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Integrating economic considerations with operational and embodied emissions into a decision support system for the optimal ranking of building retrofit options

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Abstract

In the UK, 87% of dwellings and 60% of non-domestic buildings that will be standing in 2050 have already been built. Therefore, the greatest energy savings and emissions reductions will be achieved through retrofit of existing buildings. This usually involves decision-making processes targeted at reducing operational energy consumption and maintenance bills. For this reason, retrofit decisions by building stakeholders are typically driven by financial considerations. However, recent trends towards environmentally conscious design and retrofit have focused on the environmental merits of these options, emphasising a lifecycle approach to emissions reduction. Building stakeholders cannot easily quantify and compare the sustainability impacts of retrofit options since they lack the resources to perform an effective decision analysis. In part, this is due to the inadequacy of existing methods to assess and compare the cost, operational performance and environmental merit of the options. Current methods to quantify these parameters are considered in isolation when making decisions about energy conservation in buildings. To effectively manage the reduction of lifecycle environmental impacts, it is necessary to link financial cost with both operational and embodied emissions. This paper presents a robust Decision Support System which integrates economic and net environmental benefits (including embodied and operational emissions) to produce optimal decisions based on marginal abatement cost methods and Pareto optimisation. The implication of the DSS within the current climate change policies is also discussed. Overall, the methodology developed provides stakeholders with an efficient and reliable decision process that is informed by both environmental and financial considerations.

Keywords: *Buildings, Decision making, Economics, Emissions, Retrofit, Optimisation.*

1.0 Introduction

The building sector represents a priority for the United Nation in terms of climate change mitigation since it is collectively responsible for 40% of the world's energy consumption and one third of global greenhouse gas (GHG) emissions as well as representing the largest emissions source in most developed and developing countries [1-3]. At the same time, the sector is often regarded as a 'goldmine' of GHG mitigation [4] as it has more potential than any other sector to deliver quick and deep cut in GHG emissions at zero cost or net savings [5-7]. Fortunately, innovations and technological advances in the area of renewable energy technologies, energy efficiency and inducements to change behaviour, which offer promising retrofit solutions for GHG emissions reduction available today, are greater than ever before. However, these measures often lead to increased material and energy use for their production, contributing to an increase in embodied emissions [8, 9]. Given the review by Ibn-Mohammed *et al.* [10] which highlights in detail the increasing proportion of embodied emissions that is one consequence of efforts to decrease operational emissions, recent trends, geared towards resource efficient design, have focused on the environmental merits of these options, emphasising a lifecycle approach to emissions reduction. The challenge therefore is to devise means to implement these low carbon intervention measures in the most cost-effective and optimal manner to minimise the energy consumption and environmental impact of buildings.

Improving energy efficiency, using, for example, Building Energy Management Systems (BEMS) is one option that can reduce energy consumption in buildings. However, there are many alternative measures with different combinations of cost, energy-saving potential and environmental performance. The measures adopted are therefore often the result of an optimization process measured across mainly two key performance indicators (KPIs) namely: environmental (energy efficiency improvement and emissions reduction potential) and economic (cost-effectiveness of measures) [11, 12]. These are usually evaluated using the concept of cost-effectiveness in pounds per tonne of CO_2 or equivalent, to identify the economically most efficient way to fulfil the objective by comparing the relative costs and emissions saving potentials of retrofit options. A lower numerical value of cost-effectiveness of an option corresponds to an improvement. However, the inclusion of embodied emissions can worsen the cost-effectiveness of an option, giving a higher numerical value. For instance, the cost-effectiveness of a photovoltaic system worsens when embodied emissions associated with it are considered.

Given this background, the selection of an environmentally and economically optimal set of retrofit options requires a robust decision-making methodology. This will allow these options to be compared in a consistent manner by evaluating their economic costs, operational emissions performance and environmental merits. A number of various decision aid tools have been developed to support and advise building stock owners with respect to retrofitting decisions for energy conservation [13]. Examples of recent work on the subject include studies by Costa *et al.* [14], Chidiac *et al.* [15], Yin and Menzel [16], Diakaki *et al.* [17], Loh *et al.* [18], Juan *et al.* [19], Doukas *et al.* [20], Guggemos and Horvath [21]. Building retrofit decision-making processes are generally targeted at reducing operational energy consumption and maintenance bills. For this reason, retrofit decisions by building stakeholders are typically driven by financial considerations. As such, some of the DSSs listed here have only focused on economics and operational emissions savings potentials of the retrofit options, ignoring embodied emissions.

As operational impacts from buildings are reduced, embodied impacts are increasing. As a result, there is an increased focus on the reduction of embodied emissions either through optimisation of building fabric to reduce material use or through the specification of materials with lower embodied emissions. However, methodologies employed to evaluate and compare embodied and operational emissions are typically considered in isolation when making decisions about energy conservation in buildings. There is a need for a comprehensive techno-economic evaluation methodology that integrates economic considerations with operational and embodied emissions into a Decision Support System (DSS) for the optimal ranking of building energy retrofit options. Such a system is presented in this paper.

Adopting a techno-economic evaluation methodology for energy retrofit of buildings, the DSS presented integrates economic (cost) and net emissions (embodied and operational emissions) cost or benefit parameters and an optimization scheme. The model development is underpinned by the use of Environmental-Economic Input-Output methodology [22-24] based on the 2-region Multi-Regional (UK and the Rest-of-the-World) Input-Output (MRIO) framework [25, 26] to evaluate the embodied emissions of a number of low carbon intervention options. The derivation of the operational emission savings potentials of each retrofit option is based on standard algorithms for low carbon energy sources and post implementation analysis. The model also incorporates an economic evaluation module which evaluates investment and operating cost estimates based on a standard investment appraisal technique. The novelty of this DSS lies in the application of a whole-life environmental and economic assessment approach to the integration of financial cost and both embodied and operational emissions. These variables are used within a robust optimisation scheme that consists of integrated modules for data input, sensitivity analysis and ranking based on MACC principles and Pareto optimisation. The DSS therefore allows the trade-offs between various refurbishment options to be identified and communicated, and ensure decisions that are informed both by environmental and financial considerations.

2.0 Aim and structure of paper

This paper presents the methodological framework underpinning the development of the DSS described above. The aim is to develop a best-value approach to emissions saving in buildings, taking into account operational and embodied emissions as well as cost. The structure of the paper is as follows. Section 3 presents a description of the design and the underlying principles of the proposed DSS and its components. A description of the methodology detailing the computational framework and the integration of the three variables of costs, operational emissions and embodied emissions into a single model are provided in section 4. Selection criteria for the set of GHG emissions reduction options to be appraised are presented in section 5. Results, analysis and discussion are presented in section 6. In section 7, details are provided about the approach taken to handle interaction and overlaps between measures. A discussion of the limitation of the DSS and its use as policy tools to address climate change issues. Finally, conclusions are drawn in section 8.

