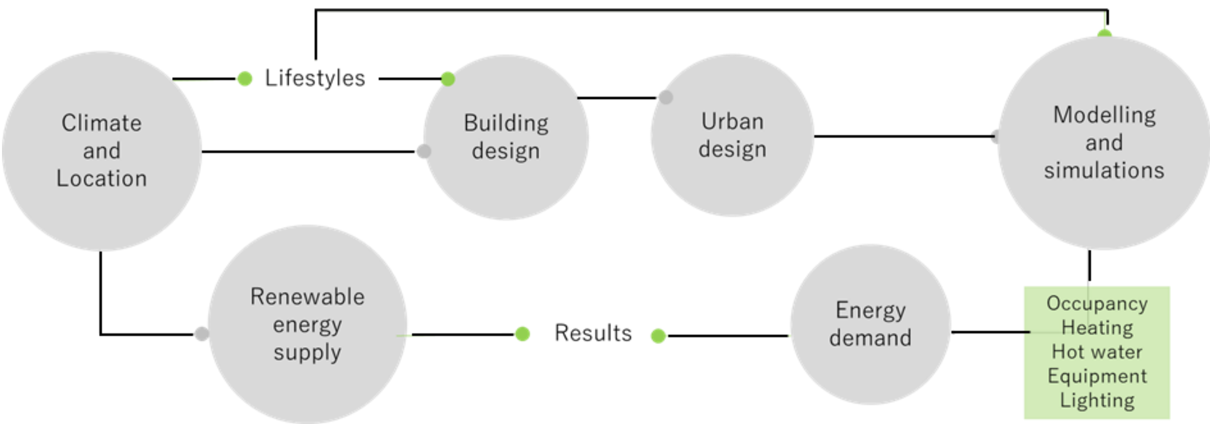


Figure 5 - Methodology mind map

The thesis uses four research methods for data collection and analysis – literature review, case studies, surveys and experiments. The literature review helped put the research in context with the subject field. Case studies were used for detailed comprehension of a specific context, in this case, sustainable and net zero developments from different decades and varying sizes. Surveys helped understand the attributes of a population for example family size or heating pattern of homes. Experiments were carried out using building simulations to determine cause and effect associations. Each step of the methodological framework is described below in brief with the research methodology used for each of these steps.

1.5.1. Climate and location – *Literature review*

An appropriate site located in the UK was used to design the prototype community. The selected site is situated in Sutton, UK. Since the UK is classified under the temperate climate, appropriate site analysis was conducted to identify design features and challenges. The details and outcomes of this methodology are covered in thesis section – 6.1.1.

1.5.2. Global energy rating systems – *Literature review*

This section compares five global energy rating systems for large scale developments. A comparative analysis is conducted to identify a pattern of similarities between these energy rating systems. Based on this analysis a rating system that would be applicable for a large-scale net zero development was derived. The five rating systems were tabulated in parallel to assess similarities and differences in categories and their respective weighting in points (refer Appendix 2). The comparative analysis and development of a net zero guide were used for designing the model houses and community. Chapter 3 discusses the details and outcomes of this methodology.

1.5.3. Lifestyles – *Survey*

Data on lifestyles were collected using surveys. An online survey was distributed to residents of Britain who have lived in the country for at least five years via ‘JISC Online surveys’ (JISC, n.d.). Data was collected online over a period of 12 months. 81 completed surveys have been used to deduce lifestyles data for the thesis. Chapter 5 deliberates on the details and outcomes of this methodology.

1.5.4. Building design – *Literature review + Case studies + Survey*

This section of the research is inferred from literature on UK housing standards, case studies' analysis discussed in 'section 2.2', energy rating systems and surveys conducted on typical British lifestyles. The data analysis helped obtain information on house sizes, house types, room areas, spatial arrangement based on function and environmental design principles. The details and outcomes of this methodology are covered in thesis section – 6.1.2.

1.5.5. Urban design - *Literature review + Case studies + Survey*

Urban design for the prototype community is inferred from literature on UK standards for housing estates, case studies' analysis discussed in 'section 4.1.2' and energy rating systems. The data analysis helped obtain information on sustainable urban design principles, transport plan and urban planning. The details and outcomes of this methodology are examined in thesis section – 6.1.4.

1.5.6. Modelling and simulation – *Literature review + Surveys + Experiment*

House design was obtained from methods described in 'section 1.5.4' along with literature to compile data for modelling. Simulation data was gathered from survey data analysis. The houses were modelled in Designbuilder, an energy modelling software. Simulations were run using the 'Energyplus' interface on Designbuilder. The details and outcomes of this methodology is covered in thesis 'section – 7.1.2'.

1.5.7. Energy demand - *Experiment*

Whole building energy simulation using Designbuilder run for a two-year simulation period is used to compile data on energy demand of the houses. Calculations using these results are carried out to identify the overall energy consumption of the prototype community. The details and results of this methodology are discussed in thesis section – 7.2.

1.5.8. Energy supply - *Experiment*

Based on location, an appropriate energy supply option was identified. A global formula was used to identify the total renewable energy produced either on site or off site. The details and results of this methodology are described in thesis section – 7.3.

Summary

This chapter facilitates a better understanding of net zero and the need to standardize and implement it in large scale developments. The chapter explained the need for a more rigorous study and examination of net zero as it is not a defined benchmark but is pursued ambitiously by many countries across the globe under the guidance of monumental organisations such as the UN. Chapter 2 investigates definitions of net zero, evaluation methods and existing frameworks and principles for net zero to identify key underlying ideologies of this concept.

Chapter 2
Literature review

2.1. Understanding net-zero energy

Progress over the past two decades indicates net zero energy is no longer a concept of the distant future but a realistic solution that addresses global ecological issues. Net zero and even net positive energy are said to work at the building scale as discussed in Chapter 1. However, its feasibility and workability in larger scales of development must be scrutinised and standardised for better application and true success of the scheme. The ambivalence of this concept starts at defining it. There are significant differences in the definition of net zero worldwide (Attia, 2018). Science Based Targets initiative, a global partnership of organisations that work on climate action indicates that the lack of a common definition results in inconsistency in net zero targets and thereby has a minimised effect on climate change (The Carbon Trust, 2022). The term ‘net zero communities’ is often referred to by other terms such as carbon neutral, climate neutral or sustainable communities (Carlisle, et al., 2009). Therefore, it is essential to standardise net zero and establish a clear, common definition that can be used globally.

2.1.1. Defining net zero

The first set of recognised definitions for net zero energy buildings was established by the National Renewable Energy Laboratory (NREL) in 2006 (Torcellini, et al., 2006). The report discussed definitions for net zero energy addressing four contexts - site energy, source energy, costs and energy related emissions. In 2009, the NREL adapted these definitions to suit net zero communities. Defining a net zero energy community is more complex than defining a net zero energy building because alongside building energy use the system must also consider energy use for industry, vehicle and community-based infrastructure (Carlisle, et al., 2009). According to NREL, a net zero energy community is designed to be highly energy efficient to enable reduction in both building and infrastructure energy demand which is met by renewable energy supply.

Similar to Torcellini's definition of net zero energy buildings, a net zero community has been defined in four contexts. These are:

- Net-Zero Site Energy:

  The energy consumption of the community is met entirely by renewable energy produced on site. That is, energy demand on site / year = energy supply on site / year
- Net-Zero Source Energy:

  Energy used to generate and deliver energy to the community is met by the renewable energy produced on site. In other words, energy supply from source / year = energy regeneration on site / year. This system usually includes conversions for tranfer of energy from site to source and vice-versa.
- Net-Zero Energy Costs:

  The cost paid to buy energy from the source is met by the income obtained from exporting energy produced on site to the grid. That is, cost to buy energy from grid /year = cost to sell energy to grid / year
- Net-Zero Energy Emissions:

  The community generates as much emissions free energy as it consumes from an energy source that produces emissions. That is, emissions free energy produced by community / year = energy produced by source with emissions / year

Based on these definitions one may understand that a community that meets any one of the above four criteria may be classified as a net zero community. Furthermore, these definitions are constrained to merely the energy aspect of the development and to an extent emissions. It can be noted that these definitions do not include embodied energy and carbon emissions as part of their analysis. In 2018, Attia included 'Life Cycle Zero Energy Buildings' in this list. A life cycle zero energy building produces enough energy from renewable sources within the site to meet both operational and embodied energy of a building over its lifetime (Attia, 2018). Net zero is multi-dimensional and it is essential to consider other important factors that will affect energy consumption, sustainability and the quality of life in the community. These include human aspects like economy, health, lifestyles and environmental aspects like water and waste management. Hence, taking into account the varying perceptions of the concept, a net zero community can be defined using the following parameters:

- The community has an exceedingly reduced energy demand which is met by renewable energy produced locally
- The community addresses sustainability in terms of water, economy, food, and transport
- The community aims to reduce both operational as well as embodied carbon if not achieve zero carbon emissions
- The community reduces, re-uses and recycles waste produced
- The community provides a healthy environment for its residents to live in including indoor environment quality and usable outdoor spaces.

This thesis focuses on and quantifies energy demand and supply. The other aspects of sustainability as defined above have been considered and included in the urban design of the community.

2.1.2. Evaluating net-zero energy and net-zero carbon

The UK Government alongside organisations such as UK Green Building Council (UKGBC) and Building Research Establishment (BRE) have set out some frameworks and tools to achieve and evaluate its 2030 and 2050 net zero targets (HM Government, 2012). However, literature indicates a lack of methodologies for calculating net zero. In 2015, researchers of the International Energy Agency's Solar Heating and Cooling Programme (IEA SHC Task 40) proposed a set of 12 methods to evaluate net zero energy buildings. According to Marszal et al, the following parameters must be clearly addressed before defining and evaluating net zero energy buildings. These are:

a. Metric of the balance

The unit of measurement for 'zero' balance can be determined by multiple constraints. These include primary energy, emissions, energy related emissions, cost of energy, etc. The unit is primarily influenced by the project goals, the investor, stress on climate change or energy costs (Torcellini, et al., 2006). As proposed by IEA SHC Task 40, primary energy is the preferred unit of measurement for net zero. Some methodologies also use more than one unit as net zero could address both zero energy as well as emissions.

b. Period of balance

The period for which the net zero calculation is being performed can differ vastly. It could be measured on a yearly basis or for the complete life cycle of the building. The typically used period of balance is an annual balance. That is, net zero is achieved over the year. However, one method proposed by Hernandez and Kenny uses the life cycle balance (Marszal, et al., 2011). This balance includes operational as well as embodied energy of the building thereby allowing assessment of a more realistic environmental impact.

c. Type of energy use

Energy calculations in the past only accounted for thermal energy which includes heating, domestic hot water and cooling. However, as suggested in the IEA SHC Task 40 methods, energy use must also include energy associated with occupant's behaviour under operational energy and embodied energy linked with building construction and infrastructure.

d. Type of balance

Marszal et al, explain two possible balances for a zero-energy building. The first method is energy consumption versus renewable energy supply. The second, energy from source versus energy returned to grid. According to their study, the energy requirement and renewable energy supply balance is the preferred method (Marszal, et al., 2011).

e. Renewable energy supply options

Renewable energy can either be generated on-site or off-site. On-site generation like solar or micro wind can be within the building footprint or within the building site. In contrast, off-site generation like biomass includes energy production in a location outside site boundaries or purchasing renewable energy from a source off-site. Figure 7 indicates possible renewable energy supply options developed by Marszal et al (Marszal, et al., 2011).

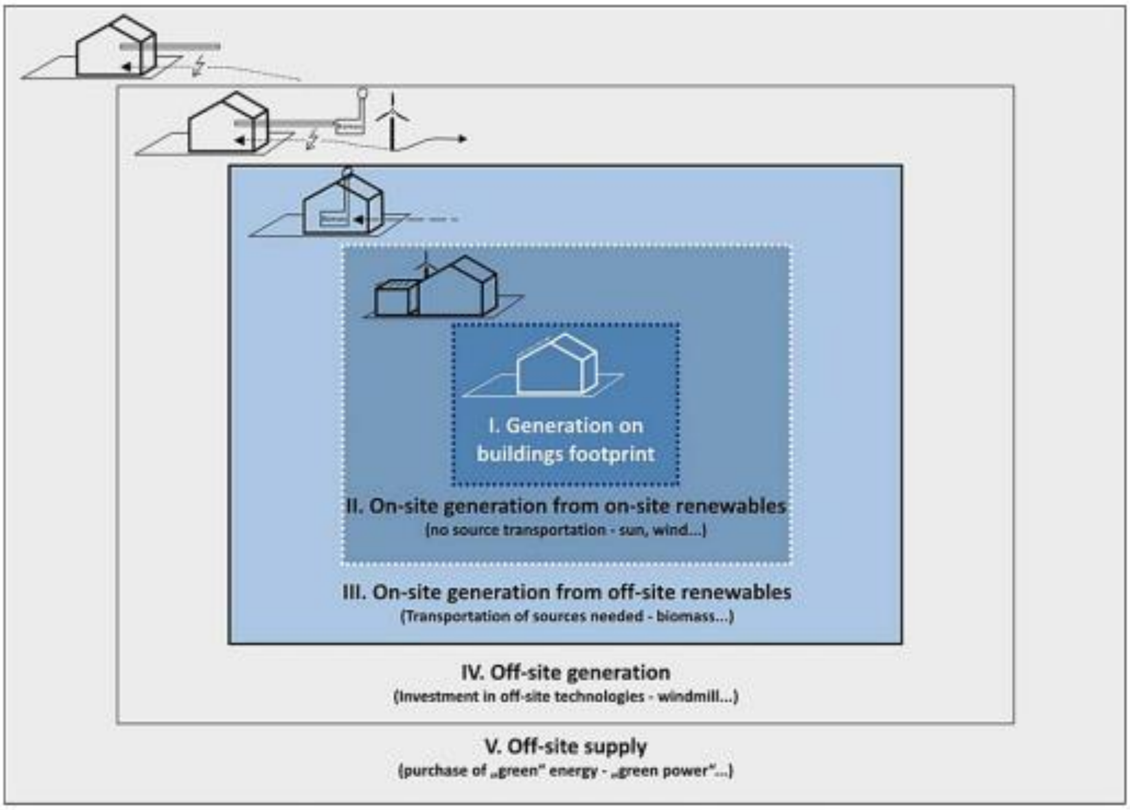


Figure 6 - Renewable energy supply options (Marszal, et al., 2011)

f. Connection with energy infrastructure

The building consumes as well as produces energy. Hence, it could either be on-grid or off-grid. On-grid net zero buildings are connected to the grid and export energy to the grid, while off-grid buildings are disconnected from the grid and store energy produced on site. In other words, are self-sufficient. A self-sufficient net zero building is able to supply its own energy due to its capacity to store energy for nocturnal as well as seasonal use (Lausten, 2008). The on-grid system allows for purchase and selling of energy to the grid thereby avoiding the need for on-site storage which can be challenging. However, these buildings may draw energy that has been produced from fossil fuels and thereby not meeting significant reductions in emissions.

g. Requirements

To be able to develop a robust net zero building it is essential to address some key thresholds at the design stage. While IEA SHC Task 40 does not address these in detail, Attia elaborates seven performance thresholds that are key for a net zero building. These are:

- Carbon emissions threshold

It is essential to calculate carbon emissions that are associated with both the primary energy requirement and embodied energy. Carbon emissions linked with embodied energy typically from building materials must be curbed for long term benefits. For the UK, the Zero Carbon Hub proposes carbon compliance limits of 10 to 11 $kgCO_2/m^2$ floor area per year for homes (Zero Carbon Hub, 2014). Likewise, an operational energy related carbon emissions threshold of 3 $kgCO_2/m^2$ annually is suggested for the EU (Attia, 2018). Embodied carbon does not have set limits. However, rating systems such as BREEAM and LEED address emissions associated with embodied energy as part of their certification.

- Minimum energy efficiency threshold

The Environment Design Pocketbook compiles 'good practice' benchmarks to evaluate the energy demand of a building as shown in Table 1 (Pelsmakers, 2015). As indicated in Table 1, the Passivhaus standard has a total energy demand threshold of 120 kWh/m^2 floor area per year and a zero-carbon dwelling almost 25% more than the Passivhaus standard.

Table 1 - Approximate building energy demand benchmarks for dwellings (Pelsmakers, 2015)

Benchmark	Space heating	Hot water	Lighting, fans, pumps, cooling	Appliances, equipment	Cooking, catering	Total energy demand
	kWh/m^2 per year					
Dwelling, Building Regulations	60	55	10	25	15	165

Zero carbon dwelling	39-46	55	10	25	15	144-151
Dwelling, Passivhaus standard	15	55	10	25	15	120

- Heating-cooling balance

In countries with low temperatures, the primary focus is typically on heating demand. Cooling, if needed, can be achieved passively. However, in countries with hot summers and cool winters, there is a need to balance both heating and cooling energy requirements. The zero-carbon dwelling standard for heating/cooling demand is proposed as 39-46 kWh/m^2 per year (Pelsmakers, 2015), whereas the Passivhaus standard for the same is limited to 15 kWh/m^2 per year (Attia, 2018). For countries with mild winters this is achievable fairly easily with high insulation and air tightness. For extremely cold climates, limiting the heating demand to the Passivhaus standard can be challenging. It is therefore critical to address the heating cooling balance based on climate classification and propose appropriate active/passive strategies and threshold values.

- Indoor environment quality limits

  The thermal performance of a building is closely linked with indoor comfort. It is essential to ensure that comfort is not compromised as a result of reducing thermal energy demand. There is often overheating in summers in buildings that have high performance envelopes. Likewise, in the case of building skin with poor insulation and air tightness, there is a risk of discomfort during the cooler months. According to CIBSE TM 36 (2005), the optimum internal temperature in summer for the living room is 25°C and bedroom is 21°C. Overheating occurs when temperatures touch 28°C for the living room and 25°C for bedrooms, for approximately 30-60 hours of yearly occupied time (CIBSE TM36, 2005). For comfort, recommended optimal indoor temperatures are 18-21°C in winters and 22-27°C in summers (Pelsmakers, 2015). For a climate like the UK, it is important to provide an efficient envelope while including passive cooling strategies for the summer months.

- Renewable energy generation threshold

  As discussed by Marszal et al., it is crucial to reduce energy demand and then meet the energy requirement with renewable energy supply either on-site or close to site (Marszal, et al., 2011). While local governments and national policies first encourage the inclusion of on-site renewable energy sources, this can be challenging in the case of dense urban localities with limited solar access, pollution and lack of space. Hence, it is important to note that renewable energy supply is location and site dependent and must allow for other supply options as proposed by IEA SHC Task 40 and Marszal et al (See Fig. 5).

- Occupancy density

  Where there is a possibility for variation in occupancy density, there is a significant effect on energy use. It is important to forecast and account for change in occupancy density and occupant behaviour. Calculating the occupancy density can help assess if the energy demand can be matched with on-site renewable energy supply.

- Cost threshold

  It is important to be able to design a net zero building with cost effectiveness. Net zero buildings require high insulation and renewable energy sources such as PV panels which are expensive. A rough estimate must be developed at the design stage to enable cost control strategies. The larger the net zero development, the lower the investment cost (Attia, 2018).

The parameters proposed by Marszal et al., Attia and Pelsmaker are in alignment and help develop a foundation for designing and testing a net zero development (Marszal et al., 2011; Attia, 2018; Pelmakers, 2015). It should be noted that the parameters and definitions are described for net zero buildings; these must be adapted to suit the community scale.

2.1.2.1. Calculation for net zero energy

A development based on a system boundary is defined by a load and a form of energy generation. Load includes energy demand and energy infrastructure efficiency. Similarly, generation consists of storage as well as conversion losses. Typically, on-site renewable energy can be used to partially satisfy the development's load and feed any surplus back to the grid based on load matching and availability of storage on site. The exchange of energy between a development and the grid is defined by the delivered energy (from development to grid) and feed-in energy (from grid to development). The balance between these two is critical to define and evaluate a net zero energy development. The balance uses a crediting system that allows it to account for the complete energy process which includes properties of natural resources, conversion process and the grid. Equations 1 and 2 calculate the import and export of energy required for the net zero energy balance (Sartori, et al., 2010).

$$\text{import} = \sum_i \text{delivered\_energy}(i) \times \text{credits}(i) \qquad (1)$$

$$\text{export} = \sum_i \text{feed-in\_energy}(i) \times \text{credits}(i) \qquad (2)$$

where, i = energy carriers

For a net zero energy development, the relation between import and export can be defined as shown in equation 3. Hence, for a development to meet net zero or net positive energy, more energy must be delivered to the grid than the energy feed-in from the grid.

$$\text{export} - \text{import} \geq 0 \qquad (3)$$

2.2. Frameworks

In 2012, the UK Government set out a national plan to increase the number of nearly zero energy buildings. The plan targeted all new homes in England built from 2016 to be zero carbon. The Government strategy included two key changes – reduction in energy demand of buildings by using better thermal efficiency, incorporating energy efficient lighting and appliances or by controlling occupant behaviour to use energy more intelligently; decarbonising heating and cooling systems by updating to low carbon heating technologies such as air or ground source heat pumps (HM Government, 2012). New legislation aims to phase out gas and oil boilers by 2035 (HM Government, 2021). The Directive 2010/31/EU on Energy Performance of Buildings formulated for the national plan highlighted key methods and energy uses to be included in the building regulation standards for zero carbon buildings for calculating energy performance (Office Journal of the European Union, 2010). These are:

- Thermal characteristics of the building including thermal capacity, insulation, passive heating, cooling and thermal bridging.
- Heating and hot water supply system
- Air conditioning system
- Natural and mechanical ventilation system including air tightness.
- Lighting system
- Design including position and orientation of building and outdoor climate

- Passive solar systems
- Indoor thermal comfort
- Internal loads

A more recent development in framework includes the Sustainability and Net Zero design guide developed by the Government Property Agency. The guide incorporates research on standards and documents for sustainability and net zero to identify a common definition and net zero methodology to deliver net zero carbon buildings. The document draws heavily from standards such as UKGBC Net Zero Carbon Buildings Framework, RIBA 2020 Plan of Work, LETI Climate Emergency Design Guide and BREEAM 2018 Energy Rating System (Government Property Agency, 2022).

2.2.1. UKGBC net zero framework

The framework was established as a simple guide that would be developed into a strict standard over a period in conjunction with other organisations such as RIBA and policy makers. The framework presents two definitions for net zero carbon using operation energy and construction. Where carbon emissions related to a building's operational energy over a year is zero or negative, the building is net zero carbon – operation energy. When the carbon emissions related to different stages of a building from construction until completion while considering materials used is zero or negative, the building is net zero carbon – construction (UKGBC, 2019). Defining net zero in terms of operational and embodied energy helps developers to choose an appropriate path to achieve net zero. The UKGBC methodology entails five vital steps (UKGBC, 2019):

- Establish scope – NZC operational energy vs construction

- If chosen scope is NZC Construction, reduce construction impact by undertaking whole life carbon assessment and measuring embodied carbon impact from materials and construction processes.
- Reduce operational energy use by considering efficient building fabric and passive design, system efficiency, energy management through BMS and occupant behaviour, indoor air quality and occupant wellbeing.
- Increase renewable energy supply either on or off-site
- Offset remaining carbon using recognised framework

The framework was aimed at developing a refined definition for net zero that can have a more universal understanding and application. While the focus typically remains on operational energy, UKGBC attempts to expand industry familiarity with embodied and whole life carbon which are more challenging to achieve but are likely to have a more significant impact on climate action targets. The methodology includes periodical measurements and calculations of energy and carbon emissions starting at the concept and design stage until completion. The framework provides a simple reporting template to verify if the building meets net zero carbon.

2.2.2. RIBA Sustainable Strategy

RIBA's Plan of Work compiles frameworks that can be used by architects throughout a project. In 2020, RIBA included sustainable strategies and tasks to be used during design and construction to achieve the government-set net zero targets for 2030 and 2050 (RIBA, 2020). From the 17 UN Sustainable Development Goals, RIBA identifies eight sustainable outcomes that can be measured and are achievable by architects. The document details these outcomes in terms of a metric, principles to achieve these and performance verification techniques. The eight outcomes include (RIBA, 2019):

- Net zero operational carbon – $kWh/m^2/year$

  Principles include passive design, energy efficient lighting and appliances, occupant friendly building management systems, on/off site renewable energy supply. Performance is verified using measured end use energy and analysed using CIBSE Climate Action Plan and TM67.

- Net zero embodied carbon – $kgCO_2/m^2/year$

  Address whole life carbon cycle, minimise embodied carbon by using low embodied energy materials, aim for zero construction waste to landfill, offset remaining carbon emissions.

- Sustainable water cycle – l/person/year

  Reduce water use and recycle rainwater and grey water. Performance verification using water consumption measurements.

- Sustainable connectivity and transport – $kgCO_2$/person/year

  Prioritise site selection with good connectivity to public transport, encourage pedestrian and cycle friendly development, include infrastructure for electric vehicles, encourage car sharing and incorporate a green transport plan.

- Sustainable land use and ecology

  Encourage construction on brownfield sites, retain existing site features, aim for zero local pollution from development, create mixed use developments, include a range of green spaces on site, encourage urban food production on site.

- Good health and wellbeing

Design spaces to include appropriate occupancy density, good indoor air quality, good daylighting, good acoustic comfort and adaptive thermal comfort standards. These are typically measured using post occupancy evaluations.

- Sustainable communities and social value

  Encourage safety and security and social interaction by providing communal spaces and amenities.

- Sustainable life cycle cost - £/m^2

  Measure costs for energy, maintenance and management and overall running costs. Conduct whole life cycle analysis.

All the above sustainable outcomes heavily draw from BREEAM and CIBSE's tools for measurement, assessment and certification. The elaborate guide aims at bridging performance gaps to achieve a more realistic net zero outcome (RIBA, 2019).

2.2.3. LETI Climate Emergency Design Guide

The London Energy Transformation Initiative (LETI) was founded in 2017 to support UK's net zero targets and climate change initiatives. The organisation consists of a group of volunteers that are architects, engineers, developers, sustainability specialists, academics and other experts from the building and construction sector. A key document produced by LETI to enable application and achievability of net zero is the Climate Emergency Design Guide. The comprehensive guide compiles techniques, tools, benchmarks and targets to achieve net zero carbon goals for new buildings. According to the guide, net zero carbon comprises five key elements (London Energy Transformation Initiative, 2020):

- Operational energy

Based on LETI's thorough energy modelling, the energy use intensity targets have been set for residential and commercial buildings. New buildings that aim to achieve net zero carbon must be designed to meet these targets. For instance, residential buildings must aim for an energy use intensity of 35 kWh/m^2/year. Likewise, design to achieve a space heating demand target of 15 kWh/m^2/year. The project must also aim to maximise on-site renewable energy production to be able to achieve net zero.

- Embodied Carbon

  Recommendations include life cycle assessment and using materials with low embodied carbon. LETI also suggests building light in terms of structure.

- Future of heat

  Reduce heating demand, design for passive cooling, minimise system temperatures for better system efficiency, use heat recovery and district heating where feasible. LETI have developed a Heat Decision Tree which identifies constraints in terms of heating thereby enabling selection of appropriate low carbon heating technologies.

- Demand Response

  Passive design to reduce peak energy loads, generate and store electricity on site, microgrids to enable the development to be independent of the national grid, incorporate building management systems and design for occupant behaviour.

- Data disclosure

  Measure and report energy consumption and supply data, heating consumption data and carbon offset data. The LETI recommends updating data on online platforms such as Greater London Authority website and Carbonbuzz every five years.

LETI's Climate Emergency Design Guide provides a detailed framework while drawing from UK Government strategies and input from organisations such as UKGBC, RIBA, BRE and CIBSE. The three frameworks discussed above vary in complexity. For instance, UKGBC's net zero framework provides definitions for net zero and a simplified methodology whereas RIBA has a more comprehensive guide which encourages achievability and evaluation of net zero. Likewise, LETI's guide provides a detailed set of recommendations, targets to achieve and methods for net zero. LETI aimed to make the guide practical and highlighted the importance of following certain targets at the design stage to avoid a performance gap post-occupancy (London Energy Transformation Initiative, 2020). Nevertheless, the underlying principles of net zero and how these can be achieved are more or less the same in all the three frameworks. The guides also state operational energy/carbon as a first step as this is more achievable before developments target embodied energy/carbon or whole life carbon as these can be very challenging to achieve (UKGBC, 2019).

2.2.4. UK Building Regulations

2.2.4.1. Approved Documents

Approved Documents are advice given by the Department of Levelling up, Housing and Communities to meet the UK Building Regulations. For new build dwelling and commercial buildings, compliance with Part L of Building Regulations is required. Part L comprises four approved documents which discusses conservation of fuel and power for varying building typologies. These approved documents standardise energy performance and carbon emissions performance for new and existing buildings. Alongside general guidance on building performance, the documents provide examples and solutions to meet compliance for typical building conditions, such as U-value calculations (Department of Levelling Up, Housing and Communities, 2010).

2.2.4.2. Code for Sustainable Homes

The Code for Sustainable Homes is an assessment method used for rating the performance of new dwellings. Department for Communities and Local Government contracted BRE (Building Research Establishment) to develop a technical guidance to design, build and assess sustainable homes in the UK (Department for Communities and Local Governments, 2010). Established with a framework typical to rating systems, the Code for Sustainable Homes entails nine parameters of environmental impact:

- Energy and CO_2 Emissions
- Water
- Materials
- Surface Water Run-off
- Waste
- Pollution
- Health and Well-being
- Management
- Ecology

These parameters are similar to the criteria of the BREEAM Rating system (discussed in Chapter 3). The performance targets are more rigorous to achieve when compared to Building Regulations standards. The standard includes mandatory requirements under each of the above nine parameters. In addition to these, points are awarded based on other requirements achieved in each parameter. One to six stars are awarded based on score achieved with one star (or Code 1) being awarded for obtaining 36-47 points and six stars (or Code 6) for a score of 90-100 (Department for Communities and Local Governments, 2010). The Code allowed local councils to adopt their own sustainability levels (between Code 3 to 6) for planning. In 2015 the Code was withdrawn by the Government as a measure to regulate housing standards. Components of the Code were incorporated into Part L of Building Regulations (Ministry for Housing, Communities and Local Government, 2014).

2.2.4.3. Standard Assessment Procedure (SAP)

The Standard Assessment Procedure is the methodology used to evaluate energy and environmental performance of houses by the UK Government. The Department of Environment alongside BRE developed SAP, a guidance document in 1992. The SAP is based on the BRE Domestic Energy Model (BREDEM) which provides methods for calculating the energy performance of a home. The SAP has been a part of Part L Building Regulations since 1994. It is predominantly used to demonstrate compliance with building regulations and produce Energy Performance Certificates (EPCs), etc. SAP 10 is the most recent version in use which was updated alongside Part L 2022 to include fuel costs, CO_2 emissions and primary energy factors (Department for Energy Security and Net Zero, 2013).

2.3. Principles

2.3.1. Trias Energitica

The first set of rules of thumb for designing a sustainable building was developed in 1979 by a study group in TU Delft called the 'Trias Energitica' (Attia, 2018). The three-step process includes:

- Reducing energy demand and losses
- Sustainable sourcing of energy supply as opposed to energy from fossil fuels
- Efficient use of cleanest form of fossil fuels possible

The aim of 'Trias Energitica' was to encourage designers to follow the steps in order to be able to achieve a highly energy efficient building.

2.3.2. Attia's NZE building design principles

Similar to 'Trias Energitica', Attia's principles constitute four levels (Attia, 2018). These are:

- Reduction in energy demand which includes consumption for heating, cooling, domestic hot water, lighting, equipment and ventilation.
- Improvement in indoor environmental quality to ensure thermal comfort and avoid overheating.
- Energy supply from renewables to meet energy demand
- Reduction in primary energy use and carbon emissions which includes energy from the grid mainly produced from fossil fuels.

While 'Trias Energitica' set the tone for the design of energy efficient buildings decades ago, Attia's principles are more appropriate for the current global scenario as they incorporate emissions and indoor thermal comfort. Both establish principles at the building scale. Hence, it is critical to identify ideologies for designing sustainable communities. According to Torcellini et al., net zero energy is entwined with other parameters of sustainability. In 1994, NREL designed the Sanborn principles for sustainable development (Hardwood, et al., 1994). Table 2 compares these to Bioregional's principles of sustainability. It can be noted that both sets of principles highlight similar parameters.

Table 2 -Comparison between Sanborn's and Bioregional's principles of sustainability

Sanborn (1994)	*Bioregional (2009)*

Ecologically responsible	Land use and wildlife
Buildings are efficient, healthy, sensible and use renewable energy	Zero carbon Sustainable materials
Transport is accessible	Sustainable transport
Water is sustainable	Sustainable water
Community minimises waste	Zero waste
Community is socially just	Equity and local economy
Promotes local and sustainable food	Local, sustainable food
Culturally creative	Culture and heritage
Incorporates natural beauty and man-made beauty	-
-	Health and happiness

In addition to the above discussed principles, zero energy development Architect Dunster recommends four key technical principles to follow when making a zero-energy development (Dunster, et al., 2008). These include:

- Acknowledge all core principles from Table 2 at the design stage.
- Design for the climate, thereby addressing the two critical challenges – reduction in energy demand and identifying available renewable energy sources.
- Encourage comfortable living on a low footprint; aim for a high-density development.
- Ensure carbon emissions are reduced by cutting out the fossil fuels at the design stage.

Literature analysis of definitions, frameworks and principles indicated the same fundamental principles to achieve net zero. First, set the scope of the project. For example, are we designing a net zero energy or net zero carbon development? Second, aim to address the following aspects – reduce energy demand through passive design and energy efficient lighting and equipment, produce renewable energy (preferably on-site), reduce embodied carbon emissions through appropriate materials selection, reduce carbon emissions from transport and infrastructure, offset remaining carbon emissions, consider indoor environment quality and thermal comfort, and design for occupant behaviour and comfort.

Summary

This chapter reviewed existing literature on net zero through definitions, principles defining net zero, evaluation techniques and net zero frameworks being tested and used in the UK. The literature review indicated a lack of standardisation of net zero. Chapter 3 discusses evaluation tools that could be used to standardise net zero for easy application and assessment in large scale developments.

Chapter 3

Methods of evaluating a net zero development

3.1. Global rating systems

There is extensive on-going research on net zero aimed at systematising the widely applied concept. Over time, methodologies to define and evaluate net zero and principles to design a net zero development have been proposed. However, these are either limited to the scale of the building, or abstract. It is crucial to identify established systems that have been standardised with appropriate documentation to assess energy alongside sustainability comprehensively. Energy rating systems are widely used strict standards that analyse and rate sustainability not merely from the perspective of energy. These tools are typically developed either by government or public sector organisations and often use existing building regulations and standards, making these substantial and credible assessment systems. Their methodology can be very useful to systematise a framework for net zero as they address all key parameters discussed above such as energy, emissions, water, etc.

Energy rating systems provide a guide to design and test energy efficient and sustainable developments. These typically vary from country to country. However, the concept and core methodology remain the same. Each system has a set of criteria and components under each criterion to meet. Meeting these, awards the development with credit points based on which they are given a rating. Five globally acknowledged energy rating systems that are pioneers in building energy rating have been selected to help develop a rigorous guide. These systems have been shortlisted as their application has been expanded to test large scale developments. These are:

- BREEAM Communities

  Building Research Establishment Environmental Assessment Method (BREEAM) was the earliest environmental assessment system introduced in 1990 for new buildings by the Building Research Establishment (BRE). Since its launch, BREEAM has expanded its application to over 50 countries for a variety of building typologies like commercial, industrial and institutional buildings (BRE, 2012). BREEAM Communities was initially launched in 2008 as an attempt to evaluate sustainability more comprehensively for the community scale. The 2012 version was simplified and made efficient for easy application by all stakeholders which is still in use. The assessment system has a total of 126 credits to achieve from addressing eight criteria (also referred to as identifiers by BRE) and categories (also referred to as assessment issues) under each criterion. Table 3 shows the list of criteria, code, credits available and value of credits (%) for each criterion (BRE, 2012).

Table 3 – BREEAM Communities list of criteria, code, available credits and percentage value of credits for each criterion

Criteria	*Code*	*Credits available*	*Value of credits (%)*
Governance	GO	8	6.4
Wellbeing - Local economy		5	4
Wellbeing - Environmental Conditions	SE	17	13.5
Wellbeing - Social and economic		25	19.8
Resources and Energy	RE	31	24.6
Land use and Ecology	LE	18	14.3
Transport and Movement	TM	15	11.9
Innovation	IN	7	5.5

Note: Value of credits = (Credits available/Total credits) x 100, total credits =126

Based on the credit score obtained, developments achieve one of the following ratings - Unclassified (<30), Pass (≥30), Good (≥45), Very Good (≥55), Excellent (≥70) and

Outstanding (≥85). The assessment method requires stakeholders to demonstrate compliance with government regulations and sustainability standards in order to achieve credits. For example, take category Cycling Network (TM 03) under criteria Transport and Movement. The stakeholder must aim to enhance cycling as an alternative mode of transport by providing a cycling network that is safe and efficient. The category has one credit to achieve. As a minimum requirement, a movement framework must be established which covers a detailed cycle network plan. In order to achieve the credit, documents must demonstrate connection between cycle routes to existing routes from surrounding areas and between the community focal points, safe, direct and well-lit routes, that cycle routes are segregated from vehicular and pedestrian traffic, that adequate signs for navigation are provided. The category also indicates cycle path widths to incorporate based on vehicular traffic speed (BRE, 2012). As mentioned in Chapter 2, Government establishments and renowned bodies such as RIBA and UKGBC have used BREEAM for decades to develop standards and frameworks (HM Government, 2012). Hence, BREEAM acts as a reliable assessment tool to evaluate energy efficiency, sustainability and environmental impact of a development.

- IGBC Townships

  The Confederation of Indian Industry (CII) established the Indian Green Building Council (IGBC) in 2001 to provide a 'sustainable built environment for all'. Unlike BREEAM, IGBC is established only for the Indian subcontinent. However, this can be applied to the five key climate classifications all of which can be found in India. IGBC has assessment tools for many building typologies. Some of its rating system tools even address niche areas such as interiors and rapid transit systems. A critical development by IGBC includes the net zero rating tools which have been defined individually for net zero energy, net zero water and net zero waste. The IGBC net zero energy building rating system was launched in 2018 and addresses the reduction in energy consumption and costs, energy supply and storage and thermal comfort. IGBC Township was established in 2010 as a method to address energy efficiency, water efficiency and waste management in large scale developments. The assessment system includes five main criteria with total achievable credit points of 200 (Indian Green Building Council, 2010). Table 4shows the list of criteria, code, credits available and value of credits (%) for each criterion.

Table 4 - IGBC Township list of criteria, code, available credits and percentage value of credits for each criterion

Criteria	*Code*	*Credits available*	*Value of credits (%)*
Site Selection and Planning	SSP	40	20
Land Use Planning	LP	44	22
Transportation Planning	TP	30	15
Infrastructure Resource Management	IRM	70	35
Innovation in Design and Technology	IDT	16	8

Note: Value of credits = (Credits available/Total credits) x 100, total credits =200

Four certification levels can be achieved based on the credit points obtained – Certified (100-119), Silver (120-139), Gold (140-159) and Platinum (160-200). The rating system includes some mandatory requirements that must demonstrate compliance in addition to requirements that can be met in the capacity of the project and stakeholders involved. For example, category 'Basic Amenities within the Community' under criteria Land Use Planning states that it is mandatory to provide or identify at least ten basic amenities such as a pharmacy and a grocery shop within 800m of the residential zone and at least four of some other key amenities such as schools and banks within a 2km radius from the residential area (Indian Green Building Council, 2010). Regardless of geographical context, the rating system is versatile and can be adapted to other locations with a similar climate classification. Also, IGBC is one of the global rating systems that addresses net zero energy and has net zero principles similar to other global bodies such as UKGBC.

- PEARL Community Rating system

  The Pearl Rating System for Estidama was developed by the Abu Dhabi Urban Planning council in 2010. The Estidama is said to be the first programme made for the Middle East. Like BREEAM and IGBC, the PEARL rating system can also be used to assess many building typologies. The PEARL Community Rating System has a total achievable credit points of 159 with seven criteria (Estidama, 2010). Table 5shows the list of criteria, code, credits available and value of credits (%) for each criterion.

Table 5 - PEARL Community list of criteria, code, available credits and percentage value of credits for each criterion

Criteria	*Code*	*Credits available*	*Value of credits (%)*
Integrated Development Process	IDP	10	6.3
Natural Systems	NS	14	8.9
Liveable Communities	LC	38	23.8

Precious Water	PW	37	23.3
Resourceful Energy	RE	42	26.4
Stewarding Materials	SM	18	11.3
Innovating Practice	IP	3	-

Note: Value of credits = (Credits available/Total credits) x 100, total credits =159 (excluding Innovating Practice which are offered as bonus credits)

The assessment tool provides five ratings to PEARL Communities of which, 1 Pearl rating consists only of mandatory credits making it a mandatory level to achieve. This is followed by 2 Pearl, 3 Pearl, 4 Pearl and 5 Pearl ratings which can be achieved by meeting all mandatory credits plus 55, 75, 100 and 125 credit points respectively. Stakeholders must demonstrate compliance with the Urban Planning Council guidelines. For example, like IGBC, PEARL has a mandatory requirement to demonstrate 'provision of facilities and amenities' (LC – R3) under criteria liveable Communities. Evidential documents include a site plan indicating existing facilities around the community, proposed facilities within the community which have been identified based on demographics, land use and user needs, access to a public path, pedestrian path, cycle path and public transport points within 350m radius of amenities and car parking provision. The hot-dry climate of the Middle Eastern region can be a challenging location to achieve energy efficiency given the excessive demand for cooling and scarcity of water. Hence, a rating system like PEARL which caters specifically for this region which can be very useful.

- Green Star Communities

The Green Building Council of Australia (GBCA) launched Green Star sustainability rating system in 2003. The rating system is established for Australia and endorsed by the Government. However, Green Star has a wider application across the globe, specifically in the southern hemisphere. Unlike other rating systems which have tailored tools specific to building typology, Green Star has one assessment tool for buildings in general. However, a specific tool for housing was introduced in 2021 (Green Building Council of Australia, 2021). In 2012, GBCA produced the Green Star Community guide for assessment of large-scale developments. The rating tool has 110 achievable credit points and five criteria (Green Building Council Australia, 2016). Table 6 shows the list of criteria, code, credits available and value of credits (%) for each criterion.

Table 6 – Green Star Community list of criteria, code, available credits and percentage value of credits for each criterion

Criteria	*Code*	*Credits available*	*Value of credits (%)*
Governance	GOV	28	24.5
Liveability	LIV	22	20
Economic Prosperity	ECO	21	19.1
Environment	ENV	29	36.4
Innovation	INN	10	9

Note: Value of credits = (Credits available/Total credits) x 100, total credits =110

Based on credit points scored communities can achieve One Star (10 credit points) to Six Star (75+ credit points) rating. However, Green Star only certifies communities that have ratings of Four Star (which is best practice for sustainability) or above. Green Star communities does not have prerequisites like the other rating systems. However, some minimum requirements have been highlighted under certain categories. For example, category ‘Healthy and Active Living’ under criteria Liveability has one minimum requirement which is to provide footpaths. There is only a total of four minimum requirements of which three come under ‘Liveability’ and one under ‘Environment’ (Green Building Council Australia, 2016). Green star is said to be a very strict rating tool making it challenging to achieve a rating that is best practice or above.

- LEED Cities and Communities

Leadership in Energy and Environmental Design (LEED) certification programme was established in 1993 by the U.S. Green Building Council (USGBC). It has since evolved and been refined to assess and certify various building types and larger scales of developments like neighbourhoods and even cities. Like IGBC, a significant development in LEED’s certification tools includes LEED Zero launched in 2019 which tests net zero energy, carbon emissions and water using simplified calculation methods (U.S. Green Building Council, 2020). LEED Cities and Communities rating system was launched in 2016. This tool has nine criteria and a total of 110 achievable credit points (U.S. Green Building Council, 2019). Table 7shows the list of criteria, code, credits available and value of credits (%) for each criterion.

Table 7 – LEED Cities and Communities list of criteria, code, available credits and percentage value of credits for each criterion

Criteria	*Code*	*Credits available*	*Value of credits (%)*
Integrative Process	IP	5	4.6
Natural Systems & Ecology	NS	13	11.8
Transport and Land Use	TR	18	16.4
Water Efficiency	WE	12	10.9
Energy and GHG Emissions	EN	31	28.2
Materials and Resources	MR	11	10

Quality of Life	QL	10	9
Innovation	IN	6	5.5
Regional Priority	RP	4	3.6

Note: Value of credits = (Credits available/Total credits) x 100, total credits =110

The rating system awards four ratings (like IGBC) based on credit points achieved – Certified (40-49), Silver (50-59), Gold (60-79) and Platinum (80+). Unlike the other rating systems which use government (or government approved) standards and regulations for compliance, LEED over the decades developed and refined its own standards with inhouse experts possibly due to the rating system's application being pan world. However, a few categories use the ASHRAE standard as reference. The assessment tool has a set of required criteria for which the stakeholders must provide evidence to meet the eligibility for LEED rating. For example, category 'Green Spaces' under criteria Natural Systems and Ecology requires stakeholders to provide green space of at least 11.25 m^2/person within the city, indicate that 90% of the housing units have a green space within 800m of walkable distance and ensure that green spaces have a minimum area of 670 m^2. A set of documents such as a master plan indicating green spaces, calculations showing minimum green space thresholds achieved, description of housing units provided with green space within walking distance, should be provided to demonstrate compliance (U.S. Green Building Council, 2019). Since LEED is not specific to location its application can be seen in many countries apart from the U.S.A making it a more versatile and adaptable rating system.

Some key examples that aimed to achieve the net zero status have used these systems for overall energy rating assessment. These include BedZED in Sutton, UK which was compared with BREEAM's system and Dubai Sustainable City and MASDAR City which used PEARL. The technical guide for each selected system was thoroughly studied and tabulated in parallel to enable comparative analysis between them. This helped identify similarities and differences in categories and weightings (in points) under each criterion.

3.1.1. Criteria and Categories

The five rating systems were tabulated in parallel for comparative analysis. The study indicated several similarities in categories such as energy, materials, urban design, water and waste, making it possible to establish a pattern between the systems and thereby, group them under similar criteria. However, some categories were moved from one criterion to another where it seemed fit. 11 criteria were identified based on the similarities in categories. Table 8 indicates the five rating systems tabulated in parallel highlighting categories that have been repositioned where appropriate under the 11 criteria which are:

- Social, Economic and Environmental Wellbeing
- Ecology
- Site
- Urban Planning and Design
- Transport
- Energy and Emissions
- Materials
- Water
- Waste
- Innovation
- Accredited professional
- Miscellaneous

Table 8 – Five rating systems tabulated in parallel for comparative analysis[1]

		Pearl	159		LEED (cities and communnities)	110		IGBC	200		BREEAM	126		Green star	110
Social, econmical and environmental wellbeing	IDP R1	Intergrated development strategy	R	IP R1	Integrative Planning and Design process	R	SSP MR 1	Local regulations	R	GO 1	Consultation plan	1			
	IDP 4	Sustainbility awareness	2										GOV 6	Sustainability awareness	2
	LC R1	Plan 2030	R	NS 3	Resilience planning	6				GO 2	Consultation and engagement	2	GOV 3	Engagement	6
										GO 3	Design review	2	GOV 2	Design review	8
				IP 1	Green building policy and	5							ECO 6	Incentive programs	2
													GOV 4	Adaptation and Resilience	4
										SE 14	Local vernacular	2			
				QL R3	Econmic growth	R	LP 4	Employment opportunities	8				ECO 1	Community investment	4
				QL 1	Affordable housing	2				SE 1	Economic impact	2	ECO 2	Affordability	4
													ECO 3	Empoyment and economic resilience	2
													ECO 5	Return on investment	2
													ECO 7	Digital infrastructure	2
										SE 17	Training and skills	3	ECO 4	Education and skills development	3
										GO 4	Community management of facilities	3	GOV 5	Corporate reponsibility	3
				QL R2	Social Infrasructure	R							GOV 7	Community participation and governance	2
				QL 2	Public health	6							LIV 1	Healthy and active living	5
													LIV 2	Community development	4
				QL 3	Emergency management and response	2									
	IP 1	Showcase of regional & cultural practices	1	RP 1	Regional priority	4	LP 5	Social and cultural initiatives	6				LIV 4	Culture, heritage and identity	3
Ecology	NS R1	Natural systems assessment	R	NS R1	Ecosystem Assesment	R									
	NS R2	Natural systems protection	R	NS 1	Natural resources conservation and restoration	5				LE 1	Ecology strategy	1	GOV 8	Environmental management	2
	N3	Ecological enhancement	2							LE 4	Enhancement of ecological value	3	ENV 6	Ecological value	2
	N1	Reuse of land	2				SSP 4	Redevelopment of contaminated areas	6						
	N2	Remediation of contaminated land	2												
	N4	Habitat creation and restoration	6				SSP 1	Preserve existing trees and water bodies	6						
							SSP 2	Retain natural topography	6						
	IDP 3	Construction environmental management	2	NS R2	Constrcution Activity Pollution Prevention	R	IRM 7	Construction waste reduction	6						
				NS 2	Light pollution reduction	2				SE 16	Light pollution	3	ENV 9	Light pollution	1
										SE 4	Noise pollution	3			
										LE 3	Water pollution	3			
Site				TR 6	High priority sites	2							ENV 5	Sustainable sites	2
							LP MR 1	Land use optimisation	R	LE 2	Land use	3			

[1] Table 3 Table 4 Table 5 Table 6 Table 7

Table 9 (cont.)– Five rating systems tabulated in parallel for comparative analysis[2]

		Pearl	159		LEED (cities and communnities)	110		IGBC	200		BREEAM	126		Green star	110
Urban planning and design	IDP R3	Community dedicated infrastructure basic commissioning	R							SE 2	Demographic needs and priorities	1			
	LC R2	Urban systems assessment	R	QL R1	Demographic assessment	R				SE 6	Delivery of service, facilities and amenities	7			
	LC R3	Provisions of amenities and facilities	R				LP MR 3	Basic amenities within community	R	SE 7	Public realm	2			
	LC 10	Regionally reponsive planning	2				LP 1	Mixed use development	10	SE 9	Utilities	3			
	LC 12	Safe and secure community	1							TM 2	Safe and appealing streets	4	LIV 7	Safe places	2
	RE 1	Community strategies and passive cooling	6												
	RE 2	Urban heat reduction	2				SSP 6	Urban heat island effect	8	SE 8	Microclimate	3	ENV 8	Heat island effect	1
	LC R4	Outdoor thermal comfort strategy	R												
	LC 9	Improved outdoor thermal comfort	4												
	LC 7	Active urban environments	1	NS R3	Green Spaces	R	SSP 3	Public landscape areas	6	LE 5	Landscape	5			
	LC 3	Open space	3												
	LC 4	Accessible community	2												
	LC 5	Housing diversity	2				LP 2	Housing typologies	8	SE 5	Housing provision	2			
	N5	Food systems	2				SSP 5	Local fruits and vegetable producs	8				LIV 6	Access to fresh food	2
	RE 3	Efficient infrastructure: Lighting	6				IRM 4	Energy efficiency in infrastructure equipment	8	SE 11	Green infrastructure	4			
	RE 4	Efficient infrastructure: District cooling	6												
	RE 5	Efficient infrastructure: smart grid	4												
							TP MR 2	Design for differently abled	R	SE 15	Inclusive design	3			
										RE 2	Existing buildings and infrastrcutre	2			
Transport	LC 1	Transit supportive practices	2	TR 1	Compact mixed use and transit oriented	6							ENV 4	Sustainable transport and movement	3
	LC 2	Neighborhood connectivity	3	TR 3	Access to quality transit	2	TP 1	Public transportation facilities	6	TM 4	Access to public transport	4			
							TP 3	Road and street network	6	TM 6	Public transport facilities	2			
	LC 6	Community walkability	4	TR 2	Walkability and Bikeability	4	TP 5	Pedestrian network	6	TM 5	Cycling faciiilities	2	LIV 5	Walkable aecss to amenities	2
							TP 4	Bicycle network	6	TM 3	Cycling network	1			
	LC 8	Travel plan	1	TR 4	Alternative fuel vehicles	2									
				TR 5	Smart mobility and transportation policy	2	TP 2	Eco-friendly transportation facilities	6	TM 1	Transport assessment	2			
							TP MR 1	Long term transportation planning	R	SE 12	Local parking	1			

[2] Table 3 Table 4 Table 5 Table 6 Table 7

Table 10 (cont.) – Five rating systems tabulated in parallel for comparative analysis[3]

		Pearl	159		LEED (cities and communnities)	110		IGBC	200		BREEAM	126		Green star	110
	RE R1	Community energy stratedy	R	EN R1	Power access, reliability and resiliency	R				RE 1	Energy strategy	11	ECO 8	Peak electricity demand reduction	2
	RE R2	Building energy guidelines	R							SE 10	Adapting to climate change	3			
	RE R3	Energy monitoring and reporting	R				IRM 9	Measurement and verification plan (Post occupancy)	2						
	RE 6	Renewable energy: onsite	8	EN 3	Renewable energy	6	IRM 5	On-site renewable energy	16						
	RE 7	Renewable energy: offsite	3				IRM 6	Off-site green power	12						
Energy and emissions	RE 8	Energy efficient buildings	7	EN 2	Energy efficiency	4									
	IDP 1	LC costing	4	EN 1	Energy and GHG emissions management	19				RE 7	Transport carbon emissions	1	ENV 2	GHG strategy	6
				EN 4	Low carbon	-									
				EN 5	Grid harmonization	2									
	LC R5	Minimum Pearl rated buildings within	R												
	LC 11	Pearl rated buildings within	10				LP 3	Green buildings	12	RE 4	Sustainble buildings	6	LIV 3	Sustainable buildings	4
	IDP R2	Sustainable building guidelines	R												
				MR 3	Responsible sourcing for infrastructure	2				RE 6	Resource efficiency	4	ENV 3	Materials	5
	SM R1	CCA treated timber elimination	R												
Materials	SM 1	Modular pavement and hardscape	1												
	SM 2	Regional materials	2												
	SM 3	Recycled materials	5				IRM 8	Recycled content	8	RE 5	Low impact materials	6			
	SM 4	Reused and certified timber	3												
										SE 3	Flood risk assessment	2			
										SE 11	Flood risk management	3			
	PW R1	Community water strategy	R	WE R1	Integrated water management	R				RE 3	Water strategy	1	ENV 1	Integrated water cycle	7
	PW R2	Building water guidelines	R												
	PW R3	Water monitoring and leak detection	R	WE R2	Water access and quality	R									
	PW 1	Community water use reduction: landscaping	14												
Water	PW 2	Community water use reduction: Heat rejection	5												
	PW 3	Community water use reduction: water features	4												
	PW 4	Stormwater management	6	WE 1	Storm water management	5									
	PW 5	Water efficient buildings	8	WE 3	Smart water systems	2									
				WE 2	Wastewater management	5	IRM 2	Waste water treatment 100%	6						
							IRM 3	Waste water reuse 75%, 95%	6						
							IRM MR 1	RW harvesting 50%	R	LE 6	RW harvesting	3			
							IRM 1	RW harvesting 75%, 95%	6						
	SM R2	Basic construction waste management	R	MR R1	Construction and demolition waste management	R									
	SM R3	Basic operational waste management	R	MR R2	Solid waste management	R							ENV 7	Waste management	2
Waste	SM 5	Improved construction waste management	2	MR 1	Organic waste management	2									
	SM 6	Improved operational waste management	2	MR 2	Recycling infrastrcture	5									
	SM 7	Organic waste management	2	MR 3	Smart waste management systems	2									
	SM 8	Hazardous waste management	1												

[3] Table 3 Table 4 Table 5 Table 6 Table 7

Table 11 – Five rating systems tabulated in parallel for comparative analysis[4]

		Pearl	159		LEED (cities and communnities)	110		IGBC	200		BREEAM	126		Green star	110
Innovationn	IP 2	Innovating practice	2	IN 1	Innovation	6	IDT 1.1	Innocation design and technology	3	IN 1	Innovation	7	INN	Innovation	10
							IDT 1.2	Innocation design	3						
							IDT 1.3	Innocation design and technology	3						
							IDT 1.4	Innocation design and technology	3						
Accredited professional							IDT 2	IGBC Accredited professional	4				GOV 1	Accredited professional	1
Misc.	IDP 2	Guest worker accomodation	2				LP MR 2	Basic facilities for constrcution workforce	R						

Note: Data obtained from respective rating systems' technical manuals (Estidama, 2010; Indian Green Building Council, 2010; BRE 2012; Green Building Council Australia, 2016; U.S. Green Building Council, 2019)

For example, 'LC (life cycle) costing' (IDP 1) and 'Sustainable building guidelines' (RE 4) have been moved from 'Integrated development process' to the 'Energy and emissions' criterion in PEARL (Code RE for Resourceful energy). Likewise, 'Adapting to climate change' which falls under the 'Social and economic wellbeing' category in BREEAM has been repositioned in this criterion. For IGBC, 'Construction waste reduction' (IRM 7) has been moved from 'Integrated resource management' to 'Ecology'. Similarly, 'Environmental Management' (GOV 8) in PEARL has been repositioned from criterion 'Governance' to 'Ecology'. Refer Appendix 2 for detailed list of Criteria and categories for each rating system prior to recategorization.

3.1.2. Weighting of Criteria

Once, the categories were repositioned to fit the appropriate criteria, the weighting (%) for each criterion was calculated as shown in Equation 1 below.

$$\text{Weighting (\%)} = CP_{category} / CP_{total} * 100 \qquad (1)$$

where, $CP_{category}$– Total credit points under criteria

[4] Table 3 Table 4 Table 5 Table 6 Table 7

CP_{total} – Total rating system credit points

Example a: BREAAM

Criterion 'Site' has one category 'land use' (code LE2) and is weighted at 3 credit points. Total credit points for BREEAM are 126. By using equation 1, the weighting for site as percentage can be calculated as follows:

Weighting (%) for site = 3/126*100 = 2 (approx.)

Example b: LEED

LEED too has only 'High priority sites' (code TR6) with 2 credit points under criterion 'Site'. Total credit points for LEED are 110. Using the above equation, the weighting percentage for LEED – 'Site' is as follows:

Weighting (%) for site = 3/126*100 = 2 (approx.)

Table 9 shows the weighting of each criterion for the five rating systems after repositioning of categories to the appropriate criteria. An average weighting is calculated for each criterion based on the weightings of the different rating systems.

Table 12 – List of weightings for each criterion under each rating system and calculated average weightings for each criteria

Revised Criteria	Pearl	LEED	IGBC	BREEAM	Green star	Average
	%					
Social, economic and environmental wellbeing	2	23	7	12	51	19
Ecology	9	6	12	10	5	8
Site	0	2	0	2	2	1
Urban planning and design	26	0	24	29	5	17
Transport	6	15	15	10	5	10
Energy and emissions	20	28	21	17	11	19
Materials	7	2	4	8	5	5

Water	23	11	9	7	6	11
Waste	4	8	0	0	2	3
Innovation	1	5	6	6	9	5
Accredited professional	0	0	2	0	1	1
Misc.	1	0	0	0	0	0

3.1.3. Comparative analysis

The analysis indicated that the weighting system for the same criterion can vary greatly for different rating systems (see Fig. 8). The graph below represents the percentage contribution of each criterion for the five rating systems (see Appendix 2 for weighting percentage calculation). Some key findings are evident from the graph. Four of the five systems (except IGBC) highlight strategies on emissions. Urban design has been thoroughly strategized for most systems bar Green Star with Energy being prioritised in all systems alongside socio-economic strategies. Of all criteria, Green Star prioritises Social, economic and environmental wellbeing with a weighting of 51% followed by LEED at 23%. Whereas, PEARL weights this criterion at 2%. Ecology had an average weighting between 6-16% in all systems. Two of five rating systems did not analyse site (PEARL, IGBC). However, this was compensated for in the urban planning and design weighting of approximately 25% in both systems. Other anomalies include PEARL's weighting of water at 23% compared to the average 7-11% of other systems, possibly due to location related water scarcity, and IGBC and BREEAM weighting waste at zero.

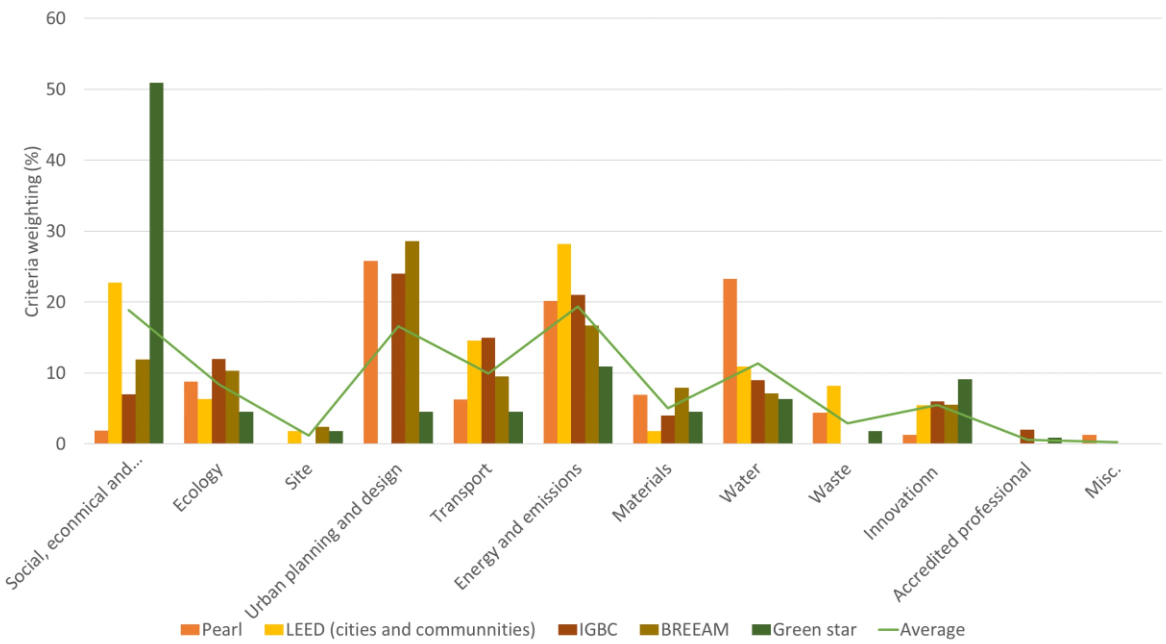


Figure 7 - Comparative analysis of criteria weighting in % (by author)

3.1.4. Derived Rating System

Based on the detailed analysis of each rating system and comparisons between them a combined rating system has been developed. As described, the weighting of each of the above criterion was measured and an average weighting was calculated for each criterion to develop a weighting scale for the amalgamated rating system. The criteria for the derived rating system and their weightings are detailed in Table 10.

Table 13 - Derived rating system criteria, average weighting from comparative analysis and derived weighting

Criteria	Average	Derived weighting
Social, economic and environmental wellbeing	19	15
Ecology	8	10
Site	1	20
Urban planning and design	17	
Transport	10	10

Energy and emissions	19	20
Materials	5	5
Water	11	10
Waste	3	5
Innovation	5	
Accredited professional	1	5
Misc.	0	

A few changes have been made to the criteria in the derived rating system. Some criteria have been separated and grouped with others as these had similar components and to balance weighting of the criteria. For instance, Environment has now been paired with 'Ecology', leaving 'Social and economic wellbeing' as one criterion weighted at 15% and 'Ecology and environment' as one, weighted at 10%. Likewise, 'Site and urban planning and design' have been combined as site analysis and urban design are concurrent and weighted at 20% together. 'Transport' and 'Materials' weighting has remained the same. 'Energy and emissions' criterion is rounded to 20% with 'Water' at 10%. 'Waste' is weighted at 5% and 'Innovation', 'Accredited professional' and 'Miscellaneous' are now grouped together as the 'Other' criterion. It has a percentage weighting of five too. It can be seen that 'Energy and emissions' and 'Site, urban planning and design' now each have the highest weighting of 20%. This seemed appropriate as the aim is to design and test a net zero community, where energy and sustainable design are key. The new system's criteria weighting though altered, remains more or less similar to the average weightings derived from the comparative analysis.

3.1.5. Criteria Categories in detail

The comparative analysis of the five rating systems showed many similarities between them. The consolidation of these systems helped group the various categories under the eight broad criteria listed above. The final step of the study involved detailing the categories included within each of these criteria. The categories for each criterion described below have been reiterated from the existing criteria of the five rating systems studied.

Social and economic wellbeing (15%):

- Integrative planning where stakeholders, especially the community are encouraged to engage in planning
- Adhering to local regulations
- Affordability of developing such a community and its economic impact
- Economic resilience and growth involving employment opportunities and community growth in terms of skills
- Heritage preservation, local vernacular is maintained, the community is encouraged to engage in socio-cultural initiatives

Ecology and environment (10%):

- Assessing ecosystem and conserving and restoring natural resources like water bodies and agricultural lands where appropriate
- Remediation of contaminated sites
- Preserving existing landscape, both hard and soft
- Assessing site topography and making best use of this
- Air, noise and light pollution control during construction

Site, urban planning and design (20%):

- Site selection and analysis which includes assessing solar and wind access, urban heat island, microclimate, outdoor thermal comfort
- Site zoning, layout, planning and sustainable urban design strategies developed based on site analysis
- Responsive planning that addresses needs of the community, to have a mixed-use development and services dedicated to the community
- Incorporating urban landscapes and local food production within the development
- Diversity in housing design based on demographic needs with accessible community facilities and inclusive design
- Energy infrastructure located within site to address lighting, heating and cooling needs

Transport (10%):

- Connectivity of community to public transport systems
- Sustainable transport and movement within community including pedestrian and bicycle networks and alternate fuel vehicles
- Adequate parking facilities

Energy and emissions (20%):

- Energy strategy to minimise energy demand at the building and thereby site scale
- On-site and off-site renewable energy supply planned
- Energy efficient building by incorporating sustainable design strategies and addressing thermal comfort
- Carbon emissions involved in operation and transport and analysing embodied carbon
- Include certified green buildings within the community

Materials (5%):

- Responsible sourcing of materials
- Recycling and reusing materials where feasible

Water (10%):

- Water strategy including assessing and reducing demand, efficiency in terms of supply, using smart water systems to assist with this
- Managing wastewater by addressing treatment and reuse of storm, grey and black water and harvesting rainwater

Waste (5%):

- Managing construction waste
- Solid waste management in terms of segregation and recycling

Other (5%):

- Innovation in design and technology
- Involvement of energy accredited professional
- Providing appropriate facilities for workers during construction

3.1.6. Application of derived system

There is often ambiguity in starting a project that constitutes a large-scale net zero development. There is credible literature on net zero energy/carbon buildings and there are notable case studies around the world that claim to achieve net zero energy/carbon (see 'Section 2'). However, a detailed study of net zero communities was felt insufficient given the growing popularity of this term. It was considered essential to develop a guide for the same. The aim of this study was to develop a rating system that can be used as a guide/benchmark that would assist in designing and testing a prototype net zero community. Developing this rating system proved useful as a starting point and guide to design and test a net zero community that will be situated in Sutton, UK.

While each of the selected rating systems is excellent in its own terms, combining these helped develop a rating system that acknowledges all the crucial aspects of sustainability. Criteria like waste, water and site that were addressed in detail in some and not so much in others would now be addressed thoroughly in the derived rating system thereby creating a guide that is more detailed. It is to be noted that rating systems are often used from the conceptualisation stage, through the design and construction stages and into the operational phase of the development. Most criteria such as transport, site, urban planning and design, water and waste strategy, energy and emissions and materials can be controlled during the concept and design phases. Hence, if a hypothetical community were to be designed, almost all of the criteria could be addressed during the design phase bar the ones marked with red dots above. Hence, this rating system acts as a genesis to design a net zero community.

3.2. Developing a net zero community framework

Research in net zero has indicated the lack of a system that could enable easy application and assessment of net zero developments. Chapter 2 discussed performance indicators of a net zero building (Attia, 2018), principles of low/zero energy sustainable communities by Bioregional and Sanborn alongside current frameworks and standards developed by the UK Government, UKGBC and RIBA. Integrating learnings from these and the rating systems above a net zero framework can be devised to design and evaluate a net zero community. The framework has been detailed as a checklist in Table 11. The following checklist with key parameters derived from the five rating systems is used to design and test the prototype community for this thesis. Blue ticks indicate parameters that have been addressed for this thesis.

Table 14 - Checklist for net zero development

Parameters	Addressed	Method	
Social, economic wellbeing and awareness			
Integrative planning – community engagement and involvement in planning	✓	Survey	Data collection
Green policies and incentives – local regulations	✓	Location + site	Theory
Affordability	-		
Economic impact – costs involved in developing community	-		
Economic resilience and growth – employment opportunities	✓	Urban design	Design
Community growth – skills	-		
Regional priority – socio-cultural initiatives, heritage preservation, local vernacular	✓	Site analysis	Theory
Ecology and environment			
Natural systems/ecosystem assessment	✓	Site selection	Theory
Natural resources conservation and restoration – water bodies, wetlands, agriculture lands	-		
Remediation of contaminated sites – brownfield sites	✓	Site selection	Theory
Preservation of existing landscape – trees and water bodies	✓	Site selection and analysis	Design

Retain site topography?	✓	Site analysis	Design
Pollution control – during construction, light, noise and water	-		
Site, urban design and planning			
Site selection and analysis	✓		Design
Site layout and planning	✓		Design
Responsive planning – mixed-use, neighbourhood, community dedicated facilities, services and amenities	✓	Location + site	UD
Safety and security	✓		Theory + design
Sustainable urban design strategies – solar orientation, wind, UHI, microclimate, outdoor thermal comfort	✓	Location + site	UD + modelling + simulations
Urban landscapes – parks and greenspaces	✓		UD + modelling + simulations
Accessible community facilities	✓	Demographics and site	UD
Housing diversity and typologies based on demographic needs	✓	Demographics and site	Calculations + design
Local food production	✓	Demographics and site	Theory + calculations + design

Energy efficient infrastructure – lighting, heating and cooling, equipment	✓		Design + calculations
Inclusive design	✓		Design
Transport			
Connectivity and access to quality transit – proximity to public transport	✓	Location + site	Mapping
Sustainable transport and movement - Pedestrian network, Bicycle network, alternate fuel vehicles	✓	Demographics + site	UD
Parking - reduced parking footprint, local parking	✓	Demographics + site	UD
Energy and emissions			
Energy strategy - minimise energy demand, on-site/off-site renewable energy supply	✓		Design + calculations + modelling + simulations
Energy efficient buildings – Sustainable building design, thermal comfort, certified green buildings	✓		Design + calculations + modelling + simulations
Carbon emissions – embodied, operation, transport	✓		Calculations
Materials			
Responsible sourcing of materials	✓	Location + site	Theory + mapping

Recycle and reuse	✓	Location + site	Theory + mapping
	Water		
Water strategy and efficiency – assessment and reduction of demand, supply, guidelines, smart water systems	✓		Theory
Waste water management – treatment, reuse	-		
Stormwater management - rainwater harvesting	✓		Theory + design
	Waste		
Construction waste management	-		
Solid waste management – segregation of waste at site	✓		Theory + design
	Other		
Innovation in design and technology	-		
Involvement of energy accredited professional	-		
Providing facilities for workforce during construction	-		

The above table indicates parameters that were used for designing and evaluating a prototype net zero community. For instance, most economic related parameters bar employment opportunities within the community have not been considered as the thesis does not discuss cost. Alternatively, all parameters of ‘Site, Urban design and planning’ have been taken into consideration while designing the prototype community. Likewise, all of ‘Transport’, ‘Energy and emissions’ and ‘Materials’ aspects have been considered in the development of the community. Some aspects of ‘Water’ and ‘Waste’ are included as part of the design process. Additionally, ‘Other’ has not been considered at this stage in addition to some aspects such as conserving natural resources and pollution. In brief, parameters that can be controlled at the concept and design stage have been considered in depth to develop the net zero community.

Summary

This chapter presented a net zero guide that can be used to design and test a large-scale net zero development. Five globally acknowledged energy rating systems used to evaluate large scale energy efficient developments have been compared, analysed and amalgamated to develop this net zero guide.

Summary

This chapter discusses five globally acknowledged rating systems that are used as tools to evaluate net zero. A comparative analysis between these rating systems helped establish a net zero guide which will be used to design and test the prototype community situated in Sutton, UK.

Chapter 4

A review of large-scale net zero case studies

4.1. Case studies

4.1.1. Examples from history

The initial traces of sustainable communities can be seen during the second industrial revolution when cities were becoming increasingly crowded and air pollution was growing vastly. The Garden City is a concept visualised by Ebenezer Howard, a town planner in the late 19th century as a solution to over populated and polluted urban centres (Fishman, 1982). This concept was conceived as an attempt to provide a clean, healthy and economically friendly environment for people of all social classes, especially the working class, to live in. The Town-Country as described by Howard's "three magnets" would include the key characteristics of an urban centre without compromising on the rural aspects of an abundance of greenery and nature. Howard aimed to establish a cooperative society, a city with cooperative industries, workers manufacturing and selling their goods within the city and food requirements of the city being met by farms surrounding the Garden City.

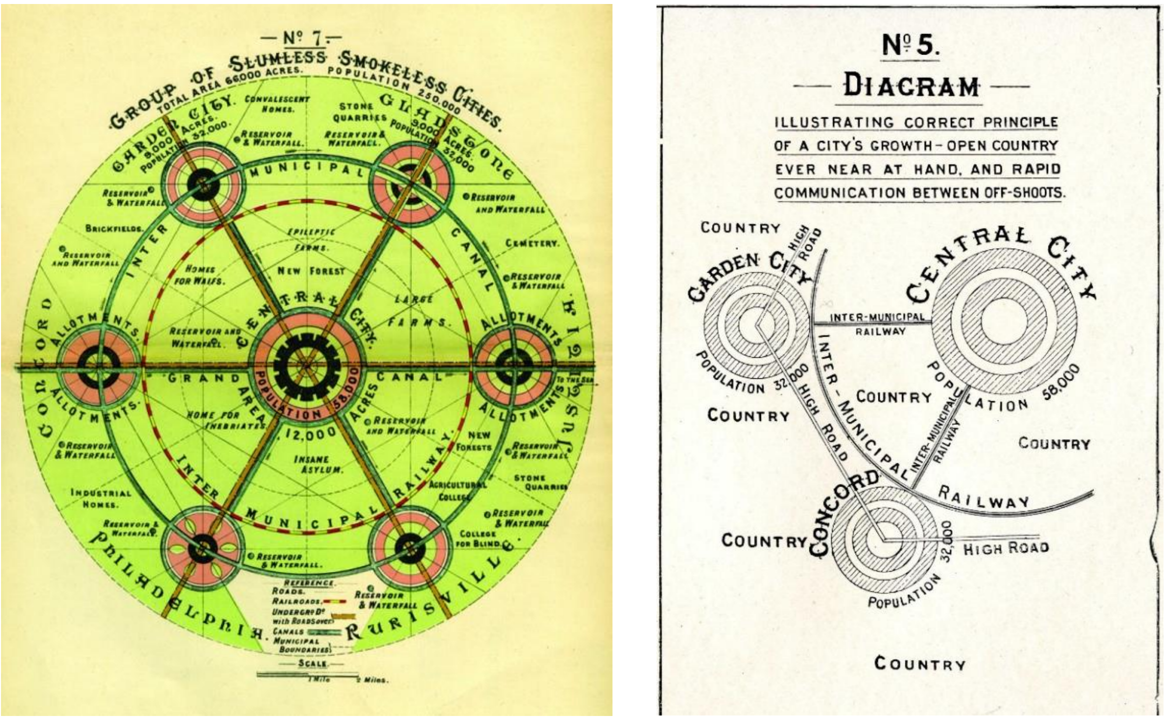


Figure 8- Social City, six garden cities connected to the urban centre (left), social city in limited realisation (right) (Howard, 1898)

Garden cities were envisaged as being self-sufficient Town-Country centres surrounded by greenbelts, including a mix of residential neighbourhoods and amenities for cultural and industrial activities. According to Howard's theory, the Garden City would be developed in a concentric pattern on a site of 6000 acres (about 2400 hectares) for a population of 32000 residents (Fishman, 1982). The settlement would include public parks and six radial boulevards (37m wide) extending from the centre. Once the population limit of 32000 was reached, a prototype of this self-contained settlement would be developed nearby.

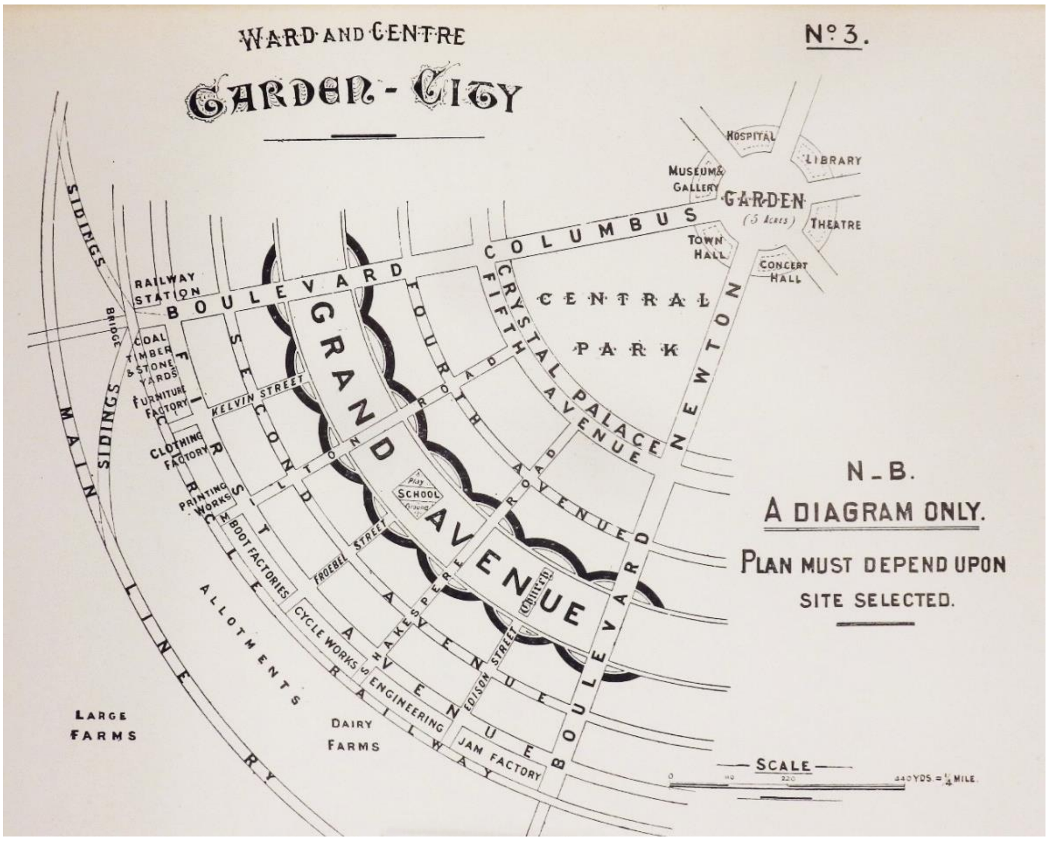


Figure 9- Ward and Centre Diagram, Garden City concept by Ebenezer Howard (Howard, 1898)

The Garden City was planned to be an industrial city where residents were housed close to their workplaces to reduce the need to commute. However, it was important to segregate the residential zones from the factories to ensure a healthy and less polluted environment. Howard decided to locate the factories on the periphery, situated close to the main transport network. The Garden City would be divided into wards with each ward containing a sixth of the population (see Fig. 10). The wards comprised residential units with a school in the centre. The focal point of the town would be dedicated to civic and leisure activities distributed around a large central park. Howard envisioned a group of these garden cities which will be linked to one another and the urban centre by road and rail (Fig. 6).

Developing the first prototype Garden City, Letchworth in the district of Hertfordshire, England, was a mammoth task for Howard. His idea was not received as well as he thought it would be. The aim to establish a cooperative society with no individual land ownership was lost in the process of amassing supporters and investors for the project. Howard was desperate to build the first Garden City that would bring about a massive reform in society especially for the working class. Despite the struggles, the increase in businesses in the beginning of the 20th century encouraged a need for work spaces and the central city could not accommodate this. Soon Letchworth grew popular and started to attract manufacturers and residents.

The Garden City concept addresses the three pillars of sustainability – society, economy and most importantly environment. The popularity of the concept which originated in England led to the Garden City movement with many countries attempting to create satellite cities inspired by Howard's idea. In 1899, Howard established the Garden City Association, now known as the Town and Country Planning Association (TCPA) to acquire backing for his idea. The Garden City movement is said to have inspired several urban planners which led to the development of a number of garden cities in North America and Europe. Even today, the UK government has proposed to deliver 17 new garden towns and villages, the aim being to provide homes, jobs and facilities to boost local economies (Ministry of Housing, Communities & Local Government, 2017).

Letchworth Garden City

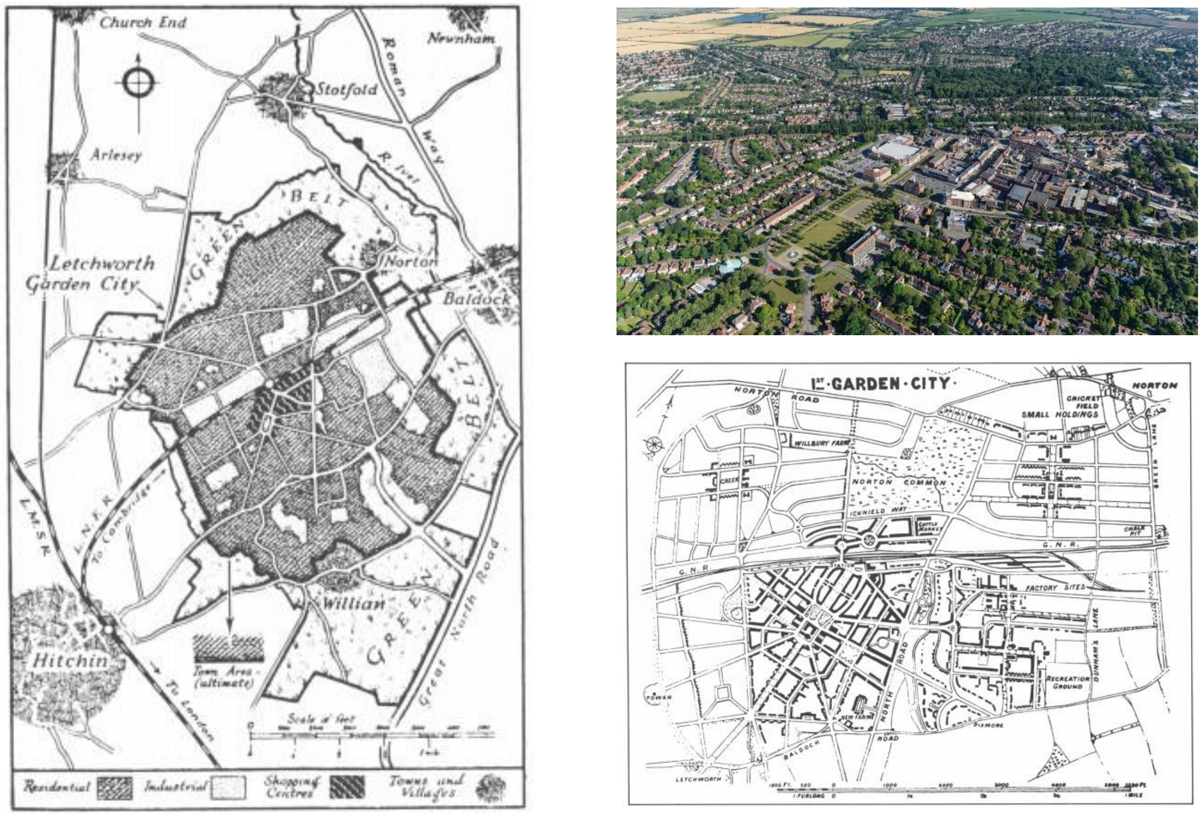


Figure 10 - Letchworth Garden City plan by Parker and Urwin (left, right bottom), Aerial view of Letchworth Garden City (right top)

In 1902, the Garden City Pioneer Company Ltd was set up to obtain funds and identify a site to establish Howard's Garden City idea. The foundation for the Letchworth Garden City was laid in October of 1903 in Hertfordshire near London. The pioneer Garden City established over a century ago is still in existence and functioning with a population of about 33,000 people providing employment opportunities for approximately 15000 people. Letchworth is said to be built on an axis with the development ramifying from a central green square. The plans drafted by architects Parker and Urwin were extracted from Howard's ideologies. However, they did not follow his rigid plan (Fishman, 1982) (See Fig. 11). Streets are lined with trees similar to Howard's boulevards and the satellite city is planned with clear zoning of activities such as residential, industrial and commercial. The city has an industrial park situated near the power plant. This is separated from the residential area by the railroad. The Garden City has an area of about 5500 acres and is surrounded by a rural green belt. With many open green spaces and amenities within walking distances, Letchworth aims to provide a healthy and culturally rich community for people of different social classes to live in (The International Garden Cities Institute, n.d.).

Hellerau

The first Garden City of Germany, Hellerau is located less than 5 miles away from the city of Dresden. Today, it is a heritage settlement and part of Dresden city. The settlement was designed for a population of 8000. As of 2010, the city is home to about 6000 residents. Resembling Letchworth, Hellerau too has distinct sites for factories and industries and aims to provide employment within the community. The city has an integrated transport system connecting it to various neighbouring settlements. In comparison to the Garden City concept of accommodating 32000 residents in an area of 6000 acres, Hellerau is developed on a 400 acres (about 160 hectares) site for a quarter of the intended population possibly implying a higher urban density. From Fig. 12 it can be noted that, Hellerau does not follow Howard's concentric circle theme. The development has a more organic settlement pattern (The International Garden Cities, n.d.).

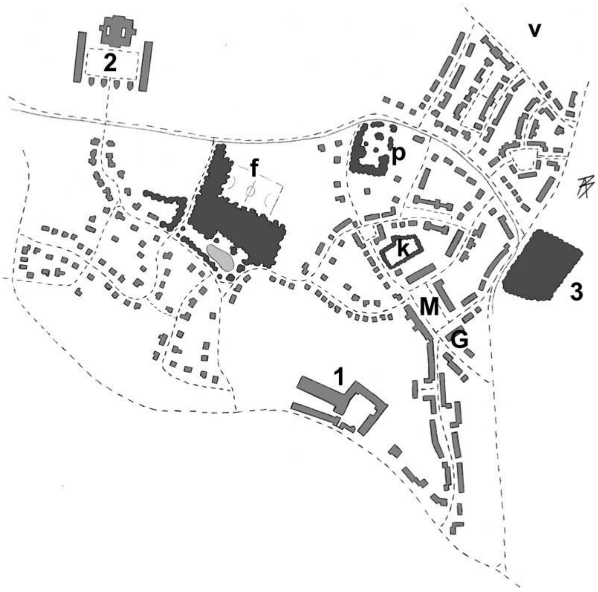


Figure 11- Hellerau Garden City plan (left), aerial view of Hellerau Garden City (right)

Colonel Light Gardens

Inspired by the Garden City movement, Colonel Light Gardens was established in South Australia in the 1920s and formerly known as Mitcham Garden Suburb. The initial design was derived from Garden City principles. However, the Australian government introduced the 'Thousand homes Scheme' forcing the site to accommodate more homes thereby impacting availability of space for amenities. The suburb was built on a 400 acres (about 160 hectares) site and is said to lodge about 3200 residents (2006 census), almost half Hellerau's population. The settlement was designed with two shopping areas to include key amenities such as a town hall, a theatre and a fire station. The site was also zoned to accommodate schools, care homes, churches and medical facilities, similar to Letchworth. Open green spaces were incorporated generously and local food production by residents was encouraged which was an addition to the existing principles of a Garden City where food is acquired from the surrounding farms (The International Garden Cities Institute, n.d.).

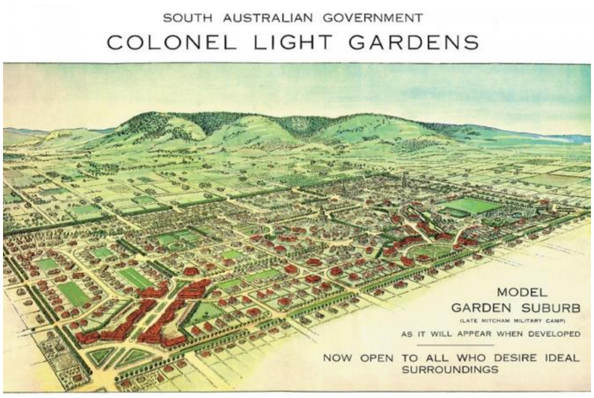


Figure 12- Colonel Lights Garden conceptual scheme (left), aerial view of Colonel Lights Garden (right)

The three examples discussed above are a few of the many notable garden cities and towns that were developed in the 19th century. The pioneering theory of Howard's Garden City and trials in the form of Letchworth and Welwyn Garden cities can be used as a foundation for evolving sustainable developments that address a range of issues like housing, environment, energy, health, mobility, economy and the community (Vernet & Coste, 2017). However, as can be seen in the cases of Hellerau and Colonel Lights Garden, the scale of the settlement possibly plays a key role in the feasibility and success of the Garden City theory. Howard's 'radicalist' ideologies made him keen to develop a prototype Garden City which he thought would be replicated all across the UK and in many other countries. However, the struggles of almost a decade to realise a Garden City like Letchworth were discouraging. It seemed unfeasible to pursue developing another one of its kind (Fishman, 1982). Howard's overall idea of the Garden City has some valuable principles which can be extracted and applied to developing sustainable communities. The TCPA have adapted Howard's Garden City principles to suit the 21st century (Town and Country Planning Association, n.d.). These are:

- Land value capture for the benefit of the community.
- Strong vision, leadership and community engagement.
- Community ownership of land and long-term stewardship of assets.
- Mixed-tenure homes and housing types that are genuinely affordable.
- A wide range of local jobs in the Garden City within easy commuting distance of homes.
- Beautifully and imaginatively designed homes with gardens, combining the best of town and country to create healthy communities, and including opportunities to grow food.
- Development that enhances the natural environment, providing a comprehensive green infrastructure network and net biodiversity gains, and that uses zero-carbon and energy-positive technology to ensure climate resilience.

- Strong cultural, recreational and shopping facilities in walkable, vibrant, sociable neighbourhoods.
- Integrated and accessible transport systems, with walking, cycling and public transport designed to be the most attractive forms of local transport.

The pioneer Garden City was often misinterpreted and terms such as garden town, village, city were also misused for any suburban neighbourhood beyond city boundaries (Vernet & Coste, 2017). Some perceive the Garden City as a low-density, unsustainable and voluminous model of suburbanization (Duany, et al., 2014). Nonetheless, regardless of how a sustainable community is defined, it is important to acknowledge that it could not exist without the Garden City (Hugel, 2017). From TCPA's Garden City principles it can be noted that these are similar to both Sanborn and BioRegional's sustainability principles as discussed in 'Section 2.2'.

4.1.2. **Current examples**

Over the past decade, the design and construction of large-scale net zero energy developments has gained momentum. Since net zero's popularity, many proposals of net zero communities and cities have been published globally, for example, Dongtan in China (Design Build Network, 2008). However, it is important to identify built and tested examples of developments that aim and state they achieve net zero. Four net zero developments of varying scales have been identified to understand the process of creating a net zero development; if net zero truly works for these communities; and what their successes and failures are in this regard.

Case study 1: Solar Settlement in Schlierberg

Figure 13 - Aerial view of Solar Settlement, Freiburg

The Solar Settlement was built between 1999-2006 by Architect Rolf Disch. The aim of the project was to design a sustainable community with plus-energy houses (houses that produce more renewable energy over a year than they consume). The community includes innovative systems for water management and movement. However, only a part of the project was developed due to lack of finances. With an urban density of 54 units/ha, the settlement includes 59 terrace houses and the 'Sun ship' (amenities building) to the west abutting the main access road. As of 2015, the total number of residents in the community is 170.

Location:

The community is located in Freiburg, Germany, a few miles away from the sustainable settlement of Vauban. Based on Duany's 'rural to urban transect', the site falls in the general urban zone (bordering suburb) (Duany, 2002). Table 12 compiles details of the development's proximity to key amenities and public transit systems. It can be noted that the development is about 3 kms away from the town centre and well connected to other important services and facilities such as a supermarket and hospital via tram and bus.

Table 15 - Proximity and access to public transport and amenities for Solar Settlement

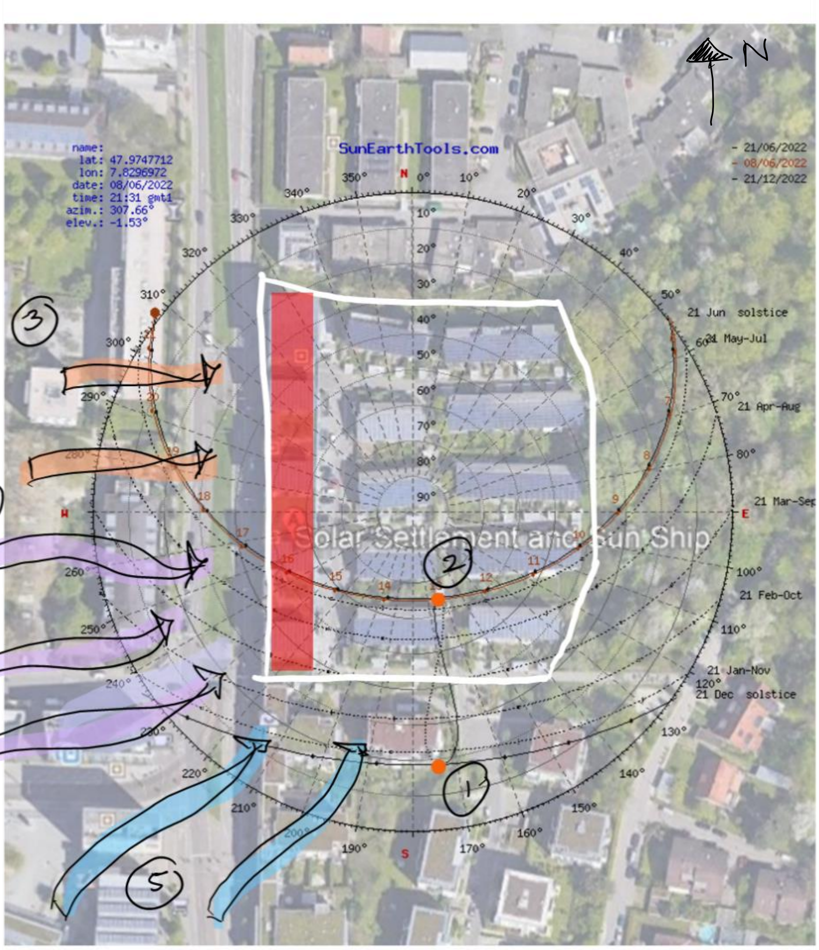
Distance	Amenities	Accessibility

Within community	Pharmacy, bar, bank, offices	-
Within 150m	Grocery store, primary school, café, bus stop, tram access	Walkable
Within 250m	Major retail (ALDI), restaurant	Walkable
Within 350m	Nursery	Not accessible by public transport
Within 500m	Parks, sports and fitness centre	Parks not accessible by public transport
Within 1km	Hospital, school	Accessible by public transport
Within 3km	Town centre, Business district, shopping mall, cinema, clinic, College/University	

Climate:

Freiburg is known to be one of the sunniest locations of Germany, implying promising solar energy generation. The location is said to have a total annual irradiation of 1,100 kWh/m^2. From the images in Figure 14, it is evident that the design takes advantage of the abundant solar energy using roof top solar panels. The climate classification for Freiburg is temperate with warm summers and cold winters. The warmest month is July with an average temperature of 20 °C and the coldest, January, with an average temperature of 2°C. The annual average temperature for Freiburg is 9°C (see Appendix 1 for Climate details). The settlement should have a considerable heating demand to tackle the low temperatures during winter (timeanddate, 2020).

Figure 15 shows the site map indicating the sun path and wind directions for the settlement. Given the considerable degree of solar access of the location and specifically the site, appropriate shading must be provided to cut out the summer sun to reduce solar gain and an increased cooling demand. Analysing wind from the diagram, it can be noted that the site has little to no exposure to the westerly summer winds and winds from west-south-west and west during spring and autumn due to the Sun ship building (marked red in Fig. 15). However, the site is partially exposed to the southwest winds during the colder months. The average wind speed for the location is 11 km/h with March being the windiest. Wind access to site during the colder months may create wind draughts in the internal streets and also impact the heating demand of the houses. The wettest month is June, with Freiburg having an annual rainfall of 413.3 mm (timeanddate, 2020).



1 – Winter solstice sun angle – 18.5°

2 - Summer solstice sun angle - 65.5°

3 – Summer wind direction – W

4 – Spring and autumn wind direction – WSW - W

5 – Winter wind direction - SW

(timeanddate, 2020)

Figure 14 - Site map indicating sun path and wind direction for Solar Settlement, Freiburg

Design:

The settlement has a grid pattern with the majority terrace houses and nine penthouses. The community is vehicle free with the residential zone designed to be pedestrian and cycle friendly. 138 car parking spaces have been provided in the Sun ship building below ground. The Sun ship is a four-storey building that includes offices (floors 2-4) and retail spaces

(Ground). Its fifth level houses 9 penthouses. It can be noted from Figure 16 that the residential zone has been positioned away from the main road to the back (east end) of the site and the amenities building is placed abutting the main access road. This encourages access to amenities for the general public and also shielding from vehicular traffic noise as well as air pollution. Adjacent to the site on the East are woods and scattered residential and commercial buildings to the North and South.

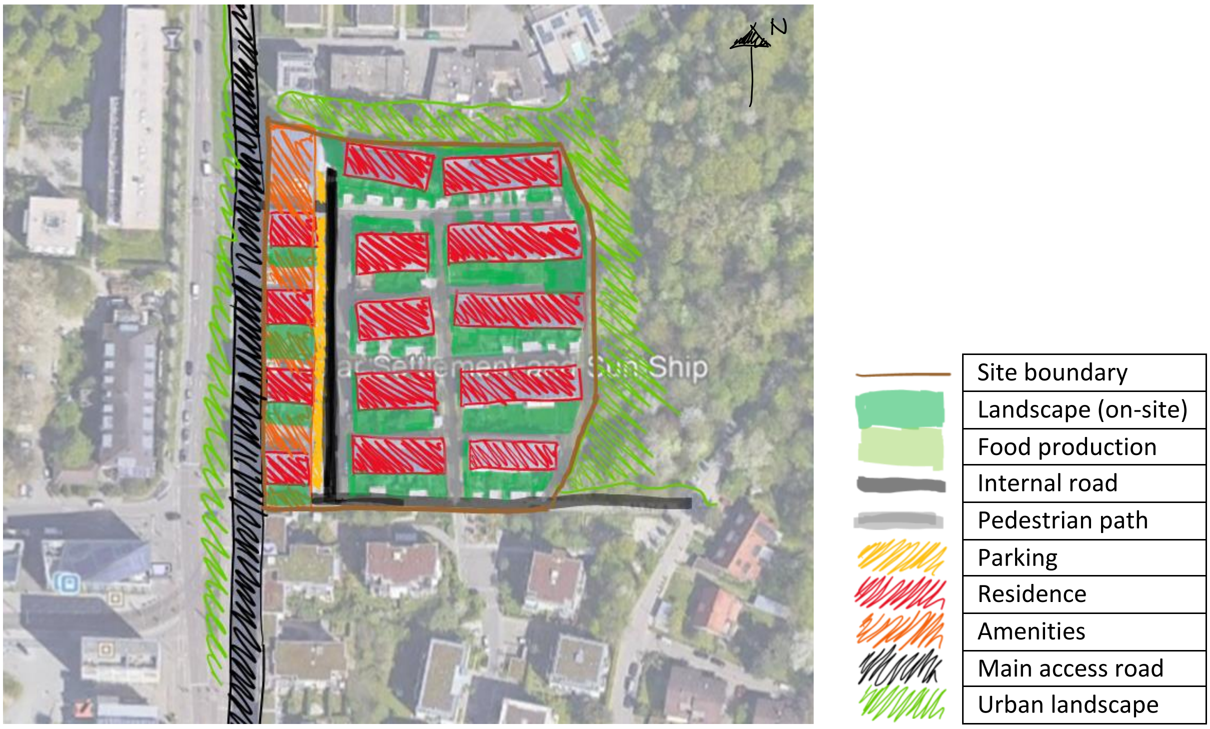


Figure 15 - Understanding zoning and spatial organisation of Solar Settlement

The community includes houses of varying sizes from 81 m^2 to 210 m^2 (Karlsruhe, 2016). There are two to five bed terraced houses as well as non-terrace houses with household sizes ranging from one to five residents per house. While most houses are two storeys tall, terrace houses to the North of the site have been designed to be three-storeys (See Fig. 14). All houses are oriented to face south to take advantage of the sun with roof top solar panels which also extend onto the balconies to act as shading (see Fig. 17). The total area of photovoltaics is 3150 m^2. The residences have been designed to the Passivhaus standard and the community is said to have an energy surplus which is fed back to the grid (National Stadtentwicklungs Politik, 2012). The timber frame construction achieves good U-values with external wall and roof construction achieving U-values of 0.12 and 0.11 W/m^{2}K respectively (Heinze & Voss, 2009).

Figure 16- Side elevation of house showing shading from solar panels (left), view of internal road (right)

Energy:

According to a monitoring report by University of Wuppertal, the residences in the development consume minimal energy which is met by the energy generated from roof top solar panels (Heinze & Voss, 2009). The efficient fabric with low U-values and ventilation system with heat recovery play key roles in energy demand reduction. Additionally, use of energy efficient appliances and appropriate occupant behaviour have a significant impact on the consumption of energy. The community uses a district heating system with a CHP plant run on woodchips and natural gas. The average house in the development consumes 79 kWh/m^2 per year (gas and electricity). This demand versus the energy supply from roof top photovoltaics produces an annual energy surplus of 36 kWh/m^2. According to the report, an average German house would consume about 185 kWh/m^2 and the development would need to generate twice the energy to meet this demand. The roof area would be insufficient to accommodate more solar panels in this case (Heinze & Voss, 2009).

Discussion:

The monitoring exercise conducted by University of Wuppertal indicated that, while the average house produces surplus energy, many houses deviated from this average balance. The differences were due to some critical findings:

- A discrepancy in house size with respect to the solar panel area
- End terrace houses consumed more heating energy
- Variations in occupants' behaviour

About 30% of the total energy consumption was utilised for space heating and hot water. About 70% of the total energy consumption was from electricity use. Hence, a majority of the energy demand was from electricity usage dominated by occupant behaviour and electricity consuming appliances. Controlling these parameters could decrease the energy demand further. Moreover, the electricity that is produced from solar energy is fed back to the grid completely rather than used locally or stored first, an approach introduced in Germany to avoid large scale energy mismatch. Despite its limitations, the Solar Settlement functions as a highly sustainable community that can meet its low energy demand from on-site renewable energy supply while considering other key environment factors as part of sustainable urban design and planning.

Case study 2: BedZED

Figure 17 - Aerial view of BedZED

Situated in London, UK, BedZED is designed to be a zero-carbon development. Designer Bill Dunster along with organisation Bioregional conceived the idea in the late 90's and construction was between 2000-2002. BedZED was designed to include energy efficient homes that have a reduced energy demand and produce as much or more renewable energy on-site to meet this demand. Similar to Solar Settlement in terms of urban density, BedZED has 48 housing units per hectare. The 1.7-hectare site houses 82 residential units, 19 live-work units, offices, a nursery and a clubhouse. The community is home to 209 residents and 57 visitors who use the amenities (Hodge & Haltrecht, 2009).

Location:

In close proximity to Sutton town, BedZED is located in Hackbridge in the London Borough of Sutton. According to Duany's 'rural to urban transect', the site falls in the suburban zone (Duany, 2002). Table 13 compiles details of the development's proximity to key amenities and public transit systems. It can be noted that the community includes a sports field on-site. However, this is currently not used for recreation and a small portion of the field has been converted to a community garden space. The development is situated close to Hackbridge train station and abuts the main access road with bus stops located nearby enabling easy access to various key amenities and nearby towns.

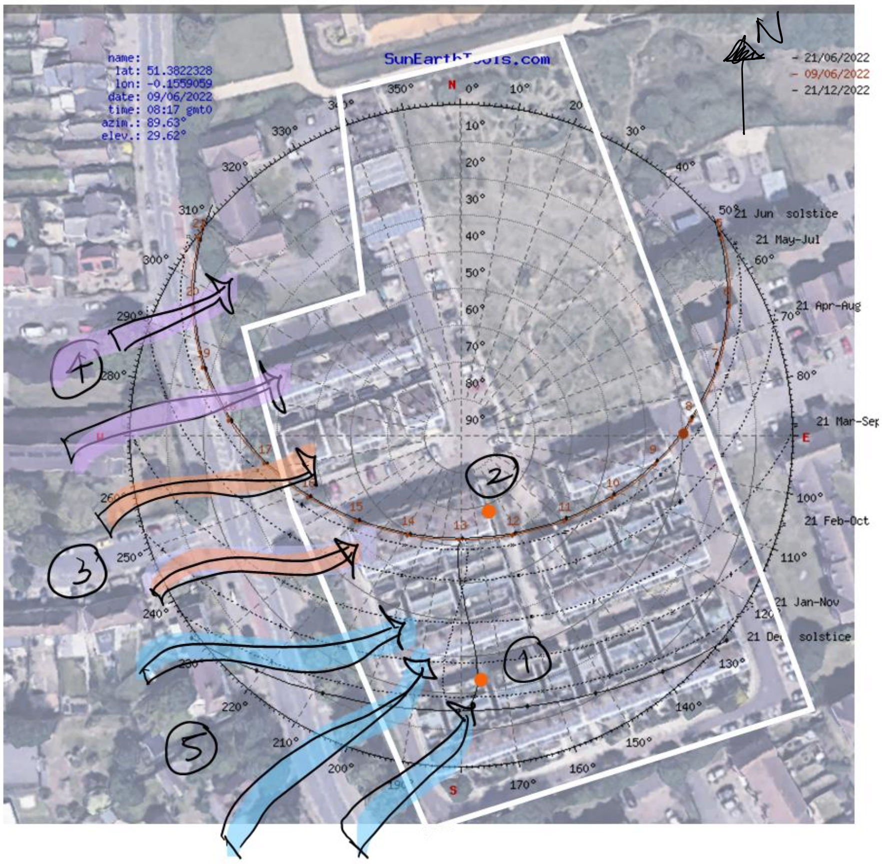
Table 16 -Proximity and access to public transport and amenities for BedZED

Distance	Amenities	Accessibility
Within community	Nursery, offices, club house and sports field	-
Within 100m	Bus stop	Walkable
Within 400m	Pharmacy, clinic, grocery store, primary school, parks, bar, dining	Walkable
Within 500m	Hackbridge train station	Accessible by public transport
Within 1.5 - 2km	Hospital, school, college/university, sport centre	Accessible by public transport
About 3km	Sutton town centre, business district, shopping mall, cinema, major retail (ASDA in Sutton)	

Climate:

The BedZED site falls under the temperate climate classification and has an annual average temperature of about 11°C. The warmest month, July, has an average temperature of 19 °C and the coldest, January, has an average temperature of 6°C (see Appendix 1 for Climate details). The community is expected to have a significant heating demand in the colder months. Figure 19 shows the sun path and seasonal wind direction for BedZED. It can be noted that the winter sun angle is low and design should accommodate maximising solar gain during the winters. Analysing wind from the diagram, the terrace houses have been positioned parallel to the summer, spring and autumn wind direction. This encourages wind movement between buildings, through walkways and access routes. With stronger winds compared to

Freiburg, Sutton is windiest during peak winter (January) and has an annual average wind speed of 14 km/h. Wind during the colder months from the southwest may have a bearing on the heating demand of the houses abutting the road to the southwest of the site. Sutton's wettest months are October to December with an annual precipitation of 596.6 mm (timeanddate, 2020).