3.0 Design of the decision support system

3.1 System Definition and Structure

For every refurbishment project relating to non-domestic buildings, questions such as: "*What options are applicable to reduce building emissions now and in the future? How cost effective are these measures? What will be the return on investment? How much CO_2 will each option save? What are the net emissions benefits of the option? What is the best combination of options and what strategy should be adopted?"* will be considered in a different way by an investor and an environmentalist. The sole desire of the investor is a high financial return, whereas the environmentalist will prioritise GHG emission reduction. These are questions that require an engineering solution as much as an economic one. Answering the questions effectively depends not only on the level of expertise available but also on the capability of decision aid tools available to the analyst. The aim of the DSS presented in this paper is therefore to identify the most financially and environmentally promising investment strategy, given an initial financial resource constraint; and the range of potential strategies that balance cost, return-on-investment, and net GHG emissions reduction (where both embodied and operational emissions are considered). Choosing the right options can be achieved by following basic steps: measure performance; identify opportunities; prioritise; implement measure; validate savings.

The methodological framework for the DSS is based on 5 modules (Figure 1) which include: (i) a module for the computation of the baseline energy consumption of the building. This involves measuring energy use and energy intensity of the building at a determined level of detail for the purpose of establishing a benchmark for future comparison to itself; (ii) a module that include technically feasible low carbon intervention measures and computes their potential energy and CO_2 savings; (iii) a module which computes the embodied emissions related to each low carbon intervention measure; (iv) an economic evaluation module which evaluates investment and operating cost estimates and is based on an appropriate investment appraisal technique; (v) an optimisation module which integrates the measures of financial cost, operational and embodied emissions into a robust method of ranking and sequencing building energy retrofit options.

3.2 System Requirements

As shown in the preceding section of this paper, the information requirements for the DSS are cost, operational emissions (OE) and embodied emissions (EE). For each of the identified low carbon intervention options, including energy efficiency measures, renewable energy generation technologies and inducements to change behaviour, analysis of their potential operational emissions savings is undertaken. This is based on performance calculation methods using standard algorithms for low carbon energy sources and post implementation analysis. Furthermore, the embodied emissions related to each low carbon intervention measures are evaluated. This will allow for the computation of the net emissions saving of the option. Net emissions saving (E_{net}) in this context is the operational emissions savings (OE) of a measure across the time frame considered minus the initial embodied emissions (EE) incurred in producing the measure. The lifecycle costs and emissions of the options are evaluated to assess and compare the abatement costs and emissions reduction potential of the building retrofit options against the defined criteria.

3.3 System Output

The planned output will give an indication of financial benefits (fuel savings and CO_2 emission reductions) and the environmental merit of the measures over their life span. This will indicate the scenarios where measures that lead to net emissions reduction and also save money, and will put into perspective measures where the investment cost cannot be recovered. The methodological approach takes into account the use of selected carbon abatement technologies that will satisfy a multiplicity of criteria (environmental, demand, cost and resource constraints); sensitivity analysis; hierarchical course of action; and the evaluation of 'best' case scenario.

4.0 Methodology

4.1 Case study building

The overall research is part of a Living Lab case study project to retrofit De Montfort University's Queens Building, with the aim of transforming it into an exemplar of sustainability and energy efficiency. Opened in 1995, it was the "Independent Newspaper Green Building of the Year" and also won several other awards. The entire building is passively cooled and naturally lit–at the time it was Europe's largest naturally ventilated building with a floor area of 10,000m². Further information on the case study building, including its envelope characteristics, occupancy and related details are available in NPCS [27]. Today it is no longer the icon it once was due mainly to changes in use, and in this sense it is representative of much UK building stock. Currently, the energy rating on the Energy Performance Certificate is a D (on a scale of A-G). The present research is part of an overall plan to transform it into a low carbon 'intelligent' building that demonstrates the latest technologies in the fields of renewable energy, carbon reduction and building management systems. It is expected that the outcome of the plans will demonstrate how to achieve (and eventually surpass) the UK Government's carbon reduction targets in a sustainable and cost-effective manner.

4.2 Baseline evaluation

This involves the establishment of the base line or base case (the 'do nothing' option) energy (gas and electricity) consumption of the building. The main purpose of this step is to evaluate the characteristics of the energy systems and the patterns of energy use for the building. It entails the measurement of energy use and energy intensity of the target building at a determined level of detail for the purpose of establishing a benchmark for future comparison. This was established by defining boundaries (i.e. load distribution, occupancy pattern, etc.), choosing a baseline year, gathering energy use data (half-hourly by fuel source and energy tariffs) and computing baseline energy consumption and carbon footprint using appropriate greenhouse gas emissions factors [28].

The building in its present form including its associated operational energy consumption and CO_2 emissions as well as running costs forms the baseline as the set point for comparative carbon benefit/savings analysis. The building's CO_2 baseline is a key element of the optimal retrofit pathway since the CO_2 savings for each of the CO_2 reduction options are expressed as a percentage of *part* of the baseline. For instance, one CO_2 reduction measure could be the implementation of voltage optimisation. The CO_2 savings associated with voltage optimisation would be expressed as a percentage of the electricity element of the energy use in the building's baseline.

4.3 Evaluation of operational emissions savings from options

The energy saving predictions from each measure are based on performance calculation methods using standard algorithms for low carbon energy sources and post implementation evaluation using appropriate energy data analysis techniques (e.g. degree day analysis). The chosen evaluation method for a measure will depend on the nature of the measure. Operational emissions savings from the installation of selected renewable energy technologies are based on standard algorithms for low carbon energy sources [29, 30]. Savings from BEMS, voltage optimisation are based on post implementation evaluation using an energy data analysis technique. Savings from other measures such as LEDs are based on performance calculation methods.

4.4 Evaluation of embodied emissions associated with options

This section describes the methodological approach for computing the embodied emissions associated with each of the identified building energy retrofit intervention measures. The I-O process utilises economic data of cash flow among various sectors of industry. The data are organised into an I-O table made available by the national government. The I-O table takes the form of a square matrix which illustrates the financial input of products in £ (as in the case for UK) from each sector of the economy **(row)** required to produce total output of each industry sector **(column)** also expressed in £.

The I-O table contains three key aggregated set of information namely Intermediate Consumption (**Z**) in £, Final Demand (**Y**) in £ and Total Output (**X**) in £. Assuming an input-output table is organised into n sectors, the intermediate consumption would be a $n \times n$ matrix. Each cell of this matrix describes the deliveries between two particular sectors. The **rows** and **columns** of the matrix describe the supplying and receiving sectors respectively. The intermediate consumption is the resources (input) given in £ required by a given sector of an industry to produce an output in £. Final demand are demands for products in £ used by household, government, export etc. Total output is the £ equivalent of outputs produced by each industry.

The relationship between the three variables within the framework of economic input-output analysis is given by:

$$X = (I - A)^{-1}Y \qquad (1)$$

Since industries purchase from other industries to produce their own goods and services, the I-O table is therefore used to determine these indirect deliveries (from one industry to another) by deriving a **technology matrix**, also known as a **matrix of direct requirement coefficients**. This is a matrix indicating sector-to-sector flows of purchases. It is the requirement from each of the economic sector needed to produce a unit output and is denoted by A. Equation 1 is the Leontief Inverse Matrix.