1 – Winter solstice sun angle – 15.1°

2 - Summer solstice sun angle – 62.1°

3 – Summer wind direction – WSW

4 – Spring and autumn wind direction – WSW

5 – Winter wind direction - SW

Figure 18 - BedZED site map showing sun path and wind direction

Design:

The community comprises terrace houses arranged in a grid pattern. The design includes a village square and 84 car parking spaces restricted to the site's perimeter making the community pedestrian and bicycle friendly. A large sports field (4335 m^2) is located to the north east of the site adjacent to the clubhouse. Figure 21 describes how designers maximised usage of site area without compromising on solar access to homes during winters. Unlike Solar Settlement where the residential zone is clearly segregated from the commercial spaces, BedZED has a mixed residential and commercial setup. Enabling access for the low winter solstice sun implied increasing the distance between parallel rows of houses and thereby limited use of the site area. This was resolved by incorporating commercial spaces to the north of the terrace houses (Dunster, et al., 2008).

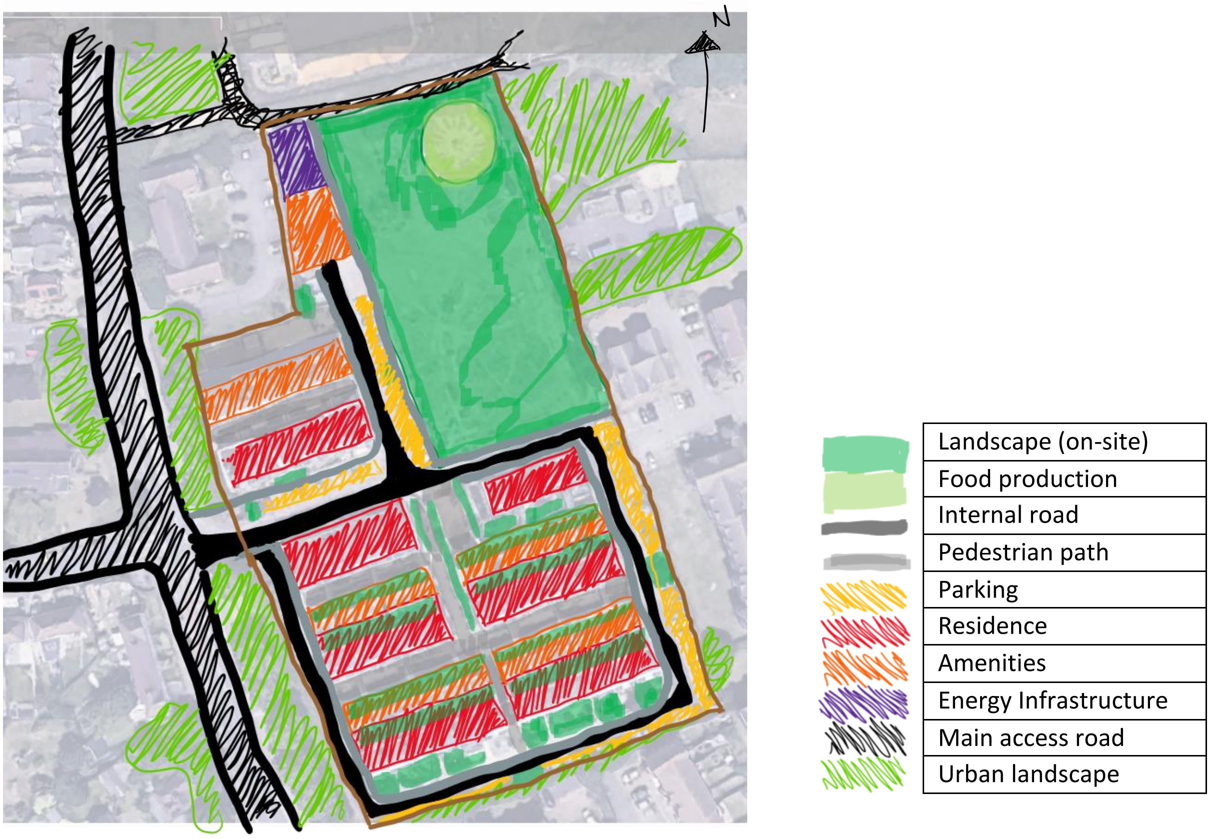


Figure 19 - Understanding zoning and spatial organisation of BedZED site

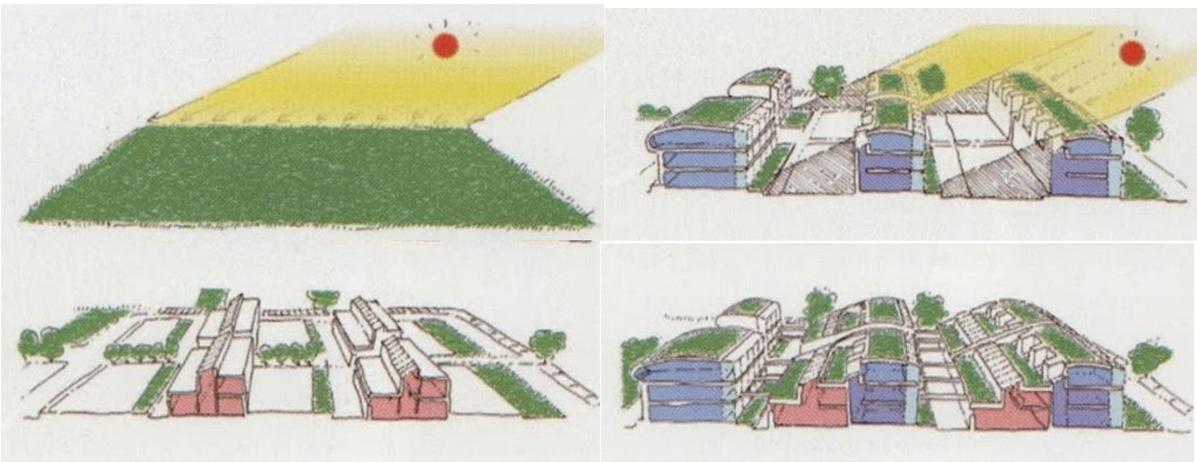


Figure 20 - BedZED site (top left), design concept for houses with winter sun access (top right), design concept for commercial spaces (bottom left), final design concept combination of houses and commercial spaces (bottom right) (Lazarus, 2009)

The development includes 2-3 bed maisonettes, 4 bed townhouses, 1-2 bed flats and live work units with floor areas ranging from 48 m^2 to 142 m^2. Each house includes roof top solar panels, a green roof and a terrace garden (currently actively used by about 25% households). In terms of thermal comfort, all homes are required to be maintained at 18°C. Sufficient heat was to be provided by passive solar gain, internal heat gains and residual heat from a hot water cylinder. Houses are fitted with wind cowls which act as heat exchangers, drawing out warm, stale air and bringing in cool, fresh air from outside. Designed using passive strategies, the housing units have a wall U-value of 0.11 W/m^{2}K and roof U-value of 0.1 W/m^{2}K with high levels of insulation (Lazarus, 2009).

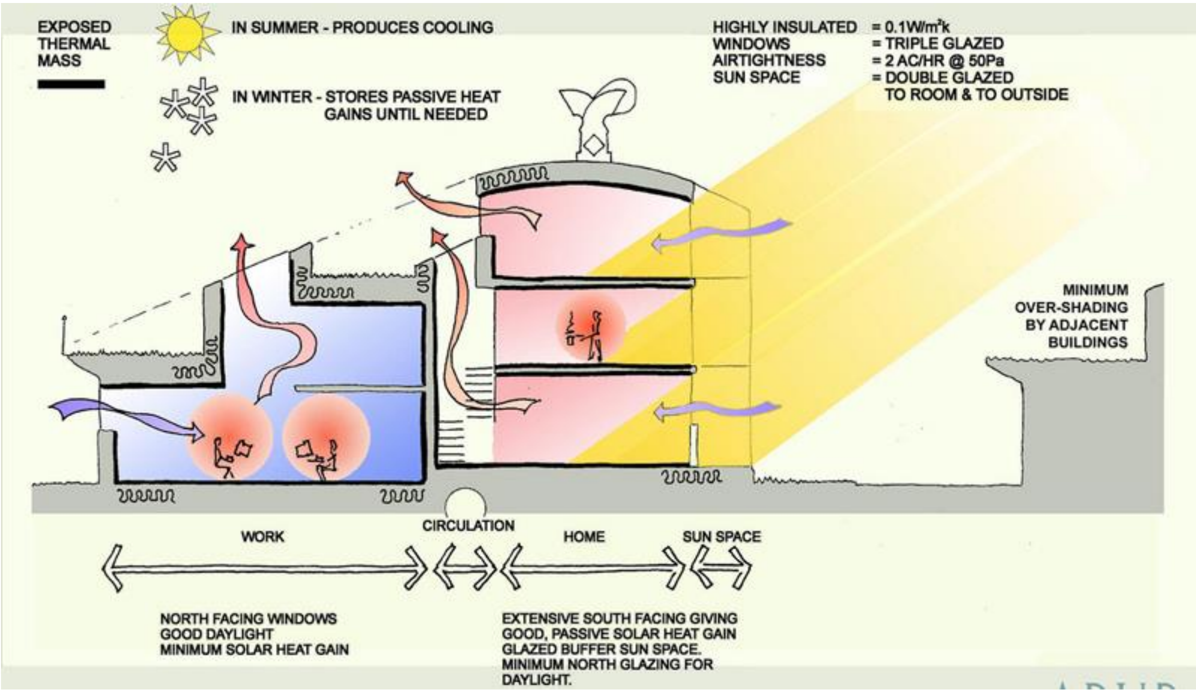


Figure 21- Passive design strategies used in BedZED (Lazarus, 2009)

The community encourages local, sustainable food production. However, very few residents follow this with keenness. The sports field is presently not fit for sports related activities and a small portion of it is now assigned as garden allotments. About 10 households (12%) actively use these allotments. Apart from sustainable building and urban design BedZED also includes efficient water management systems and a green transport plan. A Green Water Treatment Plant (GWTP) is included on site to treat waste water. Additionally, the community harvests rain water and treats surface run off water. In attempts to reduce carbon emissions, BedZED offers vehicle sharing for commuting and live work units to encourage work from home and reduced travel amongst other features under its sustainable travel plan (Hodge & Haltrecht, 2009).

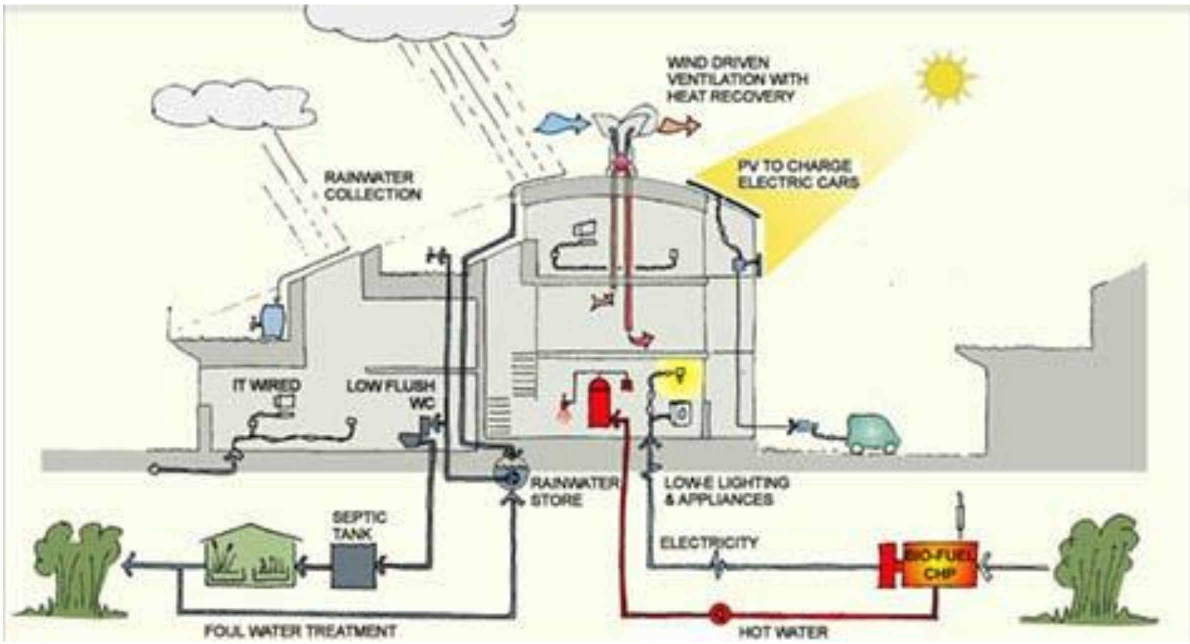


Figure 22- Water and energy infrastructure at BedZED (Lazarus, 2009)

Energy:

A thesis on BedZED gathered monitored data for the development for two years between 2011-2013 (Young, 2015). The mean annual energy use standardised to floor area was found to be 125 kWh/m^2/year which was almost 67% more than the predicted energy use. Comparing the development to other standard new builds constructed at the time using 1995 building regulations, the average energy consumption of standard buildings was approximately 167 kWh/m^2/year implying BedZED performed 23% better. The study also found that the community was able to meet its electricity demand but not the heating (Hodge

& Haltrecht, 2009). BedZED was designed to be self-sufficient in terms of clean energy. The energy demand was to be met by renewable energy supply from two sources:

- The community has a total area of 777 m^2 of photovoltaics which accounts for approximately 20% of the total energy use
- BedZED was designed with an in-house Combined Heat and Power (CHP) Plant fuelled by woodchips. The prototype plant was planned to be automated and designed to function all the time. The design predicted that the CHP would produce all of the community's energy demand.

Discussion:

BedZED, where ZED stands for zero (fossil fuel) energy development, was planned to be a zero-carbon community. Apart from reduced energy demand and on-site renewable energy supply, the community includes other features such as local food production and efficient water, waste and transport management systems that make it highly sustainable. Regardless of the planner's efforts, BedZED could not meet the zero-carbon status. A few key findings indicated where the community may have fallen short. These are:

- Performance gap between predicted and actual energy use and generation.
- Failure of the CHP to meet the target and operate automatically. Within a few years of commission, the CHP was made inactive due to technical issues. Not only was the automated system required to be manned at all times, the CHP could not produce the required energy output.
- The waste water treatment plant (GWTP) was shut down in 2005.
- BedZED is said to be designed for enthusiasts who are keen to lead a healthy and sustainable lifestyle. Residents are expected to be mindful of their activities as these

play key roles in curbing carbon emissions, such as local food production and a green transport plan. However, these are not pursued with keenness by many households.

As discussed, the community performed well in terms of electricity but not heating. A possible reasoning for this could be that all houses were equipped with high end, energy rated appliances. A 2007 monitoring report by Bioregional identified that about 39% households used electric heating on days typical heating was not sufficient. This indicates an overall inefficiency in the heating design. Likewise, supplementary cooling was also required during warmer days. In the event where homes were unoccupied and the temperature fell below 18°C, a trickle heat source would automatically be activated (Hodge & Haltrecht, 2009). The thermal comfort and thereby heating demand heavily depended on occupancy. Despite its shortcomings, BedZED has set a standard for sustainable living and design of zero energy/carbon communities around the world.

Case study 3: The Sustainable City

Figure 23 - Aerial view of the Sustainable City, Dubai

The Dubai Sustainable City was established in 2015 by Diamond Developers. Situated in UAE, the city is built on a 46-hectare site area and contains residential, commercial, educational, medical and leisure zones. The site has 500 residential units which is an urban density of 11 units/ha. The total population of the development is 6000 of which 2700 are residents. The city is stated to be the first operational net zero energy development in Dubai and set the standard for net zero developments globally (Propsearch.ae, n.d.).

Location:

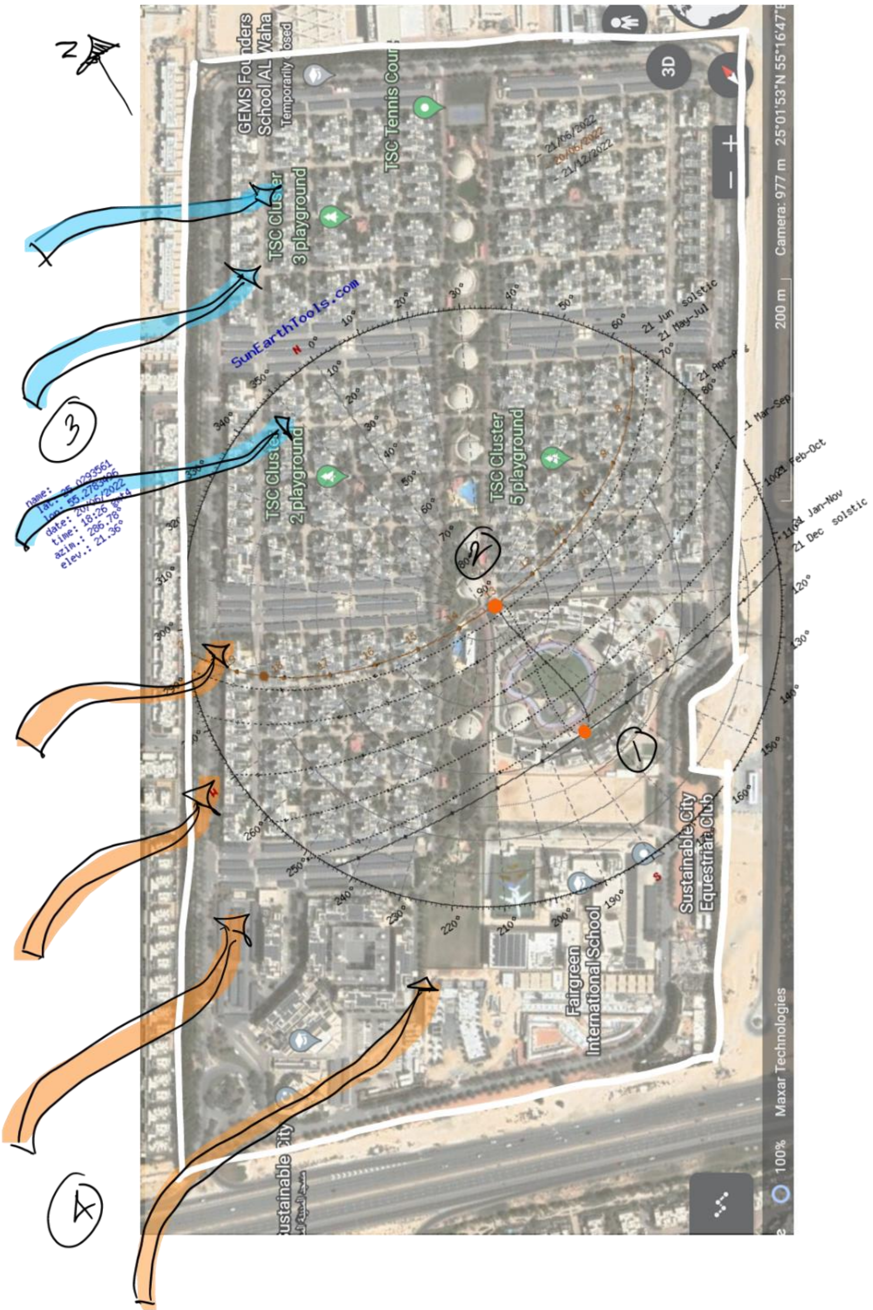
The city is located in downtown Dubai, Jumeirah City, in close proximity to Dubai International airport. According to Duany's 'rural to urban transect', the city falls in the general urban zone (Duany, 2002). Table 14 compiles details of the development's proximity to key amenities and public transport systems. The sustainable city is located about 15km away from the main city of Jumeirah and there is no direct public transport system that connects the development to the city centre. This indicates an increased need to use private transport to access key amenities such as hospitals and the business district. The site does mitigate the requirement to go beyond the community by providing many facilities within the development as indicated in the table below.

Table 17 - Proximity and access to public transport and amenities for the Sustainable City

Distance	Amenities	Accessibility
Within community	Pharmacy, clinic, grocery store, nursery, primary school, parks, café, dining, sports/fitness centre, bank, offices	-
About 300m	Bus stop (site perimeter)	Walkable
About 4km	Major retail, cinema (neighbouring sector)	Not directly accessible by public transport
About 7km	School (neighbouring sector)	Not accessible by public transport
Within 15km	Hospital, college/university, shopping mall, metro station, town centre, business district (Jumeirah)	

Climate:

The climate classification for Dubai is hot and dry. Summers are hot with temperatures typically reaching 41°C and winters are pleasant. The hottest month is August with an average temperature of 36 °C and the coldest is January which has an average temperature of 20°C (see Appendix 1 for Climate details). The annual average temperature for the location is about 28°C. The community is expected to have a significant cooling demand as the summers get increasingly hot and last about a third of the year. Additionally, the annual irradiance for Dubai is about 2200 kWh/m^2 (Dubai Electricity and Water Authority, 2017). From the above images it is evident that the design takes advantage of the abundant solar energy using roof top solar panels (timeanddate, 2020).



1 – Winter solstice sun angle – 41.5°

2 - Summer solstice sun angle – 88.5°

3 – Winter wind direction – WNW - NW

4 – Summer wind direction – W-WNW-NW

Figure 24 – Dubai Sustainable City site map showing sun path and wind direction

Figure 25 shows the sun path and wind direction for the Sustainable City in Dubai. It can be noted that the summer sun angle is high. Design should address solar gain as a key concern and provide appropriate shading. Buildings in this climate classification are ideally placed close to one another to create mutual shading. However, the Sustainable City villas have ample spacing between them. Analysing the wind direction from the diagram, it can be seen that the buildings are not oriented to take advantage of the wind. Hence, wider spacing may have been encouraged to assist wind movement through the buildings. The average wind speed for this location is 13 km/h with the windiest period between May to August. A key analysis from understanding the climate indicated the scarcity of rainfall in the region. The location sees very little rainfall and only during the winters. The precipitation for the year is 0.4 mm. Hence, design must develop water strategies to address this.

Design:

The development contains five clusters of villas organised in a grid pattern to the back of the site with the amenities placed to the front of the site abutting the main road. A large commercial complex with shops, restaurants, businesses, offices, health care in addition to other critical and leisure facilities sits at the site entrance (southwest) accessible to both residents and public. Located to the south is the innovation centre, international school, a rehabilitation hospital and an equestrian club. Similar to the other case studies, the Sustainable City too is a vehicle free, pedestrian and cycle friendly community. Vehicular movement is restricted to the perimeter of the site and clearly segregated from pedestrian and cycle paths with vegetation that act as buffers and provide shading. About 3000 parking spaces have been provided walkable from the residential clusters. The community also offers battery operated buggies to residents to move within the community (Propsearch.ae, n.d.).

A central spine running the length of the site has an urban farm containing biodomes that cater for local food production and are accessible to the residents creating an interactive, community friendly space. Additionally, the city recycles grey water. Each residential cluster includes:

- Waste segregation stations to encourage recycling

- Five plazas which create comfortable and safe open spaces for play areas. The central plaza of each cluster has a cooling tower which helps keep outdoor temperatures low and encourages residents to use outdoor spaces even on a very hot summer day.
- 100 detached villas
- 3 to 4-bedroom villas and 5-bedroom townhouses. All houses have roof top solar panels in the form of canopies shading the terraces.

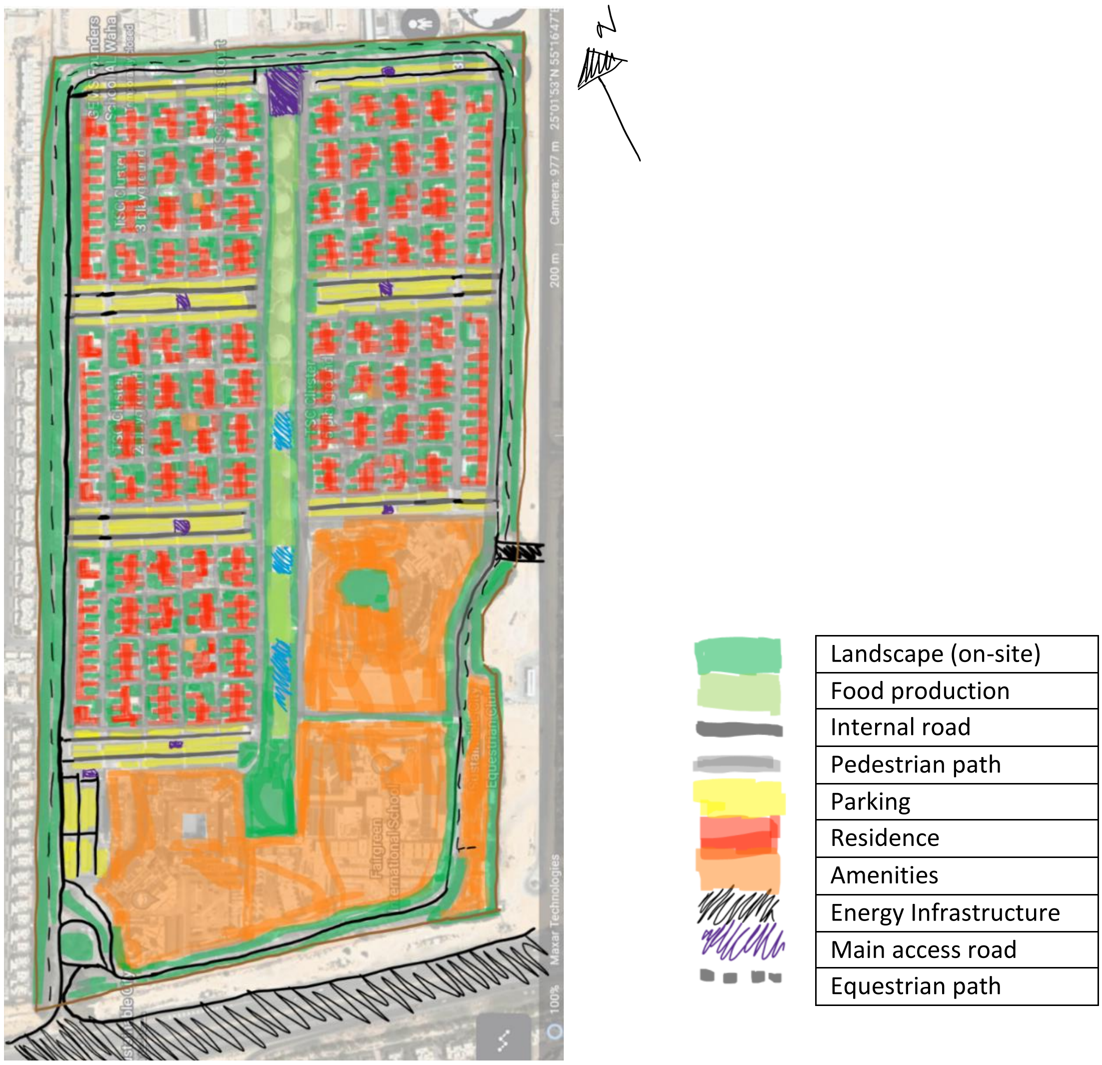


Figure 25 – Understanding zoning and spatial organisation of the Sustainable City site

Energy:

The first monitoring report for the Sustainable City's performance was released in 2018. According to the report, the development is said to achieve net positive energy. The villas have an average energy use intensity of 97 kWh/m^2/ year. This is stated to be 40% lower than the Green Building Standard for Dubai (The Sustainable City, 2017). The solar power production per villa from roof top solar panels was measured to be between 5.2 and 9.8 kWp (peak power). The solar power produced from the common areas was about 3.5 MWp. Overall, there was an annual surplus of solar energy contribution of approximately 2,500,000 kWh according to the report. About 150% of the electricity was produced by parking roof top solar panels (Dadlani, 2021).

Discussion:

The Sustainable City in Dubai was designed using the three pillars of sustainability – sociocultural, economic and environmental features. The development includes many sustainable features in terms of passive design, water and waste management, transport and movement, sustainable materials, local food production and key amenities within the neighbourhood. While the community has been designed with both building and urban passive strategies, a case study of the city conducted by British University in Dubai indicated that the current settlement pattern may not be taking advantage of the wind direction. Hence, changing the orientation of the villas and the interior streets to suit the wind pattern may be beneficial (El-Bana, 2015). The performance data from monitoring the development between 2016-2017 indicated that the city had a net positive energy balance in all common areas and significant reductions in carbon emissions.

Case study 4: Masdar City

Figure 26-Aerial view of Masdar city

Established in 2006 by the Abu Dhabi Government, Masdar City is another pioneer project of UAE. Using vernacular Arabian architecture, the desert city aims to be carbon neutral and zero waste (Foster and Partners, 2014). A city spread out on a 600 hectares site is said to eventually be home to a population of 50,000 once completed. The construction of the city has been planned in phases. The first phase was scheduled to be completed by 2016 but has now been extended to 2025. Currently, the city has a total population of over 6000 of which 1300 are residents who either work or study in the city. The planned urban density for the development is 140 people/ha. Masdar city is still under construction.

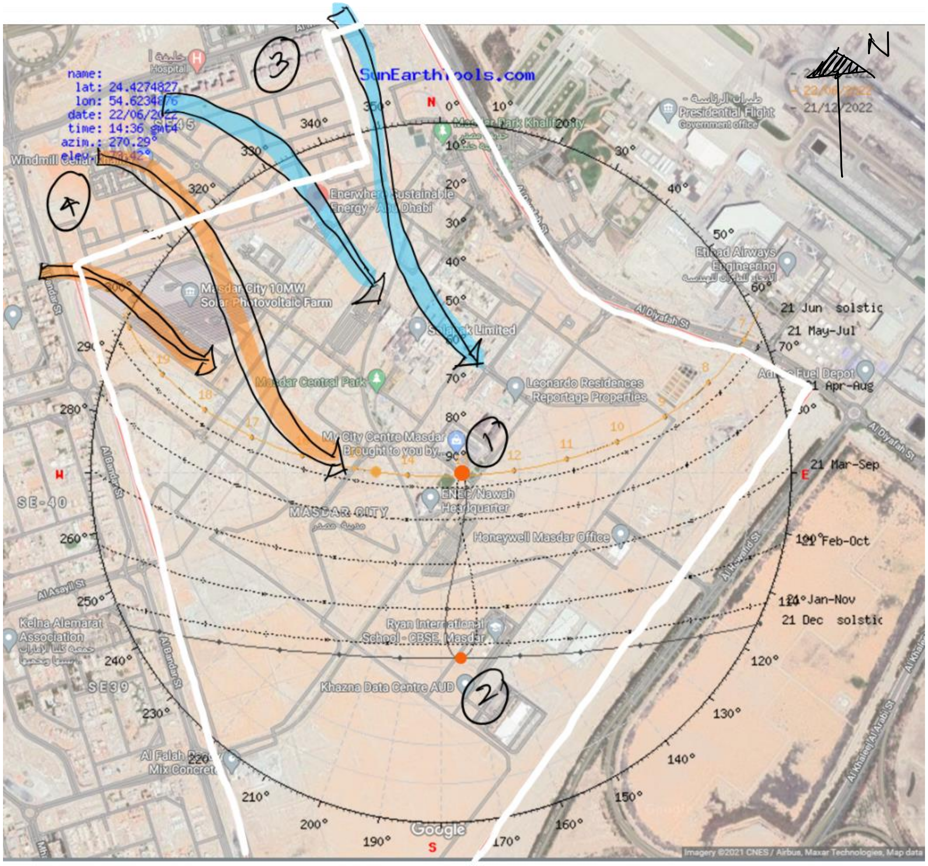
Location:

The city is situated in Abu Dhabi, UAE, 17km from downtown Abu Dhabi and close to Abu Dhabi airport. According to Duany's 'rural to urban transect', the city falls in the general urban zone. Table 15 compiles details of the development's proximity to key amenities and public transport systems. Given the scale of the development many key amenities are designed to be within the community. Abu Dhabi does not have a public transport system. Hence, facilities that are not within the community can be accessed only by private transport.

Table 18 - Proximity and access to public transport and amenities for Masdar City

Distance	Amenities	Accessibility
Within community	Pharmacy, grocery store, major retail, college/university, parks, café, dining, sports/fitness centre, offices, town centre, business district	-
About 3km	Nursery, school, cinema, shopping mall (neighbouring sector, Khalifa city)	Not directly accessible by public transport
About 5km	Hospital, bank (neighbouring sector, Khalifa city)	Not directly accessible by public transport

Climate:



1 – Summer solstice sun angle – 89.1°

2 - Winter solstice sun angle – 42.1°

3 – Winter wind direction – NNW - NW

4 – Summer wind direction – NNW -NW

Figure 27 – Masdar city site map showing sun path and wind direction

Like Dubai, Abu Dhabi's climate classification is hot and dry. Temperatures touch 40°C and over between May and September. The hottest month is August with an average temperature of 37 °C and the coldest month is January with an average temperature of 19°C (see Appendix 1 for Climate details). The average temperature for the year is about 28°C. The community will have to meet a significant cooling demand as almost half of the year is hot. Like Dubai, the location sees a very high annual irradiation. Masdar city includes a 10 MW solar PV plant to take advantage of the abundant solar energy (timeanddate, 2020).

Figure 28 indicates the sun path and wind direction for Masdar city. It can be noted that the summer sun angle is almost overhead. Design should address solar gain as a key concern and provide appropriate shading. Designers have used a vernacular urban settlement pattern where buildings are placed close to one another to create mutual shading. Analysing wind from the diagram, it can be noted that the buildings are oriented to take advantage of the wind. The average wind speed for this location is 14 km/h with most of the year, especially the warmer months experiencing an average wind speed of 15 km/h. A key analysis from understanding the climate indicated limited rainfall in the region. Unlike Dubai, this location does see precipitation for almost 8 months of the year, though it is small. The annual precipitation for Abu Dhabi is 52.3 mm. Design should include efficient water strategies to address shortage (timeanddate, 2020).

Design:

Masdar city is designed using a loose grid settlement pattern. A central pedestrian spine separates the city into two. Amenities are arranged along this spine. The settlement and streets pattern aim to reduce outdoor temperatures within the city. A wind tower included in the central plaza of the city aims to reduce temperature at street level by 15-20°C using passive downdraught evaporative cooling (see Fig. 30). According to Masdar city designers, Foster and Partners, the design was informed by vernacular architecture. Streets were designed to be short and narrow and buildings placed at the perimeter create wind turbulence to flush cool air into the streets (see Fig. 29). The entire development is raised above ground by about 7m to assist with cooling.

Figure 28 - Understanding zoning and spatial arrangement of Masdar city site

As in the case of the other three developments studied, Masdar city also aims to be a vehicle free community. The 7m high space below the city is used for a Private Rapid Transit (PRT) system designed for commuting within the city. The site includes parks distributed across it in an organic pattern to create open spaces for leisure and interaction. In addition to 1 MW roof top solar panels, the city has a large (10 MW) solar farm situated to the northwest of the site that caters for the development's energy demand of the city (see Fig. 30). The city design includes:

- Residential - apartments and villas (62%)
- Commercial – offices, businesses (12%)
- Institutional
- Research and development (7%)
- Hotels and serviced apartments (3%)
- Light industrial (4%)
- Retail (2%)

Figure 29 - 10 MW solar farm inside Masdar City (top left), ETFE panels used as insulation and shading (top right), wind tower (bottom left), courtyard and façade design (bottom right)

Buildings are designed to PEARL standards and aim to achieve 3-4 PEARLS benchmark. Innovative building materials and techniques as part of façade design and courtyards are a few of the passive design strategies included in Masdar city that aim to keep the city cooler than the rest of Abu Dhabi. Additionally, the city aims to reuse and recycle 100% of its waste generated (including construction waste). As of 2020, the city has an apartment complex with 500 1-2 bed units, offices and a University from Phase 1 of its construction (Masdar, n.d.).

Energy:

Masdar city's monitoring report for the years 2017-2019 indicated a cooling energy consumption of 25.1 GWh/year and electricity consumption of 52.5 GWh/year. The solar farm within the site produced approximately 17.5 GWh annually. Approximately a quarter of the total energy demand is met by on site energy production. However, Masdar city's clean energy programme has solar and wind farms established in UAE, UK and other parts of the world. The total renewable energy produced from the UAE sources amounted to about 1200 GWh per year as of 2019. The energy produced within UAE could supposedly support the energy demand of over 260,000 homes. The sustainability report also included measured data from completed projects. Three office buildings had an average energy intensity of 135 kWh/m^2/year which is approximately 35% lower than Abu Dhabi building baseline. Likewise, the Etihad Eco-residence consumed 72 kWh/m^2/year which was about 65% lower than a typical Abu Dhabi residence. While the development aimed for net zero waste, the 2019 report showed appropriate waste management of over 65% of the operational waste (Masdar, 2019).

Discussion:

With sustainability as its crux, Masdar city aims to be the world's first zero carbon, zero waste city that is run by renewable energy. The city was initiated in 2006 and is still under construction. While most of the city is yet to be constructed, the planners of the city have established a clean energy plan globally which would not only address the energy demand of

Masdar city but also power many developments globally. At present the city is said to achieve the following:

- Net positive energy (renewable energy production > energy consumption) and significant carbon reductions (of over 750,000 tonnes per year just from UAE) from on-site and off-site renewable energy.
- 40% reduction in water consumption by using energy efficient water fixtures, wastewater management, sea water desalination to meet water consumption
- Efficient waste management where waste is either recycled or used to generate electricity.

The development uses sustainable materials such as 100% sustainably sourced timber and 90% recycled aluminium. Moreover, low carbon concrete is used in place of regular concrete. The steel used is 100% recycled and locally sourced palmwood is used where appropriate in the place of hardwood (Design Build Network, 2012). Built to high energy efficient standards the city had a budget of $22 bn which was later reduced to $19.5 bn. Regardless, the city is due to be completed by 2030 based on availability of funding. With more apartments and offices being built, the city aims to attract a larger population over the years (Arabian Business, 2016).

4.1.3. Learnings from case studies

Analysis of past and current examples of sustainable developments resulted in some critical inferences that are useful to design and test a prototype net zero community. Firstly, location of the development and site selection play a key role in transport planning and thereby the potential for reducing in carbon emissions from transport. Depending on the site it may not be feasible to provide all key amenities within the development. However, these must be within a reasonable distance or easily accessible by public transport systems. Where there is poor access to public transport, there is likely to be a higher usage of private transport as is the case with Dubai Sustainable City and Masdar City. Secondly, the size of the community increases as their distance from the urban centre increases. This is because there is a possible increase in land availability and larger site area. While this could imply housing a larger population, key amenities are often located in the urban centre and the proximity to these decreases. Where there is availability of land and funding, it is easy to establish a large development that includes these amenities. Garden cities, Sustainable city and Masdar city are located further away from the urban core and aim to include most facilities within their site boundaries. Availability of a larger site area within the urban centre can be challenging. Hence, in this case one should identify key amenities in close proximity to a site and include amenities that can be accessed by both public and residents - as seen in Solar Settlement. Thirdly, all current examples are designed to suit their climate. Designers aimed to maximise passive design strategies to cut out unwanted energy demand at the design stage both at building and urban scale. However, in both Solar Settlement and Sustainable City, the climate analysis indicated that wind direction was not apparently considered in detail for urban design.

Furthermore, all cases considered had many sustainable features such as:

- On-site energy infrastructure
- Water and waste management
- Local food production and urban landscapes within the site
- Sustainable materials with low impact on embodied carbon emissions where possible
- Efficient mobility plan

All current examples have performed well in terms of energy and to an extent carbon emissions. Despite having an efficient clean energy plan, BedZED could not achieve its zero-carbon target. Likewise, Solar Settlement also uses fossil fuel energy from the grid and sells surplus clean energy back to the grid rather than storing it thereby still having a significant impact on emissions. Hence, it is advantageous to have options for either storage or other sources of clean energy supply if not on-site, away from site as in the case of Masdar City.

A critical aspect that the case studies overlook is lifestyles. Energy use is likely to vary between households. As discussed for Solar Settlement, houses varied from the average energy consumption due to differences in house and household sizes. However, the variation can also be closely associated with how residents consume energy. Some may want more heating/cooling, some may have longer baths/showers and consume more hot water. In the case of BedZED, designers were keen on providing a green lifestyle. Residents of the community are influenced by design to lead a healthier and more sustainable lifestyle. They are encouraged to eat healthily, walk and cycle more for commuting and follow water efficient lifestyles. However, as found from the review, only a limited number of households are actively involved in local food production or buying from local farms and organic stores which are integral to BedZED's green lifestyle. Regardless, designers acknowledge that energy use depends on users' activities and lifestyles.

Published in 2018, a documentary directed by Sacha Bollet & Benoit Demarle describes the process of building Masdar city, a large-scale sustainable city that would cost 22 billion dollars (Building Green - Masdar City, exploring the future, 2013). The video critically analyses key sustainable features of Masdar City, including interactions with important personnel of the planning and maintenance teams. The plot also interprets the challenges faced by Masdar city to complete Phase 1 of its construction and its shortcomings thereof. The documentary indicated that 1000s of sensors across the city measure energy use down to the hour. In the case of an energy spike, the residence that consumes more energy than average can be identified and notified as quoted by the facilities manager. Moreover, some residents complain about cooling being insufficient as the system is set to not go below 22°C. However, the documentary confirmed that Masdar city follows sustainability strictly and where there are concerns, residents are 'educated' on how to follow a sustainable lifestyle. The case studies helped understand the impact of climate - informed, passive urban and building design, a clean energy plan, efficient water, waste, transport and mobility systems and most importantly user lifestyles which will play a key role in the design of the prototype net zero community in this thesis.

Summary

This chapter reviewed seven past and current examples of large scale sustainable and net zero developments. The analysis indicated several similarities in principles and design. Learnings drawn from these case studies will be used to design the prototype community situated in the UK.

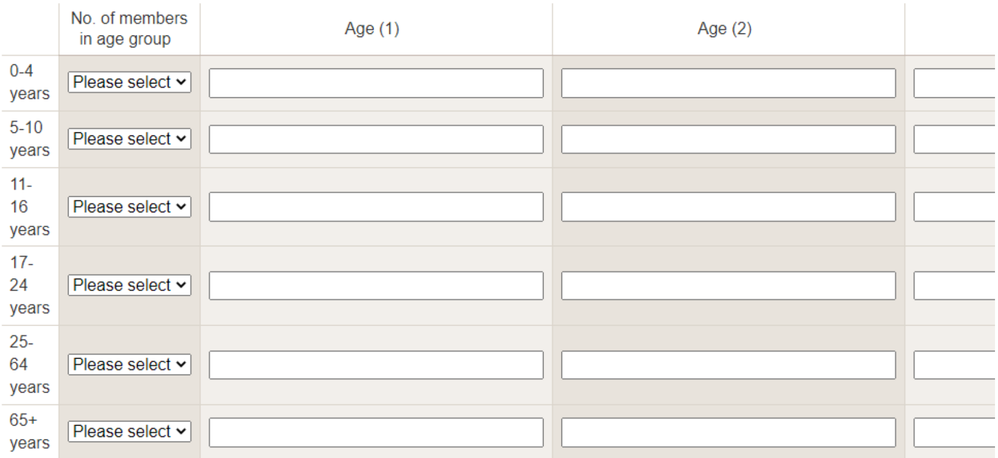
Chapter 5

Typical British Lifestyles

5.1. Data collection

The case studies in 'Chapter 4' indicated the importance of lifestyles in conceiving a net zero development. How households consume heating, hot water and use equipment play a crucial role in the overall energy consumption. Occupant behaviour is a major source of ambiguity in estimating building energy use. Studies have demonstrated that variation in energy use of over 300% (between predicted and actual use) may be caused due to occupant behaviour (Barthelmes, et al., 2017). Hence, understanding how different households consume energy plays a critical part in developing an energy efficient community. The prototype community designed for this thesis was situated in Sutton, UK. Hence, it was crucial to identify literature on occupant behaviour in the UK. According to Richardson, et al., extensive literature on active occupancy of members in a household is not easily accessible (Richardson, et al., 2008). BREDEM (Building Research Establishment Domestic Energy Model) provides some literature on the occupancy and heating pattern of a generic British household. Likewise, the English Housing Survey is a national survey conducted annually in the UK to study the country's housing stock. However, the survey focuses more on the building envelope and energy performance (from EPCs) to understand energy efficiency of housing in England (Department for Levelling Up, Housing and Communities, 2020-21). The International Energy Agency (Annex 66) states that surveys are an efficient way to collect substantial and useful information on occupant behaviour (Day, 2017). Similarly, Richardson et al., discuss Time Use Surveys adopted to gather statistical time series data on occupancy to study presence and activity of all occupants in a household. For this survey, time diaries were distributed to members aged 8 and above from various households to record their presence and activities in the house over 10-minute slots for a typical weekday and weekend day (Richardson, et al., 2008). However, the Time Use surveys only gathered information on occupancy and household energy consumption depends on other key factors related to occupant activity such as equipment use, domestic hot water consumption, heating requirement and lighting use in a household. Hence, it is critical to learn the different lifestyles of British homes to understand occupancy alongside other related activities that contribute to the energy consumption of a household. For this purpose, a pilot survey on typical British lifestyles was conducted to accumulate input data to assist with building design and energy model simulation. The survey was distributed online via 'JISC Online surveys' to residents of Britain who have lived in the country for at least five years or over (JISC, n.d.). Data from 81 participants was collected over a period of 12 months. The survey constituted five sections and was aimed at collecting the following key statistics:

- Household size
    - Number of members per house categorised by age

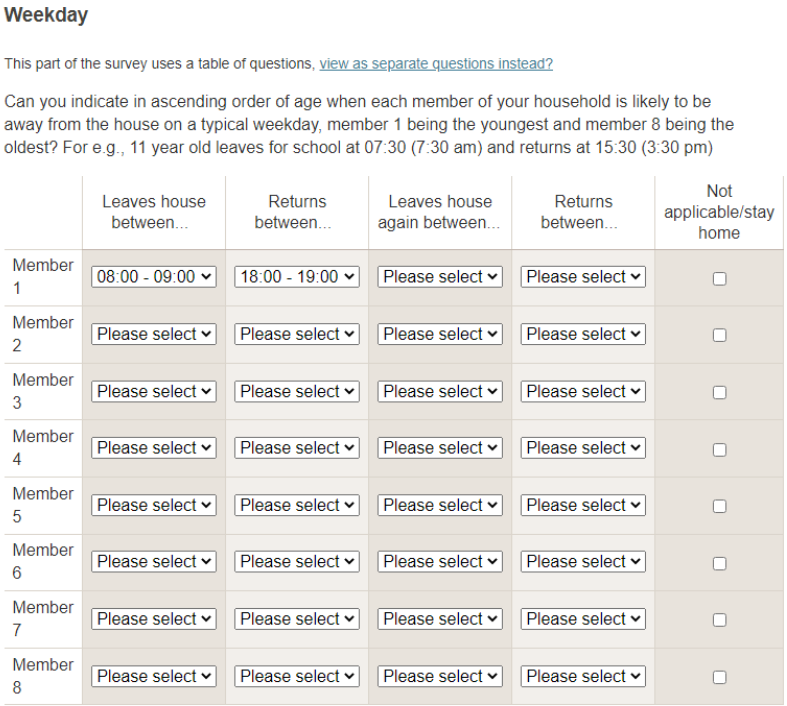


	No. of members in age group	Age (1)	Age (2)	
0-4 years	Please select			
5-10 years	Please select			
11-16 years	Please select			
17-24 years	Please select			
25-64 years	Please select			
65+ years	Please select			

Figure 30 - Survey question on household size based on household members

    - Number of bedrooms per house
- Household type
    - Apartment/bungalow/detached/semi-detached/mid terrace/end terrace
    - Occupation (e.g.: 2 full-time working adults)
- Occupancy

- When occupants leave and return in a day during weekdays and weekends



Weekday

This part of the survey uses a table of questions, view as separate questions instead?

Can you indicate in ascending order of age when each member of your household is likely to be away from the house on a typical weekday, member 1 being the youngest and member 8 being the oldest? For e.g., 11 year old leaves for school at 07:30 (7:30 am) and returns at 15:30 (3:30 pm)

	Leaves house between...	Returns between...	Leaves house again between...	Returns between...	Not applicable/stay home
Member 1	08:00 - 09:00	18:00 - 19:00	Please select	Please select	☐
Member 2	Please select	Please select	Please select	Please select	☐
Member 3	Please select	Please select	Please select	Please select	☐
Member 4	Please select	Please select	Please select	Please select	☐
Member 5	Please select	Please select	Please select	Please select	☐
Member 6	Please select	Please select	Please select	Please select	☐
Member 7	Please select	Please select	Please select	Please select	☐
Member 8	Please select	Please select	Please select	Please select	☐

Figure 31 - Survey question on household occupancy pattern

- Heating
  - When the heating turns on and off in a day during weekdays and weekends
  - Type of heating system used (e.g.: combination boiler)
- Hot water
  - When the shower, bath, washing machine and dishwasher are used in a day (times used, e.g., early morning/evening/night/etc.) and week (days used, e.g., weekdays/weekends/all days/etc.)
- Equipment
  - When the various household equipment is used in a day (times used, e.g., early morning/evening/night/etc.) and week (days used, e.g., weekdays/weekends/all days/etc.)

Can you indicate the typical overall uses/day **or** uses/week for the following, typical days these are used and when each of the following are used by all members of the household? For e.g., two members using the hair dryer everyday must be indicated as 2 under typical overall uses/day. If one member uses the dryer at 08:00 (8 am) and the other 18:00 (6 pm), select Early morning + Evening for when it is used.

	Uses/day	Uses/week	When is it used?	Days it is used (e.g., all days)	Not applicable
Hob/cooker	Please select	Please select	Please select		☐
Oven	Please select	Please select	Please select		☐
TV	Please select	Please select	Please select		☐
Stereo	Please select	Please select	Please select		☐
Hair dryer	Please select	Please select	Please select		☐
Hair straightener	Please select	Please select	Please select		☐
Clothes iron	Please select	Please select	Please select		☐
Tumble dryer	Please select	Please select	Please select		☐
Coffee maker	Please select	Please select	Please select		☐
Microwave	Please select	Please select	Please select		☐
Kettle	Please select	Please select	Please select		☐
Toaster	Please select	Please select	Please select		☐
Vacuum cleaner	Please select	Please select	Please select		☐
PC/Laptop	Please select	Please select	Please select		☐
Space heater	Please select	Please select	Please select		☐
Fan/Air conditioner	Please select	Please select	Please select		☐

Figure 32 - Survey question on various household equipment usage

The information collected from household type and size were used for designing houses. The data from occupancy, heating, hot water and equipment was used to develop DesignBuilder schedules to obtain energy demand.

5.2. Data analysis

The online survey had 81 participants of which seven survey samples had to be rejected due to anomalies and absence of data. Data from 74 participants was analysed to identify information for design and energy modelling. To check if the sample size of the study was sufficient for this stage of the analysis the following statistical calculation was carried out. Since, the study uses a descriptive survey to understand the lifestyles of the population, the sample size is estimated using proportion of population (see Equation y) (Du, et al., 2023).

$$N = \frac{(Z_{(1-\alpha/2)})^2 \, p(1-p)}{E^2}$$

Where, N is sample size, Z is the value from standard normal distribution reflecting the confidence level that will be used (usually 1.96 for 95% confidence interval), α is the probability of type-I error (typically 0.05), p is population proportion error and E is the margin of error. For the worst-case scenario, p is taken as 0.5 that is, 50% of the population is said to depict the characteristic in study. A margin of error (E) of 10% is considered.

$$\text{i.e.,} \quad N = \frac{(1.96)^2 \times 0.5\,(1-0.5)}{0.1 \times 0.1}$$

$$= \frac{3.842 \times 0.25}{0.01}$$

$$N = 96$$

A sample size of about 96 is required for this study. However, this is the sample size derived for the worst-case scenario. Du et al., in their study on thermal comfort also calculated the sample size for an optimal case which uses a p value of 0.8.

$$N = \frac{(1.96)^2 \times 0.8\,(1-0.8)}{0.1 \times 0.1}$$

$$= \frac{3.842 \times 0.16}{0.01}$$

$$N = 62$$

Hence, for an optimal case where 80% of the population show a certain characteristic, a sample size of 62 is sufficient. The survey sample of 74 (as used in the thesis) which has a population proportion of 80% constitutes a 9% margin of error (E). The following key analyses were made from the 74 surveys in terms of design and modelling data.

5.2.1. Design data

To deduce information for typical design, the survey includes a section on house type and size asking respondents to identify the type of house they reside in and rooms/spaces constituting their home. The findings on typical house type are indicated in Table 16. Of the 74 respondents, about 27% reside in either apartments or mid/end terrace homes. This is followed by semi-detached and detached homes (approx. 20%). Only 9% of the survey sample resided in bungalows.

Table 19 - Typical house types

House types	Houses	%
Apartments	20	27
Bungalow	7	9
Detached	13	18
Semi-Detached	15	20
Mid/end terrace	19	26
Total houses	74	100

To identify house sizes, a survey question providing a list of rooms allowed respondents to select the ones that are part of their homes (see Appendix 2 for details). The analysis indicated that 39% of the respondents have an open kitchen in their home. Table 17 details house sizes based on number of bedrooms. Where participants selected 'study' as part of their house, the number of bedrooms was converted to the nearest 0.5. For instance, if participants selected 2 bedrooms and a study as part of their household, the household is considered as a 2.5 bedrooms house. Analysis on house size showed that the majority of the survey sample resided in three- and four-bedroom houses (about 25% each). Less than 5-10% had studies as part of their homes indicating fewer 1.5-, 2.5- and 3.5-bedroom homes. 15-20% of the participants stayed in one-to-two-bedroom houses.

Table 20 - Typical house sizes based on number of bedrooms

Bedrooms	Houses	%
1 Bedroom	11	15
1.5 Bedroom	1	1
2 Bedroom	15	20
2.5 Bedroom	3	4
3 Bedroom	19	26
3.5 Bedroom	7	9
4 Bedroom	18	24

Additionally, the survey also gathered data on typical family/household sizes based on number of members present in each household categorised by age (see Fig. 32). Information on household size comprises two parts. First is data on number of members which helps identify household composition such as 2 people 3-bedroom household (i.e., 2P3B household). Second is household members' age groups which are used to understand activity related to occupancy, heating, hot water and equipment usage. For instance, members of the household that fall in the 0-4 years age category will have minimised equipment usage which is likely to reduce the overall energy demand of the household. Likewise, households with members in the 65 years and over age group are expected to have a higher heating and lighting energy requirement (Age UK, 2013). Table 18 informs survey data assimilated on household sizes based on number of members.

The average household size from the survey sample was calculated to be about 2.5. This is close to the 2011 National Statistics Labour Force Survey (LFS) value of 2.3 (United Nations Department of Economic and Social Affairs, 2019). 2011 LFS also indicated that 2-3 member households constituted about 50% of the overall national household distribution. The survey on typical British lifestyles showed that the sample had 60% of 2-3 member households. Likewise, 1 member households also held a significant position in the national statistics, almost twice as much as the survey population indicated (see Table 18). 4-5 member households from the survey were about 6% more than LFS 2011 findings.

Table 21 - Typical household sizes based on number of members in the household

No. of members	Houses	%	LFS 2011 (%)
1 member (1P)	13	18	33
2 members (2P)	27	36	50
3 members (3P)	18	24	
4 members (4P)	14	19	16
5 members (5P)	2	3	
6 members +	-	-	2

<u>Household composition</u>

A critical system that helped with analysis and data extraction was developing codes for household composition based on members' occupation and age groups. Note that only the occupation of the respondent was recorded. The survey categorised occupations into the following:

- Full-time
- Part-time
- Working from home/Stay home
- Retired
- Student
- Other

Based on the age group, occupation and occupancy pattern, household compositions and their corresponding codes were deduced. Table 19 shows member's occupation based on age and the corresponding code for each of these occupations. This technique helped identify similarities and differences between households with the same and varying household compositions in terms of modelling data which is explained in 'Section 5.2.2'.

Table 22 - System developed to identify household composition using member occupation and corresponding code

Member's occupation based on age	Code	Code colour
Full-time working adult	FT	
Part-time working adult	PT	
Work from home/ Stay home adult	SH	
Retired	R	
Child	C	

Infant	I	
Student	S	

Using the system developed from Table 20, a combination of household composition can be constructed. To simplify and control the variations in the number of household combinations possible, 1.5, 2.5, 3.5 bedrooms are considered as 2-, 3- and 4-bedroom households. A total of 62 household compositions were identified from the surveys using this system (see Table 20). The Office of National Statistics identified 33 such household compositions. However, these were based on family composition, number of children present and occupation of adults and independent children present in the household (Aragon, et al., 2017).

Table 23 - Household composition code system developed based on household size

House size	Household size				
	1 member (1P)	2 members (2P)	3 members (3P)	4 members (4P)	5 members (5P)
1 bedroom (1B)	1R 1FT 1S 1SH	2FT 2S 1S1FT 1S1SH 2SH			
2 bedrooms (2B)	1R 1S	1PT1SH 2FT 1S1SH 2SH 1FT1PT	1FT1SH1C	2FT2C 1PT1SH2C	2FT3C

3 bedrooms (3B)	1FT 1SH 1S	2R 1FT1SH 1S1PT 1FT1PT 1S1SH 1FT1S	1FT1S1C 1FT2C 1S2SH 1PT1SH1C 1PT1SH1S 3SH	2FT2C 1FT1SH2C 2C 3FT1S 2SH2S	
4 bedrooms (4B)	1S 1FT	2R 2FT 1FT1SH 1R1FT 2SH	2FT1C 2FT1S 3S 1S2R 1PT1S1SH	1FT1SH2S 1FT1SH1S1C 2FT1S1C 2FT2C 4S 1S1SH1PT1R	2FT1PT2R

For instance, take 1R under 1 bedroom house (highlighted in Table 20). The code for a single retired adult staying in a one-bedroom household is '1R_1P1B', where, 1R is single retired adult, 1P is one member household and 1B is one bedroom household. Likewise, a household with two full-time working adults and two children residing in a 3-bedroom household will have the code '2FT2C_4P3B' (highlighted in Table 20). In this manner, the coding system helped established similarities in household compositions. For example, from the table above note that one-, three- and four-bedroom households have a household size of one full-time working adult (1FT). Similarly, '2FT2C' is seen in two-, three- and four-bedroom households.

5.2.2. Modelling data

A critical component of the survey includes understanding the activities of various households in terms of the four crucial parameters affecting energy consumption- occupancy, heating, hot water and equipment. The data obtained from these sections of the survey was used to help develop DesignBuilder schedule codes for each of the parameters based on the household. The study showed how the same household composition can have varying occupancy, heating, hot water and equipment usage. Likewise, two households with different household composition could have similarities in any or all the four important parameters in some cases.

Occupancy

Understanding the occupancy pattern of households is critical to lifestyle analysis. This section of the survey helps to reveal when the house is fully/partially occupied or unoccupied. In the case where a house is unoccupied, it is likely that there will be no heating, lighting or hot water requirement for the period of time the home is empty. Where the house is occupied almost all the time, for example, for a retired couple, there is a possibility of increased usage of heating, hot water, lighting and equipment. Occupancy may also be defined in terms of active and inactive occupancy in a home (Widen, et al., 2009). Inactive periods include sleeping or occupants not using a particular room during some hours of the day. Distinguishing these helps understand and control energy parameters bar heating which may need to be turned on regardless of occupant activity unlike equipment (Aragon, et al., 2017).

Occupancy data was recorded for typical weekdays, weekends and weekdays that were dissimilar to the typical weekday (see Appendix 3 for details). Table 21 shows a sample of weekday occupancy for surveys 19, 22 and 40. 19 has a household composition of '1FT_1P3B' and 22 and 40 both have a household composition of '2FT1S1C_4P4B'. That is, households constituting one full-time working adult in a three-bedroom house (survey 19) and two full-time working adults, one student and one child living in a four-bedroom house (surveys 22 and 40). Highlighted below is a portion of the survey data showing the weekday occupancy pattern of the two households. It can be seen that survey 22 house is unoccupied for 7 hours (between 8 am and 3 pm) when compared to survey 40 house which is empty for 10 hours (between 7 am and 5 pm). The house of survey 19 is also unoccupied for 10 hours (between 8 am and 6 pm).

Table 24 - Comparative analysis of occupancy between two similar and one varying household composition

	22	40	19
2. Are you...	Working full time	Working full time	Working full time
No. of members - 0 - 4 years			
No. of member - 5 - 10 years			
No. of members - 11 - 16 years	1	1	
No. of members - 17 - 24 years	1	1	
No. of members - 25 - 64 years	2	2	1
No. of members - 65+ years			
5.1.a. Member 1 - Leaves house between...	07:00 - 08:00	06:00 - 07:00	07:00 - 08:00
5.1.b. Member 1 - Returns between...	18:00 - 19:00	17:00 - 18:00	18:00 - 19:00
5.2.a. Member 2 - Leaves house between...	07:00 - 08:00	06:00 - 07:00	
5.2.b. Member 2 - Returns between...	15:00 - 16:00	17:00 - 18:00	
5.3.a. Member 3 - Leaves house between...	07:00 - 08:00	06:00 - 07:00	
5.3.b. Member 3 - Returns between...	16:00 - 17:00	17:00 - 18:00	
5.4.a. Member 4 - Leaves house between...	09:00 - 10:00	06:00 - 07:00	
5.4.b. Member 4 - Returns between...	19:00 - 20:00	17:00 - 18:00	

Note: Refer to Table 19 for colour code

BREDEM model 12 specifies a typical occupancy schedule for British homes. The typical weekday occupancy is between 4 pm and 9 am, where 7 hours of the day the home is unoccupied (between 9 am and 4 pm). For weekend occupancy, the house is considered to be occupied throughout the day (Aragon, et al., 2017). Additionally, some literature on domestic occupancy patterns in the UK, study household composition and related occupancy schedule during active and inactive periods for both weekdays and weekend. Table 22 compares literature on occupancy schedules to surveys 18, 47, 3 and 70 which have matching household compositions. It shows that, household composition 2 – a full time working couple home has more or less a similar occupancy schedule compared to data from literature for unoccupied hours (about 9.5 hours). Likewise, a retired couple household, as expected, is present at home almost all day on a typical weekday in all cases. A discrepancy can be noted in household composition 1 (family of four) where the survey data indicated that the house is unoccupied for 9 hours as opposed to 7-7.5 hours specified in the literature.

Table 25 - Comparative analysis of occupancy between literature and data collected from author's survey

Household composition	Occupancy pattern			
	Author's survey	Marshall et al	Beizee et al	Cheng et al
1	18 - Two full-time working adults & two children (2FT2C)	Working family	Family: two working adults and two school-aged children	-
Weekday	Hours unoccupied: 9 (09:00 - 18:00)	Hours unoccupied: 7.5 (08:30 - 16:00)	Hours unoccupied: 7 hours (09:00 - 16:00)	

Weekend	Occupied all hours	N/A	Hours unoccupied: 5.5 (10:30 - 16:00)	
2	47 - Couple working full-time (2FT)	Working couple		One or more occupants work full time
Weekday	Hours unoccupied: 10 (07:00 - 17:00)	Hours unoccupied: 9.5 (08:30 - 18:00)	-	Hours unoccupied: 9 (09:00 - 18:00)
Weekend	Hours unoccupied: 1-4 hours (varying times based on occupants)	N/A		Occupied all hours
3	3 - Retired couple (2R)	Daytime-present couple		No occupant working, one or more retired
Weekday	Occupied all hours	Occupied all hours	-	Occupied all hours
Weekend	Hours unoccupied: 2 (10:00 - 12:00)	N/A		Occupied all hours
4	70 - One part-time & one full time working adult (1PT1FT)	-	-	One or more occupants work part time
Weekday	Hours unoccupied: 4 (13:00 - 17:00)			Hours unoccupied: 5 (09:00 - 15:00)

Weekend	Hours unoccupied: 2-5 hours (varying times based on weekend day)		Occupied all hours

<u>Heating</u>

For temperate climate, the heating demand plays a key role in energy consumption, but occupancy patterns also play a critical role in heating energy consumption. Survey data indicated an average heating period of 11 hours per day for weekdays (grey dotted line in Fig. 34) which is two hours more than the BREDEM model (red dotted line in Fig. 34) which has a typical heating period of 9 hours for weekdays (Anderson, et al., 2002). Figure 34 shows the heating hours for weekdays for all households.

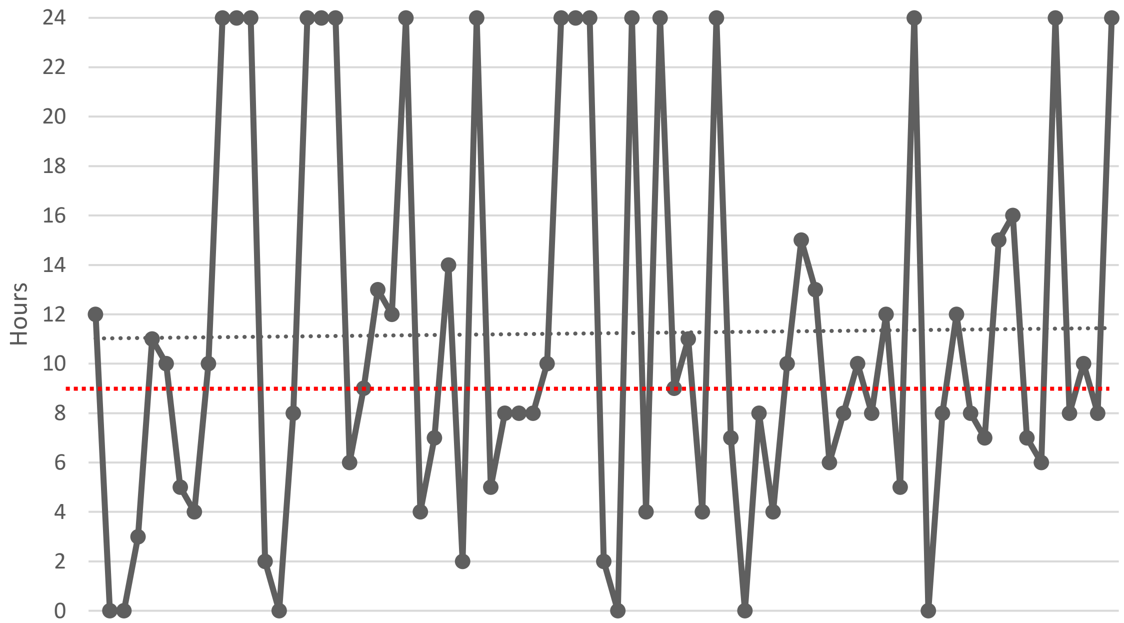


Figure 33 - Weekday heating hours of survey households

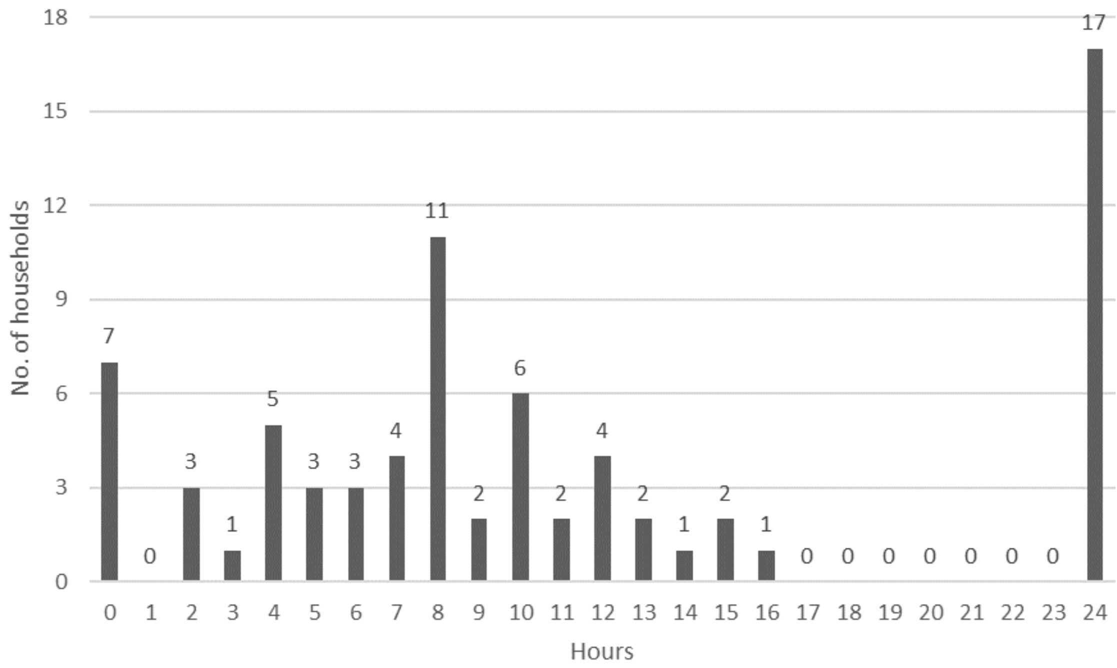


Figure 34 – Frequency distribution of no. of households to heating hours per day

The analysis indicated that 50% of the households either met or exceeded the BREDEM typical period of 9 hours. 23% homes had the heating on all day (24 hours). While 9% of the houses had no heating at all through the day. Some respondents commented that they either used small portable heaters or hot water bottles to keep warm instead of turning on the heating system for the entire home, presumably to save on fuel bills. Some households that used less than the BREDEM model heating hours was related to the house being unoccupied for longer hours during the day and occupants scheduled their heating to be turned on only when the home was occupied.

<u>Hot water</u>

The survey addresses hot water consumption for four main uses – shower, bath, washing machine and dishwasher. While this too is dependent on occupancy pattern and activity, the survey gathered data on when domestic hot water was used for each need in a day and week. Table 23 shows the number and percentage of respondents' houses that use washing machines, dishwashers and a bath. Less than 40% of the survey population use dishwashers in their homes. Likewise, about 45% of the respondents used baths in a week. The study indicated that all houses use washing machines. The survey also collected information on when the shower is used. This helped in form lighting schedules for the houses (discussed in detail in 'section 6.2').

Table 26 - Number of houses using washing machine, dishwasher and bath in a week

	No. of houses	%
Washing machine	74	100
Dishwasher	27	36.5
Bath	33	45

<u>Equipment</u>

Data on household equipment usage was collected by asking respondents to identify, from a list, all equipment in their households and how often they use it in a day and/or week. Figure 36 shows a graph of equipment types and corresponding percentage of households using them. The analysis indicated that some equipment was more commonly used/owned such as cooking equipment (hob and oven), TV, kettle, microwave, vacuum cleaner and laptop. Some other devices like stereo, hair straightener, coffee maker, space heater and fans were less commonly used. Equipment like a hair dryer, tumble dryer and clothes iron were in the middle range, that is, about 40-50% homes used these on a weekly basis. The survey indicated all homes used the hob, typically once or twice a day, some homes perhaps more (2-3 times a day). Likewise, toasters were used by about 75% of the respondents at least once a day.

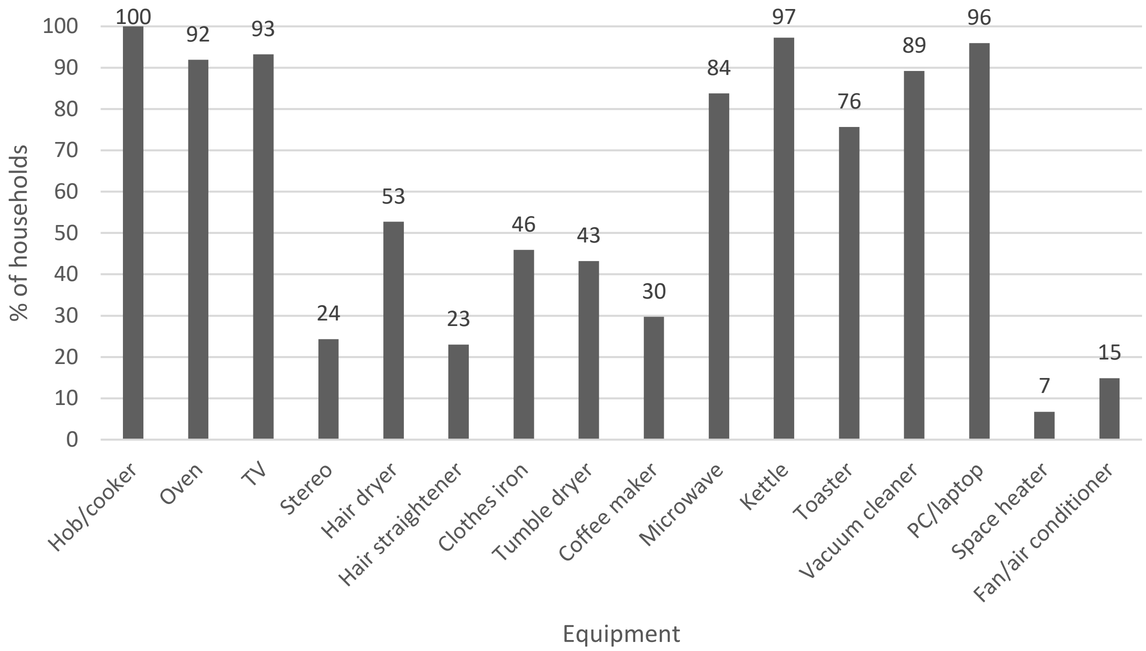


Figure 35 - Percentage of homes using different household equipment in a day

5.3. Inferences

The survey is a crucial step in this thesis as it helps understand real household compositions and lifestyles prevalent in the UK now. There is often a performance gap when executing energy efficient developments and as literature indicates, user lifestyles are neglected and not considered to be critical influencers of energy. This thesis aims to bridge this gap and develop a prototype community using the lifestyles generated from the surveys. The thesis aspires to be realistic as if the respondents of the survey were residing in this prototype community. The data collection process included some challenges. What was intended to be interviews had to be distributed as an online survey. The aim was to collect data from over 150 interviewees at various public locations. However, this was curbed due to the outbreak of the pandemic. Nevertheless, this study helped inform the planned prototype community and its development:

- The prototype community would contain 26 four bedroom, 22 three bedroom, 15 two bedroom and 11 one-bedroom houses.
- The house type would be mid/end terrace houses or apartments based on site (discussed in 'section 6.1.1')
- Occupancy densities would be derived based on household size of each survey for one to five member households
- Each of the 74 households would be simulated separately by using the appropriate schedules generated from survey data analysis.
- Data from each survey would be used to define occupancy, heating, equipment and lighting schedules for energy model simulations.
- Lighting schedules would be developed based on active occupancy schedule.

- Hot water usage data would be disregarded as the parameter is refractory. For instance, how often a member of a household washes their hands is intractable. Hence, a default hot water schedule regulated by occupancy pattern was used.

The survey was designed in a way to enable data collection in a manner from which it was easy to develop schedules for energy model simulations (see Appendix 3 for survey questions). The development of schedules from the surveys is discussed in detail in ‘section 6.2’.

Summary

Presented in this chapter was the survey designed to gather information on typical British lifestyles. The chapter discusses key parameters such as house type and size, household size, occupancy, heating and equipment usage that will be used to design and test the prototype net zero community. Inferences from survey data analysis used to develop the design and schedules for building energy modelling and simulation have been deliberated in Chapters 6 and 7.

Chapter 6

Designing a prototype net zero community

6.1. Design

6.1.1. Site selection and analysis

The case studies' analysis indicated that three of the four developments (bar BedZED) are situated in the 'general urban zone' as defined by Duany's 'rural to urban transect' (Duany, 2002). Hence, it is plausible to situate the prototype community in the general urban zone. The community that has been designed for this thesis is based in the UK. Therefore, it was important to identify an appropriate site here. Since the prototype community is theoretical, in lieu of identifying a new site and repeating the site analysis, it seemed reasonable to assume that the community could be situated on the existing BedZED community site which is in the UK and the site analysis for this was covered in detail as part of 'section 2.3.2'. That is, assume that the BedZED community site is vacant and the prototype community is built on this hypothetically vacant site. Note that the project merely uses the BedZED community site and it was not intended to compete with the BedZED project.

Location:

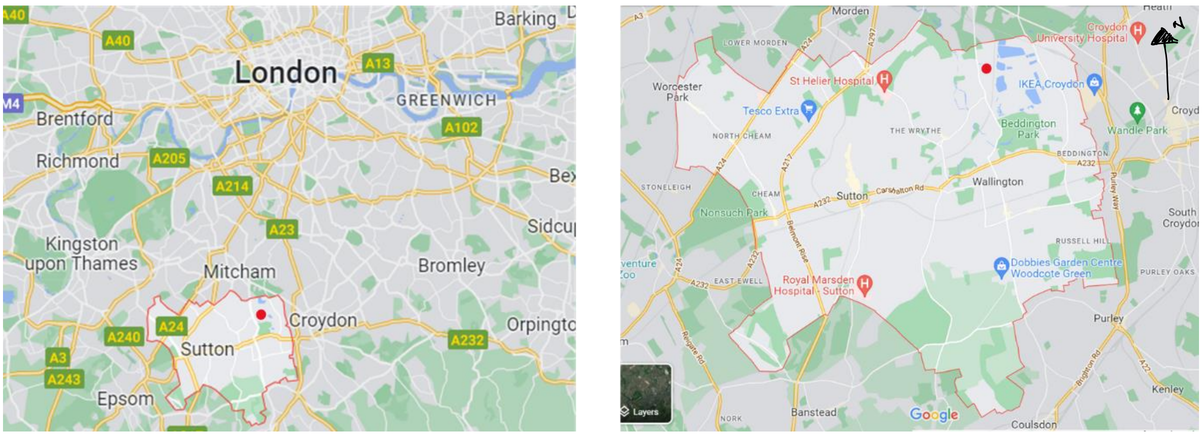
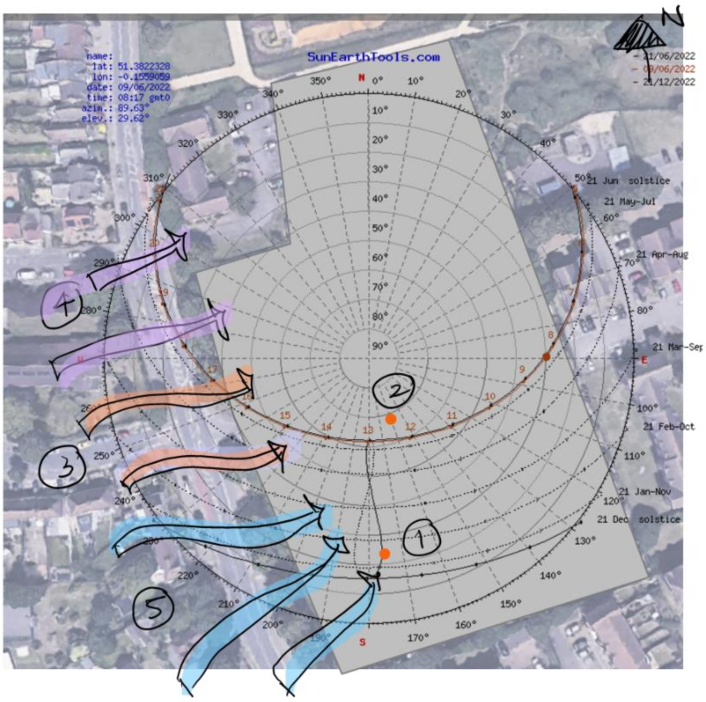


Figure 36 - Proximity of selected site to Central London (left), site location in London borough of Sutton (right)

The selected site for the prototype community is situated in Hackbridge, London Borough of Sutton, UK (red dot). Details of the site such as proximity to public transport and key amenities have been discussed in ‘section 2.3.2’. Figure 37 shows the location of the site with respect to Central London and to Sutton town.

Climate:

The climate data for the site can be deduced from ‘section 2.3.2’ which discusses the climate of Sutton. Figure 38 shows the seasonal wind direction and sun path for the site. As discussed, it is essential for the design to address the low winter sun angle to maximise solar gain in the colder months and to consider seasonal wind to avoid the strong winter winds from the south west and take advantage of the summer winds from west south west. Addionally, design must aim to maximise natural light in the houses. Note that the site is oriented 19° west of north (see Fig. 38).



1 – Winter solstice sun angle – 15.1°

2 - Summer solstice sun angle – 62.1°

3 – Summer wind direction – WSW

4 – Spring and autumn wind direction – WSW

5 – Winter wind direction - SW

Figure 37 - Site map showing sun path and wind direction

Renewable energy sources:

The UK Government records five key sources of renewable energy for the country – wind, solar, biomass, hydro and geothermal. As of 2020, biomass accounted for the majority (about 61%) of the overall renewable energy production. This was followed by wind energy production at 27%. Solar energy and geothermal energy constituted about 5% together and hydroelectricity, 2% (Department for Business, Energy and Industrial Strategy, 2021). Marszal et al, emphasize renewable energy supply options as a key parameter to evaluate net zero. They suggest renewable energy production either on-site through solar and micro-wind or off-site via biomass (Marszal, et al., 2011). The aim of the prototype community was to address renewable energy supply on-site, first. As the community is situated in a developed suburb, having large wind turbines within the site or in close proximity to it would not be feasible or safe. Micro wind turbines could be considered. However, varying or low wind speeds given the location and the power of a small turbine (say 1m) could produce as little as 30W wind power after losses (Rowlatt, 2009). Additionally, wind turbines in general are prone to be noisy and, in some cases, even dangerous. Hence, the community was designed to rely primarily on on-site solar energy to meet its energy requirements. Additionally, houses were equipped with ground source heat pumps. In the scenario where on-site renewables do not meet the energy requirement, off-site renewable energy options could be considered (discussed in detail in 'section 6.4').

6.1.2. House design

Based on literature, case studies' designs (see 'section 2.3.2') and household sizes derived from survey data analysis (see 'section 5.2'), four house prototypes have been designed. Data collected from the surveys indicated that the prototype community should constitute either apartments or terrace houses. To prevent overshadowing of adjacent buildings optimum distance must be maintained between them. A spacing of 1.5 -2.5 times the height of the building is recommended. For instance, consider a four-storey apartment with each floor being 3m high. The spacing between the two apartments should be at least 24m (3m x 4 floors x 2) to avoid overshadowing. Hence, to be able to accommodate 74 one – four-bedroom houses as apartments in addition to key services and amenities within the site would be challenging. For this reason, the community constitutes one to two storey mid/end terraced houses. The minimum spacing between the houses should be 12m to prevent overshadowing. Four terrace house prototypes have been devised based on survey data, national technical housing standards and climate design (Ministry of Housing, Communities & Local Government, 2015). These were multiplied appropriately to accommodate the survey population and in turn the prototype community's housing composition.

Four-bedroom house:

26 four-bedroom houses were included in the model community. This prototype house has a total floor area of 126.8 m^2. The house is designed on two levels. Figure 40 shows floor plans of both levels and the spaces included on each floor. The houses have all open kitchen design and a study niche incorporated under the staircase. A 2m x 1m service cut-out is connected to the utility, toilet, kitchen and bath which also provides ventilation. Table 24 compiles a

checklist of spaces that address sustainable design principles appropriate for the temperate climate.

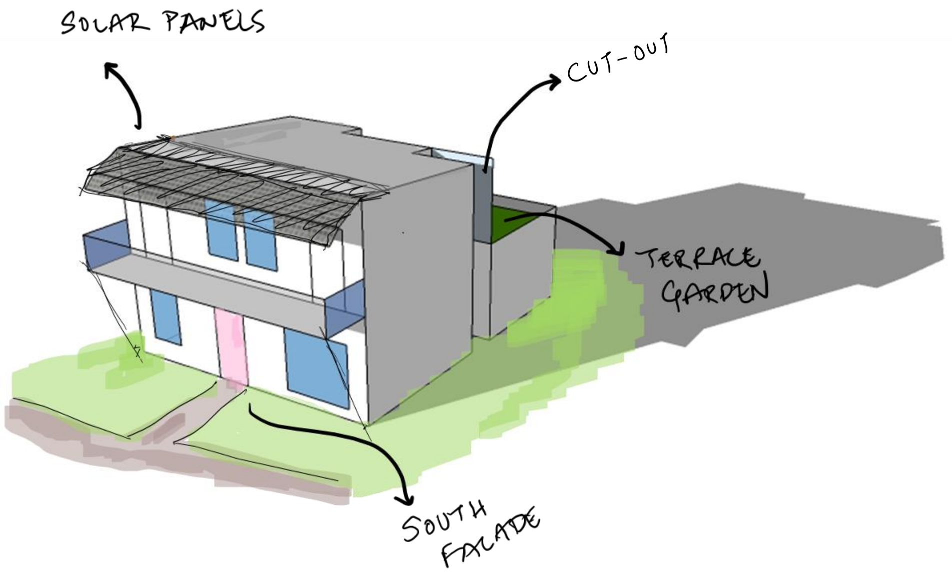


Figure 38 - South east view of four-bedroom house

Figure 39 - Four-bedroom house floor plans - ground floor plan (left), first floor plan (right)

Table 27 - Checklist of spaces addressing key sustainable design principles

Space	Floor	Optimise solar gain	Optimise natural light	Exposure to south west wind
Living	Ground	✓	✓	✓
Dining		✗	✓	✗

Kitchen		✗	✓	✗
Study		✗	✓	✗
Bedroom 1		✗	✓	✗
Bedroom 2		✓	✓	✓
Bedroom 3	First	✓	✓	✓
Master bedroom		✓	✓	✓

Designed to maximise solar gain and natural light, ancillary spaces such as the staircase, toilet, bath and store are oriented to the east and west and primary spaces like the living and bedrooms (three of four) are south facing to benefit from the sun in the colder months. The upper-level bedrooms have access to a south facing balcony. The dining-kitchen is located to the north as the kitchen is more susceptible to heat gain from cooking. Additionally, houses are designed to include a terrace garden facing north to use during warmer months with access to upper-level walkways connecting adjacent houses. Figure 41 shows a section through the house demonstrating stack ventilation.

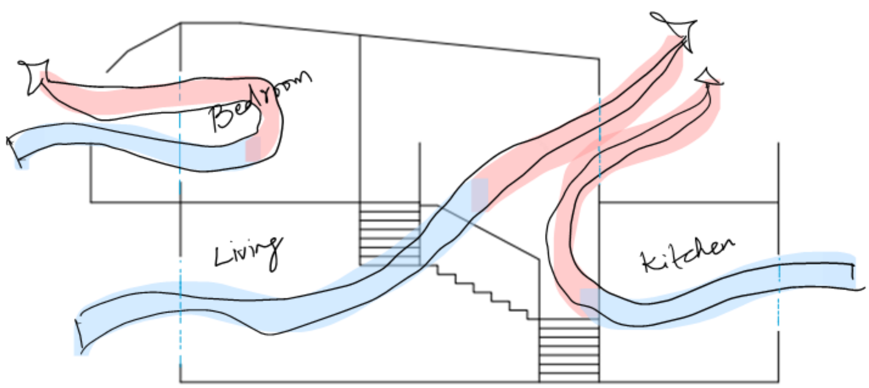


Figure 40 – Section through four bedroom house showing stack ventilation

Each house includes solar panels that act as a shading device for the balcony facing south. As seen in Fig. 42, the solar panels have varying angles to optimise incident solar radiation for different seasons.

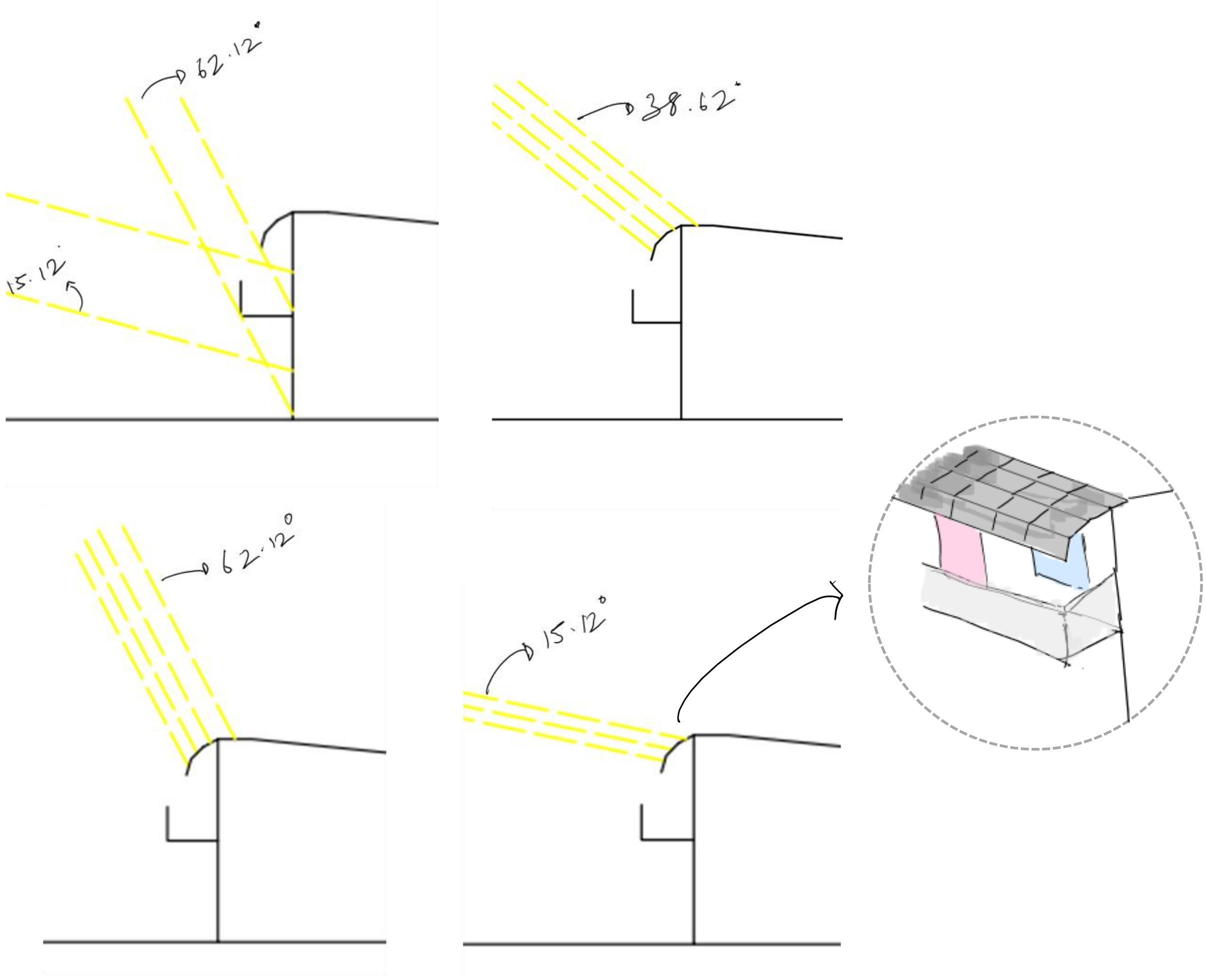


Figure 41 – Solar panels and shading detail – shading device cutting out summer sun and permitting winter sun (top left), solar panel oriented to exploit spring/autumn sun (top right), solar panels capitilaising summer sun (bottom left), solar panel oriented to exploit winter sun (bottom right), perspective sketch of solar panels (blow up)

Three-bedroom house:

The three-bedroom house has a similar design to the four-bedroom house. The model community consists of 22 units of this house prototype. This house has the same spatial planning as the four-bedroom house except that the ground floor has only one bedroom (facing north) as opposed to two of the four-bedroom units (see Fig. 44). With a floor area of 117.8 m^2, the south facing bedroom (9 m^2) from the four-bedroom house design is converted to an outdoor space that is dedicated to either bin or cycle storage. Table 25 summarises the sustainable design principles incorporated in the three-bedroom prototype.

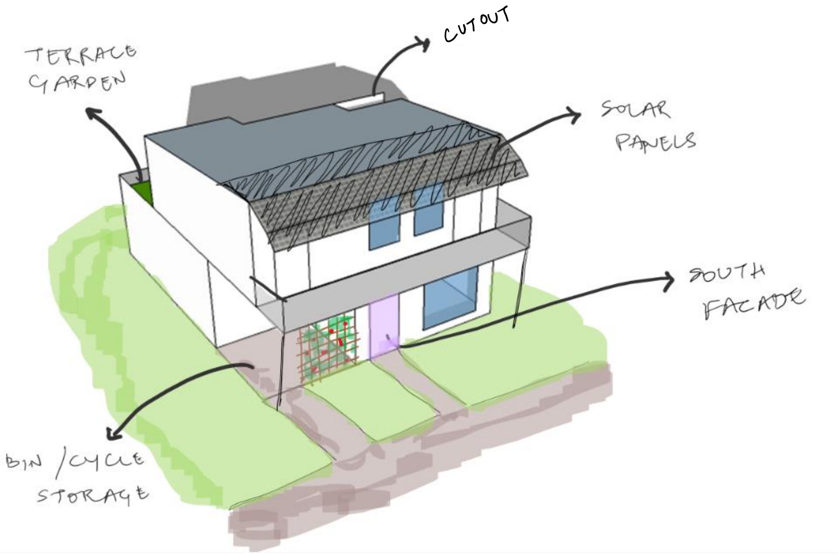


Figure 42 - South west view of three-bedroom house

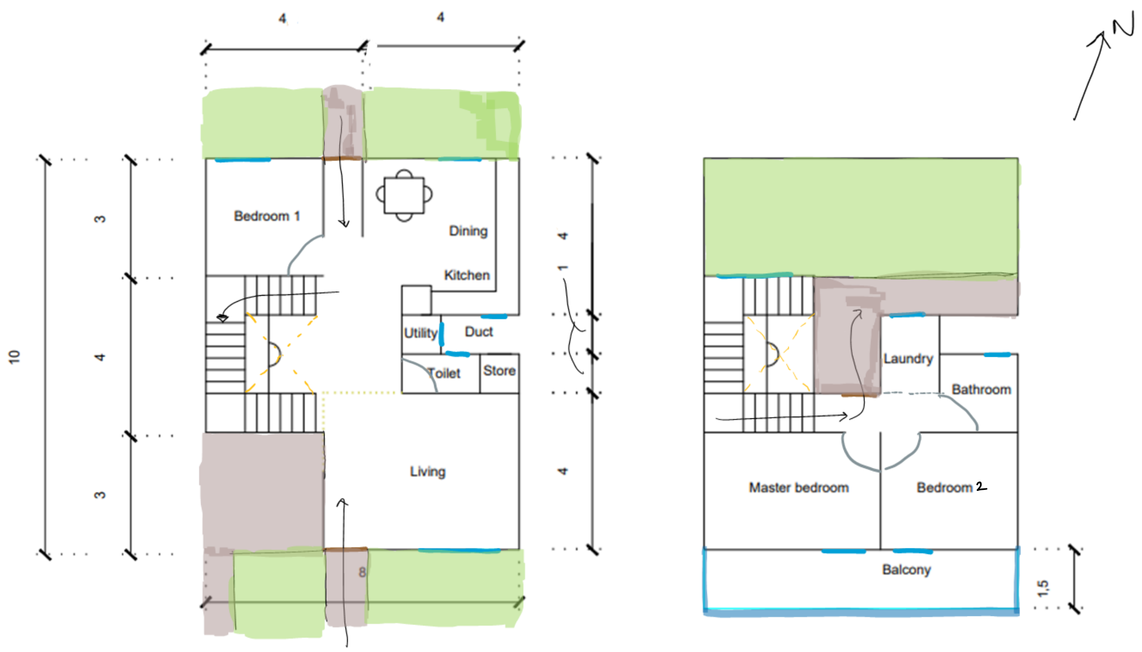


Figure 43 - Three-bedroom house floor plans - ground floor plan (left), first floor plan (right)

Table 28 - Checklist of spaces addressing key sustainable design principles

Space	Floor	Optimise solar gain	Optimise natural light	Exposure to south west wind
Living	Ground	✓	✓	✓

Dining		✗	✓	✗
Kitchen		✗	✓	✗
Study		✗	✓	✗
Bedroom 1		✗	✓	✗
Bedroom 2	First	✓	✓	✓
Master bedroom		✓	✓	✓

One & two-bedroom houses:

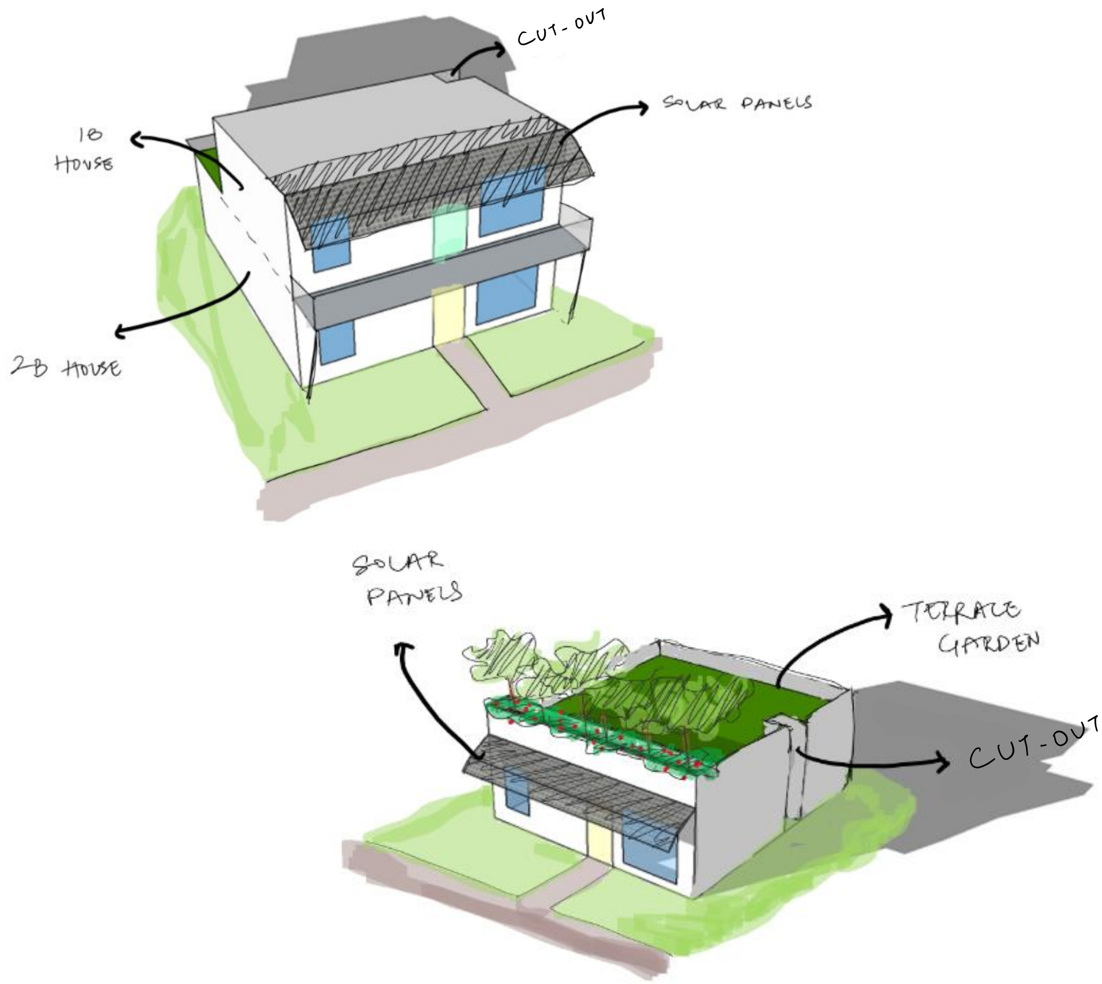


Figure 44 - South west view of one + two-bedroom house (top), south east view two-bedroom house (bottom)

The prototype community comprises 15 two bedroom and 11 one-bedroom units. Both one and two-bedroom homes are single storey. 11 of the 15 two-bedroom homes are combined with one-bedroom units to create two storey structures. The remaining four two-bedroom units are included as single storey units. The design incorporates 71 m^2 two-bedroom flats on the ground floor and 47 m^2 one-bedroom units on the upper floor.

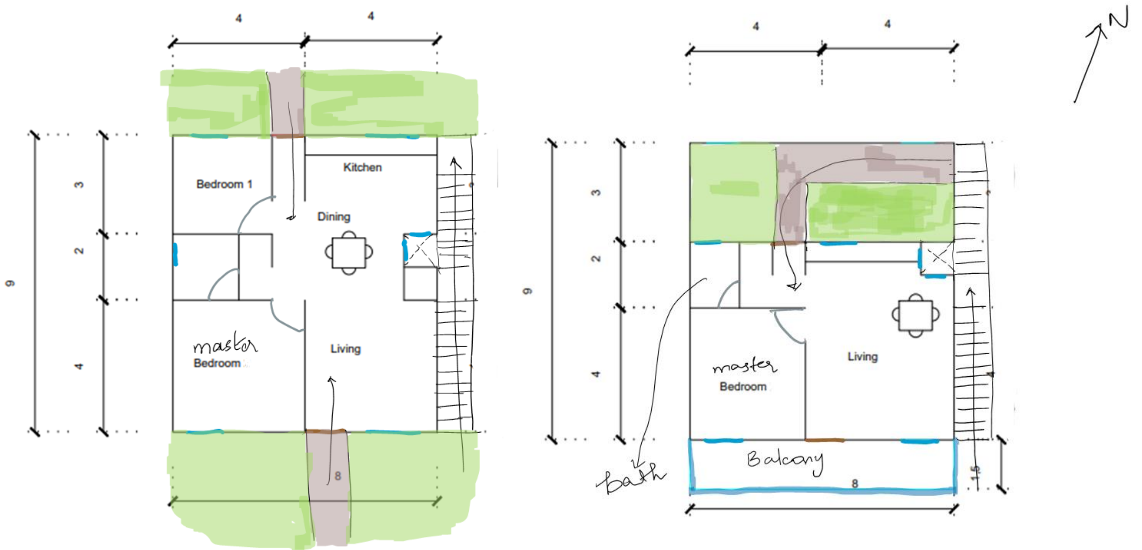


Figure 45 - Ground floor plan - two-bedroom flat (left), first floor plan - one bedroom flat (right)

The one- and two-bedroom units are similar to the four-bedroom model, with ancillary spaces oriented to the east and west. However, these units include smaller ducts (1 m^2) and baths sharing service ducts with adjacent three or four-bedroom homes to the west. The duct aims to ventilate and bring as much natural light into the living-dining space. The one-bedroom units on the upper floors have access to terrace gardens on the north. These houses are accessed by a set of stairs and through the terrace garden which, as discussed, connect adjacent houses. Indicated in Table 26 are the different spaces in one and two-bedroom houses and the sustainable design principles used for spatial planning. Since the houses are single storey each, natural ventilation typically occurs through cross and single-sided ventilation (see Fig. 47).

Table 29 - Checklist of spaces addressing key sustainable design principles

Space	House size	Optimise solar gain	Optimise natural light	Exposure to south west wind
Living		✓	✓	✓

Dining	Two bedroom	✗	✓	✗
Kitchen		✗	✓	✗
Bedroom 1		✗	✓	✗
Master bedroom		✓	✓	✓
Living + dining	One bedroom	✓	✓	✓
Kitchen		✗	✓	✗
Master bedroom		✓	✓	✓

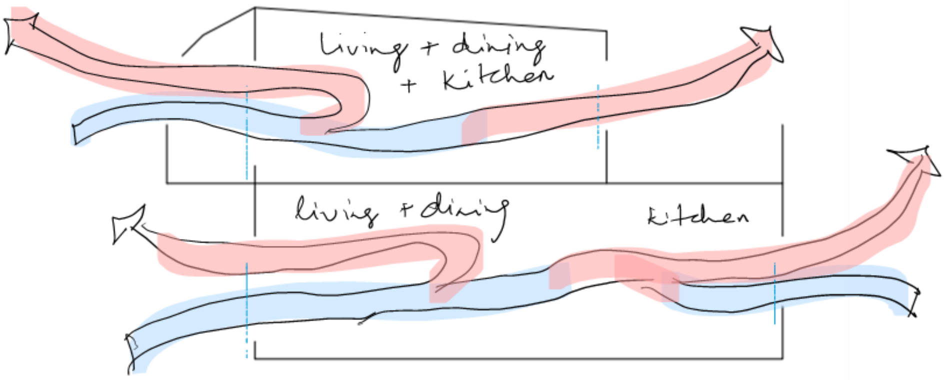


Figure 46 - Section through one + two-bedroom home showing cross ventilation

6.1.3. Construction

As critical as sustainable design principles and lifestyles are, incorporating efficient fabric design makes a significant difference to the energy consumption of a building. This can be achieved by using appropriate thermal mass and insulation in construction. Sourcing and procuring local and recycled/recyclable materials help reduce energy and emissions in terms of manufacture and transport. Table 27 shows the list of selected materials and their technical information.

Table 30 - List of materials and their technical data

Material		Approx. embodied carbon ($kgCO_2/kg$)	Thickness used (mm)	Thermal conductivity (W/mK)
Concrete block (medium density)	*Wall thermal mass*	0.073	100	0.51
Cast concrete	*Roof thermal mass*	0.112	150	1.3
Rockwool	*Insulation*	1.05	300	0.038
Cement plaster	*Flat roof/wall finish*	0.12	10	0.79
Slate tiles	*Pitched roof finish*	0.005	4	1.49
Reifa board	*Green roof*		18	

Of all construction types, blockwork cavity wall proved to be the most efficient. The model houses use insulated cavity construction. Typically, concrete blocks with high density are preferred for construction as these are structurally stronger and more stable. However, the embodied carbon of a high-density concrete block is almost double the medium density concrete block. Hence, the construction uses medium density concrete blocks, which provide optimum structural stability while having a lower impact on carbon emissions. Initially, the insulation material shortlisted was cork as cork has very low embodied carbon (0.19 $kgCO_2/kg$) and thermal conductivity (0.038-0.04 W/mK). However, research on the material indicated that it was not harvested locally and has to be transported from Spain and Portugal which could have a significant impact on emissions from transportation. Hence, locally available rockwool which has relatively low embodied carbon when compared to other materials such as fibre glass (1.35 $kgCO_2/kg$), mineral wool (1.28 $kgCO_2/kg$) and expanded polystyrene (3.29 $kgCO_2/kg$) was selected. Also, the thermal conductivity of rock wool is the same as cork thereby having no effect to the overall U-value calculation of the construction. Passivhaus recommends a U-value of 0.1-0.15 W/m^2K for wall, roof and floor construction for Continental climate which is similar to temperate (Passipedia, n.d.). Based on the materials selected, the following U-values have been calculated:

- Wall – 0.103 W/m^2K
- Pitched roof – 0.105 W/m^2K
- Flat roof – 0.106 W/m^2K

It can be noted that the U-values are in line with the Passivhaus standard. Figure 48 indicates the closest manufacturing plants for concrete/cement products (London), rockwool insulation and slate tiles (Wales) to the site (marked red). These materials are available within approximately 250 km radius. In addition to these local materials, the design also incorporates a green roof system. However, this is not the conventional extensive green roof that is likely to increase the weight of the roof structure. The Reifa board is an innovative green roof technology. Boards are simply assembled on a typical roofing system that are topped with a layer of waterproofing membrane (Dammzons Ltd., n.d.). This has a significantly low impact on emissions from construction when compared to a conventional green roof. This system reduces the overall labour and cost of construction as the structure does not have to be over designed to bear the weight of a heave green roof.