By adding environmental information, such as greenhouse gas emissions, to each sector, an environmental burden (a "footprint") can then be assigned to these financial transactions. This characterises the environmental impact of an additional £1 of output from each industry and is given by the expression:

$$E = D_{IM} . (I - A)^{-1}Y \qquad (2)$$

Let Total (direct and indirect) Intensity Matrix $T_{IM} = D_{IM} . (I - A)^{-1}$

$$\therefore E = T_{IM} . Y \qquad (3)$$

Hence total lifecycle emissions (E) from a product is given by the matrix multiplication of

$$\text{Total Intensity Matrix } (KgCO_2e/£) \times \text{Final demand } (£) \qquad (4)$$

The final demand given in monetary quantities (£) is calculated by multiplying the physical quantity in which an abatement option is quantified (e.g. KW_p) and its unit cost (£/unit; example £/ KW_p). In matrix notations, the final demand matrix would be a column matrix with dimension $(n\ x\ 1)$.

4.4.1 Environmental-Economic Input–Output method, within a Multi-Regional Input–Output Framework

Adopting environmental-economic input–output (EE-IO) method, within a Multi-Regional Input–Output (MRIO) Framework, it is possible to estimate the environmental loads and implications of consumption associated with international trade flows, be it for GHG emissions, land use and water use [31, 32]. The distinctive feature of MRIO framework is that it allows for the tracking of the production of a given product in a given economic sector, quantifying the contributions to the value of the product from different economic sectors in various countries or regions captured in the model [32]. It therefore gives an account of the global supply chains of products consumed.

In this paper, the methodical approach is used to assess the embodied emissions associated with each of the abatement options under consideration. In the MRIO framework illustrated in Figure 2, the technology options under consideration are integrated into a generalised 2-region (UK and Rest of the World) environmental-economic input–output framework in order to account for economy-wide indirect GHG emissions. The MRIO matrix is interconnected with the matrix representation of the physical product within an environmental I-O framework. This approach allows for the tracking of embodied emissions related to products manufactured both inside and outside the UK.

The basic entities in the MRIO Supply and Use table are industries and commodities (i.e. products). The basic assumption is that Domestic (or UK) and ROW products are supplied to both UK and ROW industries as supply chain inputs and Domestic and ROW industries also produce products for use in the UK and in the ROW. The framework is interpreted as follows. Consider for instance the first column in Figure 2 which consists of 4 segments with each containing 224×224 disaggregated economic sectors. Segment 1 in column 1 is empty as the intersection is UK industries by UK industries. Segment 2 is labelled Domestic Supply; implying products from the UK are supplied to UK industries. Segment 3 is also blank as the intersection is UK industries by RoW industries. Segment 4 is named Imports; which indicates, the UK industry use imported products from the RoW. Overall, the entire Supply and Use table is a 896×896 matrix.

The principle described is then applied to evaluate the embodied emissions of the technology options under consideration as shown in Figure 3. Based on the Supply and Use Table, containing 224×224 disaggregated economic sectors within the MRI-O framework, the intervention options (i.e. products) are classified into the appropriate economic sector by mapping the 2003 and 2007 Standard Industry Classification (SIC) for the UK [33]. Thereafter, the options are categorized either as produced domestically in the UK or imported from the RoW. The procedures for environmental input-output embodied emissions computation methodology is then applied, ensuring the final demand (Y) is recorded in the appropriate segment (i.e. as domestic or imports) of the Final Demand Matrix. A range of intervention option including their standard industry classification and assumed location of manufacture are shown in Table 1.

As an example, assuming the embodied emissions of a $400\mathrm{m}^2$ Photovoltaic System at $£300/\mathrm{m}^2$ is to be evaluated. The final demand is equivalent to: $400\ \mathrm{m}^2 \times £300/\mathrm{m}^2 = £120{,}000$. Using the UK SIC, PVs are classified under *Electronic valves and tubes and other electronic components*. This corresponds to sector 137 in the format of the supply and use table used for this analysis. If the PV were manufactured in the UK (i.e. domestic), then the demand for UK produced PV corresponding to £120,000 is recorded in the final demand matrix (a 896 x 1 column matrix) corresponding to row 364. On the other hand, if the PV were manufactured outside the UK (i.e. imported from the RoW), then the final demand of £120,000.00 is recorded in the final demand matrix corresponding to row 812. The matrix multiplication of the total intensity matrix (TIM) and final demand is then carried out to obtain the embodied emissions associated with the PV. The procedure is repeated for the remaining low carbon intervention options under consideration.

It is to be noted that the methodology suffers from a number of well-recognised limitations such as Proportionality and Homogeneity Assumptions [22]. For example, the limitation associated with the homogeneity assumption manifests itself in the analysis because PVs and LEDs are classified in the same sector; 137- *Electronic valves and tubes and other electronic components*. It is obvious that Sector 137 for example does not consist of homogeneous products produced from identical inputs and processes. Despite these limitations, the methodology offers an extended system boundary of analysis and provides standardised, uniform and faster way of calculating reasonable embodied emissions estimates for these intervention options [34].

4.5 Economics and performance criteria evaluation

This section describes the assessment of the cost/benefit of each particular low carbon retrofit intervention option. The abatement costs of the emissions reduction options are calculated based on total costs (mainly investment costs) and benefits (fuel savings and CO_2 emission reductions) over the time period considered. For each of the identified intervention options, the following information is generated: energy saved or energy generated (kWh) per annum by the option; equivalent CO_2 saved per annum by an option as a function of the base case building energy consumption; total investment cost of the option; cost of energy (gas and electricity).

From the above data, the following information is generated; Cost of energy saved or generated per annum. This is given as:

$$\text{Energy saved or generated (kWh)} \times \text{cost of energy(£/kWh)} \tag{5}$$

The Net Present Value (NPV) of the cost of energy saved or generated is then computed. The NPV concept allows cash flows occurring over a wide time-scale to be considered at their value at today's prices. This requires the discounting of all future savings to their equivalent present value using the formula [35]:

$$\mathrm{NPV} = \mathrm{C}\left[\frac{1-(1+\mathrm{r})^{-\mathrm{n}}}{\mathrm{r}}\right] \tag{6}$$

This gives the net present value, NPV, for an annual energy saving[1], C, occurring for n number of years with a real discount rate of r.

For each low carbon option under consideration, associated with savings in fuel is a saving in CO_2e discharge with respect to the baseline. By dividing the cost of the abatement option in terms of £/kWh by the CO_2 savings in terms of tCO_2e/kWh, a savings cost in pounds per tonne of CO_2e (£/tCO_2e) can then be calculated.

The cost-effectiveness (i.e. cost per tonne of CO_2 saved, £/tCO_2e) is computed to evaluate the performance of the low carbon intervention options using the relation:

$$C_{eff}\ (£/tCO_2) = \frac{\text{Cost of energy saving}(£/kWh)}{CO_2 \text{ savings made } (tCO_2/kWh)} \qquad (7)$$

Equation 7 can also be written as

$$C_{eff} = \frac{\text{Total Investment Cost } (£) - \text{NPV of the cost of enery saved } (£)}{CO_2 \text{ saved per year } (tCO_2e) \times \text{Number of years}} \qquad (8)$$

Equations 7 and 8 represent the Marginal Abatement Cost (MAC) which is the cost per tonne of GHG emissions of the abatement project (i.e. a project to reduce net GHG emissions).