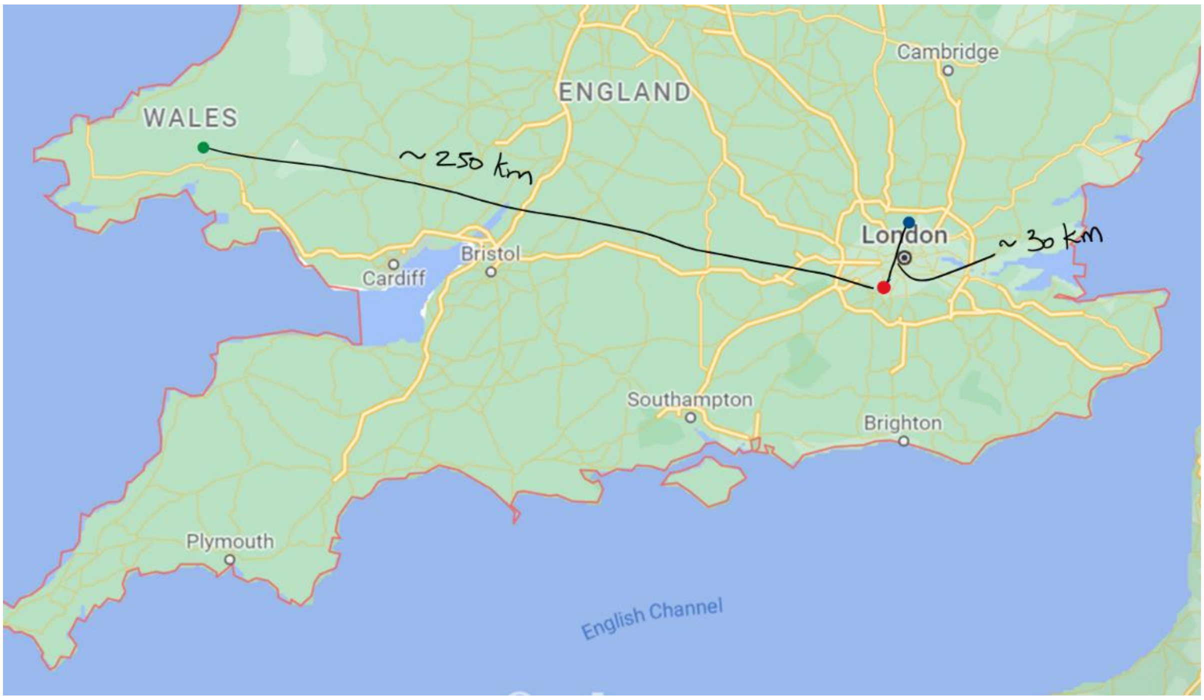


Figure 47 – Map showing proximity to construction materials

Building Research Establishment (BRE) provides a Green Guide to Specification that specifies the environmental impact of various building materials and construction elements for different building typologies (Anderson, et al., 2009). The guide rates materials from A+ to E based on Environment Profiles Methodologies and Life Cycle Assessment. These methods identify and assess the environmental effects of materials over their life cycle (BRE Global, 2008). The guide helps select appropriate materials that have a low environmental impact. According to the guide a blockwork cavity wall has an A+ rating. Likewise, cast concrete roof construction has a rating of B. This does not perform as well as steel truss and timber joist structures which have A/A+ rating. However, it was important to achieve a very low U-value to have an overall positive impact on reducing heating demand and thermal comfort, hence concrete with insulation proved to be a more efficient system in this case. Similarly, the guide indicated that rockwool has an A+ rating (Anderson, et al., 2009).

6.1.4. Urban design

The model community aims to accommodate 74 houses (one – four-bedroom units) alongside amenities that can be useful for residents as well as visitors residing near the community. Spatial planning is crucial to maximise use of site area while optimising solar gain and designing to encourage wind movement through the settlement for the temperate climate. As discussed in 'section 6.1.2', building spacing plays a key role in site planning. Assuming the site is flat and rows of terraced homes are arranged in parallel, facing south, a minimum spacing of 12m between the rows of houses is critical to prevent overshadowing (see Fig. 49). This is an arrangement similar to 'Case study 1: Solar Settlement' (see 'section 2.3.2'). However, in this spatial pattern, only about 50 of the model houses (from 'section 6.1.2') can be accommodated leaving no site area for amenities and the remaining 24 units. Hence, reducing the spacing between the houses without compromising on solar gain and natural light is the challenge.

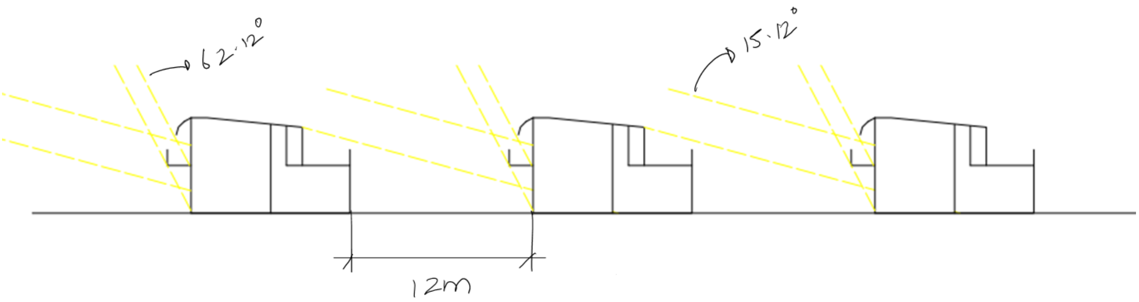


Figure 48 – Building spacing for flat site to maximise solar gain

Figure 50 proposes a stepped settlement, with 1m incremental steps. This arrangement includes the same rows of terraced homes facing south, arranged in parallel while ensuring reduction in building spacing by about 4m. This way, more housing units can be accommodated and the void area created under the steps provides a covered structure for services that can be separated from the residential zone. Additionally, this helps address a key sustainable feature that all case studies discussed in 'section 2.3.1' include, which is, a pedestrian friendly, vehicle free community. The stepped structure restricts vehicular movement at the ground level and offers parking spaces for residents as well as public.

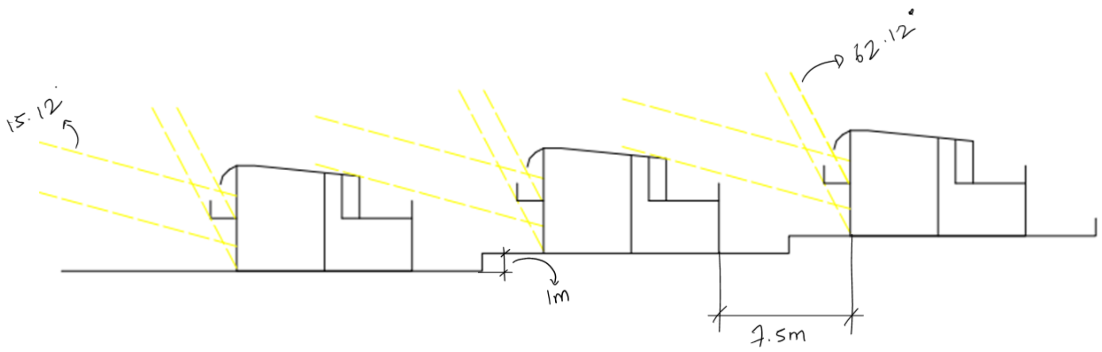


Figure 49 – Building spacing for stepped site to maximise solar gain

Ideally, the homes facing south have opportunity to maximise on solar gain. However, urban design must also encourage movement of wind through the site in summers and cut out harsh cold winter winds. A 15°-30° tilt is encouraged to benefit from prevailing wind. Since the site is oriented about 19° west of north, the parallel rows of houses can be oriented to suit this. This settlement pattern and street arrangement encourages the west south west winds prevailing in the warmer months and in a way blocks the south west winter winds. Likewise, since the houses are oriented no more than 15°-30° east or west of south, optimum solar gain can be achieved.

Site plan:

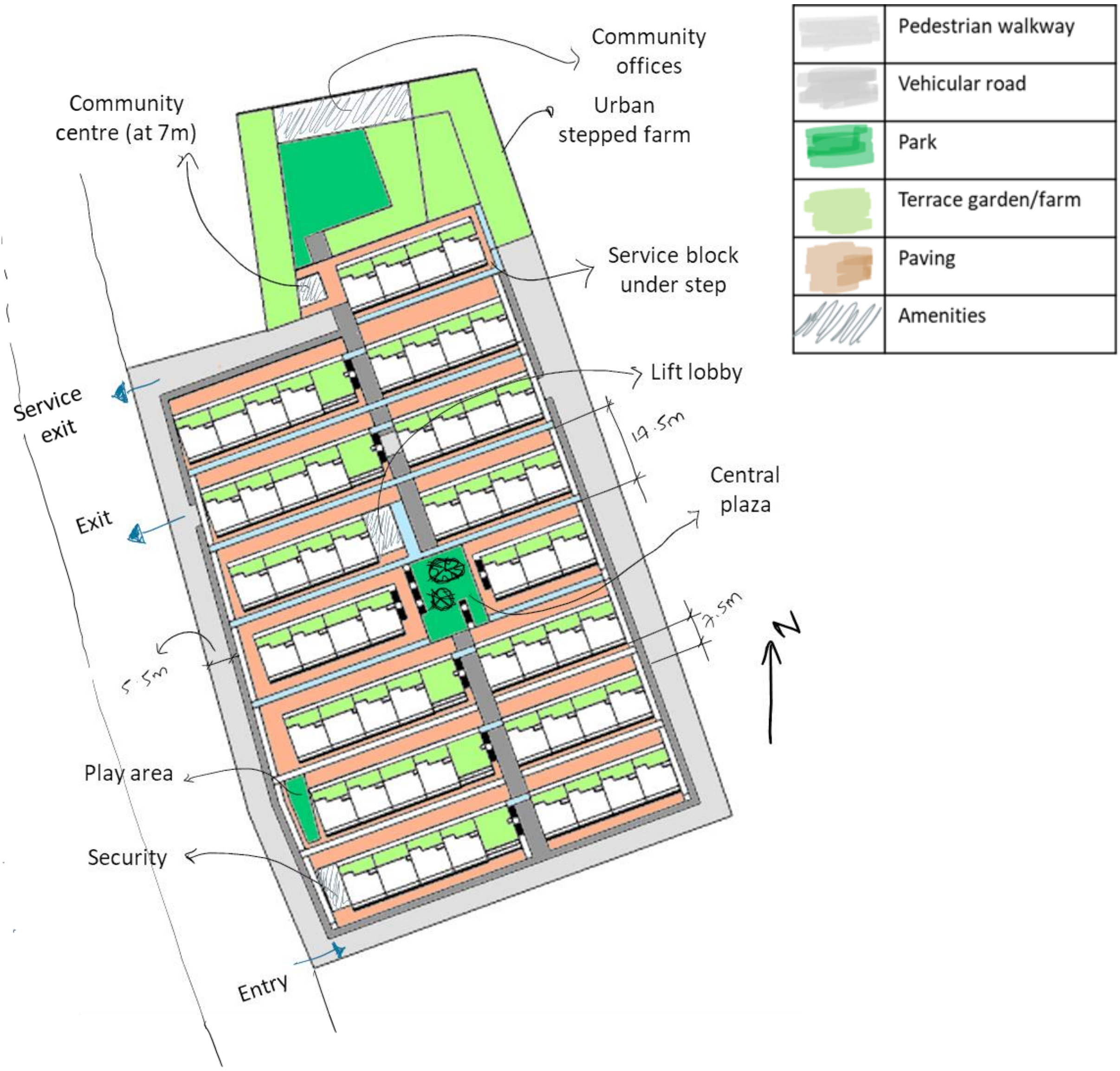


Figure 50- Site plan

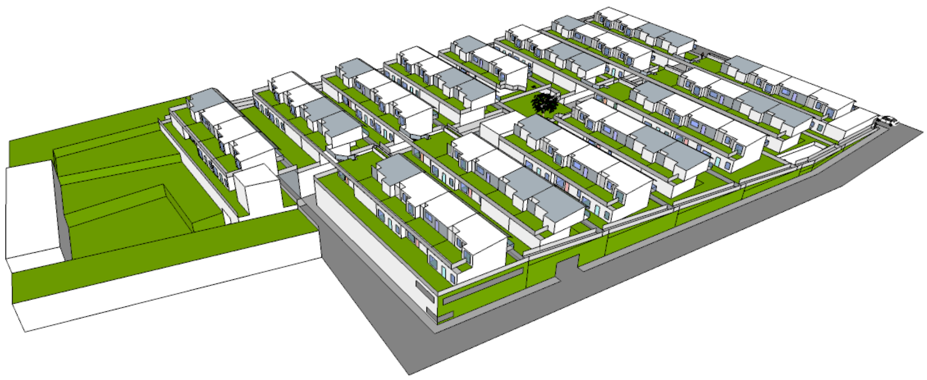


Figure 51 – North west view of community

Based on the stepped design, site plan shown in Fig. 51 has been devised. The site design has seven steps, each incrementing at 1m with the first row of houses at ground level (0m) (see

Fig. 52). Informed by proximity to key amenities, the model community is designed to include the following:

- 74 one to four bed terraced houses – level 0m to 7m
- Play area – level 1m
- Central plaza cut out at level 3m

Figure 52 – Central plaza

- Community centre – level 7m
- Stepped vertical farm for food production catering to the community's food requirements

Figure 53 - North east view of site showing stepped garden, community office building and community centre

- Community office and café – 3 storey building located at the north end of the side. The office caters for the community and urban farm management and has a café with a view of the stepped farm accessible by the public.

- Parking – under levels 3m - 6m
- Services – under level 7m

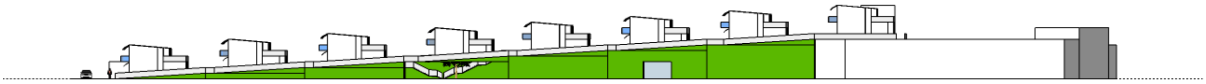


Figure 54 – East elevation of community

Figure 55- Central walkway linking south end of site to north end at ground level

Figure 57 depicts pedestrian and vehicular movement on site. All vehicles have a single-entry point to the site. While resident and public vehicles exit through the parking, service vehicles are redirected via the service block (see Fig. 57).

Figure 56 - Vehicle exit points (left), ramp and entrance security point (right)

The different levels of the stepped settlement are accessible by 1.5 m wide ramps situated on the east and west ends of the site (see Fig. 57). Likewise, the transport plan shows a pedestrian walkway network on the periphery and through the central walkway making all residential zones of the site accessible (marked orange in Fig. 58). The central walkway connects the south end of the site to the north end as shown in Fig. 56. Site transport planning indicated two challenges:

- Security check points
- Restricting access to certain zones of the site to public and in some cases residents

To address this, two security check points have been introduced, one at site entry and another at the site exit. These cater for pedestrian and vehicular monitoring. Additionally, three restricted access points have been included in design, one at the parking level to prevent the public from entering the residential zone and two near the service block to prevent both residents and public from accessing it (marked as a blue dashed line in Fig. 58).

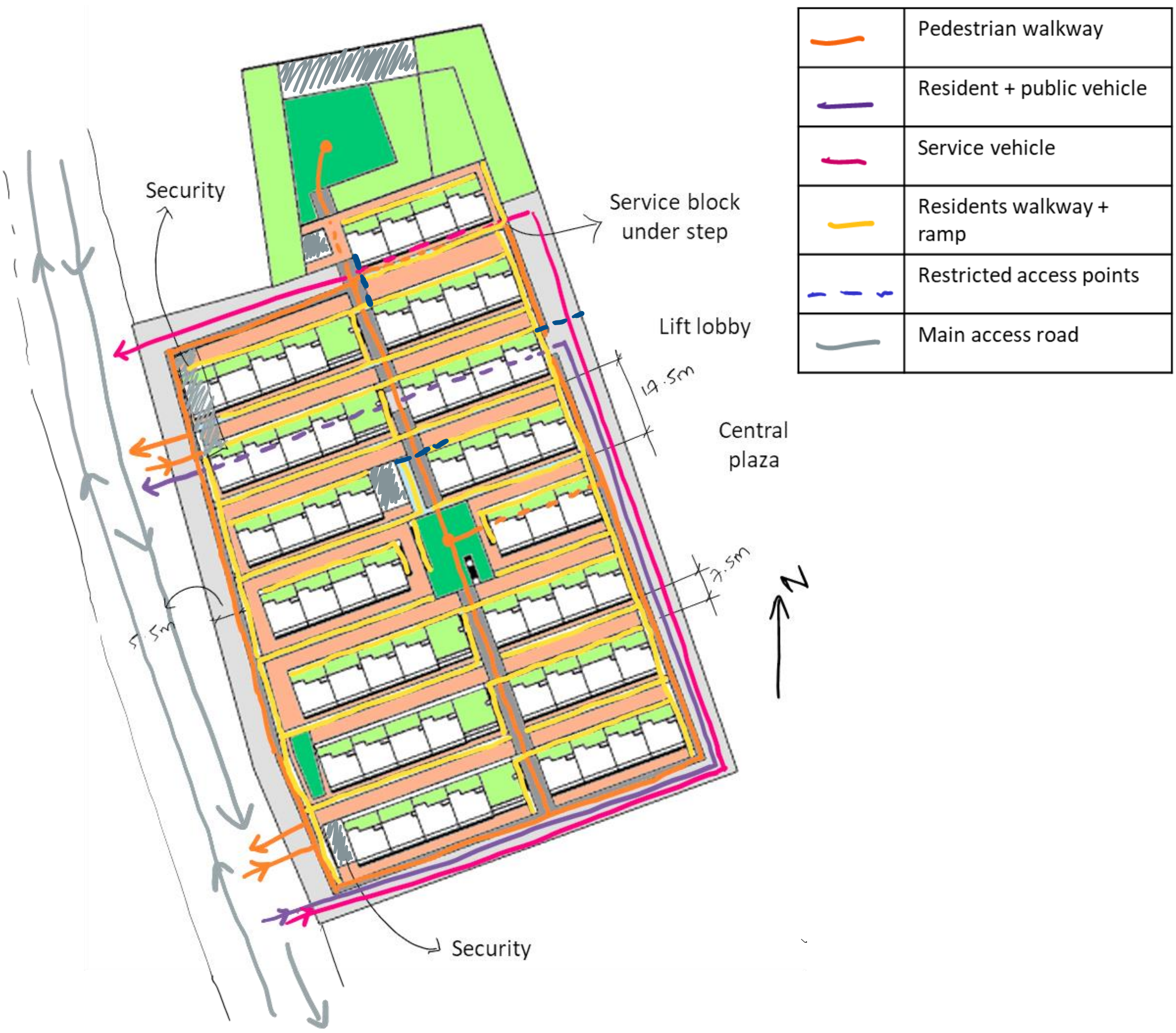


Figure 57 – Site transport plan

Summary

The chapter presented design development of the prototype community situated in Sutton, UK. The chapter discusses site selection, building and urban design based on site selection and climate, survey data collection and demographics, learnings from case studies, developed net zero framework and building regulations, alongside construction techniques including material selection based on BRE’s Green Guide.

Chapter 7
Energy Modelling and Simulations

7.1. Modelling

7.1.1. **Validating the Energy Model**

To obtain the energy demand of the households, the prototype houses from 'section 6.1.2' were modelled on 'DesignBuilder', an energy modelling software. Whole building energy simulations were run using the 'Energyplus' interface on Designbuilder to determine the energy requirement of the different models. Model validation can be performed using three methods (Neymark & Judkoff, 2006):

- Empirical validation – Where the calculated results obtained from a model is compared to monitored data from a real building or laboratory.
- Analytical validation – Where the results from a model are compared to solutions obtained from numerical calculations or analytical methods.
- Comparative validation – Where model results are compared to results from other validated or physically correct models.

To validate the energy model to be used as a prototype, a model building (four-bedroom house from Chapter 6) was simulated on DesignBuilder using model input data obtained from UK Building Regulations, 1995. The total energy demand obtained from this was compared to 1995 Building Regulations energy requirement standards. That is, model results obtained from DesignBuilder were compared to the validated model of 1995 Building Regulations, thereby using the comparative validation method. Designbuilder by default uses data from CIBSE and ASHRAE for weather and the varying model parameters such as occupancy, lighting, heating, etc., to obtain credible energy and indoor environment quality results. The software library is also inbuilt with information on UK Building Regulations and standards for construction and materials. However, some information specific to the Building Regulations such as HVAC system type, equipment density, air tightness, glazing and lighting data were obtained from Approved Document L 1995 Building Regulations (Department of Environment and Welsh Office, 1994) to use for the prototype model. Table 28 shows the input data used for the Building Regulations model.

Table 31 - Model parameters for 1995 Building Regulations model validation

Section	Model data parameter	Model data value	Notes
Site	Location	Sutton, London	
	Weather data	London Gatwick Airport	TRY weather data (2002)
	Site orientation	341°	
Activity	Occupancy density (people/m^2)	0.032	Calculated 4 members / 126.8 m^2
	Holidays (days)	10	Designbuilder default
	DHW consumption (l/m^2-day)	3.94 l	Calculated (Department of Environment and Welsh Office, 1994)
	Heating setpoint temperature	21°C	(Department of Energy and Climate Change, 2009)
	Heating setback temperature	12°C	Designbuilder default
	Natural ventilation – minimum indoor temperature	23°C	(Department of Energy and Climate Change, 2009)
	Minimum fresh air (l/s-person)	10	Designbuilder default
	Fuel	Electricity from grid	
	Power Density (W/m^2)	3.6	Calculated (Department of Energy

			and Climate Change, 2009)
Construction	Wall	Cavity wall 1995 Part L	From DesignBuilder library U-value – 0.45 (Department of Environment and Welsh Office, 1994)
	Flat roof	Flat roof 2000 regs	From DesignBuilder library U-value – 0.25 (Department of Environment and Welsh Office, 1994)
	Pitched roof	Roof – Part L Reference Building	
	Model infiltration – Constant rate (ac/h)	0.6	Calculated (Department of Energy and Climate Change, 2009)
Glazing	Glazing type	Double glazing – no shading	From Designbuilder material library (Department of Environment and Welsh Office, 1994)
	Opening position	Top	
	Glazing area opens	30%	Designbuilder default
Lighting	Lighting template	Fluorescent lights	From Designbuilder library (Department of Environment and Welsh Office, 1994)
	Interior lighting normalised power	3.3	Designbuilder default

	density (W/m^2 – 100 lux)		
	Lighting level (lux)	150	(The Engineering Toolbox, 2004)
	Exterior lighting – absolute power (W)	100	Designbuilder default
	Exterior lighting schedule	On 24/7 Override off in daytime	
HVAC	HVAC template	Radiator heating, boiler hot water, natural ventilation	From Designbuilder library (Department of Energy and Climate Change, 2009)
	Mechanical ventilation	Off	
	DHW template	Same as HVAC	Designbuilder default
	DHW delivery temperature	65°C	
	Cooling	Off	
	Natural ventilation outside air (ac/h)	5	Calculated (Department of Environment and Welsh Office, 1994)
	Mixed mode	On	

Where specific model information was not available from Approved Document L, default Design Builder values were used for simulation. Default schedules from the DesignBuilder library developed from CIBSE TM59 guide were used for occupancy, heating and equipment. An energy demand of about 167.4 kWh/m^2/year was obtained from the Building Regulations model using DesignBuilder. The energy requirement of a typical building built to 1995 Building Regulations is 165 kWh/m^2/year indicating that the DesignBuilder model is validated can be used as a prototype model to obtain credible energy results for the prototype community situated in Sutton, UK (Anderson, et al., 2002).

7.1.2. **Protoblocks**

As opposed to merely modelling the four prototype houses from 'section 6.1.2', 67 house prototypes that are variations of the four model houses based on their position on the site were modelled on Designbuilder. This rigorous process helped arrive at more accurate results as mid and end terrace homes based on exposure to harsh winter winds and varying heights may vary in terms of thermal performance. For this, end and mid terrace houses were differentiated for each house size and step level. This is illustrated in Fig. 59, where mid terrace 1m or end terrace 3m – northeast houses are marked in red.

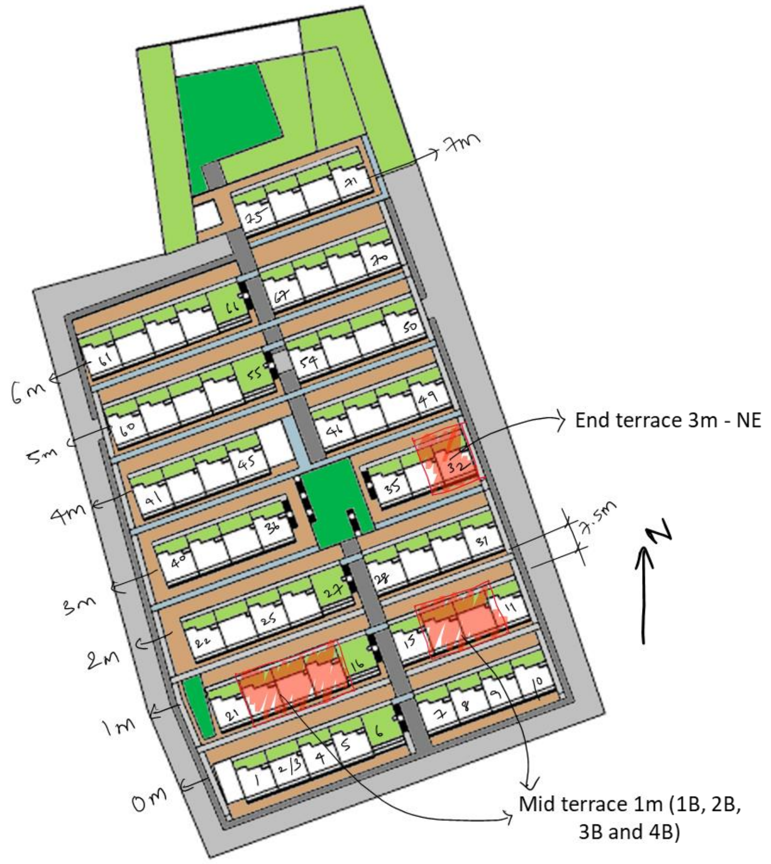


Figure 58 – Site plan with allocated house numbers highlighing mid and end terrace houses on different levels

Figure 59 shows step levels and dedicated house numbers for ease of record and further application. For example, at level 0m, house numbers 4 and 9 are both four bedroom (4B) mid terrace homes. Hence, only one of these was modelled for calibration as it is likely that both these houses would have a similar thermal performance. In contrast, house 10 which is a 4B end terrace house could have a higher heating demand as the east façade is exposed possibly leading to more heat loss. Likewise, house 75 at level 7m, a 4B 'end terrace home – southwest' is more susceptible to the cold winds from the southwest and higher wind speeds given the height thereby affecting its thermal performance.

Based on the implications of urban design for thermal performance as explained above, a thorough list of all the houses and their position on site was prepared (see Appendix 4). 67 'protoblocks', that is, the prototype house along with the adjacent and neighbouring buildings in combination, were modelled in Designbuilder. The prototype house was modelled as a 'building block' and adjacent units as 'component blocks' (DesignBuilder, n.d.). Table 29 lists one bedroom (1B) house protoblocks. Marked in red in Table 29 are houses in which case only one of each type has been modelled. That is, one mid terrace 1m, one mid terrace 3m and one mid terrace 5m. Of the 11 1B houses, eight have been modelled for calibration (see Fig. 60).

Table 32 - 1B protoblocks

Household no.	Household size	Location	Model code
2	1B	mid terrace 0m	1_1_1
● 12	1B	mid terrace 1m	1_1_2 }
● 18	1B	mid terrace 1m	1_1_2 }
23	1B	mid terrace 2m	1_1_3
● 33	1B	mid terrace 3m	1_1_4 }
● 37	1B	mid terrace 3m	1_1_4 }
42	1B	mid terrace 4m	1_1_5
● 51	1B	mid terrace 5m	1_1_6 }

57	1B	mid terrace 5m	1_1_6
62	1B	mid terrace 6m	1_1_7
72	1B	mid terrace 7m	1_1_8

Figure 59 – 1B protoblocks modelled on DesignBuilder

The following assumptions have been made for energy modelling and simulation of the above protoblocks:

- Adjacent blocks are adiabatic. That is, there is no exchange of heat between the blocks. These are indicated as brown blocks in Fig. 60.

- All eight protoblocks have uniform model information. Designbuilder default schedules have been considered for this purpose. The only controlled parameter was construction (detailed in 'section 6.1.3'). The details of templates used for the 1B protoblocks are indicated in Appendix 4.

Calibration:

Energy simulations for the eight 1B protoblocks were run on Designbuilder for a two-year period to obtain results on total fuel consumption, heating fuel consumption and indoor air temperature. From the fuel consumption data, an average fuel consumption was calculated for the 1B protoblocks (see Table 30). Percentage differences of energy consumption of each protoblock to the average energy consumption helped find the protoblock that was nearest to the average energy demand. The protoblock closest to the average was identified as the master protoblock that was used to run simulations for the 11 1B households using model data derived from the surveys.

Table 33 - Energy results of 1B protoblocks

House		Total energy consumption		Average	Percentage difference
		kWh/year	kWh/m^2/year		%
mid terrace 0m	1_1_1	10253.4	218.2	218.3	-0.06
mid terrace 1m	1_1_2	10249.3	218.1		-0.10
mid terrace 2m	1_1_3	10253.6	218.2		-0.06
mid terrace 3m	1_1_4	10262.6	218.4		0.03
mid terrace 4m	1_1_5	10261.4	218.3		0.02
mid terrace 5m	1_1_6	10265.9	218.4		0.06
mid terrace 6m	1_1_7	10267.4	218.5		0.08
mid terrace 7m	1_1_8	10262.8	218.4		0.03

It can be noted from Table 30 that all the protoblocks have more or less the same energy demand barring a small difference of 0.1 to 0.4 kWh/m^2/year. The difference in energy consumption was due to a small variation in heating requirement of each household. The average energy consumption of the protoblocks was 218.3 kWh/m^2/year. Protoblock '1_1_5' - mid terrace house at 4m is the model closest to the average energy consumption having a percentage difference of just 0.02%. Hence, this protoblock was used for all 1B simulations subsequently. Likewise, this method was used to identify the master protoblock for two-, three- and four-bedroom houses (2B, 3B and 4B). Appendix 4 includes a list of all protoblocks and corresponding energy consumptions derived from Designbuilder.

7.1.3. **Modelling the prototype community**

As discussed in Chapter 5, surveys on typical British lifestyle helped assimilate data on the five critical energy controlling parameters – occupancy, lighting, heating, hot water and equipment. Based on the data obtained from each survey, model data and schedules were devised for 74 households for energy modelling and simulation in Designbuilder. To successfully run energy simulations, Designbuilder requires a user to input model data for five sections. These are:

- Activity

  Details on occupancy, domestic hot water (DHW) consumption, temperature set-points and equipment usage

- Construction

  Material details for all surfaces and model infiltration data

- Openings

Data on type of glazing (e.g., triple glazing), opening percentage and position (e.g., top hung)

- Lighting

  Details on lighting type (e.g.: LED), interior and exterior lighting usage data

- HVAC

  Information on type of HVAC system, mechanical ventilation, heating, cooling, natural ventilation and DHW settings

Discussed below are model households developed from surveys 22 and 40. Both households have the composition – '2FT1C1S_4P4B', which is 2 full time working members + 1 child + 1 student, 4 members 4 bedrooms household. The two households have been used to provide examples of model data input from surveys and the corresponding results obtained from energy simulations for each household (discussed in section 6.3). Since both the households have the same household composition, it enables comparative analysis of model data as well as energy results of both households. The model data has many parameters that remain constant for both household models. However, some parameters vary between the two households. These are:

- Schedules for occupancy, heating, equipment and lighting
- Equipment power density (W/m^2) that is, that is plug load per floor area.

Note that, although the house size is same, that is, 4B and the household size is 2 members (assume 2FT), the occupancy density ($people/m^2$) and DHW consumption (litre/person) will also change in this case. However, all other parameters such as construction, opening, lighting and HVAC bar the schedules and equipment details will remain constant. Details of the constant model parameters for household '2FT1C1S_4P4B' are discussed in Appendix 4.

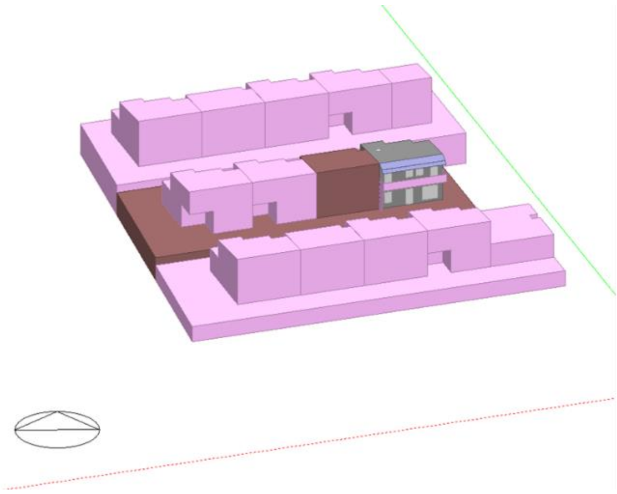


Figure 60 - 4B protoblock used for whole building energy simulations

Occupancy schedule:

The occupancy pattern is defined by the number of members present in the household over 24 hours. Represented in percentage, a house that is unoccupied is depicted as 0, in the case of a fully occupied home, the occupancy is depicted as 1 (i.e., 100%). For example, a 4P4B household with three of the four members present in the house will have an occupancy 0.75. Based on this occupancy percentage derived from number of members present in the house per hour, a 24 hours schedule is prepared. Indicated in Fig. 62 and 63 are occupancy patterns for typical weekdays, Saturdays and Sundays for household 22 and 40.

Typical Weekdays:

- Household 40 remains unoccupied (1.e., 0) for 9 hours during the day between 8am and 5pm.
- Household 22 has no occupancy between 11am to 4pm implying that household 40 has twice as many unoccupied hours as 22 on a typical weekday.

Saturdays:

- At least 2-3 members of household 22 stay in through Saturday, that is variation in occupancy between 0.5 and 0.75 (see Fig. 62).

- Household 40 has occupancy of 0.5 between 8am and 6pm on Saturday.

Sundays:

- Household 40 has full occupancy on Sundays (i.e., 1).
- Household 22 has almost 0.75 occupancy during midday and evening, and 100% occupancy most of the remaining time bar one hour between 10-11am when 2 members are away on Sundays.

Regardless of same household composition, there are significant variations in occupancy between the two households. Given the longer periods of inoccupancy in household 40, it is likely that this will have a lower energy consumption in comparison to 22.

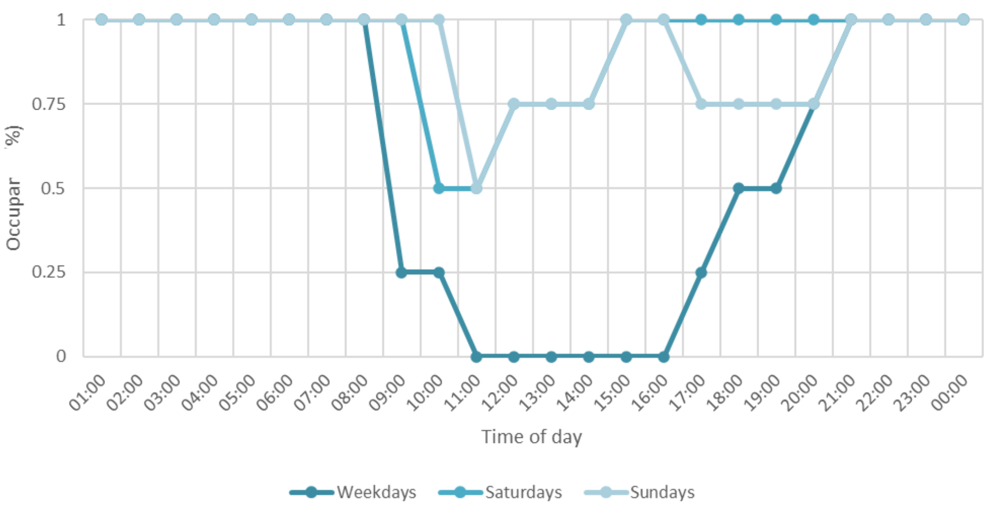


Figure 61 - Occupancy schedule for survey 22 for typical weekdays, Saturdays and Sundays

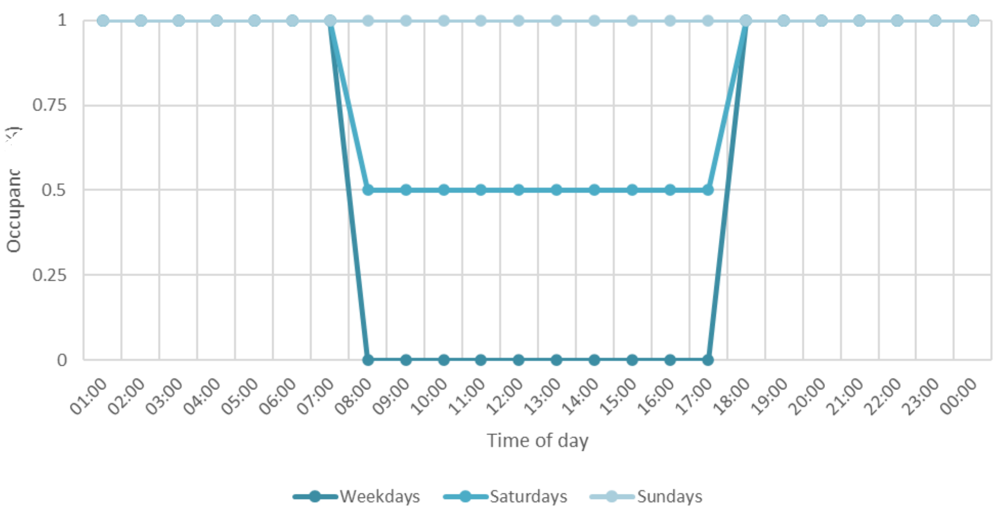


Figure 62 - Occupancy schedules for survey 40 for typical weekdays, Saturdays and Sundays

Equipment schedule:

For each household, the equipment used was selected from the list specified in 'section 5.2.2'. Average power consumption per hour of use of each equipment was calculated and a total power consumption (watts) from all equipment usage was derived from this. Based on this, a percentage component for each equipment was deliberated. Table 31 shows the average power consumption per hour of use of each equipment.

Where, Average power consumption per hour of use = Rated power (watts)*time for which equipment is used (hour)/24 hours

Table 34 - Equipment list with their rated power, time used and average power consumption per hour of use

Equipment	Rated power (Watts) (Energy Use Calculator, n.d.)	Typical time equipment is used (hour)	Average power consumption per hour of use (Watts)
Fridge	60	24	60.00
Dishwasher	1800	2	150.00
Washing machine	500	1	20.83
Clothes dryer	800	0.75	25.00
TV	100	3	4.17
Hob	2000	0.5	41.67
Toaster	830	0.05	1.73
Hair dryer	1800	0.25	18.75
Hair straightener	100	0.5	2.08
Oven	3000	0.5	62.50
Microwave oven	1000	0.05	2.08
Coffee maker	1000	0.125	5.21

Clothes iron	1800	0.5	37.50
Kettle	3000	0.05	6.25
Misc.	100	1	4.17
Space heater	2000	1	83.33
Fan	50	1	2.08
Vacuum cleaner	175	0.5	3.65
Stereo	100	1	4.17

Using the average power consumption per hour, the equipment usage and schedules for households 22 and 40 were derived. Fraction of power consumption of each equipment was calculated to formulate the schedules (see Table 32).

Table 35 – Average power consumption over 24 hours for households 22 and 40

	22		40	
Equipment	Average power consumption over 24 hours		Average power consumption over 24 hours	
	Watts	Fraction	Watts	Fraction
Fridge	60.00	0.13	60.00	0.13
Dishwasher	150.00	0.32	150.00	0.33
Washing machine	20.83	0.04	20.83	0.05
Clothes dryer	25.00	0.05	25.00	0.06
TV	4.17	0.01	4.17	0.01
Hob	41.67	0.09	41.67	0.09
Toaster	1.73	0.00	1.73	0.00
Hair dryer	18.75	0.04	18.75	0.04
Hair straightener	2.08	0.00		

Oven	62.50	0.13	62.50	0.14
Microwave oven	4.17	0.01	4.17	0.01
Coffee maker			5.21	0.01
Clothes iron	37.50	0.08	37.50	0.08
Kettle	18.75	0.04	6.25	0.01
Misc.	12.50	0.03	12.50	0.03
Space heater				
Fan				
Vacuum cleaner	3.65	0.01	3.65	0.01
Stereo				
Total power consumption (W)	463.3		453.9	
Equipment power density (W/m^2)	3.7		3.6	

Table 32 shows that both households more or less used the same household equipment. Household 22 has an equipment power density of 3.7 W/m^2 and household 44, 3.6 W/m^2, minor difference due to the increased kettle usage by household 22. From survey data, information on when and how often the different equipment was used was determined. Equipment schedules were formulated based on this. For example, household 40 uses the hob and oven in the evening (5-8 pm) on a typical weekday. Assuming an hour of cooking (6-7 pm), equipment usage is calculated as 0.23 that is, hob (0.09) + oven (0.14) (see Table 32). Fig. 64 shows equipment usage of 0.35 between 6-7pm which includes usage of hob, oven and the fridge that remains on all the time. Distinct peaks in equipment usage can be seen in Fig. 64 and 65 which are typical to the occupancy pattern in each household.

Typical weekdays:

- Equipment usage is evident in the mornings before members leave the house (about 0.3) and evenings when members return and there is active occupancy before sleeping (0.45).

Weekends:

- Household 40 has minimal equipment use in the weekend
- Household 22 shows increased usage in the mornings and evenings similar to weekday, and to some extent during midday.

Nevertheless, household 22 has a decreased equipment use during the weekend when compared to weekday use. Since household 22 has a higher equipment use during weekends when compared to 40, it is likely that the energy consumption from equipment use will be higher for 22.

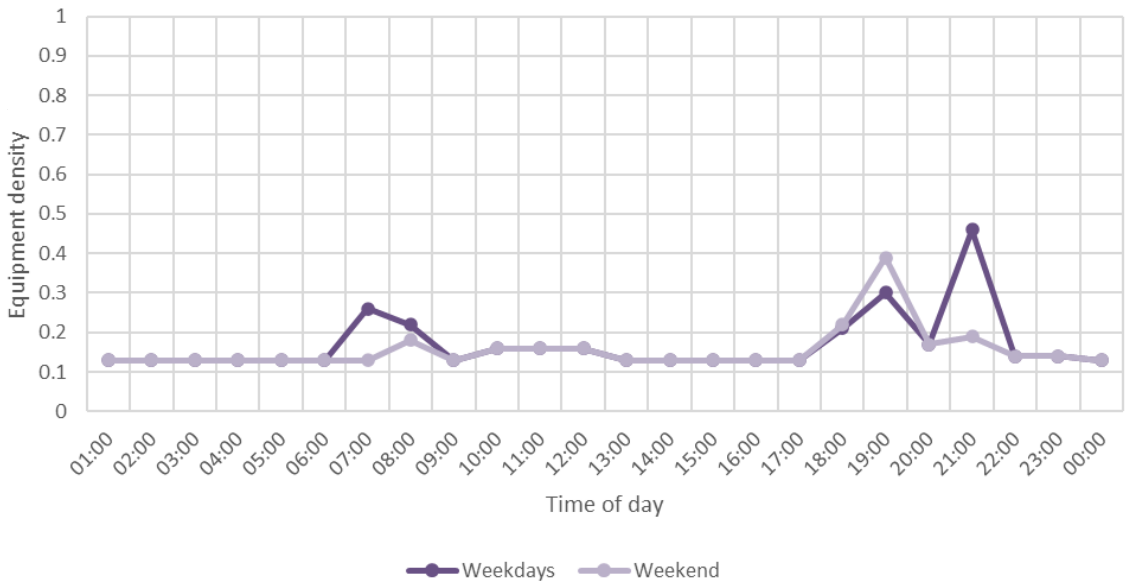


Figure 63 – Equipment schedule for survey 22 for typical weekdays and weekends

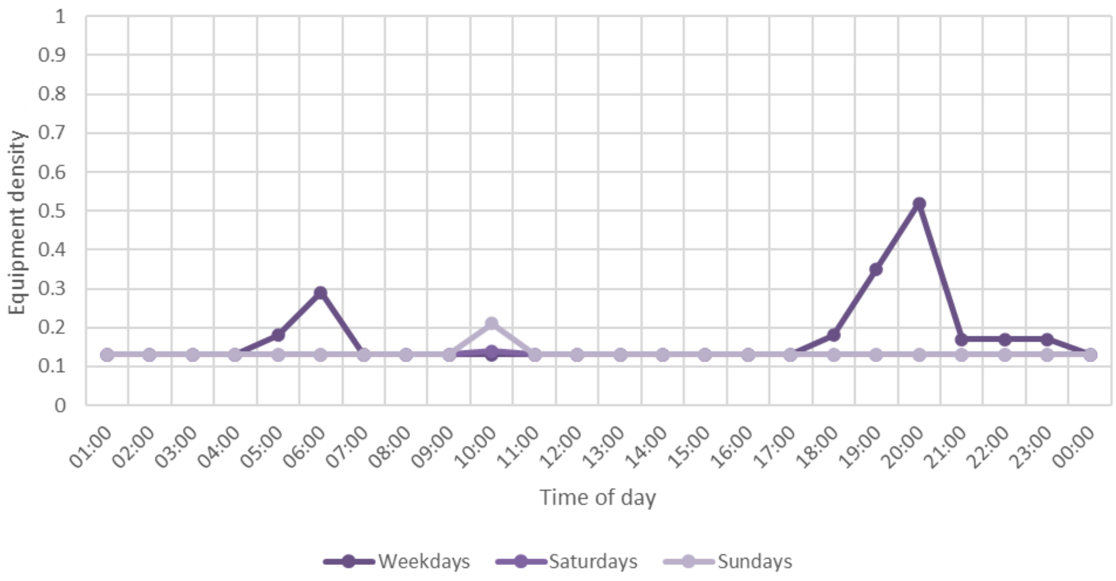


Figure 64 – Equipment schedules for survey 40 for typical weekdays, saturdays and Sundays

Lighting schedule:

Information on lighting was not collected through the surveys. How often lights are switched on and off cannot be included as a controlled parameter. Hence, lighting schedules are hypothesised based on occupancy pattern, equipment use and movement in a house. Based on the percentage of area of different rooms and when each of these are likely to be used, lighting schedules were designed. Table 33 indicates area and percentage of total area of each room in the four-bedroom household. For example, if the household uses bedroom 1,2, dining + kitchen and living between 6pm and 9pm, then the percentage of lighting use for this period can be calculated as 0.45 (see Table 33).

Table 36 - Areas and corresponding percentage components for spaces in four-bedroom house

Room	Level	Area (m^2)	%
Bedroom 1	Ground floor	9	0.07
Bedroom 2	Ground floor	9	0.07
Bedroom 3	First floor	10.5	0.08
Master bedroom	First floor	13.5	0.11

Living	Ground floor	20	0.16
Dining + kitchen	Ground floor	16	0.13
Bath	First floor	4	0.03
Miscellaneous	Ground floor	22	0.17
Miscellaneous	First floor	22.8	0.18
Total area		126.8	1.0

Note: Miscellaneous includes circulation staircase and corridor, storage, laundry and toilet

It can be noted from Fig. 66 and 67 that 100% of the lighting is never used in either of the households. Active occupancy plays a critical role in designing the lighting schedule. Survey data indicated use of cooking equipment and TV in the evenings and nights typically. Hence, it is possible that most members are in the kitchen, dining and living, which are at the lower level of the house there by indicating minimal lighting use on the upper floor. Where the occupancy is 0 or there is inactive occupancy (sleeping), lighting is presumed to be 0. In the case where the house is occupied during the day (weekends), about 50% lighting of each room likely to be used (such as two bedrooms and living/kitchen/dining) is considered to accommodate for task lighting and overcast days. For example, in household 40 member 2 (student) and member 3 (full time working adult) stay in between 10 am and 3 pm. Considering 50% lighting of bedroom 2 (i.e., 0.03) and living (i.e., 0.08) the fraction of lighting used during this period is calculated to be about 0.1 (See Fig. 67). Since the lighting energy is contingent on occupancy, household 22 is likely to have a higher consumption.

Figure 65 – Lighting schedule for survey 22 for typical weekdays, Saturday and Sunday

Figure 66 – Lighting schedule for survey 40 for typical weekdays, Saturday and Sunday

Heating schedule:

The heating pattern for the households has been devised based on survey data and occupancy. Where the heating is on, it is represented as 1 and when it is off, it is 0. Fig. 68 and 69 indicate the heating schedules for households 22 and 40. Typical heating periods are seen in the morning, evening and night for both households. In the case of household 22, heating is turned off (i.e., 0) during the period of inoccupancy and during inactive occupancy for both weekdays and weekends. Likewise, household 40 has heating turned off during unoccupied hours. However, the heating turns on at 4pm while the house remains unoccupied until 5pm on typical weekdays. Nonetheless, household 40 has fewer hours of heating when compared to 22, especially during the weekends. Therefore, it is likely that the heating energy household 22 will be more in comparison to household 40.

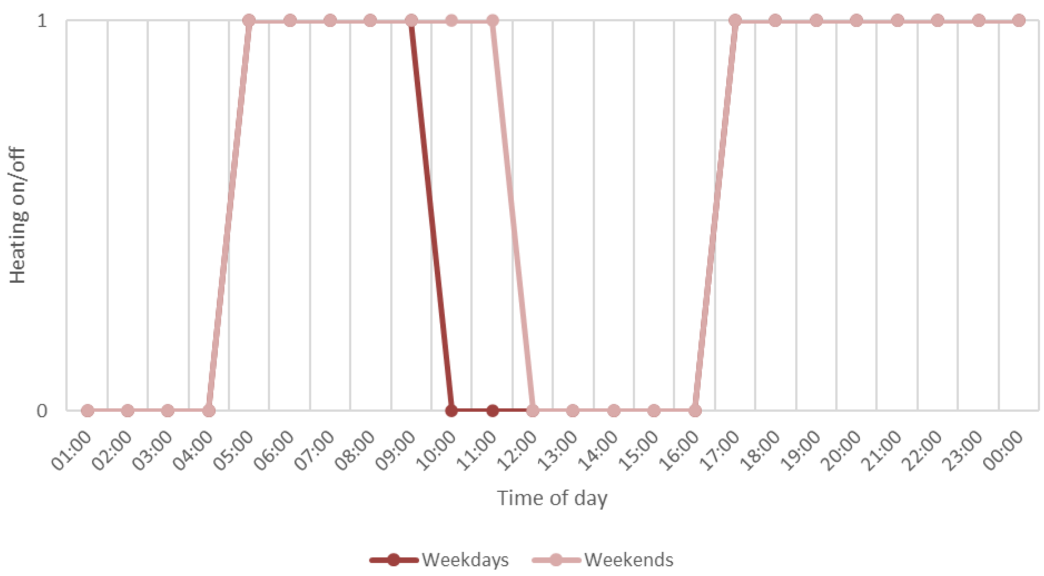


Figure 67 - Heating schedule for survey 22 for typical weekdays and weekends

Figure 68 - Heating schedule for survey 40 for typical weekdays and weekends

Section 7.2 discusses the energy results obtained from simulating houses based on model data defined by the above methodology, specifically comparing households 22 and 40.

7.2. Energy demand from houses

Based on the above methods, occupancy, lighting, equipment and heating schedules were developed for 74 models using the appropriate protoblock for each household. Whole building energy simulations of these models were run for a two-year period helped collect energy data on heating, lighting, equipment and DHW. Figures 69-72 shows energy consumption results for equipment use, lighting, heating and DHW obtained from modelling households 22 and 40 from 'section 6.2.2'.

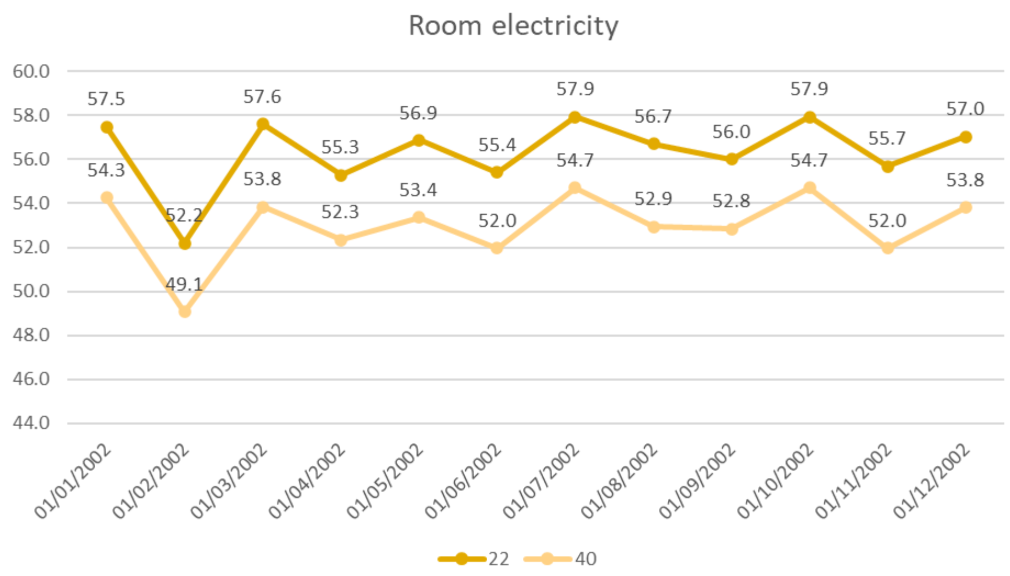


Figure 69 – Comparative analysis of room electricity results for households 22 and 40

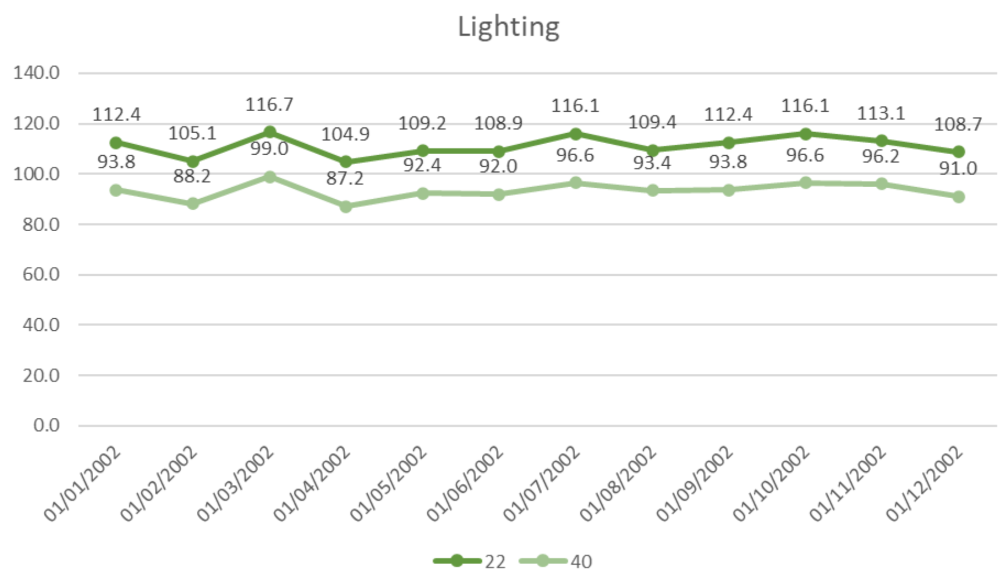


Figure 70 - Comparative analysis of lighting energy results for households 22 and 40

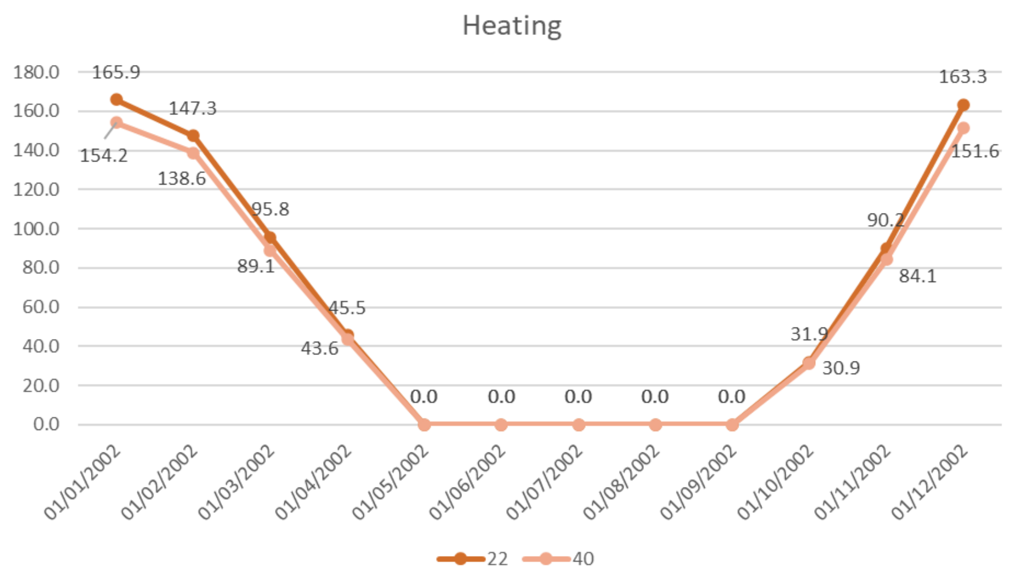


Figure 71 - Comparative analysis of heating results for households 22 and 40

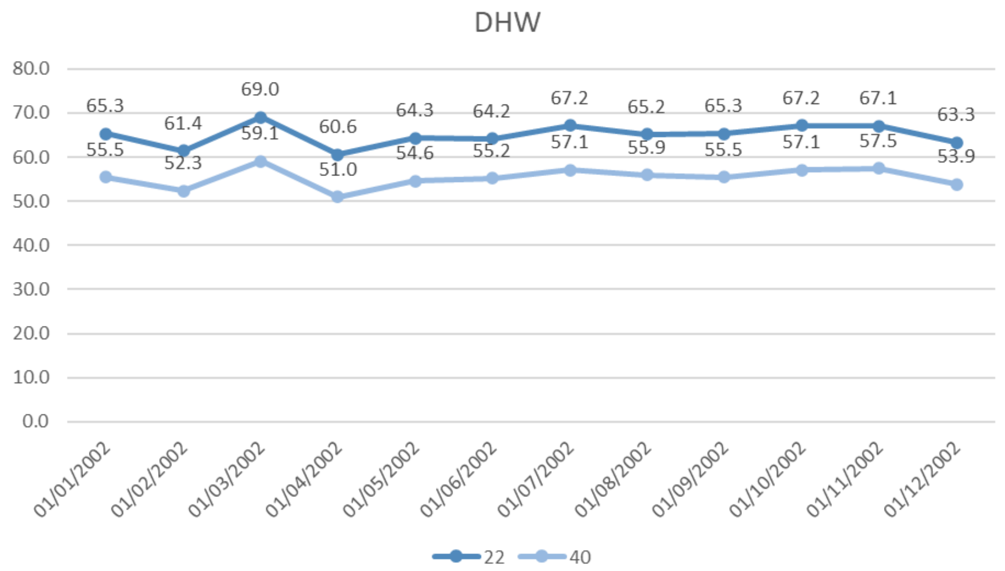


Figure 72 - Comparative analysis of DHW results for households 22 and 40

It can be noted from Fig. 70 and 72 that household 22 has about 17% higher lighting and 16% higher DHW energy demand than household 40. Energy use from equipment is 3-4 kWh/month lower for household 40 in comparison to household 22. Significant difference (about 10 kWh) in heating energy consumption is noted during the winter months between the households. Table 34 indicates the total energy consumption for the year for households 22 and 40. As hypothesised, household 22 has a higher energy demand (about 11% more) when compared to household 40 regardless of these households having the same household composition. This shows the critical impact user occupancy and lifestyle can have on household energy consumption.

Table 37 - Annual energy use for households 22 and 40

House	Room Electricity	Lighting	Heating (Electricity)	DHW (Electricity)	Exterior lighting	Total energy	
	kWh/year					kWh/year	kWh/m^2/year
22	676.1	1333.0	739.9	780.1	435.3	3964.4	31.3
40	635.8	1119.8	692.1	664.5	435.3	3547.5	28.0

In this manner energy results have been compiled and analysed for the 74 model houses comprising the prototype community. Figure 71 shows the annual energy demand results for all the houses. The overall energy demand ranges between 1600 to 4600 kWh/year (approx.). The average annual energy consumption for each house size is indicated in Table 35.

Table 38 - Average energy consumption results for 1B, 2B, 3B and 4B houses

House	Average energy consumption	
	kWh/year	kWh/m^2/year
1B	2007.2	42.7
2B	2615.4	36.8
3B	3467.6	29.4
4B	3544.3	28.0

It can be noted that 3B and 4B households show evidence of higher energy demand due to higher occupancy and larger building area (see Fig. 73). About 77% of 4B homes show an energy consumption range of about 3000-4000 kWh/year. Likewise, about 82% of 3B houses indicate 3000-4000 kWh/year energy use. Results also specified that about 64% 1B homes have an annual energy demand of about 2000 kWh or less and energy demand for 2B houses ranges between 2200-3000 kWh/year (approx.).

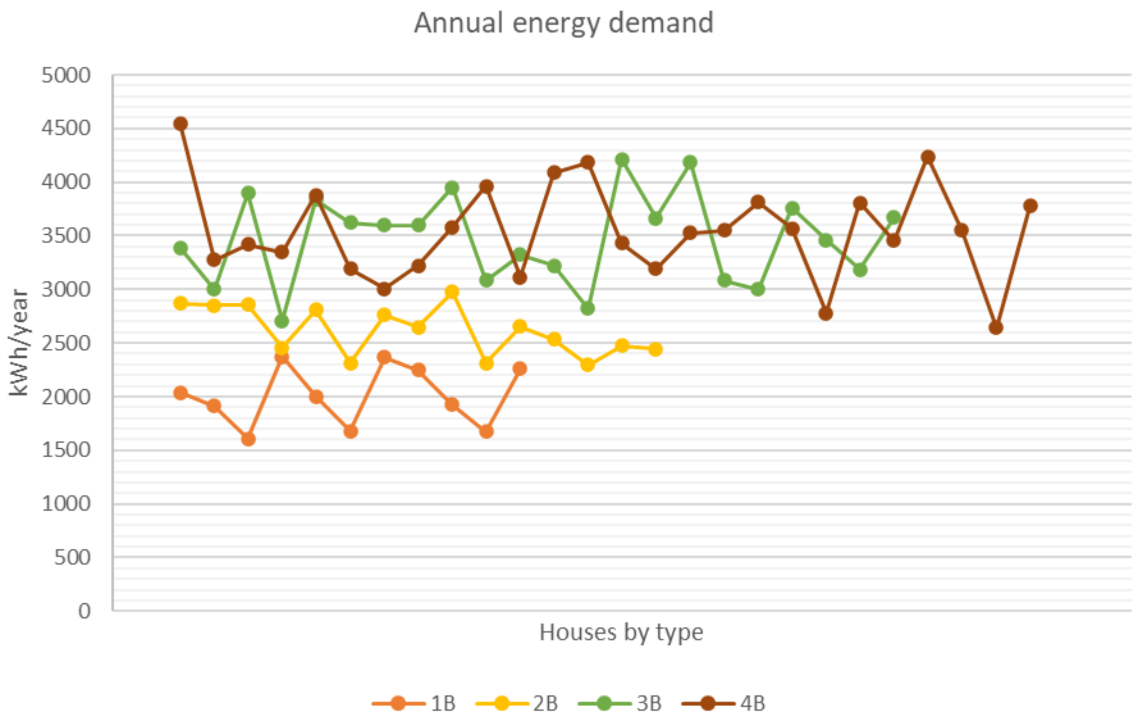


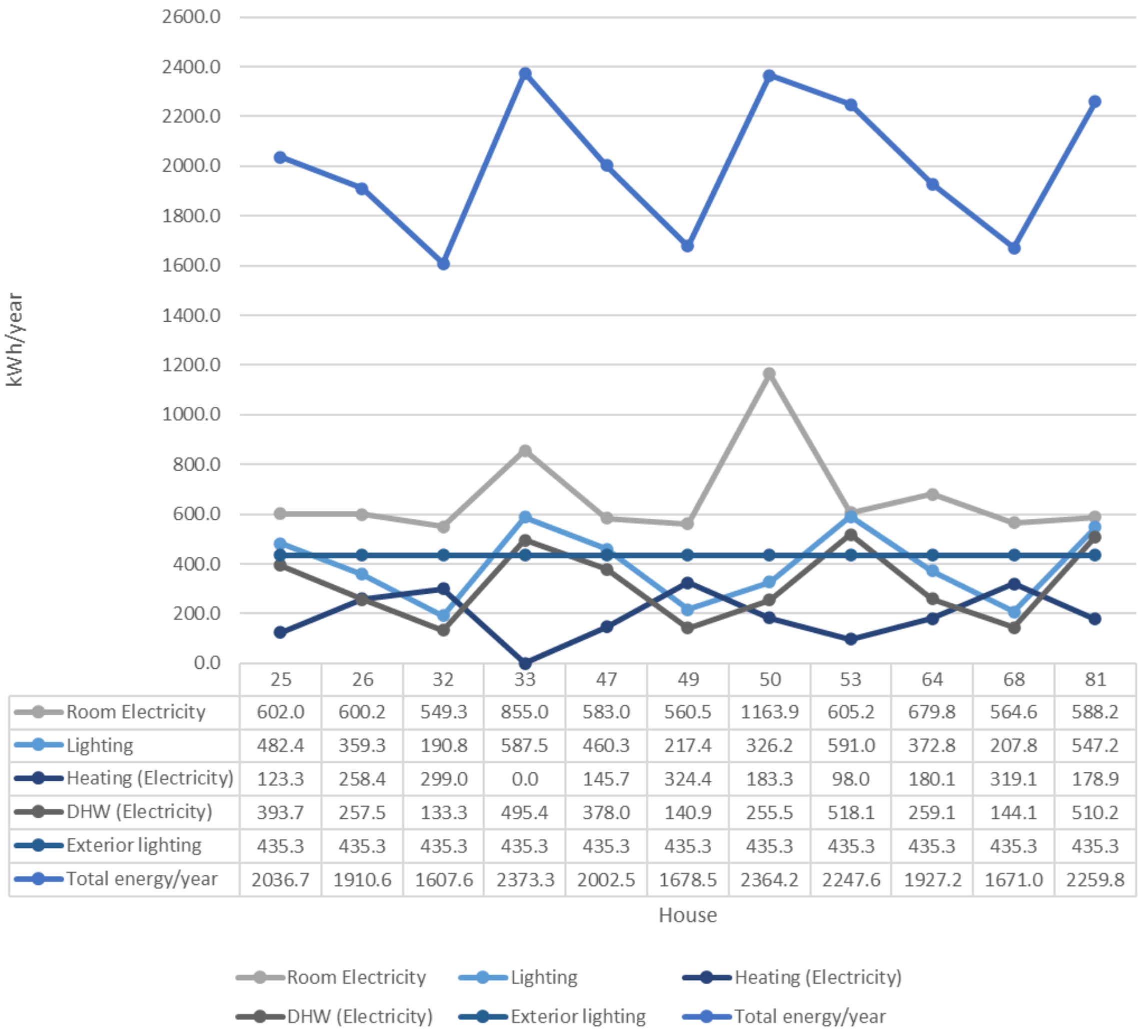
Figure 73 - Energy results for all houses by type

<u>1B houses</u>

The following section discusses energy results for 1B households. The model community comprises 11 1B houses. Figure 74 shows the energy data for heating, equipment, lighting, DHW and exterior lighting for the 11 1B houses. It can be seen from the energy results that:

- Household 50 had the highest equipment use (1163.9 kWh/year)
- Household 33 had no heating demand (informed from survey data). However, the equipment usage, DHW and lighting were high (compared to other 1B houses) thereby leading to an overall higher energy consumption.
- Household 53 had the lowest heating demand when compared to the other 1B households. Yet, its DHW and lighting consumption were the highest indicating a higher overall energy demand.

- Household 81 also showed high lighting and DHW consumption.



	25	26	32	33	47	49	50	53	64	68	81
Room Electricity	602.0	600.2	549.3	855.0	583.0	560.5	1163.9	605.2	679.8	564.6	588.2
Lighting	482.4	359.3	190.8	587.5	460.3	217.4	326.2	591.0	372.8	207.8	547.2
Heating (Electricity)	123.3	258.4	299.0	0.0	145.7	324.4	183.3	98.0	180.1	319.1	178.9
DHW (Electricity)	393.7	257.5	133.3	495.4	378.0	140.9	255.5	518.1	259.1	144.1	510.2
Exterior lighting	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3
Total energy/year	2036.7	1910.6	1607.6	2373.3	2002.5	1678.5	2364.2	2247.6	1927.2	1671.0	2259.8

Figure 74 – Annual energy results by function and house number for 1B houses

Inferences from 1B houses' energy results:

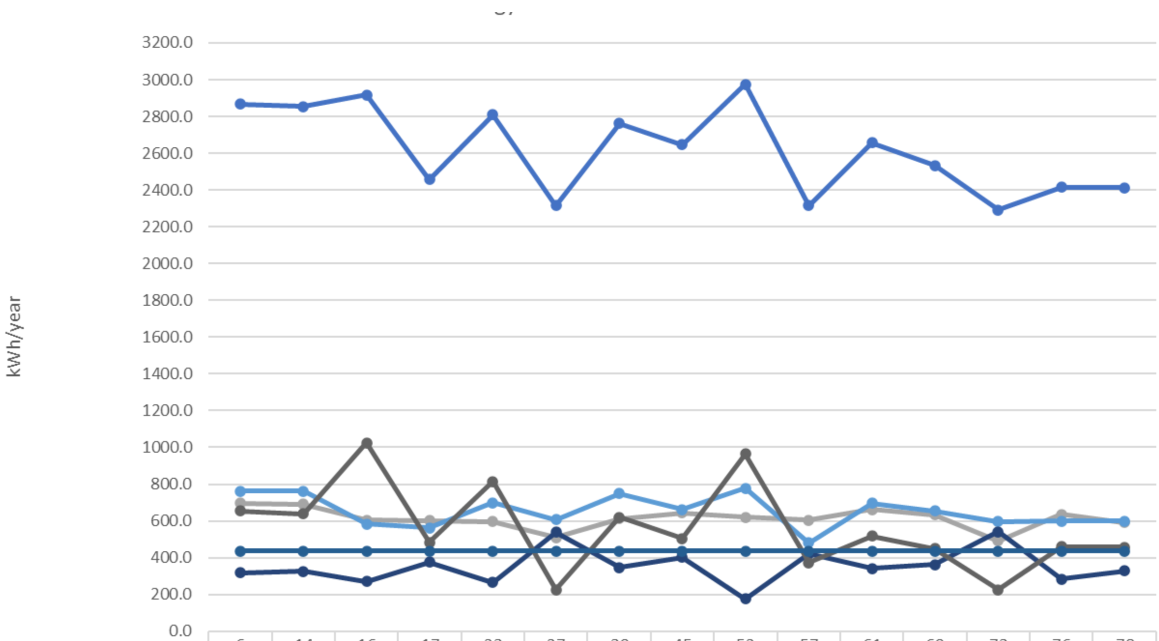
- The annual energy consumption for 1B houses ranges between about 1600 to 2400 kWh/year.
- Household 33 was the highest consumer of energy. The household composition of 33 is 1S1SH (1 student + 1 stay home member). The house is occupied at all times by at least one member, thereby indicating increased DHW and lighting use, parameters that are affected by occupancy.

- The next highest consumer is house 50, a single member household (1S). The house remains unoccupied for only 3 hours on typical weekdays. This alongside the high equipment usage resulted in its increased energy consumption.
- Household 32 consumed the least energy of the group. The house remains unoccupied between 6 am and 9 pm (15 hours) thus impacting lighting use and DHW consumption.
- The total energy consumption of 1B houses is about 22700 kWh/year or 469.8 kWh/m^2/year.

2B houses

The community includes 15 2B houses. This section discusses the energy results for the 2B. Figure 75 illustrates the energy used for heating, equipment, lighting, DHW and exterior lighting for the 15 2B houses. The following findings were gathered:

- Household 16 has the highest DHW consumption (about 1025 kWh/year) indicating overall high energy consumption.
- Household 52 has the lowest heating consumption of all the 2B homes but uses most lighting and DHW also indicating a high total energy consumption.
- Household 57 shows the lowest lighting use and relatively low DHW consumption when compared to the other 2B houses.
- Household 73 has the lowest DHW consumption of about 226 kWh/year and equipment use of 492.4 kWh/year indicating an overall low energy consumption



House	6	14	16	17	23	27	39	45	52	57	61	69	73	76	78
Room Electricity	697.4	691.4	604.2	600.8	595.7	509.0	611.9	643.6	620.9	605.0	663.2	633.0	492.4	635.6	590.7
Lighting	763.2	763.2	583.9	561.0	700.2	606.1	749.7	662.7	777.9	481.4	697.0	653.6	596.5	599.6	598.6
Heating (Electricity)	317.6	324.9	270.4	375.1	265.7	538.7	346.1	401.8	175.4	419.6	342.5	363.5	542.1	284.8	329.2
DHW (Electricity)	653.8	638.1	1024.5	483.9	813.8	226.1	619.3	504.2	964.6	374.3	518.3	449.3	226.1	459.0	458.3
Exterior lighting	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3
Total energy/year	2867.2	2852.9	2918.3	2456.2	2810.6	2315.2	2762.3	2647.5	2974.1	2315.7	2656.4	2534.7	2292.5	2414.4	2412.1

House

Room Electricity, Lighting, Heating (Electricity), DHW (Electricity), Exterior lighting, Total energy/year

Figure 75 - Annual energy results by function and house number for 2B houses

Inferences from 2B houses' energy results:

- The annual energy consumption for 2B houses ranges between about 2300 to 2900 kWh/year unlike 3B and 4B houses that showed a wider range (range of about 2600-4600 kWh/year).
- Household 52 is the highest consumer of energy with a demand of 2974.1 kWh/year followed by household 16 with 2918.3 kWh/year. The high energy demand of households 52 and 16 is likely due to high occupancy. 52 is a four-member household with one 'stay at home' member and 16, a five-member household with two full time working members and three children.
- Household 73 had the lowest energy demand of the 15 homes (see Fig. 73).

- The total energy consumption from the 15 2B homes is about 39260 kWh/year or 553 kWh/m^2/year.

<u>3B houses</u>

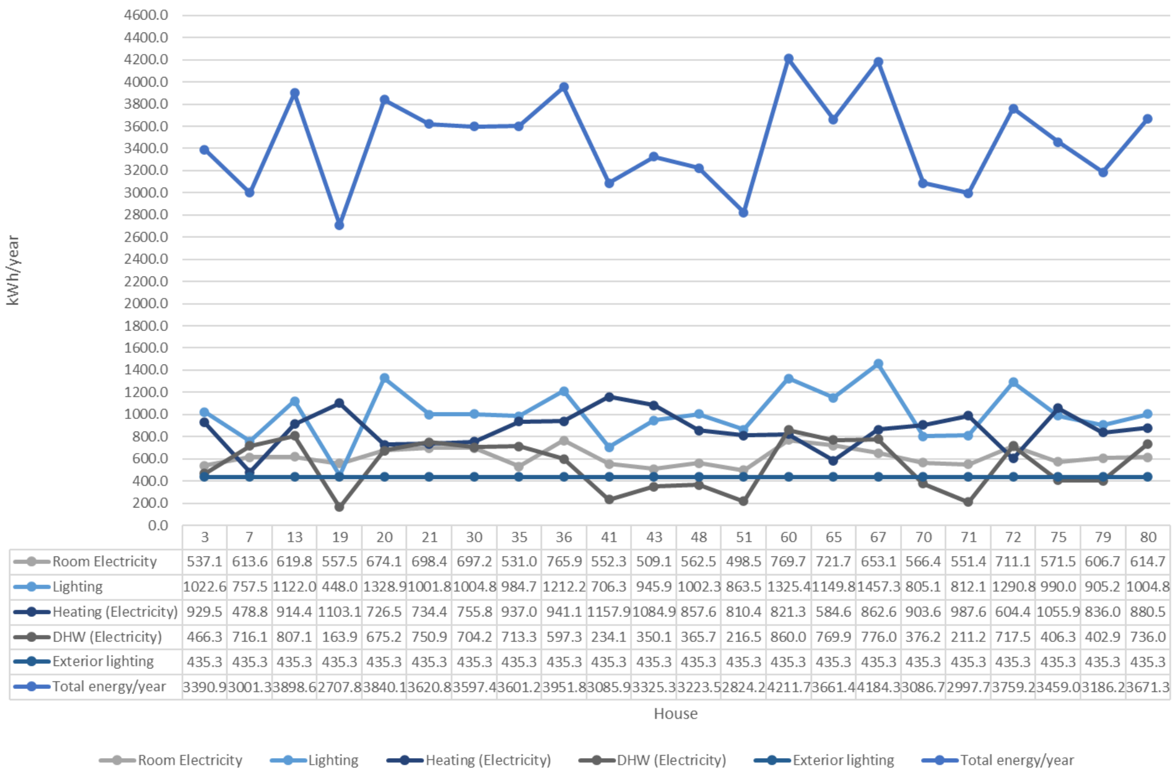
The prototype community includes 22 3B houses. The energy results for heating, DHW, equipment and lighting for 3B houses has been discussed in this section (see Fig. 76). It can be seen that:

- Household 19 has the lowest lighting and DHW consumption indicating an overall low energy demand for the house.
- House 20 showed the high lighting usage (1328.9 kWh/year)
- Household 41 indicated high heating consumption of 1157.9 kWh/year
- Household 51 has the lowest equipment usage compared to all other 3B homes
- Household 60 showed the highest equipment and DHW consumption and, very high lighting usage (second highest consumer) thereby indicating a high total annual energy demand.

Inferences from 3B houses' energy results:

- The annual energy consumption for 3B houses ranges between about 2700 to 4200 kWh/year.
- Household 19 has the lowest energy demand (2707.8 kWh/year) in comparison to all 3B houses. Both lighting and hot water consumption are low given that the household is a one full time working member house. Regardless, the house is one of the highest consumers of heating possibly due to the heating being kept on all day on the weekends.

- Household 60 is the highest consumer of energy of the 3B houses with annual energy consumption of 4211.7 kWh/year. Household 60 is a four-member household with two 'stay home' members thereby having a significant impact on lighting, DHW and equipment usage.
- House 41 indicated a higher heating energy requirement as the heating remains on all day during the weekdays regardless of the home being unoccupied.
- The total energy consumption from the 22 3B homes is about 76300 kWh/year or 647.6 kWh/m^2/year.



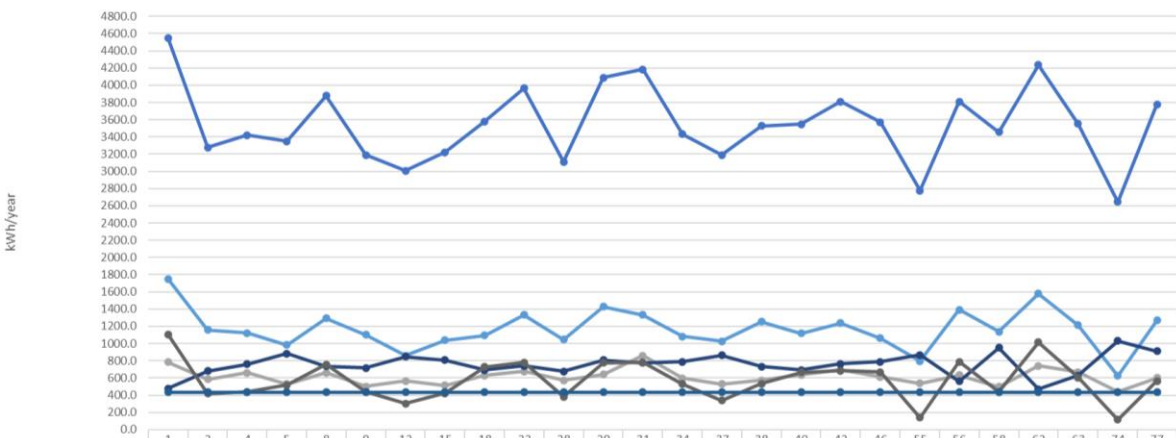
	3	7	13	19	20	21	30	35	36	41	43	48	51	60	65	67	70	71	72	75	79	80
Room Electricity	537.1	613.6	619.8	557.5	674.1	698.4	697.2	531.0	765.9	552.3	509.1	562.5	498.5	769.7	721.7	653.1	566.4	551.4	711.1	571.5	606.7	614.7
Lighting	1022.6	757.5	1122.0	448.0	1328.9	1001.8	1004.8	984.7	1212.2	706.3	945.9	1002.3	863.5	1325.4	1149.8	1457.3	805.1	812.1	1290.8	990.0	905.2	1004.8
Heating (Electricity)	929.5	478.8	914.4	1103.1	726.5	734.4	755.8	937.0	941.1	1157.9	1084.9	857.6	810.4	821.3	584.6	862.6	903.6	987.6	604.4	1055.9	836.0	880.5
DHW (Electricity)	466.3	716.1	807.1	163.9	675.2	750.9	704.2	713.3	597.3	234.1	350.1	365.7	216.5	860.0	769.9	776.0	376.2	211.2	717.5	406.3	402.9	736.0
Exterior lighting	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3
Total energy/year	3390.9	3001.3	3898.6	2707.8	3840.1	3620.8	3597.4	3601.2	3951.8	3085.9	3325.3	3223.5	2824.2	4211.7	3661.4	4184.3	3086.7	2997.7	3759.2	3459.0	3186.2	3671.3

Figure 76 - Annual energy results by function and house number for 3B houses

4B houses

The model community comprises 26 4B houses. Figure 77 shows the energy data for heating, equipment, lighting, DHW and exterior lighting for the 4B houses. The following findings were gathered from the energy results:

- House 1 showed the highest consumption of lighting and DHW. However, a relatively low heating energy demand.
- Household 31 has the highest equipment use and comparatively high lighting energy consumption (1333.3 kWh/year).
- Household 55 indicated the lowest consumption of DHW (141.2 kWh/year).
- Household 62 showed comparatively high lighting and DHW use. Whereas, low heating consumption similar household 1.
- Household 74 has the lowest equipment, lighting and DHW consumption. However, the household is the highest consumer of heat.



	1	2	4	5	8	9	12	15	18	22	28	29
Room Electricity	782.9	586.0	662.1	530.5	660.2	500.5	566.1	513.0	628.8	676.1	573.2	641.5
Lighting	1749.8	1156.2	1122.2	981.7	1293.4	1100.8	858.6	1038.7	1095.4	1333.0	1044.9	1426.4
Heating (Electricity)	475.7	679.4	761.6	883.8	734.7	717.0	846.0	808.8	691.1	739.9	676.9	807.6
DHW (Electricity)	1105.0	419.1	438.6	518.2	754.6	435.9	302.4	423.7	728.1	780.1	381.3	777.0
Exterior lighting	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3
Total energy/year	4548.7	3276.0	3419.8	3349.5	3878.2	3189.5	3008.4	3219.5	3578.7	3964.4	3111.6	4087.9

	31	34	37	38	40	42	46	55	56	58	62	63	74	77
Room Electricity	857.6	597.5	528.9	573.4	635.8	692.0	613.6	536.9	631.4	497.1	739.3	667.8	438.9	601.5
Lighting	1333.3	1080.2	1025.3	1254.3	1119.8	1237.2	1062.1	797.7	1391.8	1136.5	1577.9	1212.5	624.8	1268.1
Heating (Electricity)	777.4	788.7	862.1	730.1	692.1	763.1	789.7	866.8	561.5	950.4	469.2	630.6	1031.4	909.4
DHW (Electricity)	779.9	531.0	339.9	532.6	664.5	683.4	670.1	141.2	789.4	438.6	1014.6	605.2	113.9	565.5
Exterior lighting	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3	435.3
Total energy/year	4183.6	3432.6	3191.4	3525.8	3547.5	3810.9	3570.9	2777.9	3809.4	3457.8	4236.3	3551.3	2644.4	3779.9

Figure 77- Energy data for 4B houses

Inferences from 4B houses' energy results:

- The annual energy consumption for 4B houses ranges between about 2600 to 4600 kWh/year.
- Household 1 had the highest energy consumption of all 4B homes. House 1 is a five-member household with two 'stay home' members. Its occupancy schedule and density play a critical role in its increased energy consumption.

- The succeeding highest consumer of energy was household 62 with an energy demand of 4236.3 kWh/year. 62 is a four-member household with three ‘stay home’ members.
- Household 74 was the lowest overall consumer of energy possibly due to its low occupancy (1 member).
- Household 31, a four-member house also includes a ‘stay home’ member which has a significant impact on lighting and equipment use.
- The total energy consumption of the 26 4B homes is about 92150 kWh/year or 726.7 kWh/m^2/year.

Overall energy demand

Compiling the energy results from the 74 models, a total annual energy demand was calculated for the prototype community. As the energy supply is predominantly from roof top solar panels, it is critical to gather the energy demand for each season as solar incidence and thereby solar energy vary significantly based on season. The year is separated into quarters with each season comprising 3 months. December to February is considered to be winter, March to May, spring, June to August is summer and September to November is autumn. Table 36 indicates annual as well as seasonal energy demand results for the community.

Table 39 - Total annual and seasonal energy demand of prototype community

Annual	Winter	Spring	Summer	Autumn
kWh/year	kWh/season			
229750	75880	54300	43850	55720

Hence, energy supply from solar panels must aim to meet both annual as well as season energy demand for the community to be net zero energy all through the year. Understanding seasonal energy is critical as the winter months may have insufficient solar irradiance due to low sun angles and possibility of overcast sky conditions typical of the winter season in the temperate climate. See Appendix 5 for comprehensive energy results and corresponding calculations.

7.3. **Energy supply from houses**

This section discusses renewable energy supply from solar energy from houses. As indicated in ‘section 6.1.1’ the development will rely on on-site solar energy. Each house is designed with solar panels that act as shading for the south facing balcony (see ‘section 6.1.2’). The solar panels are oriented to maximise solar irradiance during all seasons but also provide optimum shading (see Fig. 78). Four inclinations of solar panels have been considered for this – horizontal (0°), 28°, 45° and 74° (to the horizontal). The total solar panel area per house is 20 m^2. The total area of the 28°, 45° and 74° panels are 4 m^2 each (8m total length x 0.5m total width) and the horizontal panel, 8 m^2. The solar energy incident on each of these surfaces is obtained from Designbuilder. Table 37 shows the solar incident energy on the four solar arrays and the average monthly solar incident energy collected from each house.

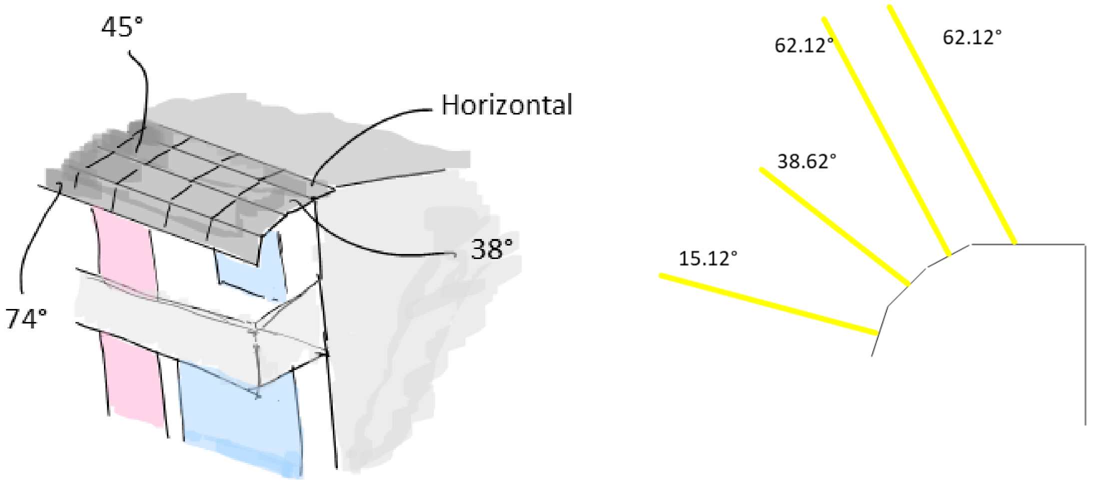


Figure 78 - Solar panels angled to optimise incident solar radiation

Table 40 - Solar incident energy from four variations of solar panel inclination

Date/Time	solar panel inclination at… 0°	28°	45°	74°	Total solar energy (kWh)
	Solar Incident (kWh)				
01/12/2002	67.9	101.5	114.0	176.6	460.1
01/01/2002	87.2	143.6	164.6	207.5	602.9

01/02/2002	132.5	187.2	205.0	298.8	823.4
01/03/2002	264.3	313.4	322.4	436.6	1336.6
01/04/2002	432.2	492.8	495.6	502.3	1923.0
01/05/2002	609.4	635.5	613.1	459.2	2317.3
01/06/2002	586.8	597.6	570.4	506.3	2261.2
01/07/2002	618.8	643.9	620.4	497.5	2380.6
01/08/2002	541.7	594.8	586.8	390.9	2114.1
01/09/2002	359.4	423.4	432.2	320.8	1535.7
01/10/2002	215.4	295.9	321.1	193.3	1025.7
01/11/2002	114.7	166.5	185.0	121.4	587.5
Total	4030.4	4596.2	4630.5	4111.1	

Table 38 shows the incident solar energy per square meter for the four variations of solar panels. Combinations of the solar panels helped identify the optimum area and inclinations of panels to maximise solar energy (see Appendix 5). Winter months are likely to have reduced solar incident energy given the lower angles of sun and overcast sky conditions leading to deficit energy, that is the energy demand is more than the energy supply. Hence, the exercise analysing combinations of solar panel inclinations was essential. Based on these findings and calculations, seasonal solar incident energy was obtained for a combination of 0°, 28°, 45° and 74° panels as indicated in Fig. 78.

Table 41 - Solar incident energy from four variations of solar panel inclination per area

Date/Time	Solar incident energy				
	0°	28°	45°	74°	Solar panel combination (0° + 38° + 45° + 74°)
	kWh/m2				kWh/m2
01/12/2002	8.5	25.4	28.5	44.2	106.5
01/01/2002	10.9	35.9	41.1	51.9	139.8
01/02/2002	16.6	46.8	51.2	74.7	189.3

01/03/2002	33.0	78.3	80.6	109.1	301.1
01/04/2002	54.0	123.2	123.9	125.6	426.7
01/05/2002	76.2	158.9	153.3	114.8	503.1
01/06/2002	73.4	149.4	142.6	126.6	491.9
01/07/2002	77.4	161.0	155.1	124.4	517.8
01/08/2002	67.7	148.7	146.7	97.7	460.8
01/09/2002	44.9	105.8	108.0	80.2	339.0
01/10/2002	26.9	74.0	80.3	48.3	229.5
01/11/2002	14.3	41.6	46.2	30.3	132.5

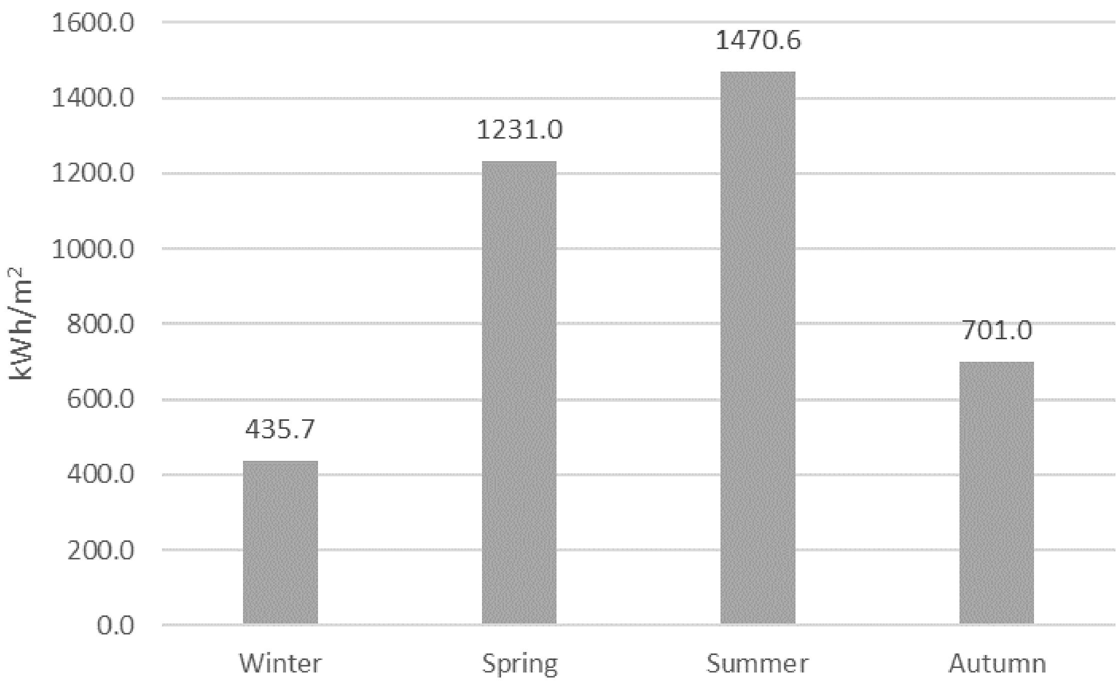


Figure 79 – Seasonal solar incident energy for the houses

To calculate the total solar energy produced from the solar panels, an online tool was used (Photovoltaic Software, n.d.). It has a comprehensive photovoltaic GIS database which is free and easy to use. The online tool uses a simple global formula to arrive at the solar energy results for the site situated in Sutton (see equation 4).

$$E = A * r * H * PR \quad (4)$$

Where, E is solar energy in kWh/annum, A is the total area of solar panels in m^2, r is solar panel yield (%), H is total annual irradiation on panels and PR is performance ratio. Performance ration measures how well a PV system performs taking into account the active area of the PV module (m^2), its efficiency and environmental factors such as temperature and irradiation. Solar panel yield informs how much solar energy is actually harvested from the panels. Here, A and H are calculated from design and Designbuilder data. Whereas, default values of 20% for 'r' and 0.75 for 'PR' have been used.

Calculating total solar panel area:

Total area of solar panels = 74 (houses) x 20 m^2 (per house) = 1480 m^2

Substituting H with seasonal solar irradiance shown in Fig. 79 and using A of 1480 m^2, the following calculations are made to obtain season solar energy from 'equation 4'.

$E_{winter} = 1480 \times 0.2 \times 435.7 \times 0.75$

$E_{spring} = 1480 \times 0.2 \times 1231 \times 0.75$

$E_{summer} = 1480 * 0.2 * 1470.6 * 0.75$

$E_{autumn} = 1480 * 0.2 * 701 * 0.75$

The total season and annual energy supply for the prototype community from solar panels obtained using the above calculations is shown in Table 39. The results indicated that a total of about 850,000 kWh/year of electricity can be produced from on-site solar energy.

Table 42 - Total annual and seasonal energy supply from houses

Season	Winter	Spring	Summer	Autumn	Annual
	kWh/season				kWh/year

Solar irradiance/season from houses	851585	96667	273116	326275	155527

Summary

The chapter presented the key methodology used which is energy modelling and simulation on Designbuilder software to obtain energy results for the prototype houses situated in the prototype community in Sutton, UK. The chapter also deliberated model validation using data from 1995 Building Regulations. Four protoblocks were shortlisted based on energy simulations to be used for large data analytics. The chapter discussed the total as well as components’ energy demands from houses and data of energy supply from roof top solar panels.

Chapter 8

Discussions

8.1. Energy demand vs supply

A key objective of the thesis is to find out if the energy demand of a prototype community designed for the UK can be met by the renewable energy supply produced from on-site renewable sources. That is, the test identifies if the developed model community achieves net zero energy. Detailed calculations from Chapter 7 helped arrive at the total annual energy demand of the community. Furthermore, energy demand was derived for the four seasons. It is critical to analyse season energy demand versus supply as winters typically have higher energy demand from heating and lower energy supply from solar irradiance as shown by the results. Table 40 shows the results for energy demand versus supply for the model community.

Table 43 - Total annual and seasonal energy demand, supply and surplus/deficit of prototype community

Houses	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Energy demand	229748	75880	54298	43850	55720
Energy supply	851585	96667	273116	326275	155527
Surplus energy	621838	20788	218818	282425	99807

Energy supply versus demand indicates that the community achieves not net zero but a net positive energy benchmark. However, assume that the community does not include battery storage for the energy produced from solar panels. Now, applying equations '1' and '2' from 'section 2.1.3' to the results shown in Table 40, import energy (i.e., energy demand met by grid) and export energy (i.e., energy supplied to the grid) can be calculated. World Bank statistics show that typical electric power transmission losses for the UK are about 8% (The World Bank, 2018). Therefore, subtracting the energy lost in transmission from the supply (feed-in energy to grid) and adding the energy that will be lost in transmission to meet the demand (energy delivered from grid), the following energy data can be obtained for the community (see Table 41). Regardless of the energy losses incurred, the model community still meets a net positive energy benchmark. The community produces about 535000 kWh/year surplus energy.

Table 44 - Total annual and seasonal energy demand, supply and surplus/deficit of prototype community after transmission losses

Houses	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Energy demand	248127	81950	58642	47358	60178
Energy supply	783458	88933	251266	300173	143084
Surplus energy	535330	6983	192624	252815	82907

Reducing the energy demand at the design stage by using sustainable design principles and fabric efficiency was a critical step to achieving net zero. A comparison of the energy demand of individual households of the model community to the standards discussed in the literature review (section 2.1.2) is shown in Table 42. The calculations for these results have been indicated in Appendix 5.

Table 45 - Comparison of model community energy demand to standards from literature (Pelsmakers, 2015)

Benchmark	Space heating	Hot water	Lighting, fans, pumps, cooling	Appliances, equipment	Cooking, catering	Total energy demand
	kWh/m^2 per year					
Dwelling, Building Regulations	60	55	10	25	15	165
Zero carbon dwelling	39-46	55	10	25	15	144-151

Dwelling, Passivhaus standard	15	55	10	25	15	120
Model community	5.6	6.3	8.8	14.8		34.8

It can be noted that the average annual heating demand per area for the model community is almost a third of the Passivhaus standard which uses an air tight construction system (typical air tightness of 0.6 ACH or less). The air tightness used for the protoblocks in energy modelling is 0.2 ACH. Furthermore, an investigation into thermal comfort of these modelled households indicated that the average internal temperature was maintained at 21.1°C thereby conforming to standards (CIBSE Guide A, 2006). The comparison also showed that the community's lighting energy demand per area for the year is close to all three standards with a difference of about 1 kWh/m^2/year. Additionally, the unregulated energy (equipment, catering and external lighting) demand of the community was also about a third of the demand quoted by standards and DHW almost 10% of the standards discussed. Overall energy demand was calculated to be 30% of the Passivhaus standard and 25% of zero carbon dwelling standard. While as much of the unregulated energy use of the prototype community was controlled by survey data, it was almost 25 kWh/m^2/year short of the standard. Adding this remainder unregulated energy to the overall annual energy demand per area for the model community produces a total energy demand of about 60 kWh/m^2/year, which is still about half the Passivhaus standard.

8.2. Lifestyles

The survey on typical British lifestyles designed for the thesis (discussed in Chapter 5) helped collect information on various lifestyles prevalent in the UK. Analysis of survey data indicated a range of households and lifestyle patterns in terms of occupancy, heating and equipment usage. However, this thesis categorises these lifestyles into three broad categories – frugal, typical and extravagant. Households with a frugal lifestyle may be conscious and careful about their energy use, whereas extravagant households may have a wasteful use of energy. For example, a frugal household may turn on the heating only when absolutely necessary, whereas, an extravagant household may leave the heating on at all times in an attempt to maintain indoor temperatures. The three lifestyles have been defined using two key parameters, heating and occupancy and have the following conditions:

- Where the number of hours of heating is less than 6 hours per day and the occupancy density is greater than zero during the unheated period, the household is considered to be frugal.
- Where the hours of heating in a day is between 6-24 hours and the occupancy density is greater than zero during the heated period, the household is categorised as typical lifestyle.
- Where the number of hours of heating is between 6-24 hours in a day and the occupancy density is 0 during the heated period, the household is extravagant.

Based on these conditions, the households have been categorised as frugal, typical and extravagant. 15 of 74 homes (about 20%) were classified as frugal, 8 of 74 households (about 11%) extravagant and 51 of 74 houses (about 69%), typical. 1B houses had more frugal lifestyle when compared to 2B, 3B and 4B houses. Similarly, 3B houses had the maximum number showing extravagant lifestyle in comparison to the other three. The results shown in 'section 7.1' are based on a community with 20% frugal, 69% typical and 11% extravagant households. Therefore, a few tests were conducted on lifestyle variations to comprehend how the energy demand vs supply balance may be affected.

<u>Case 1: 100% typical lifestyle</u>

Now consider a case where all households were typical. The heating schedules for the frugal and extravagant lifestyles have been altered to match the second condition described above. These are extrapolated from households with a similar household composition (see Appendix 5 for details). The average energy for each of the household sizes for the base case and case 1 (100% typical community) are shown in Fig. 80.

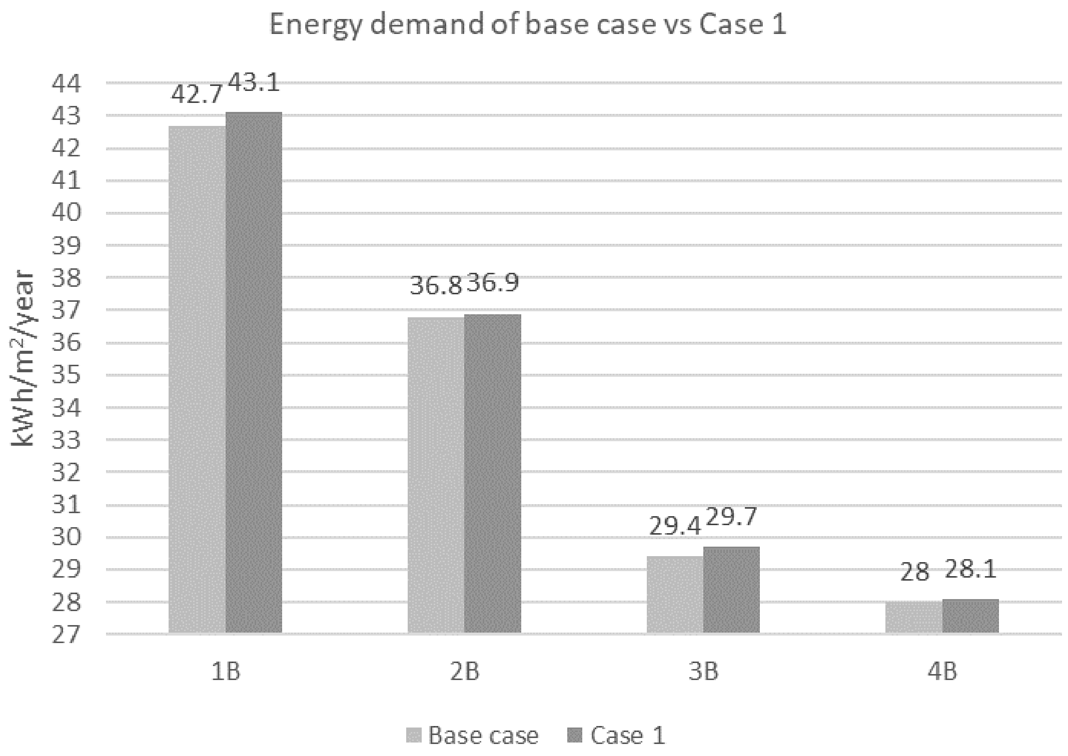


Figure 80 - Comparison of total average annual energy demand per area of base case to Case 1

It can be noted that, the difference in average household energy demand between the two cases is marginal. Indicated in Table 43 are the energy results for Case 1. The total annual energy demand for the 100% typical community is about 1200 kWh/year more than the base case. The revised results show that the community still meets a net positive energy benchmark.

Table 46 - Total annual and seasonal energy demand, supply and surplus/deficit of base case compared to Case 1

	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Base case demand	229748	75880	54298	43850	55720
Energy demand Case 1	230977	76631	54543	43850	55953
Energy supply	851585	96667	273116	326275	155527
Surplus energy	620608	20036	218573	282425	99574

Now, recalculating the energy results with transmission losses, the following data was obtained for case 1 (see Table 44). The community has an annual surplus energy of about 534000 kWh/year.

Table 47 - Total annual and seasonal energy demand, supply and surplus/deficit of base case compared to Case 1 with transmission losses

	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Base case demand	248127	81950	58642	47358	60178
Energy demand Case 1	249455	82762	58906	47358	60429
Energy supply	783458	88934	251267	300173	143085
Surplus energy	534004	6172	192361	252815	82656

Case 2: 89% typical + 11% extravagant

This case includes a community that has no frugal households, that is, the community is about 90% typical and 10% extravagant. The extravagant households have been maintained and the frugal households have been changed to typical lifestyle based on the conditions. Shown in Fig .81 are energy demand results comparing the base case, case 1 and case 2 for 1B, 2B, 3B and 4B houses. The difference in average household energy demand between the cases is minimal. Table 45 shows the energy demand vs supply results for case 2 for the year and for each season.

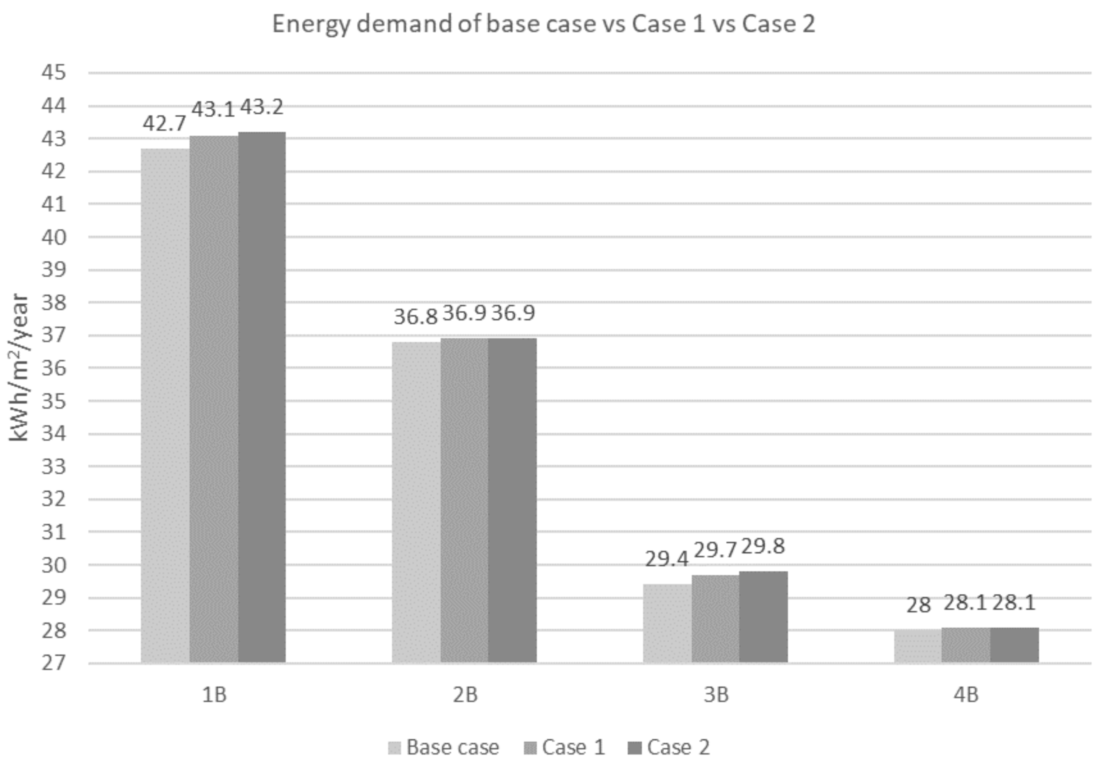


Figure 81 - Comparison of total average annual energy demand per area of base case and Case 1 to Case 2

Table 48 - Total annual and seasonal energy demand, supply and surplus/deficit of base case compared to Case 2

	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Base case demand	229748	75880	54298	43850	55720

Energy demand Case 2	231465	76912	54654	43850	56050
Energy supply	851585	96667	273116	326275	155527
Surplus energy	620120	19755	218462	282425	99478

The total annual energy demand for Case 2 is about 1700 kWh/year more than the base case. Case 2 also showed about 500 kWh/year more consumption than Case 1. The energy results revised for the 89% typical and 11% extravagant case show that the community has a surplus of about 620000 kWh/year and still meets a net positive energy benchmark. As tested for the base case and Case 1, Table 46 recalculates the energy results with transmission losses to conform with net zero or net positive energy benchmark for the annual energy. The community has an annual surplus energy of about 533500 kWh/year.