In equation 8, if the $\text{Total Investment Cost} > NPV$ of the cost of energy saved, this implies a net cost (+N) and it indicates that the intervention option under consideration reduces emissions but incur a positive cost. Similarly, if the NPV of the financial savings in energy cost exceeds the investment cost, this implies a net savings or profit (-N). This indicates that the intervention option under consideration reduces emissions and save money. The calculation is repeated for all options being considered. Given a basket of low intervention options, the marginal changes in CO_2 emissions (i.e. the total emissions reduction (measured in tonnes of CO_2) achievable from an option over the period of interest) and cost-effectiveness in effectiveness (measured in cost per tonne of CO_2 or equivalent) are calculated. A rectangular block is then plotted for each option. The width and height of the block respectively corresponds to these values as shown in Figure 4. For detailed description of MAC curve, see Ibn-

[1] Cost of electricity and gas are 10.01p/kWh and 3.85p/kWh and are used throughout this paper.

Mohammed *et al.* [36]. As illustrated option A is chosen as the most economically attractive, implying lower costs and a substantial CO_2 reduction compared to the baseline.

Given an emissions reductions target, the MACC can be used to identify which abatement strategies would best be implemented with the view to achieving the target in the most cost-effective manner. As illustrated in Figure 4, if the desired CO_2 emissions reduction target is say $400tCO_2e$, then the most cost-effective pathway to achieve those reductions would be to implement options A-D. If the target reduction were $700tCO_2e$, then options E-G would also be implemented and so on.

4.5.1 Ranking anomaly with negative cost measures

Given the formula for computing the cost-effectiveness of a measure (equations 7 and 8), it is clear that the emissions savings potential is always positive for the measure under consideration. So for an option that incurs a positive net cost, corresponding to a net financial loss, the cost-effectiveness (C_{eff}) will be positive. This suggests that a smaller C_{eff} is obtained from a lower net cost and higher emissions saving or both. For any abatement measure to be viable it must, in principle, incur a lower financial cost and deliver higher emissions savings. Thus comparing all the options with positive costs, the measure with the smallest C_{eff} provides the smallest financial outlay per tonne of CO_2 abated, and therefore represents the best value. However if an option generates a net saving, corresponding to a net financial return on investment or profit, the picture changes. A smaller (i.e. more negative) C_{eff} is achieved by a greater financial return, which is a desirable objective, or by a reduction in the potential emissions savings, which is the opposite of what is desired. This implies that the measure with the lowest C_{eff} is not necessarily the best option. For abatement options with economic net benefits, the concept leads to wrong priorities.

As an example, consider three abatement options shown in Table 4. By physical inspection of Table 4, installation of LEDs should ordinarily be the preferred abatement option in that the economic net benefit (-£294212) and the CO_2 emissions savings (2758.40tCO_2e) are higher. This should then be followed by the installation of Micro CHP (net savings of -£192742 with emissions reduction of 2117.11 tCO_2e) and then voltage optimisation (net savings of -£122089 with emissions reduction of 1095.03 tCO_2e reduction). However, the CO_2 reduction criterion (C_{eff}) as stated in equation 8, leads to incorrect ranking and consequently a faulty decision, namely to the prioritisation of voltage optimisation before LEDs and Micro CHP, since voltage optimisation has a smaller (i.e. more negative) C_{eff} of -£111.49/tCO_2e as compared to LEDs and Micro CHP with C_{eff} of -£106.66/tCO_2e and -£91.04/tCO_2e respectively.

The above example clearly shows that the standard cost-effectiveness criterion is inadequate for ranking negative-cost measures and therefore restricts the CO_2 reduction cost concept to the economically unattractive options, i.e. those that have positive net cost. A comprehensive analysis, including numerical examples, detailed explanation and mathematical proofs showing that no figure of merit is possible for negative-cost measures is provided by Taylor [37]. There is therefore the need for a different approach for ranking negative cost measures. An alternative ranking method based on Pareto principles within a multi-objective optimisation framework was adopted by Taylor [37] to rank negative-cost measures. Since the mathematical theorem of Pareto optimisation technique is well-covered in the literature (for instance [38]), only its novel application in addressing the ranking anomaly with the negative cost side of MACC is demonstrated in this paper for the sake of brevity.

In the context of the present work, the two criteria to be maximised are (i) a better emissions performance, which corresponds to a larger (more positive) value of S, and (ii) a better financial outcome, corresponding to a smaller (more negative) value of N. Therefore, a measure, say, X dominates measure Y if

$$N_X < N_Y \text{ and } S_X \geq S_Y, \text{ or}$$

$$N_X \leq N_Y \text{ and } S_X > S_Y,$$

That is, if the financial outcome (N) or the emissions performance (S) of X is better than that of Y and the other is no worse.

Consider a fictitious plot of N against S as shown in Figure 5 for a given set of negative-cost measures. The measure designated by the black point dominates all the measures represented by green points in Quadrant 4, including those on the borders defined by the dotted lines. It neither dominates nor is dominated by the blue points in Quadrants 2 and 3. If points existed in Quadrant 1, including on the dotted boundaries, then the black point would itself be dominated.

So, by applying Pareto optimisation to the problem at hand, the following procedure is taken:

- The set of measures to be ranked are defined (i.e. all those with a negative costs)
- The criterion values (-N and S) are plotted against each other to identify the measures in the Pareto front – those not dominated when plotted as in Figure 5 – and are ranked first
- The first-ranked measures from the plot are removed and a new Pareto front is identified for the remaining points. The measures comprising it are ranked second
- This process of defining a Pareto front is continued by assigning its members to the next ranking and removing them from the plot until all the points are ranked

If the procedure above is applied to the negative cost measures until all measures are accounted for, it will lead to a fairly clear ranking order and identify incorrectly ranked measures, while less discriminating than the standard metric, C_{eff}, making it consistent with profit-maximizing behavior.

4.6 Integrating embodied emissions into MACC

This section describes how economic considerations are integrated with operational and embodied emissions into the decision support system for the optimal ranking of the identified abatement options. As shown in Figure 6, operational emissions saving potential across the scenario period of the options and embodied emissions associated with the options are evaluated using methodologies described in sections 4.3 and 4.4 respectively. The results are then used alongside the operational emissions savings to evaluate the net emissions saving ($\mathbf{E_{net}}$) of the abatement options.

Consideration of embodied emissions implies that the formula for cost-effectiveness would now become:

$$\text{£/tNetCO}_2 = \frac{\text{Total Investment Cost (£)} - \text{NPV of the cost of enery saved (£)}}{\text{E}_{\text{net}}\ (\text{tNetCO}_2)} \qquad (9)$$

The implication of equation regarding its effect on cost-effectiveness is discussed in section 4.6.1.

4.6.1 Effect of embodied emissions on cost-effectiveness (£/tCO_2)

Consider first the effect of introducing embodied emissions on the width of the block. The effect of including embodied emissions is to decrease the total emissions reduction available. If the total embodied emissions corresponding to the manufacture, transport etc. of the measure is $\mathbf{e_{emb}}$ then the net emissions reduction, $\mathbf{E_{net}}$, corresponding to the new width, is

$$\text{E}_{\text{net}} = \text{gE} - \epsilon_{\text{emb}} \qquad (10)$$

Where **g** is the emissions factor (kgCO_2e/kWh) corresponding to the measure and **E** is the total energy saved (kWh) by the measure over the period of interest. Note that it is possible, in principle, for the width of the measure to be negative if the embodied emissions exceed the savings. This possibility will be excluded from the analysis on the assumption that such cases will be identified and removed from consideration before this stage.

Now consider the height of the block, representing the cost effectiveness (£/tCO_2), $\mathbf{C_{eff}}$. For operational emissions only, it is given by

$$\text{C}_{\text{eff}} = \frac{\text{N}}{\text{S}} \qquad (11)$$

Where **N** represents the net cost or net savings and **S** is the product of emissions factor **g** and total energy saved **E**.

If embodied emissions are included, **N** remains constant assuming there is no change in the costs. To take account of the effect on the emissions, it is convenient to define an effective emissions factor $\mathbf{g}'$ as the net emissions saved divided by the total energy saved

$$g' = \frac{E_{net}}{E} \tag{12}$$

The resulting cost-effectiveness is

$$C'_{eff} = \frac{N}{g'E} = \frac{N}{E_{net}} \tag{13}$$

Substituting (10) into (13),

$$C'_{eff} = \frac{N}{gE - e_{emb}} \tag{14}$$

This is numerically larger than C_{eff}, corresponding to a smaller emissions reduction for a given amount spent. The width of the block was found to be reduced by the existence of embodied emissions to $gE - e_{emb}$. So the area of the block is obtained by multiplying equations (10) and (14), giving

$$C'_{eff} \times E_{net} = gE - e_{emb} \times \frac{N}{gE - e_{emb}} = N \tag{15}$$

This equals the area of the original block. It is worth noting that if a smaller effective emissions factor $\mathbf{g}'$ is used for an option with a negative cost, **N** (i.e. net savings), it would suggest that for any given option, increasing the embodied emissions has the effect of improving the cost-effectiveness. This perverse result, illustrated in Figure 7, is in line with the findings of Taylor [37] and supports the decision not to apply embodied emissions to negative-cost data within a MACC framework.

For negative cost measures, the embodied emissions are evaluated so that the net emissions savings can be established. The method described in section 5.5.1 is used to rank the negative cost measures optimally. The outcome can be presented as a stacked bar chart that indicates both the preferred ordering and the net emissions saving available for each measure but without specifying cost effectiveness.

5.0 Criteria of selection to be considered before selecting GHG emissions reduction options to appraise (Screening the measures)

The overall aim was to devise a DSS for comparison and selection from technologies that might be relevant to the case building and not to model every possible retrofit technology that might be suitable in the future. The justification for the options considered within the current model is based on an initial general list of options including energy efficiency measures, renewable energy generation technologies and inducements to change behaviour which was generated through detailed analysis of completed retrofit projects (e.g. Tarbase Project co-authored by Jenkins *et al.* [39]). The initial long list of retrofit options was further pruned down following discussions with the energy manager of the case building. The options considered within the model are those that are: (i) feasible and capable of significant emissions reductions based on the existence of proven performance calculation algorithms; (ii) commercially available, technically proven and have been available for many years; (iii) considered acceptable for supplying the proportion of energy demand and deemed the most likely options for decision makers such as energy managers; (iv) easily classified based on Standard Industry Classification within an economic sector.

Given that the needs of buildings differ from one another and not all intervention options work well in every situation for every building, it is important to have a criterion of selection for consideration before the selection of low GHG abatement options for investment appraisal. For instance, a building located in an area where an average wind speed of at least 6m/s on site is not guaranteed may not necessarily consider wind turbine as an option. London Renewables [30] highlight the major issues that must be considered before the adoption of each technology. The current DSS therefore allow users to select appropriate options that are suitable for their specific buildings before using the DSS for emissions analysis and investment appraisals.

6.0 Results, analysis and discussion

6.1 Energy use in buildings CO_2 baseline

The 2010 baseline energy consumption of the case study building was established to be 1,159,642 kWh/year and 1,146,210 kWh/year respectively for electricity and gas. Using emissions factor of 0.5246 $kgCO_2e/kWh$ for grid-displaced electricity and 0.1836 $kgCO_2e/kWh$ for grid-displaced gas, the baseline equivalent CO_2 emissions yielded 608.35tCO_2e (electricity) and 210.44 tCO_2e (gas), totaling 818.79 tCO_2e. The pattern of energy use in the building across the baseline year is shown in Figure 8.

6.2 Indicative CO_2 savings – percentage reduction in CO_2 baseline

A range building energy retrofit options (Table 2) were analyzed in terms of their operational emissions savings potential. The percentage savings of each of the selected intervention options were computed as a function of the baseline CO_2e emissions, on a standalone basis as shown in Figure 9. Assuming all options were implemented at the same time and that measures do not interact, emissions savings of 715.7tCO_2e which is about 87% of the baseline is achievable. But in practice, measures are implemented in combination and the individual measures cannot be added up, since it significantly over-estimates the total GHG emission savings due to ***interactions*** and ***overlaps*** between certain measures. The effect of interaction on abatement potential and cost-effectiveness is discussed section 7.1.

6.3 Estimating the cost-effectiveness and emissions savings for each option

The capital cost of each intervention option is estimated. Net Present Value (NPV) concept at a discount rate of 5% for 15 years was used in the economic analysis. The results are shown in Table 3. The corresponding Pareto outputs plotted as a stacked bar chart is shown in Figure 10a. The negative cost measures are ordered according to the total savings accruing from each measure and the bars are arranged so that ranking starts on the left, sharing a resemblance with a MAC curve. As shown, Efficient lighting (LEDs) is now ranked first in that it satisfy both criteria – a better emissions performance (2758.40 tCO_2e), which corresponds to a larger (more positive) value of S, and a better financial outcome (-£294,212), corresponding to a smaller (more negative) value of N. This is then followed by Micro CHP and so on. The MAC curve for positive cost measures plotted as a function of £/tCO_2 against cumulative CO_2 savings (tCO_2e) over 15 years is shown in Figure 10b.

6.4 Embodied emissions results

The results of using the methodology for the computation of embodied emissions described in section 5.4 are presented in this section. The physical quantities of each intervention option in terms of their design specification, unit costs and final demand in monetary terms are presented in Table 4. The final demand is the product of the physical quantity of an option and its unit cost.

Embodied emissions associated with each of the options are obtained by the matrix multiplication of the total intensity matrix (TIM) derived from the Supply and Use Table and final demand of each option. The numerical results for embodied emissions are shown in Table 5 and are depicted in graphical form as in Figure 11.

As shown in Figure 11, the total embodied emissions incurred by the implementation of the options is evaluated to be 763tCO_2e, a value which far exceeds the operational emissions savings in the first year of implementation. This suggests that consideration of embodied emissions is critical in the assessment of the net emissions savings of the abatement options and should therefore be included in the selection process.

6.5 Integration of cost, operational emissions and embodied emissions into MACC

Extending the use of MACCs in a way which integrates embodied and operational emission into a robust and single ranking module, can in principle, facilitate a more holistic view of the environmental impact of emissions abatement options. Table 5 shows the estimated CO_2 saved and net emissions savings due to the implementation of the intervention options. Using equation 9, the cost-effectiveness (£/Net tCO_2e) for each option is computed. The corresponding Pareto ranking and the MAC curve are shown in Figures 12a and 12b respectively.