Table 49 - Total annual and seasonal energy demand, supply and surplus of base case compared to Case 2 with transmission losses

	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Base case demand	248127	81950	58642	47358	60178
Energy demand Case 2	249983	83065	59027	47358	60533
Energy supply	783458	88934	251267	300173	143085
Surplus energy	533476	5869	192240	252815	82551

Case 3: 100% extravagant

As an attempt to test net zero to its limits, a case where all of the community has an extravagant lifestyle is considered. Four households, one from each of the house types (1B – 4B) with high heating consumption (compared to other households) and heating on at all times during the day were identified. Households 49 (1B house), 73 (2B house), 41 (3B house) and 58 (4B house) had their heating on for 24 hours and heating energy consumptions of about 324, 542, 1158 and 950 kWh/year respectively. The heating energy consumption for all houses under each house type was extrapolated from the heating energy consumption data of households 49, 73, 41 and 58. That is, all 1B houses are considered to have the same heating energy consumption (as household 49) of about 324 kWh/year, 2B houses, 542 kWh/year and so on for this case. Figure 82 shows the energy demand results for case 3 in comparison to the base case, case 1 and case 2 for the four houses sizes.

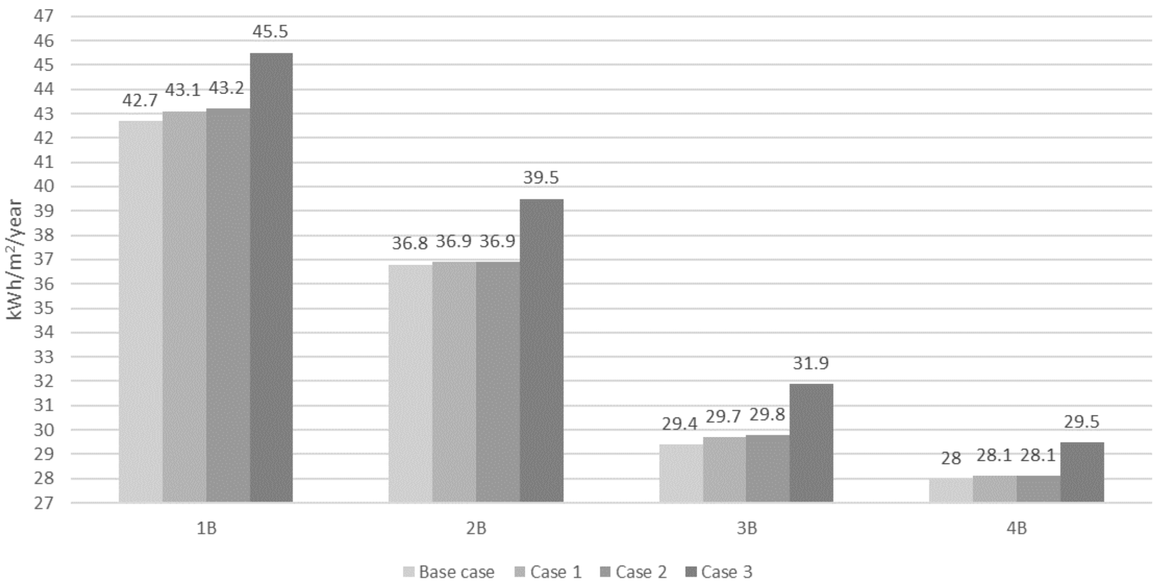


Figure 82 - Comparison of total average annual energy demand per area of Case 3 to base case, Case 1 and Case 2

Unlike cases 1 and 2 where there was marginal difference in annual average energy consumption per area, case 3 showed an increase in annual average household energy consumption per area of about 1.5-3 kWh/m^2/year. Table 47 shows the energy demand vs supply results for case 3 for the year and for each season.

Table 50 - Total annual and seasonal energy demand, supply and surplus/deficit of base case compared to Case 3

	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Base case demand	229748	75880	54298	43850	55720
Energy demand Case 3	245611	83763	58280	43850	59718
Energy supply	851585	96667	273116	326275	155527
Surplus energy	605974	12904	214836	282425	95809

It can be noted that the energy demand of case 3 is about 15000 kWh/year more than the base case. Nevertheless, the energy balance indicated a surplus energy of about 606000 kWh/year. Table 48 recalculates the energy results with transmission losses for Case 3. The community has an annual surplus energy of about 518200 kWh/year. However, the winter season has an energy deficit of about 1530 kWh/year.

Table 51 - Total annual and seasonal energy demand, supply and surplus/deficit of base case compared to Case 3 with transmission losses

	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Base case demand	248127	81950	58642	47358	60178
Energy demand Case 3	265260	90464	62942	47358	64496
Energy supply	783458	88934	251267	300173	143085
Surplus energy	518199	-1530	188325	252815	78589

To meet the energy deficit in winter, the community requires an additional energy supply of about 1600 kWh/year in winter. Using equation 4 from 'Section 6.4', the area of solar panels required to meet the deficit energy in winter can be obtained. Table 49 shows the solar incident energy per area per month and seasonal solar incident energy for solar panel inclination of 35°, a year-round optimum solar panel tilt for the UK (Viridian Solar, n.d.).

Table 52 - Solar incident energy per area per season from solar panel inclination of 35°

Date/Time	Solar incident energy 35°	
	kWh/m^2	kWh/m^2/season
01/12/2002	27	
01/01/2002	38.5	114.6
01/02/2002	49.1	
01/03/2002	79.8	
01/04/2002	124.2	361.2
01/05/2002	157.1	
01/06/2002	147	
01/07/2002	159.1	454.8
01/08/2002	148.6	
01/09/2002	107.5	
01/10/2002	77.3	228.7
01/11/2002	44	

Substituting E (1600 kWh/year), r (0.2), H (114.6 kWh/m^2/year) and PR (0.75), the following area of solar panels is obtained from equation 4.

$$A = \frac{E}{r \times H \times PR} = \frac{1600}{0.2 \times 114 \times 0.75} = 93\ m^2$$

About 95 m^2 of additional solar panels at 35° inclination is required to produce 1600 kWh/year to meet the deficit energy in winter. The additional solar panels could be accommodated on the community offices' rooftop (see Fig.83). The community offices block has a flat roof area of about 245 m^2.

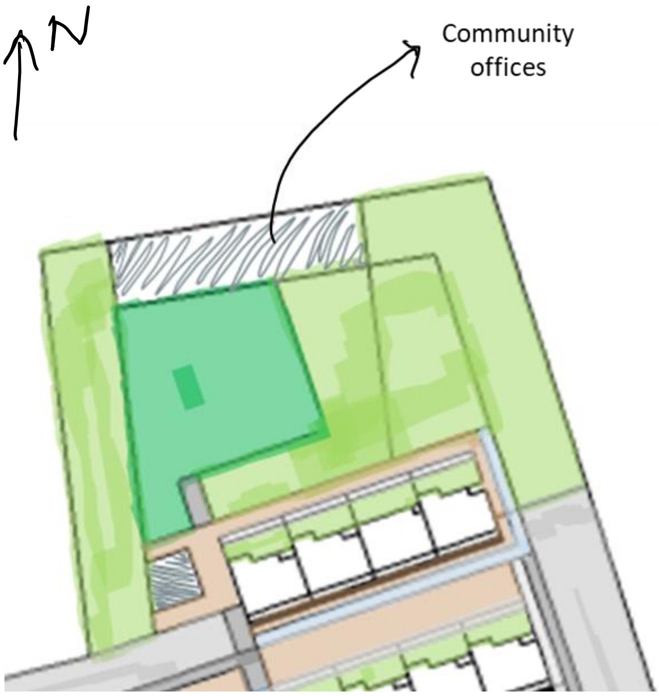


Figure 83 – Close up site plan showing location of Community offices for additional roof top solar panels

8.3. Energy demand from amenities

Alongside 74 houses, the model community includes amenities such as a community centre, offices and a café. These amenities encourage economic sustainability and social wellbeing. Sections 7.1 and 7.2 indicated that the energy demand from the houses can be met by the energy supply from the solar panel shade included on the south façade of each house. However, taking into account the energy demand from amenities could have a significant impact on the overall energy demand of the community. The prototype houses were designed to be highly energy efficient. Hence, it was important to include highly energy efficient non-domestic buildings to obtain an overall low energy demand for the community. The addition of these amenities in the energy calculations was an attempt to show realism in net zero performance without modelling these. Table 50 shows the energy data for these building typologies obtained from non-domestic examples that are accredited by BREEAM or Passivhaus.

Table 53 – Energy demand per area from amenities

Amenity	Case Study	Energy consumption (kWh/m^2/year)	Accreditation
Community Centre	Husthwaite Village Hall (Carbonbuzz, 2015)	35.4	Passivhaus
Café	Pool Innovation Centre (Carbonbuzz, 2015)	91.4	BREEAM - Excellent
Community offices			

The café is part of the community offices building and these thereby jointly use the energy consumption data from the Pool Innovation Centre for energy calculations. Table 51 indicates the annual energy demand from the amenities (inferred from RIBA+CIBSE case studies) within the model community and the total energy demand calculated from these.

Table 54 - Annual energy demand from amenities

Amenity	Floor area	Energy consumption	
	m^2	$kWh/m^2/year$	kWh/year
Community Centre	82.5	35.4	2920.5
Café Community offices	735	91.4	67179
Total			70099.5

Since the energy consumption information gathered for the amenities is provided for the whole year, the energy demand was approximated using the same percentage contribution of seasonal energy consumption to the annual energy consumption of the houses. The household energy demand for winter constituted about 33% of the total annual energy demand. Likewise, spring and autumn accounted for 24% each and summer, 19% of the total annual energy demand for the houses. Table 52 shows the estimated seasonal energy demand for the amenities based on these percentages.

Table 55 – Seasonal, annual and total energy demand from houses and amenities

	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Energy demand from houses	229748	75880	54298	43850	55720
Energy demand from amenities	70100	23152	16567	13379	17001
Total community energy demand	299848	99032	70865	57229	72721

The total energy demand of the community includes the energy consumption from the 74 households (about 229750 kWh/year) and the energy consumption from amenities (about

70100 kWh/year) which is about 299850 kWh/year (see Table 53). Now, comparing the revised total energy demand to the annual and seasonal energy supply from section 6.4, indicated how much deficit or surplus energy is obtained (see Table 53).

Table 56 – Seasonal, annual and total energy demand from houses and amenities

Whole community	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Base case demand	299848	99032	70865	57229	72721
Energy supply from houses	851585	96667	273116	326275	155527
Surplus energy	551738	-2365	202251	269046	82806

The comparative analysis of the energy supply versus demand shows that the community has an annual surplus energy of about 551700 kWh/year. However, it does incur a deficit of about 2400 kWh/year in the winter months. This can be met with energy supply from additional solar panels accommodated on the community centre roof (as discussed in section 7.2). Applying transmission losses to the energy demand and supply data from Table 54 conforms a net positive energy status for the year but a deficit of almost 18000 kWh/year (about 17% of the energy demand) in winter (see Table 54).

Table 57 – Total annual and seasonal energy demand including amenities, supply and surplus/deficit of base case

Whole community	Annual	Winter	Spring	Summer	Autumn
	kWh/year	kWh/season			
Base case demand	323835	106954	76535	61808	78539
Energy supply from houses	783458	88934	251267	300173	143085
Surplus energy	459623	-18020	174732	238365	64546

The community requires additional solar panels to support this energy deficit in winter. Working backwards, as done for the 100% extravagant community case which had a deficit energy in winter (see Section 7.2), the area of solar panels required to meet the deficit energy of about 18000kWh/year in winter can be calculated using equation 4. Consider a solar panel inclination of 35° which is the recommended year-round optimum inclination. The solar incident data for a solar panel tilt of 35° are indicated in Table 49. Substituting E (18020.5 kWh/year), r (0.2), H (114.6 kWh/m^2/year) and PR (0.75), the following area of solar panels is obtained from equation 4.

$$A = \frac{E}{r \times H \times PR} = \frac{18020.5}{0.2 \times 114.6 \times 0.75} = 1048\ m^2$$

About 1050 m^2 of additional solar panels at 35° inclination is required to produce 18000 kWh/year to meet the deficit energy in winter. Some of the additional solar panels could be accommodated on the community centre and community offices roof top. However, the available roof area for solar panels is only about 240 m^2. Hence, the community could incorporate solar panel arrays on the upper levels of the stepped vertical farm (see Fig. 84)

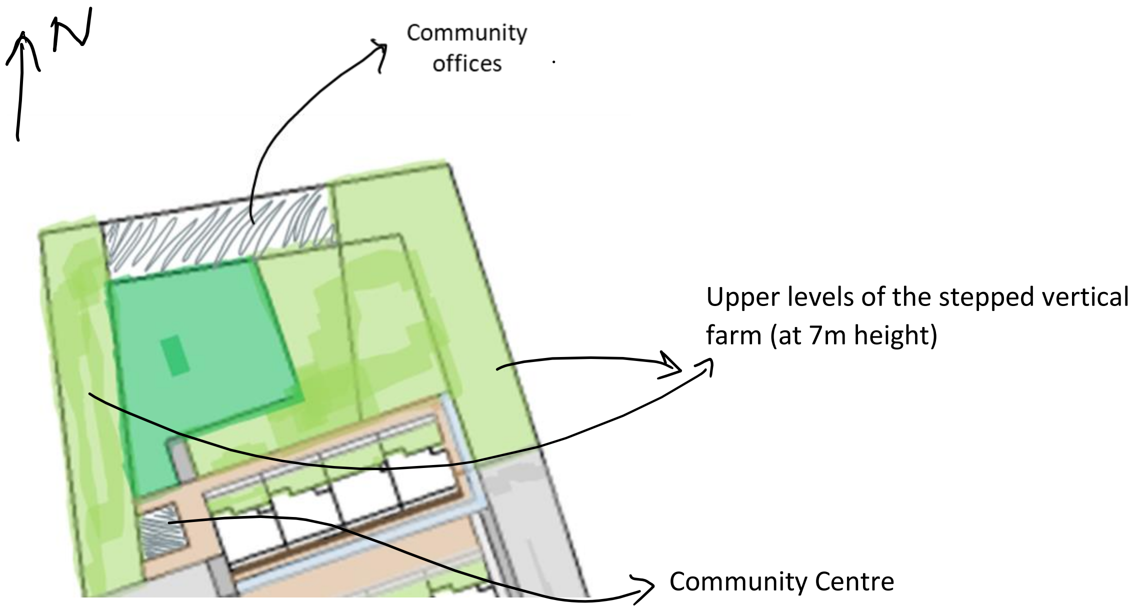


Figure 84 – Close up site plan showing location of Community offices, community centre and stepped farm for additional roof top solar panels

Table 55 shows the total area of solar panels available to accommodate additional solar panels to support the deficit energy in winter. It can be noted that there is a requirement for another 500 m^2 of solar panels to support the deficit energy.

Table 58 - Area of roof top solar panels for amenities

Area of roof top solar panels for community offices	180 m^2
Area of solar panels for stepped farm	300 m^2
Area of roof top solar panels for community centre	20 m^2
Total area of solar panels from amenities	500 m^2

Using equation 4, the 500 m^2 of solar panels produce an energy of about 8600 kWh/year in winter. The remaining energy deficit (about 10000 kWh/year) could be imported from an external clean energy source. Conversely, the solar panel tilt could be changed to suit the winter sun angle, say solar panel tilt of 72° to the horizontal. Substituting 'H' with 170.7 kWh/m^2/year (the season solar irradiance for a solar panel tilt of 72°) in equation 4 produces an energy supply of about 12800 kWh/year. However, in this case the spacing between the panels increases to avoid overshadowing and thereby reducing area of solar panels. Nevertheless, the community achieves an overall net positive energy benchmark in terms of annual energy despite the addition of energy demand from amenities.

8.4. Carbon compliance

Section 7.1 proves that a development may be highly energy efficient or self-sufficient in terms of energy. However, achieving net zero or net positive energy may not necessarily imply net zero carbon emissions. Hence, it is crucial to check if the operational carbon emissions from the development is well within the benchmark. Equation 5 is a simplified calculation method to obtain the carbon footprint from operation energy (Pelsmakers, 2015). Table 56 shows carbon emissions (from operational energy demand and supply) calculations using equation 5 for the model community.

$$\text{Carbon emissions} = \text{Energy} \times CO_2 \text{ fuel intensity} \qquad (5)$$

Where, fuel intensity for electricity = 0.519 $kgCO_2/kWh$, fuel intensity for gas = 0.216 $kgCO_2/kWh$ (SAP, 2012)

Table 59 - Carbon footprint calculations for the prototype community

	Energy demand	Emissions from demand
	$kWh/m^2/year$	$kgCO_2/m^2/year$
Heating	5.6	1.2
DHW	6.3	1.4
Lighting	14.4	7.5
Equipment	8.2	4.3
Total	34.8	14.3
	Energy supply	Emissions reduction from supply
	$kWh/m^2/year$	$kgCO_2/m^2/year$
Solar panels	686.8	356.4

Carbon compliance	= emissions from demand - emissions reduction from supply	-341.4

The Zero Carbon Hub proposes a carbon compliance of 11 $kgCO_2/m^2/year$ for terraced houses (Zero Carbon Hub, 2014). The model community does not only meet this proposed standard but exceeds performance by achieving a carbon negative footprint.

8.5. Net zero checklist

The net zero guide established in Chapter 4 from comparative analysis of five key global rating systems was used as a manual to develop the prototype net zero community. This section revisits the net zero guide and analyses the criteria and parameters that were achieved at the concept and design stage of the prototype community situated in the UK. Table 57 indicates the parameters of each criterion, how these were addressed and percentage awarded under each criterion. A total percentage is finally calculated to understand how well the community performs as a sustainable community that has successfully achieved net zero.

Table 60 - Checklist for net zero development revisited

Parameters	Method	%
Social, economic wellbeing and awareness (15%)		
Integrative planning – community engagement and involvement in planning	While the members of the community were not directly engaged in planning, the data from surveys on typical British lifestyles influenced house and urban design	8
Green policies and incentives – local regulations	Local regulations were used for building and urban design	
Affordability	Not addressed	
Economic impact – costs involved in developing community		
Economic resilience and growth – employment opportunities	Office spaces provided within the community for local businesses. Urban farm encourages residents to grow produce and sell it	

Community growth – skills	Not addressed	
Regional priority – socio-cultural initiatives, heritage preservation, local vernacular	Not addressed	
Ecology and environment (10%)		
Natural systems/ecosystem assessment	Not addressed	7
Natural resources conservation and restoration – water bodies, wetlands, agriculture lands	Site did not require this.	
Remediation of contaminated sites – brownfield sites	The community is developed on a brownfield site.	
Preservation of existing landscape – trees and water bodies	Site did not have existing landscape.	
Retain site topography?	Yes. The site is flat.	
Pollution control – during construction, light, noise and water	Not addressed	
Site, urban design and planning (20%)		
Site selection and analysis	Covered in detail in Chapter 6	15
Site layout and planning	Covered in detail in Chapter 6	
Responsive planning – mixed-use, neighbourhood, community dedicated facilities, services and amenities	Covered as part of urban design. Site analysis indicated proximity of key amenities to site. The community includes services, office spaces, cafe and a community centre on site.	

Safety and security	Check points placed at key locations on site.	
Sustainable urban design strategies – solar orientation, wind, UHI, microclimate, outdoor thermal comfort	Urban design informed from solar and wind access to site.	
Urban landscapes – parks and greenspaces	Terrace gardens, front and backyard lawns provided for each house. Permeable paving used on all paths and roads to restore ground water and prevent flooding.	
Accessible community facilities	Studied as part of site analysis.	
Housing diversity and typologies based on demographic needs	Surveys on typical British lifestyles helped understand demographic needs and provide houses of varying sizes accordingly.	
Local food production	The site includes terrace gardens and an urban stepped farm for local food growth.	
Energy efficient infrastructure – lighting, heating and cooling, equipment	Situated in the services and maintenance block towards the northern part of the site.	
Inclusive design	Ramps and lifts included in urban design making all zones of the site accessible.	
	Transport (10%)	
Connectivity and access to quality transit – proximity to public transport	Covered in site analysis	10

Sustainable transport and movement - Pedestrian network, Bicycle network, alternate fuel vehicles Parking - reduced parking footprint, local parking	Transport plan developed for pedestrian, public vehicle and service vehicle on site. Bicycle parking provided within each row of terrace houses. Vehicle free community with parking provided below structure.	
Energy and emissions (20%)		
Energy strategy - minimise energy demand, on-site/off-site renewable energy supply Energy efficient buildings – Sustainable building design, thermal comfort, certified green buildings Carbon emissions – embodied, operation, transport	Energy demand minimised. Energy results obtained from simulations indicated in Chapter 6. On-site solar energy used for renewable energy supply. Passive heating, ventilation and cooling strategies addressed in building design. Thermal comfort studied in terms of maintained indoor temperatures. Simple carbon compliance calculations performed for operational energy.	15
Materials (5%)		
Responsible sourcing of materials Recycle and reuse	Use of local materials. Not addressed	2
Water (10%)		
Water strategy and efficiency – assessment and reduction of demand, supply, guidelines, smart water systems Waste water management – treatment, reuse	Not addressed Grey water treatment in services block used for farming and gardening.	5

Stormwater management - rainwater harvesting	Rain water harvested on site, ground water recharge from permeable pavers.	
	Waste (5%)	
Construction waste management	Not addressed	2
Solid waste management – segregation of waste at site	Waste segregation encouraged at building and site level. Dedicated waste disposal areas provided near each of the terrace houses.	
	Other (5%)	
Innovation in design and technology	Stepped settlement, providing space under structure to be used for services and parking.	2
Involvement of energy accredited professional	Not addressed	
Providing facilities for workforce during construction		

The community has achieved a total of 66% (out of 100) at the concept and design stage using the net zero guide. Some key parameters were not addressed and the community may have performed just above average as a sustainable community but it has exceeded expectations in terms of achieving net zero and a carbon negative footprint.

Summary

The chapter investigated energy supply versus demand. The findings indicated that the model community has an annual energy surplus of about 535300 kWh/year (about 54% more than community need), thereby meeting a net positive energy benchmark. Discussions also identified the community to be carbon negative. Sensitivity analysis on lifestyles discussed three cases where the community had 100% typical households, 90% typical and 10% extravagant households or 100 % extravagant households. Cases 1 and 2 showed slightly higher energy demand (about 1200 and 1700 kWh/year for each case respectively) compared to the base case, which is about less than 1% increase. The analysis indicated an energy deficit of about 1500 kWh/year in the winter for Case 3. Nevertheless, the findings from the analysis showed that the community meets an overall net positive energy benchmark in all the three cases.

Chapter 9

Conclusions

9.1. Overview of the thesis

This thesis is an attempt to test the feasibility and workability of net zero in large scale developments. Of the several attempts made to tackle climate change, net zero energy and net zero carbon are key concepts that aim to curb the harmful effects of climate change. Net zero is a concept that has gained attention over the past two decades. Net zero developments are able to meet all of their energy demand through renewable energy supply. Studies have shown there is often a gap in research and practical applicability of the subject due to ambiguity in its understanding. It does not have a precise definition and countries world-wide are advocating climate change targets based on the varying conceptions they have of net zero. Some address net zero in terms of operational energy and some others in terms of emissions (operational and embodied). This thesis aimed to standardise net zero and establish a guide that can be used for the application of net zero in large scale developments.

A prototype net zero development situated in the London Borough of Sutton, UK was designed to accommodate 74 energy efficient houses alongside amenities (such as offices, café, etc.) and services. To develop and test this prototype community the following were addressed:

- Defining and evaluating net zero
  - Principles of net zero were identified along with a detailed study of five global energy rating systems for large scale developments to devise a net zero guide and standardise it.
  - A net zero balance equation was identified to apply to the prototype community to corroborate energy demand versus supply.

- Recognising current and past examples of sustainable, highly energy efficient or net zero communities
    - Case studies were identified and analysed methodically to gather data on sustainable house and urban design principles based on climate, location and site analysis, energy demand and renewable energy supply, sustainable principles for water, waste and transport, and materiality.
- Climate and location where the community will be situated
    - The prototype community is located in the London Borough of Sutton, UK which has a temperate climate classification. Building and urban design were appropriate to the temperate climate and based on detailed site analysis.
- Demographics and lifestyles of the residents that the prototype community will cater for
    - Data on typical British lifestyles were collected using online surveys. 81 surveys were completed by residents of Britain who have resided in the UK for at least five years or over, and were used to gather data on lifestyles and demographics.
    - The surveys helped assimilate data on house type and size, household sizes, occupancy, heating, DHW and equipment pattern which were used to formulate schedules to run energy simulations.
- Sustainable house and urban design appropriate to climate and location that has also accounted for demographics and lifestyles
    - The design was inferred from literature (housing standards and case studies), data collected from surveys on typical British lifestyles and analysis of five global energy rating systems for large scale developments.
    - The prototype community has a stepped structure including 74 one-to-four-bedroom houses accommodating one to five member households, a community centre, an

urban farm, a play area, central plaza, community offices, a café, parking and services under the stepped structure.

- Modelling the prototype community on energy simulation software to obtain energy consumption data for the year and seasons.
  - 67 'protoblocks', that is, the prototype house (for 1 bed, 2 bed, 3 bed and 4 bed) along with the adjacent and neighbouring buildings in combination, were modelled in Designbuilder, a whole building energy simulation software.
  - Model data to run energy simulations were gathered from surveys to obtain realistic outcomes.
  - Schedules on occupancy, heating, equipment, DHW and lighting developed from survey data were used to run the whole building energy simulations.
  - Total community energy demand per year and season was calculated from the building energy data obtained from energy simulations of protoblocks.
- Renewable energy supply available for the selected location and climate.
  - The community used on-site solar energy as its renewable energy supply. Each house includes 20 m^2 of solar photovoltaic panels that also act as shading for the south facing balcony on the first floor.
  - Solar energy incident on the solar array was obtained from the solar irradiance used in Designbuilder using real weather data.
- Investigating the energy demand of the prototype community versus renewable energy supply.
  - As a final step the thesis compares total energy demand of the community to the renewable energy supply produced from on-site solar energy.

- The community achieved a net positive energy status with an annual surplus of about 535000 kWh/year.
- Additionally, a carbon compliance study showed net negative carbon emissions with an offset of about 340 $kgCO_2/m^2$/year.

9.2. Key findings and contributions to wider research

The study indicated that net positive energy can be achieved by following sustainable building and urban design principles to obtain highly energy efficient developments. A development can achieve net negative carbon emissions in terms of operation by using appropriate construction and materials while acknowledging key aspects related to carbon emissions such as transport and energy supply. A crucial condition that impacted the energy performance (and thereby emissions) of the prototype community was user lifestyles. Chapter 4, a review on net zero case studies explained that the net zero developments failed to analyse implications of user lifestyles on the overall energy consumption of a development which led to a significant gap between predicted and measured energy data. Hence, a development that achieves a net zero status in concept may not truly achieve net zero as built. The survey on typical British lifestyles discussed in Chapter 5 could help diminish this performance gap and provide a better understanding of this gap at the concept and design stages.

The survey indicated three broad lifestyle patterns – the frugal, the typical and the extravagant. A community where 100% of the residents followed a typical lifestyle was able to achieve net positive energy. Even in the case where 100% of the prototype community followed an extravagant lifestyle, net positive energy was able to be achieved. Combining these three lifestyles, according to a realistic lifestyle mix informed by the survey, put the prototype community to the test; with different conditions that are likely to cause variations in the overall energy demand. The experiments indicated that the prototype community was highly energy efficient. The houses indicated a low heating energy demand possibly due to good fabric efficiency. An examination of thermal comfort of the households indicated that the average internal temperature was maintained at 21.1°C.

This thesis aimed to design a prototype community that was self-sufficient not only in terms of energy but economy, food, water, and waste management. Hence, the prototype community included some essential amenities and services. Nevertheless, the implications on the total annual energy demand of the prototype community still resulted in a net positive energy status. However, the colder months showed a higher energy demand (including energy from amenities) which was not sufficiently met by the energy supply from roof top solar panels.

While energy demand remained the crux of the research, energy supply was also analysed to identify an appropriate renewable energy supply option for the prototype community. While wind energy is prevalent in the UK, incorporating wind turbines in urban areas would be challenging and studies indicated micro wind may not be efficient. Water sources could not be identified near the site. Hence, hydro power was ruled out. Solar energy seemed most suited for the prototype community and solar panels were designed to maximise energy from the sun which aided the prototype community to achieve net positive energy. The reduced energy demand and increased energy supply also resulted in net negative operational carbon emissions.

The conception of a net zero development depends on many key factors. It was critical to consider various aspects beyond domestic energy demand and supply such as urban design, transport, key amenities within a commutable radius, etc., that are likely to impact the energy demand and carbon emissions of a development. While many regulatory bodies such as UKGBC and LETI address key points to achieve net zero specific to the building scale, studies indicated a lack of standardisation or a guide to achieve net zero especially for large scale developments. A substantial part of the thesis involved developing a net zero framework that can act as a pilot guide which can be developed and refined for use as a standard for net zero. As indicated by frameworks and benchmarks in Chapter 2, net zero energy can be achieved by reducing the energy demand by using efficient design (building and urban) and construction techniques, producing sufficient clean energy on/off site, using environment friendly materials to have a lower impact on carbon emissions and designing based on occupant comfort both at building and urban scale.

9.3. Challenges

It is important to note that this thesis is a theoretical attempt at validating a large concept. It was challenging to implement and test this concept for a large-scale development as net zero does not have a precise definition and is not standardised yet. While there is credible literature on the subject, net zero still lacks sufficient research for its application in large scale developments. Since, net zero is not a defined benchmark, the thesis relied on data from examples of large-scale net zero developments. While much information on these case studies was available online, the thesis could have incorporated case study visits and monitoring of these developments for a more accurate analysis and understanding of the workability and feasibility of net zero in large scale developments. The achievability of net zero depends on two critical aspects:

- Reduction in energy consumption at the building and thereby the urban scale
- Producing adequate renewable energy to offset the energy consumption of the development

Apart from the gap in research, testing this concept also entailed challenges in terms of its practical applicability. Firstly, these houses show that they perform exceedingly well in theory. However, they may have a higher energy consumption in reality leading to a performance gap. Secondly, to develop a net zero community would require huge amounts of funding and rigorous planning. For example, Masdar City is said to cost about 20 billion dollars for construction (Flint, 2020). Likewise, BedZED was estimated to cost about £14 million but required about £10 million more to complete the project (Macdonald, 2004). Therefore, the true success of net zero relies on government support in terms of funding and framing regulations specific to net zero apart from climate appropriate, energy efficient design, maximising on locally available renewable energy sources and user lifestyle.

9.4. Need for further research on net zero

For a long time, net zero has been tested and updated to deliver climate change initiatives across the globe. Although challenging, it has been possible to achieve net zero at the building scale. However, its workability in large scale developments entails rigorous examination. The past two decades have seen a shift in paradigm with nations around the world not only developing their own net zero definitions and standards but implementing these to build net zero communities and cities. Irrespective of net zero's extensive implementation there is a lack of methodical documentation of these adapted systems and successful developments world-wide. Hence, it is foremost important to standardise net zero prior to its application in large scale developments which, as discussed, requires copious funding. This thesis attempted to develop an efficient standard and guide for net zero communities. A critical part of the project included formulating a rating system and then putting this to the test using a designed hypothetical community but based on actual lifestyle variability. This guide is adapted to suit the relevant climate and location where the designed community will be situated. This can then be replicated in other locations with similar climate conditions. Likewise, the guide can be revised to suit other climate classifications.

In conclusion, it is possible to achieve net zero in large scale developments. However, the feasibility of achieving this relies on support from Governments in terms of standardising and funding it. A prototype community designed for the UK conditions and tested for net zero has successfully achieved net positive energy and net negative carbon emissions.

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Appendix 1

Current examples of net zero developments

i. Climate data

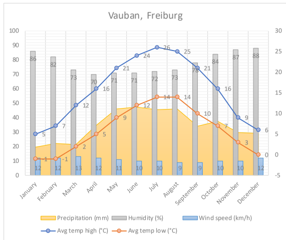
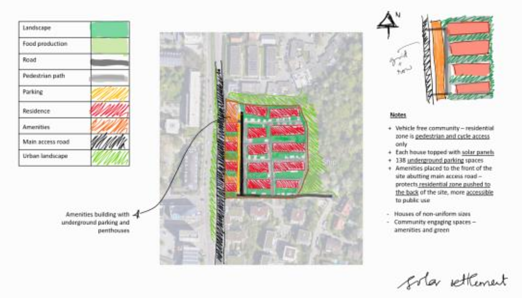
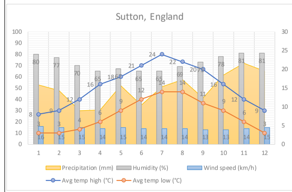
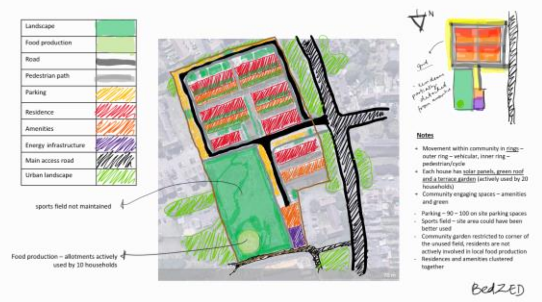
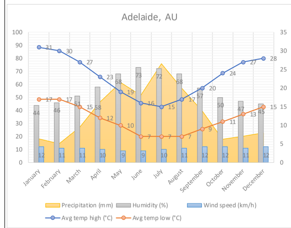
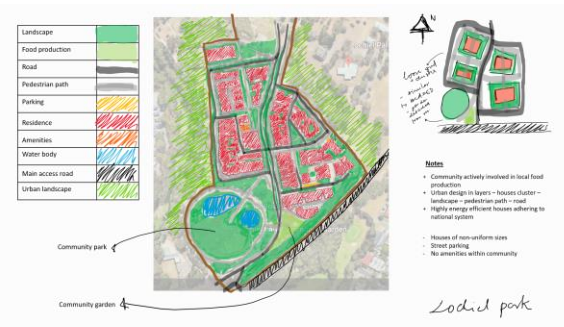
Note: Based on weather reports collected during 1985–2015. (timeanddate, 2020)

		January	February	March	April	May	June	July	August	September	October	November	December	Average	Total
Vauban, Freiburg	Avg temp high (°C)	5	7	12	16	21	24	26	25	21	16	9	6		
	Avg temp low (°C)	-1	-1	2	5	9	12	14	14	10	7	3	0		
	Humidity (%)	86	82	73	70	71	71	72	73	78	84	87	88	78	935
	Precipitation (mm)	19.6	22.2	21.5	34.5	46.1	47.3	45.5	46	34.2	37.4	29.8	29.2	34	
	Wind speed (km/h)	12	12	13	12	11	10	10	9	9	10	10	12	11	
	Wind direction	SW	SW	WSW	W	W	W	W	WSW	W	WSW	SW	SW		
Sutton, England	Avg temp high (°C)	8	9	12	16	18	21	24	22	20	16	12	9		
	Avg temp low (°C)	3	3	4	6	9	12	14	14	11	9	6	3		
	Humidity (%)	80	77	70	65	67	65	65	69	73	78	81	81	73	
	Precipitation (mm)	52.9	47.9	29.8	30.6	52.1	35	51	57.5	41.2	61.5	72	65.1	50	596.6
	Wind speed (km/h)	16	15	15	14	15	14	14	14	13	13	14	15	14	
	Wind direction	WSW	SW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	SW	SW	SW		
Adelaide, AU	Avg temp high (°C)	31	30	27	23	19	16	15	17	20	24	27	28		
	Avg temp low (°C)	17	17	15	12	10	7	7	7	9	11	13	15		
	Humidity (%)	44	46	51	58	68	73	72	68	57	50	47	45	57	
	Precipitation (mm)	18.33	14.5	27.2	46.6	61.4	51.8	75.9	57.2	39.6	17.8	20.2	22.8	38	453.3
	Wind speed (km/h)	12	11	11	10	9	9	10	11	12	12	11	12	11	
	Wind direction	SSW	SSW	SW	WSW	WNW	NW	NW	NW	WNW	WSW	SW	SW		
Longwell Green, England	Avg temp high (°C)	7	7	10	14	16	19	21	19	18	15	11	8		
	Avg temp low (°C)	3	3	4	6	9	12	14	13	11	9	6	4		
	Humidity (%)	88	84	77	74	74	72	73	78	79	83	87	88	80	
	Precipitation (mm)	59.9	43	38.4	31.7	44.2	38.4	53.3	53.5	42.9	61.2	74.3	73.8	51	614.6
	Wind speed (km/h)	19	18	19	17	18	17	17	16	16	16	18	18	17	
	Wind direction	WSW	SW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW		
Dubai, UAE	Avg temp high (°C)	24	26	28	33	38	40	41	41	39	36	31	26		
	Avg temp low (°C)	15	16	19	22	26	28	31	31	29	25	21	17		
	Humidity (%)	63	62	59	51	46	53	52	51	57	58	59	63	56	
	Precipitation (mm)	0.1	0	0.2	0	0	0	0	0	0	0	0	0.1	0	0.4
	Wind speed (km/h)	12	13	13	13	14	14	14	14	13	11	11	11	13	
	Wind direction	WNW	WNW	WNW	WNW	W	WNW	WNW	NW	NW	NW	NW	NW		
Bateen Airport, Abu Dhabi	Avg temp high (°C)	24	27	30	35	40	41	42	43	41	37	31	26		
	Avg temp low (°C)	14	15	18	22	26	28	30	31	28	24	20	16		
	Humidity (%)	64	58	51	43	39	46	46	44	51	54	58	64	52	
	Precipitation (mm)	9.5	7.1	9.4	3.3	0	0	0	0	4.4	5	3.7	9.9	4	52.3
	Wind speed (km/h)	13	15	15	15	15	15	15	15	14	12	12	12	14	
	Wind direction	NW	NW	NNW	NW	NW	NW	NW	NNW	NNW	NNW	NNW	NNW		

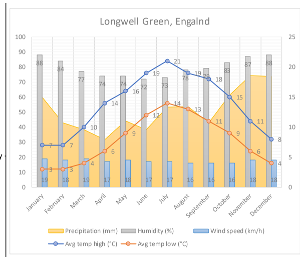
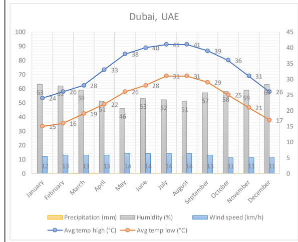
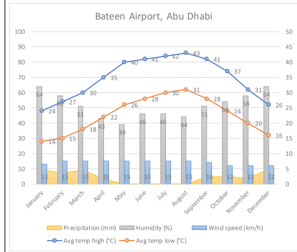
ii. Materials and U-values

	U-Values	List
Solar settlement	Wall - 0.12 Roof - 0.11 Floor - 0.16 Glazing - 0.7	Outer wall - Timber frame construction with 360 mm cellulose insulation U-value = 0.11 W / (m 2 K) Basement ceiling / floor slab - 160 mm Styrodur, 200 mm base plate, 60 mm insulation PS 15 WLG 035 U-value = 0.15 W / (m 2 K) roof - Hard concrete roofing, TJI girder with cellulose insulation (406 mm), exposed roof truss U-value = 0.1 W / (m 2 K) Air tightness - OSB 18mm recommended
	U-Values	List
BedZED	Wall - 0.11 Roof - 0.1 Floor - 0.1 Glazing - 1.2	Structure Grade 43 steel - beams and columns, re-used from former railway station Roof 200mm pre-cast concrete hollow core units, insulated with 300mm Styrofoam and sedum roof External Walls Brick and block, some cedar cladding, insulated with 300mm Rockwool Floors 200mm pre-cast concrete hollow core units 300mm expanded polystyrene External Windows, doors and roof lights - Rationel timber windows, argon filled triple glazing on all elevations except south facing, double glazing on south facing Photovoltaics BP Solar PV laminated units CHP B9 wood gas CHP designed to produce 130 kW of electricity and 200kW heat
Lochiel park	Wall - R2.5 (ins) Roof - R1.5 Floor - R4 (ins)	Floor - Concrete slab + waffle pod Roof - Metal Wall - Reverse brick veneer Windows - Double glazing, low-e, uPVC
Hanham hall	Wall - 0.11 Roof - 0.11 Floor - 0.11 Glazing - 0.7	200mm storey height aircrete panels and 200mm of external wall insulation. Timber joists, 280mm rigid urethane insulation with low emissivity foil laid in three layers, 52.5mm insulating plaster board 300mm thick aircrete pre-cast flooring system with 110mm thick urethane insulation. Triple glazed low-e doors and windows. Target was 1.5m3/h@50pa; achieved 1.48m3/h@50pa in testing.

iii. Case studies data

	Housing diversity			Site selection	Sun path	Wind	Climate	Site analysis: Access to public transport	Proximity to key amenities	Urban landscapes	Food production	Housing layout	Transport and parking	Amenities
Solar Settlement	59	170		Freiburg, Germany	Summer solstice sun angle = 65.5° Winter solstice sun angle = 18.5° Equinox sun angle = 42°	Winter - SW Summer - W Spring & Autumn - WSW - W								
	2 bed house 2 bed terrace house 3 bed house 3 bed terrace house 4 bed house 5 bed house 5 bed terrace house	1 - 5 residents		Temperate - Cfb										
		54 units/ha		General urban zone (bordering suburb)										
BedZED	82 + 19 (live-work)	Residential = 209 Adults - 160 Children - 49 BedZED (total) = 266 Adults - 160 + 47 Children - 49 + 10		Sutton, UK	Summer solstice sun angle = 62.1° Winter solstice sun angle = 15.1° Equinox sun angle = 38.6°	Winter - SW-WSW(Jan) Summer, Spring & Autumn - WSW								
	4 bed maisonette 3 bed maisonette 2 bed maisonette 1 bed flat live work	1 adult - 36 units 2 adults - 27 units 3 adults - 2 units 4 adults - 1 unit 1 adult 1 child - 4 units 2 adults 1 child - 9 units 3 adults 1 child - 2 units 1 adult 2 children - 1 unit 2 adults 2 children - 13 units 2 adults 3 children - 1 unit 3 adults 3 children - 3 units		Temperate - Cfb										
		48 units/ha		Suburban										
Lochiel park	106	150		Adelaide, AU	Summer solstice sun angle = 78.6° Winter solstice sun angle = 31.6° Equinox sun angle = 55.1°	Winter - NW - WNW Summer - SW - SSW Spring & Autumn - WNW - WSW								
	23 apartment houses 1 bed flats 2 bed flats 82 invidual dwellings 3 bed houses	Couple with children Couple without children Single person Group		Temperate - Csa										
		7 units/ha		Suburban										

ities and access to public transit

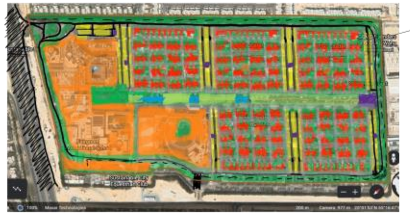
Hanham Hall	187	-	Bristol, UK				
	1 bed house 1 bed apartment 2 bed house 2 bed apartment 2 bed cottage 3 bed cottage 4 bed cottage 4 bed house (17) 5 bed house	-	Temperate - Cfb	Summer solstice sun angle = 62.1° Winter solstice sun angle = 15.1° Equinox sun angle = 38.6°	WSW thourgh the year except February SW		
		21 units/ha	Suburban				
Sustainable City	500	Residential = 2700 Total = 6000	Dubai, UAE				
	3 bed courtyard villa 4 bed courtyard villa 4 bed garden villa 5 bed townhouse	Average household size = 4.2	Arid - BWh	Summer solstice sun angle = 88.5° Winter solstice sun angle = 41.5° Equinox sun angle = 65°	Winter - NW - WNW Summer - W - WNW - NW		
		11 units/ha	General Urban zone				
Masdar city		Residential - 1300 Total - 6000 +	Abu Dhabi, UAE				
	Villas Apartments		Arid - BWh	Summer solstice sun angle = 89.1° Winter solstice sun angle = 42.1° Equinox sun angle = 65.6°	Winter - NNW - NW Summer - NW - NNW		
		140 people/ha	General Urban zone				

Refer table proximity ro keyy ame

Notes

+ Large pastures at the back of site – accessible via pedestrian paths
+ Community garden situated to the back of the site
- Community engaging spaces – amenities
- Street parking allocated randomly
- Vehicular movement through the site – no clear distinction between pedestrian, cycle and vehicle paths

Landscape	
Food production	
Road	
Pedestrian path	
Parking	
Residence	
Amenities	
Hanham Hall	
Main access road	



Notes

+ Vehicle access restricted to outside clusters and parking only. Residential zone is pedestrian and cycle access only
+ Each house topped with solar panels
+ Urban farm catering to local food requirements – central spine creating a community friendly zone
+ A play area is situated in the middle of each residential cluster
+ Movement through community either by walk, cycle or batter operated buggies
+ Amenities placed to the front of the site abutting main access road – protects residential zone pushed to the back of the site, more accessible to public use

- Situated far away from Dubai city center and business district

Landscape	
Food production	
Road	
Pedestrian path	
Parking	
Residence	
Amenities	
Main access road	
Services	
Equestrian path	

Landscape	
PTR	
Road	
Pedestrian path	
Miscellaneous	
Residence	
Amenities	
Energy infrastructure	

Notes

+ Pedestrian spine – amenities placed along the spine
+ Vehicle free community
+ Battery operated in-house PTR
+ Distribution of parks
+ Vernacular street design
+ On – site solar farm

- No public transit system – city detached from Abu Dhabi city
- Large city – roughly 20% of project has been constructed
- Solar farm size is said to be insufficient for the city

iv. Proximity to public transport and key amenities

	Solar settlement			BedZED			Lochiel park			Hanham hall			Sustainable City			MASDAR City		
Amenity + public tranport	Distance	Accessible by public transit	Notes	Distance	Accessible by public transit	Notes	Distance	Accessible by public transit	Notes	Distance	Accessible by public transit	Notes	Distance	Accessible by public transit	Notes	Distance	Accessible by public transit	Notes
Pharmacy	Within community	Walkable	1 drug store in "Sun ship"	350 m	Walkable	Near Hackbridge station	≈ 1.5 km	Yes	Neighboring town within clinic - Klemzig	150 m	Walkable	Site perimeter	Within community		Within mixed use complex	Within community		
Clinic	2.3 km	Yes	Town centre	350 m	Walkable		≈ 1.5 km	Yes	Neighboring town - Klemzig	150 m	Walkable	Site perimeter	Within community		Within mixed use complex	-		
Hospital	1 km	Not directly accessible		2 km	Yes	1 hospital	≈ 1 km	Not directly accessible		≈ 3 km	Yes		≈ 13 km	No	Jumeirah city	≈ 6 km	No	Neighboring sector - Khalifa city
Grocery store	150 m	Walkable	1 store across road. 1 organic food store within community in "Sun ship"	350 m	Walkable	1 Sainsbury's local	≈ 1.2 km	No		600m - 1 km	Yes	Lidl and M&S on High street	Within community		Within mixed use complex (not centralised, abutting main access road)	Within community		Supermarket within community (centralised)
Major retail	250 m	Walkable	1 - Aldi	≈ 3 km	Yes	ASDA present in Sutton town centre	≈ 1.7 km	Yes	Coles - Neighboring town Greenacres	1.3 km	Yes	ASDA	≈ 4 km	Not directly accessible	Neighboring sector	Within community		Supermarket within community (centralised)
Shopping mall	3 km	Yes		≈ 3 km	Yes	Sutton town centre	≈ 1.7 km	Yes	Shopping centre in neighboring town - Greenacres	≈ 2 km	Yes	Kings Chase shopping centre in Kingswood	≈ 13 km	No	Jumeirah city	≈ 3 km		Neighboring sector - Khalifa city, designed to be within community, yet to be built
Nursery	350 m	No		Within community			≈ 1.3 km	Yes	Neighboring town - Klemzig	≈ 500 m	Yes / Walkable	On High street	Within community			≈ 3 km	No	Neighboring sector - Khalifa city
Primary school	150 m	Walkable		200 - 400 m	Walkable	2 schools	500m - 1 km	Pubic transport + walk	2 schools	≈ 500 m	Walkable	2 primary schools	Within community					
School	1 km	Yes		≈ 1.5 - 2 km	Yes	3 high schools in 2 km radius				≈ 500 m	Walkable	Secondary school	≈ 7 km	No	Neighboring sector	≈ 2.5 km	No	Primary + secondary school in neighboring sector - Khalifa city
College/University	3 km	Yes	CBD	≈ 1.5 km	Yes	1 college	≈ 2 km	Yes	Senior college - Marden (neighboring town)	≈ 7 km	Yes	Bristol University	≈ 15 km	No	Jumeirah city	Within community		
Parks	500 m	No		≈ 400 m	Walkable		≈ 1 km	Yes	Nature reserve near community	≈ 200 m	Walkable	Hanham community play area - community perimeter	Within community		1 within each residential cluster and along the central spine	Within community		
Café	150 m	Walkable		350 m	Walkable	Near Hackbridge station, café on site likely a community café	≈ 1.3 km	No	Campbell town centre	≈ 400 m	Walkable		Within community		Within mixed use complex	Within community		
Bar	Within community		1 bar in "Sun ship"	≈ 400 m	Walkable	Near Hackbridge station	≈ 1.3 km	No	Campbell town centre	≈ 650 m	Walkable		-					
Dining	200 m			≈ 400 m	Walkable	Near Hackbridge station	≈ 1.3 km	No	Campbell town centre	≈ 500 m	Yes / walkable	On High street	Within community		Within mixed use complex	Within community		
Cinemas/theatres	3 km	Yes	Town centre	≈ 3 km	Yes	Sutton town centre	≈ 5 km	Yes	Adelaide city	1.2 km	Yes	Short walk from ASDA	≈ 4 km	Not directly accessible	Neighboring sector, other cinemas are available in Jumeirah city - 15 km	≈ 3 km	No	Neighboring sector - Khalifa city
Sports centre / Fitness centre	500 m	Yes		1.75 km	Yes	Clubhouse and sports field resent within community, field not in use	≈ 2 km	Yes		500 m - ≈ 1 km	Yes	Tennis and cricket club near community, fitness centre near ASDA	Within community		Within mixed use complex	Within community		
Bank	Within community		1 bank in "Sun ship"	≈ 3 km	Yes	Sutton town centre	≈ 1.3 km	No	Campbell town centre	1.2 km	Yes	Barclays near ASDA	Within community		Within mixed use complex	≈ 4 km	No	Neighboring sector - Khalifa city
Offices				Within community		Workspaces, livework spaces designed with residences							Within community		Within mixed use complex	Within community		

	Solar settlement			BedZED			Lochiel park			Hanham hall			Sustainable City			MASDAR City		
Bus stop	150 m	Walkable		75 m		Site perimeter	400 m	Walkable		150 m	Walkable	Site perimeter	≈ 300 m	Walkable	Site perimeter			
Tram access	150 m	Walkable																
Metro station													≈ 13 km	No	Jumeirah city			
Train station				500 m	No	Hackbridge train station	≈ 7 km	Yes	Adelaide city									
Other transport																Within community		PRT system developed to commute within the city
Town centre	≈ 3 km	Yes	Freiburg town centre	≈ 3.5 km	Yes	Sutton town centre	≈ 1.3 km	No	Campbelltown	600 m	Yes	Hanham town centre	≈ 13 km	No	Jumeirah city	Within community		
Business district	≈ 3 km	Yes		≈ 3.5 km	Yes	Sutton town centre	≈ 7 km	Yes	Adelaide city	≈ 6 km	Yes	Bristol city	≈ 13 km	No	Jumeirah city	Within community		

Appendix 2

Energy rating systems

i. Comparative analysis of global rating systems

ii. Average weighting of criteria - calculations table

%	Pearl	LEED (cities and communnities)	IGBC	BREEAM	Green star	Average
Social, econmical and environmental wellbeing	2	23	7	12	51	19
Ecology	9	6	12	10	5	8
Site	0	2	0	2	2	1
Urban planning and design	26	0	24	29	5	17
Transport	6	15	15	10	5	10
Energy and emissions	20	28	21	17	11	19
Materials	7	2	4	8	5	5
Water	23	11	9	7	6	11
Waste	4	8	0	0	2	3
Innovationn	1	5	6	6	9	5
Accredited professional	0	0	2	0	1	1
Misc.	1	0	0	0	0	0

Appendix 3

Survey on typical British lifestyles

i. Survey questions

Typical British household energy use and lifestyles

16% complete

Page 2: Family/Household

Occupation

Are you... * *Required*

Please select

Family/Household size

This part of the survey uses a table of questions, view as separate questions instead?

Can you tell me the number of members in your household and their corresponding age? If more than one member falls under the same age group, enter these in ascending order of age under columns Age 1,2,3 & 4.

	No. of members in age group	Age (1)	Age (2)	Age (3)
0-4 years	Please select			
5-10 years	Please select			
11-16 years	Please select			
17-24 years	Please select			
25-64 years	Please select			
65+ years	Please select			

House

Which type of house do you reside in?

Please select

Which of the following rooms do you have in your home?

- ☐ Living
- ☐ Dining
- ☐ Living+dining
- ☐ Kitchen
- ☐ Open kitchen +living/dining
- ☐ 1 bedroom
- ☐ 2 bedrooms
- ☐ 3 bedrooms
- ☐ 4 bedrooms
- ☐ 5+ bedrooms
- ☐ 1 bathroom
- ☐ 2 bathrooms
- ☐ 3+ bathrooms
- ☐ 1 toilet
- ☐ 2 toilets
- ☐ 3+ toilets
- ☐ Study
- ☐ Sunspace
- ☐ Sunspace + living
- ☐ Loft
- ☐ Basement
- ☐ Other

Does your home have solar panels?

- ○ Yes
- ○ No

< Previous   Next >

Typical British household energy use and lifestyles

33% complete

Page 3: Occupancy

Weekday

This part of the survey uses a table of questions, view as separate questions instead?

Can you indicate in ascending order of age when each member of your household is likely to be away from the house on a typical weekday, member 1 being the youngest and member 8 being the oldest? For e.g., 11 year old leaves for school at 07:30 (7:30 am) and returns at 15:30 (3:30 pm)

	Leaves house between...	Returns between...	Leaves house again between...	Returns between...	Not applicable/stay home
Member 1	08:00 - 09:00	18:00 - 19:00	Please select	Please select	☐
Member 2	Please select	Please select	Please select	Please select	☐
Member 3	Please select	Please select	Please select	Please select	☐
Member 4	Please select	Please select	Please select	Please select	☐
Member 5	Please select	Please select	Please select	Please select	☐
Member 6	Please select	Please select	Please select	Please select	☐
Member 7	Please select	Please select	Please select	Please select	☐
Member 8	Please select	Please select	Please select	Please select	☐

This part of the survey uses a table of questions, view as separate questions instead?