As shown in Figures 12a and 12b, consideration of embodied emissions reduces the potential operational emissions savings from each options and a consequent overall reduction in the total emissions savings of the abatement project. This is indicated by the shrinkage in the width of each bar representing an option, depending on the value of the embodied emissions. For positive cost measures,the height of each bar increases, making the cost-effectiveness to become worse. The difference between the initial height (before the consideration of embodied emissions) and the final height (after the consideration of embodied emissions) represents the £/tCO_2e of embodied emissions associated with the option (i.e. the change in cost-effectiveness due to the consideration of embodied emissions).

The results presented above clearly demonstrates how the consideration of embodied emissions can affect the overall picture of a climate change abatement project. It is interesting to see how the environmental performance of photovoltaic system now appears to be better than that of GSHP when embodied emissions are considered. This suggests that, depending on the scenario, and the estimated value of embodied emissions, the order and sequence of the abatement options can be significantly altered. As such, an understanding of the relationship between embodied and operational emissions of a given set of abatement options as depicted in Figures 12a and 12b can be useful in providing detailed information which can form the basis for the formulation of effective policies to cover wider scopes in emissions reduction strategies.

6.6 Effect of Government incentive and tariffs on cost-effectiveness of positive cost measures (Renewable Technologies)

As part of the UK Government's efforts to combat climate change, several intervention facilities, including policy initiatives and a range of statutory as well as voluntary legislations to accelerate the transition to a low carbon economy has been established. Of interest to the current study are the Feed-in-Tariffs (FiT) and Renewable Heat Incentives (RHI).

6.6.1 Feed-in-Tariffs (FiT)

Feed-in-Tariffs were introduced in April 2010 by the UK Government. They are part of a range of measures to act as a driver for a more rapid deployment and uptake of renewable electricity generating technologies, with a view to reducing demand. The FiT scheme intends to boost the adoption of proven technologies rather than acting as a support mechanism for innovative or new designs. As such, it is restricted to electricity generation and is based on a per-unit support payment paid for every kilowatt hour (kWh) of electricity generation. Payments are over the lifetime of the system and are generally thought to give more confidence and security to consumers and installer businesses.

There are three ways in which the scheme guarantees income generation and financial benefits from the chosen technology installed. (i) A fixed payment for every kWh of electricity generated known as the *"generation tariff"*. This price varies depending upon rated power and type of renewable energy system. Most up- to- date generation tariff for each technology can be found on Ofgem website. (ii) A fixed payment for all electricity exported directly to the grid known as *"export tariff"*. This rate only applies to the quantity of excess energy which has been generated by the installed technology and is not used on site. Both forms of tariff are linked to the Retail Price Index and are adjusted to account for inflation. (iii) The energy generated from the renewable energy technology which is consumed on site and can be referred to as *"reduced bills"* or *"cost of grid electricity offset"*. This energy reduces, or even eliminates, the amount of electricity that is required to be imported from the grid thus providing savings on the cost of imported electricity.

Figure 13 indicates a possible scenario for a $\mathbf{20kWp}$ PV installation which generates $\mathbf{17{,}000\ kWh/year}$. Assuming $\mathbf{50\%}$ of the electricity generated is used on site (in reality, on site use will vary for different installations according to occupancy pattern), with cost of electricity of 11.5p/kWh. As shown, a simple year one financial return will

be $\mathbf{(i) Generation\ Tariff = 17{,}000 \times £0.135 = £2{,}295.00}$;

$\mathbf{(ii)\ Export\ Tariff = 17{,}000 \times 50\% \times £0.045 = £382.50}$;

$\mathbf{(iii)\ Reduced\ bills = 17{,}000 \times 50\% \times £0.115 = £977.50}$; so that the total annual returns is

$\mathbf{£3{,}655.00}$

6.6.2 Renewable Heat Incentives (RHI)

The Renewable Heat Incentive (RHI) is a grant scheme launched by the Government in 2011 to encourage the implementation and use of renewable heating. It covers biomass, ground source heat pumps and solar thermal. For every kWh of heat generated, the Government pays a certain amount of money in the form of renewable heat initiatives. For instance, a Solar Hot Water System sized to meet 50% of hot water baseline demand of $\mathbf{28{,}000kWh/year}$ will get a running cost savings of $\mathbf{14000 \times 4p/kWh = £560/year}$, assuming cost of gas is 4p/kWh and a RHI of $\mathbf{14000 \times 8.9}p/kWh = \mathbf{£1246}/year$, yielding a simple total annual return $\mathbf{£1806/year}$.

Based on the background introduction to FiT and RHI[2] presented above, the effects of their consideration on the cost-effectiveness on renewable technologies are presented here. As shown in Table 6, the cost-effectiveness of each renewable technology improves making them more economically attractive. For the case of Feed-in-Tariffs, complete on site use (i.e. 100% usage without exporting to the grid) leads to a greater income than exporting part of the electricity generated to the grid to benefit from the export tariff. This implies that a renewable technology option, which benefits from the FiT scheme, becomes more economically attractive when all the energy generated is used on site. For instance, if 50% of energy generated by the PV system is exported to the grid and 50% is used on site, the overall cost-effectiveness is £456.4/ tCO_2e. With 100% on-site consumption, the cost-effectiveness is £420.11/tCO_2e as shown in Table 6. The same logic applies to all options that benefit from the FiT. For options that benefit from RHI, the cost-effectiveness also improves. It is interesting to see how the consideration of RHI makes Biomass boiler and GSHPs become negative cost measures as shown in Table 6. The MACC representation is shown in Figure 16. The options which appear in the negative regime of the MACC are also shown for illustration purposes since the concept of negative cost-effectiveness has been established not to be applicable for such measures.

The scenarios described above changes when embodied emissions are considered. The consideration of embodied emissions makes the option less cost-effectiveness. As shown in Table 7, with 50% of energy generated by the PV system exported to the grid and 50% used on site, the overall cost-effectiveness is £735.61/tCO_2e. On the other hand, when embodied emissions are considered, the cost-effectiveness is £677.11/tCO_2e with 100% on-site consumption. The same logic applies to all option that benefit from the FiT. For options that benefits from RHI, the scenario also changes with consideration of embodied emissions. For instance GSHPs which hitherto appeared to be negative cost measure now becomes a positive cost measure when embodied emissions is considered as shown in Table 7.

6.7 Sensitivity analysis

Results of the overall emissions reduction performance of abatement options can vary from study to study because it depends on several variables such as energy price, choice of discount rate etc. The choice of discount rate is based on the purpose of the analysis and the methodological approach used in each study. There are two approaches namely *prescriptive approach (also known as social perspective)* and *descriptive approach (also called industry perspective).* The prescriptive approach is mainly employed for long-term issues such as climate change or public sector projects and

[2] Most up-to-date cost information regarding FiT and RHI can be found on Ofgem website (http://www.ofgem.gov.uk/Sustainability/Environment/fits/Pages/fits.aspx). In this paper, under the FiT scheme, generation tariff is taken as13.5p/kWh for PV; 25.4p/kWh for Wind Turbine; 11p/kWh for Micro CHP. Export tariff is 4.5p/kWh. For the RHI scheme, generation tariff for SHW, Biomass and GSHP was taken to be 8.9p/kWh,5.1p/kWh and3.4p/kWh respectively.

uses lower discount rates of between 4 and 10% [40]. The use of low discount rates present the advantage of treating future generations equally, but it may also cause relatively certain near-term effects to be disregarded in support of more uncertain, long-term effects [41]. On the other hand, the descriptive approach uses relatively high discount rates of 10-30% with the aim of reflecting the existence of barriers to energy efficiency investments [40]. The choice of discount rate can significantly influence results of the overall cost-effectiveness of an abatement project and hence the need for a sensitivity analysis.