If there are any weekdays that differ considerably from the above mentioned typical weekday for each member of the household, please indicate here. E.g., shopping on Wednesdays between 18:00 (6 pm) and 20:00 (8pm)

	Day and time	Not applicable
Member 1		☐
Member 2		☐
Member 3		☐
Member 4		☐
Member 5		☐
Member 6		☐
Member 7		☐
Member 8		☐

Saturday

This part of the survey uses a table of questions, view as separate questions instead?

Can you indicate in ascending order of age when each member of your household is likely to be away from the house on a typical Saturday, member 1 being the youngest and member 8 being the oldest? For e.g., 11 year old leaves home for tennis at 09:30 (9:30 am) and returns at 12:00 (12 pm).

	Leaves house between...	Returns between...	Leaves house again between...	Returns between...	Not applicable/stay home
Member 1	Please select	Please select	Please select	Please select	☐
Member 2	Please select	Please select	Please select	Please select	☐
Member 3	Please select	Please select	Please select	Please select	☐
Member 4	Please select	Please select	Please select	Please select	☐
Member 5	Please select	Please select	Please select	Please select	☐
Member 6	Please select	Please select	Please select	Please select	☐
Member 7	Please select	Please select	Please select	Please select	☐
Member 8	Please select	Please select	Please select	Please select	☐

Sunday

This part of the survey uses a table of questions, view as separate questions instead?

Can you indicate in ascending order of age when each member of your household is likely to be away from the house on a typical Sunday, member 1 being the youngest and member 8 being the oldest? For e.g., 11 year old leaves for tennis at 09:30 (9:30 am) and returns at 12:00 (12 pm)

	Leaves house between...	Returns between...	Leaves house again between...	Returns between...	Not applicable/stay home
Member 1	Please select	Please select	Please select	Please select	☐
Member 2	Please select	Please select	Please select	Please select	☐
Member 3	Please select	Please select	Please select	Please select	☐
Member 4	Please select	Please select	Please select	Please select	☐
Member 5	Please select	Please select	Please select	Please select	☐
Member 6	Please select	Please select	Please select	Please select	☐
Member 7	Please select	Please select	Please select	Please select	☐
Member 8	Please select	Please select	Please select	Please select	☐

‹ Previous   Next ›

Typical British household energy use and lifestyles

50% complete

Page 4: Heating

This part of the survey uses a table of questions, view as separate questions instead?

Can you indicate when the heating is switched on in your home based on times of the day in hours?
If it is typical for all days of the week, ignore rows saturday and sunday.

	Turns on between...	Turns off between...	Turns on again between...	Turns off between	All day
Weekdays	Please select	Please select	Please select	Please select	☐
Saturday	Please select	Please select	Please select	Please select	☐
Sunday	Please select	Please select	Please select	Please select	☐

What type of heating system does your home have? For e.g.: Combination boiler or central heating

‹ Previous Next ›

Typical British household energy use and lifestyles

66% complete

Page 5: Hot water

This part of the survey uses a table of questions, view as separate questions instead?

Can you indicate the typical overall uses/day **or** uses/week for the following, typical days these are used and when each of the following are used by all members of the household? For e.g., two members showering everyday must be indicated as 2 under typical overall uses/day. If one member showers at 08:00 (8 am) and the other 18:00 (6 pm), select Early morning + Evening for when it is used.

	Uses/day	Uses/week	When is it used?	Days it is used (e.g., all days)	Not applicable
Shower	Please select	Please select	Please select		☐
Bath	Please select	Please select	Please select		☐
Washing machine	Please select	Please select	Please select		☐
Dishwasher	Please select	Please select	Please select		☐

‹ Previous Next ›

Typical British household energy use and lifestyles

83% complete

Page 6: Equipment

This part of the survey uses a table of questions, view as separate questions instead?

Can you indicate the typical overall uses/day **or** uses/week for the following, typical days these are used and when each of the following are used by all members of the household? For e.g., two members using the hair dryer everyday must be indicated as 2 under typical overall uses/day. If one member uses the dryer at 08:00 (8 am) and the other 18:00 (6 pm), select Early morning + Evening for when it is used.

	Uses/day	Uses/week	When is it used?	Days it is used (e.g., all days)	Not applicable
Hob/cooker	Please select	Please select	Please select		☐
Oven	Please select	Please select	Please select		☐
TV	Please select	Please select	Please select		☐
Stereo	Please select	Please select	Please select		☐
Hair dryer	Please select	Please select	Please select		☐
Hair straightener	Please select	Please select	Please select		☐
Clothes iron	Please select	Please select	Please select		☐
Tumble dryer	Please select	Please select	Please select		☐
Coffee maker	Please select	Please select	Please select		☐
Microwave	Please select	Please select	Please select		☐
Kettle	Please select	Please select	Please select		☐
Toaster	Please select	Please select	Please select		☐
Vacuum cleaner	Please select	Please select	Please select		☐
PC/Laptop	Please select	Please select	Please select		☐
Space heater	Please select	Please select	Please select		☐
Fan/Air conditioner	Please select	Please select	Please select		☐

< Previous   Finish ✓

ii. Survey 22 – data

Jisc Online surveys

Typical British household energy use and lifestyles

Response ID	Start date	Completion date
595848-595839-60293617	20 May 2020, 19:59 (BST)	20 May 2020, 20:19 (BST)

1	Have you resided in the UK for 5 years or over?	Yes

Occupation

2	Are you...	Working full time
2.a	If you selected Other, please specify:	

Family/Household size

3	Can you tell me the number of members in your household and their corresponding age? If more than one member falls under the same age group, enter these in ascending order of age under columns Age 1,2,3 & 4.	
3.1	0-4 years	
3.1.a	No. of members in age group	
3.1.b	Age (1)	
3.1.c	Age (2)	
3.1.d	Age (3)	
3.1.e	Age (4)	
3.2	5-10 years	
3.2.a	No. of members in age group	
3.2.b	Age (1)	
3.2.c	Age (2)	
3.2.d	Age (3)	
3.2.e	Age (4)	
3.3	11-16 years	
3.3.a	No. of members in age group	1
3.3.b	Age (1)	12
3.3.c	Age (2)	
3.3.d	Age (3)	
3.3.e	Age (4)	
3.4	17-24 years	
3.4.a	No. of members in age group	1
3.4.b	Age (1)	18
3.4.c	Age (2)	
3.4.d	Age (3)	
3.4.e	Age (4)	
3.5	25-64 years	
3.5.a	No. of members in age group	2
3.5.b	Age (1)	52
3.5.c	Age (2)	44
3.5.d	Age (3)	
3.5.e	Age (4)	
3.6	65+ years	
3.6.a	No. of members in age group	
3.6.b	Age (1)	
3.6.c	Age (2)	
3.6.d	Age (3)	
3.6.e	Age (4)	

House

4	Which type of house do you reside in?	Detached
4.a	If you selected Other, please specify:	
4.b	Which of the following rooms do you have in your home?	4 bedrooms
4.b.i	If you selected Other, please specify:	
4.c	Does your home have solar panels?	No

Weekday

5	Can you indicate in ascending order of age when each member of your household is likely to be away from the house on a typical weekday, member 1 being the youngest and member 8 being the oldest? For e.g., 11 year old leaves for school at 07:30 (7:30 am) and returns at 15:30 (3:30 pm)	
5.1	Member 1	
5.1.a	Leaves house between...	07:00 - 08:00
5.1.b	Returns between...	18:00 - 19:00
5.1.c	Leaves house again between...	
5.1.d	Returns between...	
5.1.e		
5.2	Member 2	
5.2.a	Leaves house between...	07:00 - 08:00
5.2.b	Returns between...	15:00 - 16:00
5.2.c	Leaves house again between...	
5.2.d	Returns between...	
5.2.e		
5.3	Member 3	
5.3.a	Leaves house between...	07:00 - 08:00
5.3.b	Returns between...	16:00 - 17:00
5.3.c	Leaves house again between...	
5.3.d	Returns between...	
5.3.e		
5.4	Member 4	
5.4.a	Leaves house between...	09:00 - 10:00
5.4.b	Returns between...	19:00 - 20:00
5.4.c	Leaves house again between...	
5.4.d	Returns between...	
5.4.e		
5.5	Member 5	
5.5.a	Leaves house between...	
5.5.b	Returns between...	
5.5.c	Leaves house again between...	
5.5.d	Returns between...	
5.5.e		
5.6	Member 6	
5.6.a	Leaves house between...	
5.6.b	Returns between...	
5.6.c	Leaves house again between...	
5.6.d	Returns between...	
5.6.e		
5.7	Member 7	
5.7.a	Leaves house between...	
5.7.b	Returns between...	
5.7.c	Leaves house again between...	
5.7.d	Returns between...	
5.7.e		
5.8	Member 8	
5.8.a	Leaves house between...	
5.8.b	Returns between...	
5.8.c	Leaves house again between...	
5.8.d	Returns between...	
5.8.e		

6	If there are any weekdays that differ considerably from the above mentioned typical weekday for each member of the household, please indicate here. E.g., shopping on Wednesdays between 18:00 (6 pm) and 20:00 (8pm)	
6.1	Member 1	
6.1.a	Day and time	
6.1.b		Not applicable
6.2	Member 2	
6.2.a	Day and time	
6.2.b		Not applicable
6.3	Member 3	
6.3.a	Day and time	
6.3.b		Not applicable

6.4	Member 4	
6.4.a	Day and time	
6.4.b		Not applicable
6.5	Member 5	
6.5.a	Day and time	
6.5.b		
6.6	Member 6	
6.6.a	Day and time	
6.6.b		
6.7	Member 7	
6.7.a	Day and time	
6.7.b		
6.8	Member 8	
6.8.a	Day and time	
6.8.b		

Saturday

7	Can you indicate in ascending order of age when each member of your household is likely to be away from the house on a typical Saturday, member 1 being the youngest and member 8 being the oldest? For e.g., 11 year old leaves home for tennis at 09:30 (9:30 am) and returns at 12:00 (12 pm).	
7.1	Member 1	
7.1.a	Leaves house between...	
7.1.b	Returns between...	
7.1.c	Leaves house again between...	
7.1.d	Returns between...	
7.1.e		Not applicable/stay home
7.2	Member 2	
7.2.a	Leaves house between...	08:00 - 09:00
7.2.b	Returns between...	13:00 - 14:00
7.2.c	Leaves house again between...	
7.2.d	Returns between...	
7.2.e		
7.3	Member 3	
7.3.a	Leaves house between...	08:00 - 09:00
7.3.b	Returns between...	10:00 - 11:00
7.3.c	Leaves house again between...	
7.3.d	Returns between...	
7.3.e		
7.4	Member 4	
7.4.a	Leaves house between...	
7.4.b	Returns between...	
7.4.c	Leaves house again between...	
7.4.d	Returns between...	
7.4.e		Not applicable/stay home
7.5	Member 5	
7.5.a	Leaves house between...	
7.5.b	Returns between...	
7.5.c	Leaves house again between...	
7.5.d	Returns between...	
7.5.e		
7.6	Member 6	
7.6.a	Leaves house between...	
7.6.b	Returns between...	
7.6.c	Leaves house again between...	
7.6.d	Returns between...	
7.6.e		
7.7	Member 7	
7.7.a	Leaves house between...	
7.7.b	Returns between...	
7.7.c	Leaves house again between...	
7.7.d	Returns between...	
7.7.e		
7.8	Member 8	
7.8.a	Leaves house between...	

7.8.b	Returns between...	
7.8.c	Leaves house again between...	
7.8.d	Returns between...	
7.8.e		

Sunday

8	Can you indicate in ascending order of age when each member of your household is likely to be away from the house on a typical Sunday, member 1 being the youngest and member 8 being the oldest? For e.g., 11 year old leaves for tennis at 09:30 (9:30 am) and returns at 12:00 (12 pm)	
8.1	Member 1	
8.1.a	Leaves house between...	15:00 - 16:00
8.1.b	Returns between...	19:00 - 20:00
8.1.c	Leaves house again between...	
8.1.d	Returns between...	
8.1.e		
8.2	Member 2	
8.2.a	Leaves house between...	
8.2.b	Returns between...	
8.2.c	Leaves house again between...	
8.2.d	Returns between...	
8.2.e		Not applicable/stay home
8.3	Member 3	
8.3.a	Leaves house between...	09:00 - 10:00
8.3.b	Returns between...	13:00 - 14:00
8.3.c	Leaves house again between...	
8.3.d	Returns between...	
8.3.e		
8.4	Member 4	
8.4.a	Leaves house between...	09:00 - 10:00
8.4.b	Returns between...	13:00 - 14:00
8.4.c	Leaves house again between...	
8.4.d	Returns between...	
8.4.e		
8.5	Member 5	
8.5.a	Leaves house between...	
8.5.b	Returns between...	
8.5.c	Leaves house again between...	
8.5.d	Returns between...	
8.5.e		
8.6	Member 6	
8.6.a	Leaves house between...	
8.6.b	Returns between...	
8.6.c	Leaves house again between...	
8.6.d	Returns between...	
8.6.e		
8.7	Member 7	
8.7.a	Leaves house between...	
8.7.b	Returns between...	
8.7.c	Leaves house again between...	
8.7.d	Returns between...	
8.7.e		
8.8	Member 8	
8.8.a	Leaves house between...	
8.8.b	Returns between...	
8.8.c	Leaves house again between...	
8.8.d	Returns between...	
8.8.e		

9	Can you indicate when the heating is switched on in your home based on times of the day in hours? *If it is typical for all days of the week, ignore rows saturday and sunday.	
9.1	Weekdays	
9.1.a	Turns on between...	04:00 - 05:00
9.1.b	Turns off between...	08:00 - 09:00
9.1.c	Turns on again between...	17:00 - 18:00
9.1.d	Turns off between	23:00 - 00:00

9.1.e		
9.2	Saturday	
9.2.a	Turns on between...	04:00 - 05:00
9.2.b	Turns off between...	10:00 - 11:00
9.2.c	Turns on again between...	16:00 - 17:00
9.2.d	Turns off between	23:00 - 00:00
9.2.e		
9.3	Sunday	
9.3.a	Turns on between...	04:00 - 05:00
9.3.b	Turns off between...	10:00 - 11:00
9.3.c	Turns on again between...	16:00 - 17:00
9.3.d	Turns off between	23:00 - 00:00
9.3.e		
9.a	What type of heating system does your home have? For e.g.: Combination boiler or central heating	Combination boiler

10	Can you indicate the typical overall uses/day or uses/week for the following, typical days these are used and when each of the following are used by all members of the household? For e.g., two members showering everyday must be indicated as 2 under typical overall uses/day. If one member showers at 08:00 (8 am) and the other 18:00 (6 pm), select Early morning + Evening for when it is used.	
10.1	Shower	
10.1.a	Uses/day	3-4
10.1.b	Uses/week	
10.1.c	When is it used?	Early morning (06:00 - 09:00)
10.1.d	Days it is used (e.g., all days)	All days
10.1.e		
10.2	Bath	
10.2.a	Uses/day	1
10.2.b	Uses/week	
10.2.c	When is it used?	Evening (17:00 - 20:00)
10.2.d	Days it is used (e.g., all days)	All days
10.2.e		
10.3	Washing machine	
10.3.a	Uses/day	
10.3.b	Uses/week	2-3
10.3.c	When is it used?	Evening (17:00 - 20:00)
10.3.d	Days it is used (e.g., all days)	All days
10.3.e		
10.4	Dishwasher	
10.4.a	Uses/day	1
10.4.b	Uses/week	
10.4.c	When is it used?	Night (20:00 - 00:00)
10.4.d	Days it is used (e.g., all days)	All days
10.4.e		

11	Can you indicate the typical overall uses/day or uses/week for the following, typical days these are used and when each of the following are used by all members of the household? For e.g., two members using the hair dryer everyday must be indicated as 2 under typical overall uses/day. If one member uses the dryer at 08:00 (8 am) and the other 18:00 (6 pm), select Early morning + Evening for when it is used.	
11.1	Hob/cooker	
11.1.a	Uses/day	1-2
11.1.b	Uses/week	
11.1.c	When is it used?	Early morning + Evening
11.1.d	Days it is used (e.g., all days)	All
11.1.e		
11.2	Oven	
11.2.a	Uses/day	1
11.2.b	Uses/week	
11.2.c	When is it used?	Evening (17:00 - 20:00)
11.2.d	Days it is used (e.g., all days)	All
11.2.e		
11.3	TV	
11.3.a	Uses/day	1
11.3.b	Uses/week	
11.3.c	When is it used?	Evening + Night
11.3.d	Days it is used (e.g., all days)	All days
11.3.e		

11.4	Stereo	
11.4.a	Uses/day	
11.4.b	Uses/week	
11.4.c	When is it used?	
11.4.d	Days it is used (e.g., all days)	
11.4.e		Not applicable
11.5	Hair dryer	
11.5.a	Uses/day	1-2
11.5.b	Uses/week	
11.5.c	When is it used?	Evening (17:00 - 20:00)
11.5.d	Days it is used (e.g., all days)	All days
11.5.e		
11.6	Hair straightener	
11.6.a	Uses/day	1-2
11.6.b	Uses/week	
11.6.c	When is it used?	Evening (17:00 - 20:00)
11.6.d	Days it is used (e.g., all days)	All days
11.6.e		
11.7	Clothes iron	
11.7.a	Uses/day	1-2
11.7.b	Uses/week	
11.7.c	When is it used?	Early morning + Evening
11.7.d	Days it is used (e.g., all days)	All days
11.7.e		
11.8	Tumble dryer	
11.8.a	Uses/day	
11.8.b	Uses/week	1-2
11.8.c	When is it used?	Night (20:00 - 00:00)
11.8.d	Days it is used (e.g., all days)	
11.8.e		
11.9	Coffee maker	
11.9.a	Uses/day	
11.9.b	Uses/week	
11.9.c	When is it used?	
11.9.d	Days it is used (e.g., all days)	
11.9.e		Not applicable
11.10	Microwave	
11.10.a	Uses/day	1-2
11.10.b	Uses/week	
11.10.c	When is it used?	Early morning + Evening
11.10.d	Days it is used (e.g., all days)	All
11.10.e		
11.11	Kettle	
11.11.a	Uses/day	2-3
11.11.b	Uses/week	
11.11.c	When is it used?	Early morning + Evening
11.11.d	Days it is used (e.g., all days)	All
11.11.e		
11.12	Toaster	
11.12.a	Uses/day	1
11.12.b	Uses/week	
11.12.c	When is it used?	Early morning (06:00 - 09:00)
11.12.d	Days it is used (e.g., all days)	All
11.12.e		
11.13	Vacuum cleaner	
11.13.a	Uses/day	
11.13.b	Uses/week	1-2
11.13.c	When is it used?	Evening (17:00 - 20:00)
11.13.d	Days it is used (e.g., all days)	Weekends
11.13.e		
11.14	PC/Laptop	
11.14.a	Uses/day	3-4
11.14.b	Uses/week	
11.14.c	When is it used?	Morning + Evening

11.14.d	Days it is used (e.g., all days)	All
11.14.e		
11.15	Space heater	
11.15.a	Uses/day	
11.15.b	Uses/week	
11.15.c	When is it used?	
11.15.d	Days it is used (e.g., all days)	
11.15.e		Not applicable
11.16	Fan/Air conditioner	
11.16.a	Uses/day	
11.16.b	Uses/week	
11.16.c	When is it used?	
11.16.d	Days it is used (e.g., all days)	
11.16.e		Not applicable

Appendix 4
Modelling

i. Protoblocks

Household no.	Household size	Location	Model code
2	1B	mid terrace 0m	1_1_1
12	1B	mid terrace 1m	1_1_2
18	1B	mid terrace 1m	1_1_2
23	1B	mid terrace 2m	1_1_3
33	1B	mid terrace 3m	1_1_4
37	1B	mid terrace 3m	1_1_4
42	1B	mid terrace 4m	1_1_5
51	1B	mid terrace 5m	1_1_6
57	1B	mid terrace 5m	1_1_6
62	1B	mid terrace 6m	1_1_7
72	1B	mid terrace 7m	1_1_8
6	2B	end terrace 0m - mid	2_1_1
16	2B	end terrace 1m - mid	2_1_2
27	2B	end terrace 2m - mid	2_1_3
55	2B	end terrace 5m - mid	2_1_4
66	2B	end terrace 6m - mid	2_1_5
3	2B	mid terrace 0m	2_2_1
13	2B	mid terrace 1m	2_2_2
19	2B	mid terrace 1m	2_2_2
24	2B	mid terrace 2m	2_2_3
34	2B	mid terrace 3m	2_2_4
38	2B	mid terrace 3m	2_2_4
43	2B	mid terrace 4m	2_2_5
52	2B	mid terrace 5m	2_2_6
58	2B	mid terrace 5m	2_2_6
63	2B	mid terrace 6m	2_2_7
73	2B	mid terrace 7m	2_2_8
5	3B	mid terrace 0m	3_2_1
7	3B	end terrace 0m - mid	3_4_1
8	3B	mid terrace 0m	3_2_2
11	3B	end terrace 1m - NE	3_3_1
20	3B	mid terrace 1m	3_2_3
21	3B	end terrace 1m - SW	3_1_1
26	3B	mid terrace 2m	3_2_4
28	3B	end terrace 2m - mid	3_4_2
29	3B	mid terrace 2m	3_2_5
32	3B	end terrace 3m - NE	3_3_2
39	3B	mid terrace 3m	3_2_6

40	3B	end terrace 3m - SW	3_1_2
45	3B	mid terrace 4m	3_2_7
46	3B	end terrace 4m - mid	3_4_3
47	3B	mid terrace 4m	3_2_8
50	3B	end terrace 5m - NE	3_3_3
59	3B	mid terrace 5m	3_2_9
60	3B	end terrace 5m - SW	3_1_3
65	3B	mid terrace 6m	3_2_10
67	3B	end terrace 6m - mid	3_4_4
68	3B	mid terrace 6m	3_2_11
71	3B	end terrace 7m - NE	3_3_4
1	4B	mid terrace 0m	4_2_1
4	4B	mid terrace 0m	4_2_2
9	4B	mid terrace 0m	4_2_2
10	4B	end terrace 0m - NE	4_3_1
14	4B	mid terrace 1m	4_2_3
15	4B	end terrace 1m - mid	4_4_1
17	4B	mid terrace 1m	4_2_4
22	4B	end terrace 2m - SW	4_1_1
25	4B	mid terrace 2m	4_2_5
30	4B	mid terrace 2m	4_2_5
31	4B	end terrace 2m - NE	4_3_2
35	4B	end terrace 3m - mid - green - SW	4_5_1
36	4B	end terrace 3m - mid - green - NE	4_5_2
41	4B	end terrace 4m - SW	4_1_2
44	4B	mid terrace 4m	4_2_6
48	4B	mid terrace 4m	4_2_6
49	4B	end terrace 4m - NE	4_3_3
53	4B	mid terrace 5m	4_2_7
54	4B	end terrace 5m - mid	4_4_2
56	4B	mid terrace 5m	4_2_8
61	4B	end terrace 6m - SW	4_1_3
64	4B	mid terrace 6m	4_2_9
69	4B	mid terrace 6m	4_2_9
70	4B	end terrace 6m - NE	4_3_4
74	4B	mid terrace 7m	4_2_10
75	4B	end terrace 7m - SW	4_1_4

ii. Model data input

Section	Model data parameter	Model data value	Notes
Site	Location	Sutton, London	
	Weather data	London Gatwick Airport	TRY weather data (2002)
	Site orientation	341°	
Activity	Occupancy density (people/m^2)	0.032	Calculated 4 members / 126.8 m^2
	Holidays (days)	10	Designbuilder default
	DHW consumption (l/m^2-day)	1.262	Calculated[5]
	Heating setpoint temperature	21°C	CIBSE Guide A (2006)
	Heating setback temperature	12°C	Designbuilder default
	Natural ventilation – minimum indoor temperature	23°C	CIBSE Guide A (2006)
	Minimum fresh air (l/s-person)	10	Designbuilder default
	Fuel	Electricity from grid	
Construction	Model infiltration – Constant rate (ac/h)	0.2	Aim for 0.6 or less (Price, et al., 2020)
Glazing	Glazing type	Sageglass Climaplus Classic, SR 2.0, No Tint	From Designbuilder material library
	Opening position	Top	
	Glazing area opens	30%	Designbuilder default

[5] BRE : Domestic Annual Heat Pump System Efficiency (DAHPSE) - Estimator - BETA (bregroup.com)

Lighting	Lighting template	LED	From Designbuilder library
	Interior lighting normalised power density (W/m^2 – 100 lux)	2.5	Designbuilder default
	Lighting level (lux)[6]	150	
	Exterior lighting – absolute power (W)	100	Designbuilder default
	Exterior lighting schedule	On 24/7 Override off in daytime	
HVAC	HVAC template	GSHP Water to water heat pump, heated floor, natural ventilation	From Designbuilder library
	Mechanical ventilation	Off	CIBSE TM 23 (2000)
	DHW template	Same as HVAC	Designbuilder default
	DHW delivery temperature	65°C	
	Cooling	Off	
	Natural ventilation outside air (ac/h)	5	Calculated
	Mixed mode	On	

[6] Find Detailed Guide to LUX Levels - SLB Blog (saving-light-bulbs.co.uk)

iii. Protoblocks energy results

			kWh/year						kWh/m2/year			Average temperature
			Room electricity	Lighting	Heating	DHW	External lighting	Total		Average	% difference	
2B	end terrace 0m - mid	2_1_1	8104.14	3246.65	1502.21	2503.35	435.35	15791.70	222.42	222.07	0.16	23.05
	end terrace 1m - mid	2_1_2	8104.14	3246.65	1468.96	2503.35	435.35	15758.45	221.95		-0.05	23.02
	end terrace 2m - mid	2_1_3	8104.14	3246.65	1479.66	2503.35	435.35	15769.16	222.10		0.01	23.02
	end terrace 5m - mid	2_1_4	8104.14	3246.65	1492.47	2503.35	435.35	15781.97	222.28		0.10	23.00
	end terrace 6m - mid	2_1_5	8104.14	3246.65	1474.71	2503.35	435.35	15764.20	222.03		-0.02	23.02
	mid terrace 0m	2_2_1	8104.14	3246.65	1506.90	2503.35	435.35	15796.40	222.48		0.19	23.07
	mid terrace 1m	2_2_2	8104.14	3246.65	1471.54	2503.35	435.35	15761.03	221.99		-0.04	23.04
	mid terrace 2m	2_2_3	8104.14	3246.65	1461.65	2503.35	435.35	15751.14	221.85		-0.10	23.03
	mid terrace 3m	2_2_4	8104.14	3246.65	1469.63	2503.35	435.35	15759.13	221.96		-0.05	23.02
	mid terrace 4m	2_2_5	8104.14	3246.65	1461.18	2503.35	435.35	15750.67	221.84		-0.10	23.03
	mid terrace 5m	2_2_6	8104.14	3246.65	1472.80	2503.35	435.35	15762.30	222.00		-0.03	23.03
	mid terrace 6m	2_2_7	8104.14	3246.65	1472.54	2503.35	435.35	15762.04	222.00		-0.03	23.05
	mid terrace 7m	2_2_8	8104.14	3246.65	1472.09	2503.35	435.35	15761.59	221.99		-0.03	23.04
3B	mid terrace 0m	3_2_1	13446.02	5386.70	2420.55	3528.87	435.35	25217.49	214.07	213.83	0.11	23.02
	end terrace 0m - mid	3_4_1	13446.02	5386.70	2391.37	3528.87	435.35	25188.31	213.82		-0.01	23.00
	mid terrace 0m	3_2_2	13446.02	5386.70	2423.37	3528.87	435.35	25178.27	213.74		-0.05	23.03
	end terrace 1m - NE	3_3_1	13446.02	5386.70	2381.32	3528.87	435.35	25172.61	213.69		-0.07	23.00
	mid terrace 1m	3_2_3	13446.02	5386.70	2375.67	3528.87	435.35	25172.61	213.69		-0.07	23.01
	end terrace 1m - SW	3_1_1	13446.02	5386.70	2373.67	3528.87	435.35	25170.61	213.67		-0.08	22.98
	mid terrace 2m	3_2_4	13446.02	5386.70	2376.76	3528.87	435.35	25173.70	213.70		-0.06	23.01
	end terrace 2m - mid	3_4_2	13446.02	5386.70	2391.44	3528.87	435.35	25188.38	213.82		-0.01	22.97
	mid terrace 2m	3_2_5	13446.02	5386.70	2373.90	3528.87	435.35	25170.85	213.67		-0.07	23.02
	end terrace 3m - NE	3_3_2	13446.02	5386.70	2392.16	3528.87	435.35	25189.10	213.83		0.00	22.99
	mid terrace 3m	3_2_6	13446.02	5386.70	2409.33	3528.87	435.35	25206.28	213.98		0.07	23.01
	end terrace 3m - SW	3_1_2	13446.02	5386.70	2406.14	3528.87	435.35	25203.08	213.95		0.05	22.96
	mid terrace 4m	3_2_7	13446.02	5386.70	2399.45	3528.87	435.35	25196.39	213.89		0.03	23.01
	end terrace 4m - mid	3_4_3	13446.02	5386.70	2420.35	3528.87	435.35	25217.29	214.07		0.11	22.95
	mid terrace 4m	3_2_8	13446.02	5386.70	2400.83	3528.87	435.35	25197.77	213.90		0.03	23.01
	end terrace 5m - NE	3_3_3	13446.02	5386.70	2400.21	3528.87	435.35	25197.15	213.90		0.03	22.95
	mid terrace 5m	3_2_9	13446.02	5386.70	2390.26	3528.87	435.35	25187.20	213.81		-0.01	23.01
	end terrace 5m - SW	3_1_3	13446.02	5386.70	2408.36	3528.87	435.35	25205.30	213.97		0.06	22.96
	mid terrace 6m	3_2_10	13446.02	5386.70	2392.18	3528.87	435.35	25189.12	213.83		0.00	23.02
	end terrace 6m - mid	3_4_4	13446.02	5386.70	2385.25	3528.87	435.35	25182.19	213.77		-0.03	22.98
	mid terrace 6m	3_2_11	13446.02	5386.70	2383.83	3528.87	435.35	25180.78	213.76		-0.04	23.01
	end terrace 7m - NE	3_3_4	13446.02	5386.70	2390.71	3528.87	435.35	25187.65	213.82		-0.01	23.00

	mid terrace 0m	4_2_1	14473.31	5798.25	2483.98	4369.93	435.35	27560.82	217.36		0.03	23.07
	mid terrace 0m	4_2_2	14473.31	5798.25	2492.21	4369.93	435.35	27569.05	217.42		0.06	23.06
	end terrace 0m - NE	4_3_1	14473.31	5798.25	2507.83	4369.93	435.35	27584.67	217.54		0.12	23.05
	mid terrace 1m	4_2_3	14473.31	5798.25	2453.76	4369.93	435.35	27530.60	217.12		-0.08	23.07
	end terrace 1m - mid	4_4_1	14473.31	5798.25	2436.11	4369.93	435.35	27512.95	216.98		-0.15	23.04
	mid terrace 1m	4_2_4	14473.31	5798.25	2460.88	4369.93	435.35	27537.72	217.17		-0.06	23.06
	end terrace 2m - SW	4_1_1	14473.31	5798.25	2519.81	4369.93	435.35	27596.65	217.64		0.16	22.99
	mid terrace 2m	4_2_5	14473.31	5798.25	2452.84	4369.93	435.35	27529.68	217.11		-0.08	23.06
	end terrace 2m - NE	4_3_2	14473.31	5798.25	2516.95	4369.93	435.35	27593.79	217.62		0.15	22.99
	end terrace 3m - mid - green - SW	4_5_1	14473.31	5798.25	2473.89	4369.93	435.35	27550.72	217.28		-0.01	23.03
4B	end terrace 3m - mid - green - NE	4_5_2	14473.31	5798.25	2475.76	4369.93	435.35	27552.60	217.29	217.29	0.00	23.04
	end terrace 4m - SW	4_1_2	14473.31	5798.25	2454.10	4369.93	435.35	27530.94	217.12		-0.08	23.03
	mid terrace 4m	4_2_6	14473.31	5798.25	2454.68	4369.93	435.35	27531.52	217.13		-0.08	23.06
	end terrace 4m - NE	4_3_3	14473.31	5798.25	2530.67	4369.93	435.35	27607.51	217.72		0.20	22.99
	mid terrace 5m	4_2_7	14473.31	5798.25	2457.25	4369.93	435.35	27534.09	217.15		-0.07	23.05
	end terrace 5m - mid	4_4_2	14473.31	5798.25	2468.50	4369.93	435.35	27545.34	217.23		-0.06	23.03
	mid terrace 5m	4_2_8	14473.31	5798.25	2464.15	4369.93	435.35	27540.99	217.20		-0.04	23.03
	end terrace 6m - SW	4_1_3	14473.31	5798.25	2460.86	4369.93	435.35	27537.70	217.17		-0.06	23.03
	mid terrace 6m	4_2_9	14473.31	5798.25	2461.82	4369.93	435.35	27538.66	217.18		-0.05	23.05
	end terrace 6m - NE	4_3_4	14473.31	5798.25	2535.77	4369.93	435.35	27612.61	217.77		0.22	22.98
	mid terrace 7m	4_2_10	14473.31	5798.25	2475.42	4369.93	435.35	27552.26	217.29		0.00	23.05
	end terrace 7m - SW	4_1_4	14473.31	5798.25	2437.51	4369.93	435.35	27514.34	216.99		-0.14	23.04

Appendix 5

Energy results

i. Energy demand results - seasons

		Energy demand kWh				Code
		Winter	Spring	Summer	Autumn	
1B	25	590.3	486.2	450.8	509.5	1S1FT
	26	606.0	450.9	383.8	469.9	1R
	32	530.2	382.0	299.2	396.4	1FT
	33	599.8	559.2	577.0	637.2	1S1SH
	47	586.4	478.8	436.7	500.6	2FT
	49	557.4	397.9	310.3	412.9	1FT
	50	699.2	564.3	517.4	583.3	1S
	53	638.6	535.6	509.0	564.4	2SH
	64	580.3	459.2	407.6	480.1	1SH
	68	552.9	396.4	310.6	411.0	1FT
	81	675.2	534.9	491.8	557.9	2S
2B	6	879.3	678.9	609.5	699.5	1FT1SH1C
	14	877.1	675.7	604.6	695.5	1FT1SH1C
	16	871.8	694.1	635.5	717.0	2FT3C
	17	778.9	583.7	490.9	602.8	1FT1PT
	23	840.0	669.9	609.0	691.7	2FT2C
	27	785.8	549.6	414.9	565.0	1R
	39	859.6	653.8	576.7	672.2	1FT1SH1C
	45	844.6	626.5	532.6	643.8	2SH
	52	856.0	708.6	671.3	738.3	1PT1SH2C
	57	752.6	551.7	446.5	564.9	2FT
	61	826.7	630.2	550.1	649.4	2SH
	69	800.1	601.3	514.5	618.8	1PT1SH
	73	780.1	544.4	408.1	559.8	1S
	76	741.0	575.9	503.6	593.8	1S1SH
	78	758.3	571.4	492.5	590.0	1S1SH
3B	3	1190.7	800.2	586.1	813.9	2R
	7	950.1	714.5	605.0	731.7	2FT2C
	13	1325.8	922.5	718.9	931.4	1FT1SH2C
	19	1041.0	642.9	369.4	654.5	1FT
	20	1248.2	912.1	751.1	928.7	1S2SH
	21	1198.8	859.6	697.5	864.9	2FT2C
	30	1194.5	853.8	684.5	864.6	3FT1S
	35	1233.5	857.2	638.6	872.0	1FT1S1C
	36	1341.5	937.5	725.3	947.6	1PT1SH1C
	41	1160.2	730.5	455.5	739.8	1FT1PT
	43	1207.0	787.8	531.4	799.0	1S1SH
	48	1121.4	762.7	563.3	776.1	1FT1S
	51	994.4	672.2	473.9	683.8	1SH
	60	1384.8	997.0	820.7	1009.2	2S2SH
	65	1157.1	872.9	741.8	889.5	3SH
	67	1386.5	991.4	802.7	1003.8	3SH
	70	1098.4	728.5	518.0	741.8	1FT1PT
	71	1092.0	709.2	472.8	723.7	1S
	72	1187.0	897.2	760.9	914.1	1PT1SH1S
	75	1237.5	819.3	572.1	830.1	1FT1SH
	79	1104.4	754.8	559.2	767.9	1S1PT
	80	1244.7	870.2	669.5	886.8	1FT2C
4B	1	1372.1	1075.5	992.0	1109.1	2FT1PT2R
	2	1096.4	768.5	620.0	791.1	2R
	4	1158.8	801.3	635.5	824.1	2FT
	5	1166.5	788.8	590.4	803.8	2FT1C
	8	1265.2	914.7	760.7	937.5	4S
	9	1079.7	751.6	588.8	769.4	2R
	12	1070.1	702.8	512.9	722.6	2FT
	15	1119.2	752.5	573.3	774.4	1FT1SH
	18	1183.2	838.8	696.6	860.1	2FT2C
	22	1298.3	932.1	779.3	954.6	2FT1C1S
	28	1050.1	730.6	579.6	751.4	1FT1SH
	29	1357.6	958.1	792.4	979.8	1S2R
	31	1390.8	985.6	799.7	1007.5	1FT1SH2S
	34	1171.3	802.0	634.1	825.2	2FT1S
	37	1125.8	745.4	553.2	767.0	1R1FT
	38	1177.7	827.0	671.9	849.2	3S
	40	1174.9	831.6	688.1	852.9	2FT1C1S
	42	1268.4	890.9	732.9	918.8	1S2R
	46	1202.8	838.0	667.1	863.0	2FT1S
	55	1007.3	652.4	448.4	669.8	1S
	56	1206.1	894.2	785.6	923.6	1FT1SH1C1S
	58	1223.5	808.6	597.4	828.3	2S
	62	1282.5	1004.7	914.1	1035.0	1S1SH1PT1R
	63	1147.0	841.4	703.0	859.9	1PT1S1SH
	74	1014.2	619.2	374.5	636.4	1FT
	77	1302.3	886.6	685.8	905.2	1PT1S1SH
	Total	75879.5	54298.1	43850.0	55720.0	

ii. Energy demand results – house data

1B	Room Electricity	Lighting	Heating (Electricity)	DHW (Electricity)	Exterior lighting	Total energy/year	Total energy/sq. m/year
25	602.0	482.4	123.3	393.7	435.3	2036.7	43.3
26	600.2	359.3	258.4	257.5	435.3	1910.6	40.7
32	549.3	190.8	299.0	133.3	435.3	1607.6	34.2
33	855.0	587.5	0.0	495.4	435.3	2373.3	50.5
47	583.0	460.3	145.7	378.0	435.3	2002.5	42.6
49	560.5	217.4	324.4	140.9	435.3	1678.5	35.7
50	1163.9	326.2	183.3	255.5	435.3	2364.2	50.3
53	605.2	591.0	98.0	518.1	435.3	2247.6	47.8
64	679.8	372.8	180.1	259.1	435.3	1927.2	41.0
68	564.6	207.8	319.1	144.1	435.3	1671.0	35.6
81	588.2	547.2	178.9	510.2	435.3	2259.8	48.1
Average energy demand - 1B household						2007.2	42.7

2B	Room Electricity	Lighting	Heating (Electricity)	DHW (Electricity)	Exterior lighting	Total energy/year	Total energy/sq. m/year
6	697.4	763.2	317.6	653.8	435.3	2867.2	40.4
14	691.4	763.2	324.9	638.1	435.3	2852.9	40.2
16	604.2	583.9	270.4	1024.5	435.3	2918.3	41.1
17	600.8	561.0	375.1	483.9	435.3	2456.2	34.6
23	595.7	700.2	265.7	813.8	435.3	2810.6	39.6
27	509.0	606.1	538.7	226.1	435.3	2315.2	32.6
39	611.9	749.7	346.1	619.3	435.3	2762.3	38.9
45	643.6	662.7	401.8	504.2	435.3	2647.5	37.3
52	620.9	777.9	175.4	964.6	435.3	2974.1	41.9
57	605.0	481.4	419.6	374.3	435.3	2315.7	32.6
61	663.2	697.0	342.5	518.3	435.3	2656.4	37.4
69	633.0	653.6	363.5	449.3	435.3	2534.7	35.7
73	492.4	596.5	542.1	226.1	435.3	2292.5	32.3
76	635.6	599.6	284.8	459.0	435.3	2414.4	34.0
78	590.7	598.6	329.2	458.3	435.3	2412.1	34.0
Average energy demand - 2B household						2615.4	36.8

3B	Room Electricity	Lighting	Heating (Electricity)	DHW (Electricity)	Exterior lighting	Total energy/year	Total energy/sq. m/year
3	537.1	1022.6	929.5	466.3	435.3	3390.9	28.8
7	613.6	757.5	478.8	716.1	435.3	3001.3	25.5
13	619.8	1122.0	914.4	807.1	435.3	3898.6	33.1
19	557.5	448.0	1103.1	163.9	435.3	2707.8	23.0
20	674.1	1328.9	726.5	675.2	435.3	3840.1	32.6
21	698.4	1001.8	734.4	750.9	435.3	3620.8	30.7
30	697.2	1004.8	755.8	704.2	435.3	3597.4	30.5
35	531.0	984.7	937.0	713.3	435.3	3601.2	30.6
36	765.9	1212.2	941.1	597.3	435.3	3951.8	33.5
41	552.3	706.3	1157.9	234.1	435.3	3085.9	26.2
43	509.1	945.9	1084.9	350.1	435.3	3325.3	28.2
48	562.5	1002.3	857.6	365.7	435.3	3223.5	27.4
51	498.5	863.5	810.4	216.5	435.3	2824.2	24.0
60	769.7	1325.4	821.3	860.0	435.3	4211.7	35.8
65	721.7	1149.8	584.6	769.9	435.3	3661.4	31.1
67	653.1	1457.3	862.6	776.0	435.3	4184.3	35.5
70	566.4	805.1	903.6	376.2	435.3	3086.7	26.2
71	551.4	812.1	987.6	211.2	435.3	2997.7	25.4
72	711.1	1290.8	604.4	717.5	435.3	3759.2	31.9
75	571.5	990.0	1055.9	406.3	435.3	3459.0	29.4
79	606.7	905.2	836.0	402.9	435.3	3186.2	27.0
80	614.7	1004.8	880.5	736.0	435.3	3671.3	31.2
Average energy demand - 3B household						3467.6	29.4

4B	Room Electricity	Lighting	Heating (Electricity)	DHW (Electricity)	Exterior lighting	Total energy	Total energy/sq. m
1	782.9	1749.8	475.7	1105.0	435.3	4548.7	35.9
2	586.0	1156.2	679.4	419.1	435.3	3276.0	25.8
4	662.1	1122.2	761.6	438.6	435.3	3419.8	27.0
5	530.5	981.7	883.8	518.2	435.3	3349.5	26.4
8	660.2	1293.4	734.7	754.6	435.3	3878.2	30.6
9	500.5	1100.8	717.0	435.9	435.3	3189.5	25.2
12	566.1	858.6	846.0	302.4	435.3	3008.4	23.7
15	513.0	1038.7	808.8	423.7	435.3	3219.5	25.4
18	628.8	1095.4	691.1	728.1	435.3	3578.7	28.2
22	676.1	1333.0	739.9	780.1	435.3	3964.4	31.3
28	573.2	1044.9	676.9	381.3	435.3	3111.6	24.5
29	641.5	1426.4	807.6	777.0	435.3	4087.9	32.2
31	857.6	1333.3	777.4	779.9	435.3	4183.6	33.0
34	597.5	1080.2	788.7	531.0	435.3	3432.6	27.1
37	528.9	1025.3	862.1	339.9	435.3	3191.4	25.2
38	573.4	1254.3	730.1	532.6	435.3	3525.8	27.8
40	635.8	1119.8	692.1	664.5	435.3	3547.5	28.0
42	692.0	1237.2	763.1	683.4	435.3	3810.9	30.1
46	613.6	1062.1	789.7	670.1	435.3	3570.9	28.2
55	536.9	797.7	866.8	141.2	435.3	2777.9	21.9
56	631.4	1391.8	561.5	789.4	435.3	3809.4	30.0
58	497.1	1136.5	950.4	438.6	435.3	3457.8	27.3
62	739.3	1577.9	469.2	1014.6	435.3	4236.3	33.4
63	667.8	1212.5	630.6	605.2	435.3	3551.3	28.0
74	438.9	624.8	1031.4	113.9	435.3	2644.4	20.9
77	601.5	1268.1	909.4	565.5	435.3	3779.9	29.8
Average energy demand - 4B household						3544.3	28.0

iii. Sensitivity analysis using lifestyles

		Energy demand kWh				Code	Lifestyl	Notes	
		Winter	Spring	Summer	Autumn				
1B	25	614.4	490.3	450.8	513.6	1S1FT	F	It was noted that internal gains (from equipment and occupancy) led to some overheating in april and october. Heating was therefore turned off for these months.	extrapolated from 48
	26	606.0	450.9	383.8	469.9	1R	T		
	32	530.2	382.0	299.2	396.4	1FT	T		
	33	702.0	580.6	577.0	646.1	1S1SH	F		extrapolated from 69
	47	612.5	483.9	436.7	504.8	2FT	F		extrapolated from 57
	49	537.8	389.6	310.3	404.4	1FT	E		x
	50	699.2	564.3	517.4	583.3	1S	T		
	53	654.6	538.4	509.0	566.4	2SH	F		extrapolated from 61
	64	616.7	469.4	407.6	489.2	1SH	F		extrapolated from 61
	68	543.0	392.8	310.6	407.2	1FT	E		x
	81	675.2	534.9	491.8	557.9	2S	T		
2B	6	879.3	678.9	609.5	699.5	1FT1SH1C	T	It was noted that internal gains (from equipment and occupancy) led to some overheating in October despite the heating being turned off.	
	14	877.1	675.7	604.6	695.5	1FT1SH1C	T		
	16	836.4	679.8	635.5	705.6	2FT3C	E		extrapolated from 40
	17	778.9	583.7	490.9	602.8	1FT1PT	T		
	23	840.0	669.9	609.0	691.7	2FT2C	T		
	27	785.8	549.6	414.9	565.0	1R	T		
	39	859.6	653.8	576.7	672.2	1FT1SH1C	T		
	45	844.6	626.5	532.6	643.8	2SH	T		
	52	856.0	708.6	671.3	738.3	1PT1SH2C	T		
	57	752.6	551.7	446.5	564.9	2FT	T		
	61	826.7	630.2	550.1	649.4	2SH	T		
	69	800.1	601.3	514.5	618.8	1PT1SH	T		
	73	780.1	544.4	408.1	559.8	1S	T		
	76	779.0	587.9	503.6	605.9	1S1SH	F		extrapolated from 69
	78	776.5	578.8	492.5	596.3	1S1SH	F		extrapolated from 69
3B	3	1190.7	800.2	586.1	813.9	2R	T		
	7	1126.0	774.9	605.0	789.1	2FT2C	F		extrapolated from 21
	13	1223.1	879.2	718.9	893.1	1FT1SH2C	E		extrapolated from 40
	19	1041.0	642.9	369.4	654.5	1FT	T		
	20	1248.2	912.1	751.1	928.7	1S2SH	T		
	21	1198.8	859.6	697.5	864.9	2FT2C	T		
	30	1194.5	853.8	684.5	864.6	3FT1S	T		
	35	1233.5	857.2	638.6	872.0	1FT1S1C	E		x
	36	1341.5	937.5	725.3	947.6	1PT1SH1C	T		
	41	1112.5	710.4	455.5	719.5	1FT1PT	E		x
	43	1207.0	787.8	531.4	799.0	1S1SH	T		
	48	1121.4	762.7	563.3	776.1	1FT1S	T		
	51	1115.2	723.5	473.9	735.4	1SH	F		extrapolated from 61
	60	1384.8	997.0	820.7	1009.2	2S2SH	T	1180.6	
	65	1342.8	941.9	741.8	952.1	3SH	F	804.4	extrapolated from 67
	67	1386.5	991.4	802.7	1003.8	3SH	T	620.0	
	70	1098.4	728.5	518.0	741.8	1FT1PT	T	826.1	
	71	1092.0	709.2	472.8	723.7	1S	T		
	72	1213.0	911.6	760.9	925.3	1PT1SH1S	F		extrapolated from 63
	75	1237.5	819.3	572.1	830.1	1FT1SH	T		
	79	1104.4	754.8	559.2	767.9	1S1PT	T		
	80	1244.7	870.2	669.5	886.8	1FT2C	T		
4B	1	1372.1	1075.5	992.0	1109.1	2FT1PT2R	T		
	2	1180.6	804.4	620.0	826.1	2R	F		extrapolated from 61
	4	1158.8	801.3	635.5	824.1	2FT	T		
	5	1166.5	788.8	590.4	803.8	2FT1C	T		
	8	1265.2	914.7	760.7	937.5	4S	T		
	9	1161.1	779.0	588.8	800.6	2R	F		extrapolated from 61
	12	1070.1	702.8	512.9	722.6	2FT	T		
	15	1119.2	752.5	573.3	774.4	1FT1SH	T		
	18	1183.2	838.8	696.6	860.1	2FT2C	T		
	22	1298.3	932.1	779.3	954.6	2FT1C1S	T		
	28	1113.6	751.6	579.6	773.8	1FT1SH	F		extrapolated from 15
	29	1357.6	958.1	792.4	979.8	1S2R	T		
	31	1269.6	937.8	799.7	965.7	1FT1SH2S	E		extrapolated from 40
	34	1171.3	802.0	634.1	825.2	2FT1S	T		
	37	1125.8	745.4	553.2	767.0	1R1FT	T		
	38	1177.7	827.0	671.9	849.2	3S	T		
	40	1174.9	831.6	688.1	852.9	2FT1C1S	T		
	42	1268.4	890.9	732.9	918.8	1S2R	T		
	46	1202.8	838.0	667.1	863.0	2FT1S	T		
	55	1063.3	678.1	448.4	697.4	1S	E		extrapolated from 74
	56	1239.8	907.7	785.6	934.8	1FT1SH1C1S	F		extrapolated from 74
	58	1223.5	808.6	597.4	828.3	2S	T		
	62	1282.5	1004.7	914.1	1035.0	1S1SH1PT1R	T		
	63	1147.0	841.4	703.0	859.9	1PT1S1SH	T		
	74	1014.2	619.2	374.5	636.4	1FT	T		
	77	1302.3	886.6	685.8	905.2	1PT1S1SH	T		
	Total	76631.1	54542.6	43850.0	55952.8				

iv. Photovoltaic-Software

Calculation of the solar PV energy ouput of a photovoltaic system

(yellow)	Yelow cell = enter your own data
(green)	Green cell = result (do not change the value)
(white)	White cell = calculated value (do not change the value)

Global formula : E = A * r * H * PR

E = Energy (kWh)	116328	kWh/an
A = Total solar panel Area (m²)	1240	m²
r = solar panel yield (%)	20%	
H = Annual average irradiation on tilted panels (shadings not included)*	625.8	kWh/m².an
PR = Performance ratio, coefficient for losses (range between 0.9 and 0.5, default value = 0.75)	0.75	

Total power of the system	248.0	kWp

Losses details (depend of site, technology, and sizing of the system)

- Inverter losses (6% to 15 %)	8%
- Température losses (5% to 15%)	8%
- DC cables losses (1 to 3 %)	2%
- AC cables losses (1 to 3 %)	2%
- Shadings 0 % to 40% (depends of site)	3%
- Losses weak irradiation 3% yo 7%	3%
- Losses due to dust, snow... (2%)	2%
- Other Losses	0%

v. Energy supply results

Date/Time	Solar panel inclination				Solar panel combinations					
	45	28	74	0	45+28	45+28+0	45+28+74	28+74	28+74+0	45+28+74+0
	kWh/m2				kWh/m2					
01/12/2002	28.5	25.4	44.2	8.5	53.9	62.4	98.0	69.5	78.0	106.5
01/01/2002	41.1	35.9	51.9	10.9	77.1	88.0	128.9	87.8	98.7	139.8
01/02/2002	51.2	46.8	74.7	16.6	98.0	114.6	172.7	121.5	138.1	189.3
01/03/2002	80.6	78.3	109.1	33.0	158.9	192.0	268.1	187.5	220.5	301.1
01/04/2002	123.9	123.2	125.6	54.0	247.1	301.1	372.7	248.8	302.8	426.7
01/05/2002	153.3	158.9	114.8	76.2	312.2	388.3	427.0	273.7	349.9	503.1
01/06/2002	142.6	149.4	126.6	73.4	292.0	365.4	418.6	276.0	349.3	491.9
01/07/2002	155.1	161.0	124.4	77.4	316.1	393.4	440.4	285.3	362.7	517.8
01/08/2002	146.7	148.7	97.7	67.7	295.4	363.1	393.1	246.4	314.1	460.8
01/09/2002	108.0	105.8	80.2	44.9	213.9	258.8	294.1	186.0	231.0	339.0
01/10/2002	80.3	74.0	48.3	26.9	154.2	181.2	202.6	122.3	149.2	229.5
01/11/2002	46.2	41.6	30.3	14.3	87.9	102.2	118.2	72.0	86.3	132.5

	Solar irradiance/season for community											
Date/Time	45+28	45+28+0	45+28+74	28+74	28+74+0	45+28+74 +0	45+28	45+28+0	45+28+74	28+74	28+74+0	45+28+74+0
	kWh/m2/season						kWh/season					
01/12/2002 01/01/2002 01/02/2002	229.0	264.9	399.7	278.8	314.8	435.7	34329.0	65060.0	59919.0	41795.0	65191.0	96667.0
01/03/2002 01/04/2002 01/05/2002	718.2	881.4	1067.7	710.0	873.2	1231.0	133467.0	194196.0	160058.0	106435.0	192653.0	273116.0
01/06/2002 01/07/2002 01/08/2002	903.5	1121.9	1252.2	807.7	1026.2	1470.6	167949.0	249144.0	187686.0	121081.0	231355.0	326275.0
01/09/2002 01/10/2002 01/11/2002	456.0	542.2	614.9	380.3	466.5	701.0	68358.0	116811.0	92179.0	57010.0	102740.0	155527.0