In this paper, a discount rate of 5% is used throughout. Sensitivity analysis is therefore conducted to establish how the change in discount rate can influence the results of the study. An increase in discount factor leads to reduced cumulative net present value of energy saved and net savings. Table 8 shows how changes in the discount rate influence the outcome of the abatement options potentials. As shown, a change in discount factor from 5% to 10% reduces the cumulative net present value and net savings from £1777359 and -£758360 to £1302426 and -£283424 respectively.

Figure 16 shows how a higher discount factor leads to corresponding increase in cumulative net savings. In general, the higher the discount factor chosen, the lesser the net savings and consequently the less economically attractive an abatement option becomes. For example, at a discount rate of 5% and 10%, the net cost of BEMS is -£65809 and -£16158 respectively, making it an option that is economically attractive and viable. However, with a higher discount rate of 15% and 20%, the net costs becomes £15325 and £36,303 respectively, making BEMS appear less economically attractive by rendering a hitherto negative cost measure to become a positive cost measure.

7.0 Discussion

7.1 Discussion on interaction and overlaps between measures and DSS limitation

Potential emissions saving from individual measures and their respective cost-effectiveness are usually considered in isolation (i.e. standalone) within the framework of a MAC curve. This is entirely appropriate for the purposes of ranking the measures. A drawback, however, is that, in reality, measures are implemented in combination and the individual measures cannot be added up, since it significantly over-estimates the total GHG emission savings due to ***interactions*** and ***overlaps*** between certain measures. Whereas, ***interactions*** involves a scenario whereby the GHG emission savings from a measure are reduced because another measure has been installed previously. For example, emission savings from a more efficient boiler is lower if building insulation is improved first. This implies that interaction usually arise between different types of measures which act on the same end use, although it can also occur between different end uses [42]. ***Overlaps*** comes into play with parallel "like for like" measures – a situation where different technologies can be used to achieve the same result in different circumstances [42]. It relates to measures that cannot be implemented because another (more cost-effective measure) has already been adopted. For example, if a gas-fired combined heat and power (CHP) system has been installed then it might not be cost-effective to introduce solar water heating subsequently. Therefore, in estimating the GHG emissions saving potential of a range of abatement options, it is essential to take account of ***interactions*** and ***overlaps*** between measures. Each time a measure is implemented, the abatement potential and cost of the remaining measures have to be recalculated. Failing to take into account interactions between measures may lead to significant double-counting and over-estimation of the overall abatement potential [43].

7.1.1 Approach taken to account for interaction

As mentioned, earlier a low carbon intervention option can be applied in isolation and its cost-effectiveness (i.e. cost per unit of CO_2 saved) can be evaluated using equation 8. However, when measures are applied in combination with one another, they interact and their emissions saving potential as well as cost effectiveness changes in response to the measure with which they combine. If it is assumed that the interaction of measures will affect the abatement potential but not the cost of the measures, it is convenient to define an interaction factor (IF) which gives an indication of the extent to which the efficacy of a measure is reduced (or occasionally, increased) when two or measures interact. To this end, the interaction factor when two measures X and Y interact with each other can be expressed as [44]:

$$\mathrm{IF(XY)} = \frac{\text{Abatement potential of measure Y when applied after X}}{\text{Standalone abatement potential of measure Y}} \qquad (16)$$

As an example, assuming the abatement potential of measure Y when applied after measure X is 60 tCO_2e and its standalone potential is 100 tCO_2e, then measures XY have an interaction factor of 0.6 (i.e.60/100). This suggests that the abatement potential of measure Y is reduced by 40% when applied after measure X. So to account for interaction, the abatement potential of measure Y is multiplied by 0.60 when applied after measure X. To this end, whenever a measure is implemented, the abatement potential of all the remaining measures which interact with each other is recalculated by multiplying them by the appropriate IF. A new value of the cost-effectiveness of each measure is then recalculated and the ranking is carried out again.

In the context of the current study, an interaction matrix, as shown fictitiously, in Table 9 is established by carrying out an initial analysis of potential mitigation strategies that will interact with each other.

As illustrated in a pairwise manner in Table 9, the interaction factors between any two options which interact with each other are computed using equation 16. The estimation of interaction factor between any two options is complex and may be time consuming [44]. These interactions can only be dealt with effectively, by carrying out detailed systems based modelling approach as there will be non-linearities in the way in which the system interacts with the building arising from the timing of the service demand and the layout of the building [42]. As such, a symmetric relationship between any two options in terms of their interaction factor (IF) has to be assumed, that is, $\mathbf{IF}\ \{\mathbf{AC}\} = \mathbf{IF}\ \{\mathbf{CA}\}$. This suggest that applying A then C must have the same effect as applying C then A. This pairwise approach (which allows the use of a matrix) may be strictly valid because it restricts the interaction with the next measure. It is noteworthy to state, however, that the symmetrical assumption between two options may not hold true in some cases, as multiple interactions are likely to occur in practice.

In the context of the overall development of the current DSS model, multiple interactions are represented as the product of cumulative two- way interaction factors. Further analysis was beyond the scope of the current research. An independent ranking module is created within the overall DSS to order the abatement measures after the consideration of interaction. Where possible, calculations to evaluate the IF between two measures are carried out based on a particular building given its individual characteristics. In other instances, the calculations of IFs are based on available secondary data and opinions from subject matter experts.

7.1.2 Limitations of the DSS

Despite the novel approach taken to the integration of the three variables of cost, operational and embodied emissions into decision support systems for the optimal ranking of building energy retrofit options, there are certain limitations which are associated with the creation and applications of the current DSS.

The model does not currently consider passive measures like wall insulation and double/triple glazing of windows in terms of their emissions savings potential because of the complexities involved in modelling different building fabric. Such estimates are better handled using a calibrated thermal model of the building in question. However, an independent module which allows users of the DSS to input cost and emissions saving parameters from different options and performance calculation methods to use the ranking mechanism of the DSS is available.

Calculations to evaluate the interaction factor between two measures are carried out separately, where possible. In other instances, the calculations of IFs are based on certain assumptions and opinions from subject matter experts, given the relative dearth of both experimental and survey data. The approach described in section 7.1.1 does not capture everything there is to interaction between measures in that it deals with pairwise interaction only. There are systems approaches which involve the use of an energy system framework, where the different emissions reduction options, in an iterative procedure, are swapped in and out of the base-line, enabling those with the lowest system cost to be identified [45,46]. With reference to Figure 4 (using the positive cost measures where the MACC approach is valid) this implies that the results for option F will depend on the implementation of option E, which option G will depend on both projects E and F, and so on. A major downside is that the results of implementing option E are independent of the less valuable options (F, G, and H), although in reality dependence might exist. Additionally, one aspect of this approach is that once an option is included in a scenario, it will be a permanent part of all subsequent scenarios [46]. This approach certainly provides a step forward compare to the approach described in this paper, it still only represents part of the whole picture. This is so, as the approach tend to underestimate (numerical) the marginal costs of the most attractive options, and to overestimate the marginal cost for the least attractive options. It therefore follows that if interaction effects are assumed to be large, then the value of a MACC is limited because the cost-effectiveness is assumed to be order-dependent – the bar changes height as you move them around. But most times, interaction have relatively small effects which only occasionally change the ordering, thereby preserving the validity of the MACC concept. In other words, the MACC gives a good estimate of the best ordering, and more detailed assessment of interactions gives a final position.

One of the main challenges associated with the consideration of other retrofit options other than the ones captured within the DSS is that, the integration of an infinite set of options into one consistent system, addressing in an efficient manner, all building sustainability issues important for stakeholders and decision makers, is very often close to impossible. This is due to differences in algorithms and performance calculation procedures, data requirements and data formats for each option. Most importantly, the retrofit options considered within the DSS are based on certain critical factors as highlighted in section 5. However, the DSS can be further developed to capture technologies such as absorption cooling, ground cooling and other options with proven performance calculation methods.

7.2 General discussions

As national and international concern over climate change related issues becomes more prevalent, the need for the development of tools to support climate mitigation initiatives and policies becomes more apparent. Indeed, the effective management of energy and reduction of emissions in buildings requires the use of tools and methodologies that support the strategic decision making process of selecting measures which are economically viable and environmental friendly [20]. A suitable system can therefore assist in the decision making process by ensuring that for instance, environmental and economic determinants related to energy management and emissions reduction in buildings are optimized. Indeed, more often than not, the choice of implemented actions tend not to be the optimum decision resulting in loss of economic returns or reduced levels of potential emissions savings. The development of this DSS shows how the framework supports the generic decision-making process and the development of evidence-based policies through: decision preparation (DSS framework supports data required as input); decision structuring (DSS framework provides model to organise data); context development (DSS framework captures information about baseline scenario and building characteristics) and decision making (DSS framework automates the decision-making process and offer evaluations on the optimal decision).

8.0 Summary and Conclusion

A review of existing Decision Support Systems for aiding retrofitting decisions for energy conservation indicates that they have mainly focused on economics and operational emissions savings, and have neglected embodied emissions. Given that recent trends towards environmentally conscious design and retrofit have resulted in a focus on the environmental merit of retrofit options, with emphasis on a lifecycle approach, a gap therefore exists in the field of DSS for emissions reduction in buildings. This paper addresses this gap by adopting a robust techno-economic evaluation methodology to develop a DSS which integrates economic considerations with operational and embodied emissions into a single model. The outputs are based on the ranking principles derived from marginal abatement cost curves (MACCs) and Pareto optimisation.

The use of MACC as a useful tool to identify options which deliver the most economically efficient reductions in GHG and prioritize mitigation options within the building sector is presented. Underlying limitations of the MACC approach and the points to be aware of, such as, effects of macroeconomic assumptions, effect of interactions of measures and the mathematical flaw associated with the ranking of cost-effective options, before applying the results of MACC for decision making is also highlighted and addressed. The resulting ranking based on MACC sometimes favours abatement options that produce low emissions savings when the measure has a negative cost. This result is unreliable and it suggests that it is not appropriate to use cost-effectiveness, measured in £/tCO_2 or equivalent, for ranking negative cost measures. Pareto optimization offers a better ranking approach. Sensitivity analysis carried out for the discount rate parameter indicates that the higher the discount factor, the lesser the net savings and consequently the less economically attractive an abatement option becomes.

The DSS model development is underpinned by the use of Environmental-Economic Input-Output (EE-I-O) methodology based on the 2-region Multi-Regional (UK and the Rest-of-the-World) framework. This allows for the evaluation of the embodied emissions of a number of low carbon intervention options. The DSS make use of the distinctive feature of MRIO framework which allows the estimation of the environmental loads (embodied emissions) and implications of consumption associated with international trade flows regarding GHG emissions associated with the options.

When embodied emissions are integrated with financial cost and operational emissions within a MACC framework, a decrease is seen in the total emissions reduction available from an option. For positive cost measures, the cost-effectiveness becomes worse due to the consideration of embodied emissions, corresponding to a smaller emissions reduction for a given amount spent. The overall ranking of the some of the options is also significantly altered when embodied emissions are considered.

Analysis of the effect of Government incentive and tariffs such as Feed-in-Tariffs (FiT) and Renewable Heat Incentives (RHI) shows that the cost-effectiveness of positive cost measures (e.g. Renewable Technologies) improves, as would be expected, when embodied emissions are not considered. But when they are included, the cost-effectiveness becomes worse. For the case of Feed-in-Tariffs, it was observed that complete on site use (i.e. 100% usage without exporting to the grid) yielded a greater income than exporting part of the electricity generated to the grid to benefit from the export tariff. This implies that a renewable technology option, which benefits from the FiT scheme becomes more economically attractive (i.e. reduced cost-effectiveness) when all the energy generated are used on site. Either way, the consideration of embodied emissions worsens the cost-effectiveness, but the cost-effectiveness of an option improves if no part of the energy generated is exported to the grid.

Overall, the DSS presented in this paper can allow trade-offs between various retrofit options to be identified and communicated and ensure decisions are better informed than before due to the inclusion of embodied emissions. This system has been created in the form of a Microsoft visual studio application which provides stakeholders with an efficient and reliable decision process that is informed by both environmental and financial considerations. A future paper will report on user feedback.

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Table 1: Standard industry classification and location of manufacture of selected options

Intervention options	Sector ID	Standard Industry Classification (Sector Description)	Location of manufacture
PV	137	Electronic valves and tubes and other electronic components	Rest of the World
Solar Hot Water	127	Other general purpose machinery	Rest of the World
Micro wind turbine	126	Machinery for the production and use of mechanical power, except aircraft, vehicle and cycle engines	Rest of the World
Ground Source Heat Pumps	126	Machinery for the production and use of mechanical power, except aircraft, vehicle and cycle engines	Rest of the World
Biomass boiler	122	Tanks, reservoirs and containers of metal; manufacture of central heating radiators and boilers; manufacture of steam generators	Domestic
Micro CHP	163	Steam and hot water supply	Domestic
Voltage optimisation	134	Electric motors, generators and transformers; manufacture of electricity distribution and control apparatus	Domestic
BEMS	134	Electric motors, generators and transformers; manufacture of electricity distribution and control apparatus	Domestic
Efficient Lighting (LEDs)	137	Electronic valves and tubes and other electronic components	Rest of the World
Thermostatic Radiator Valves (TRVs)	126	Machinery for the production and use of mechanical power, except aircraft, vehicle and cycle engines	Domestic
PIR (Occupancy) sensors	140	Medical, precision and optical instruments, watches and clocks	Domestic

Table 2: Estimated energy and indicative CO_2 savings from options against the baseline energy consumption

Intervention Options	**Energy saved or generated (MWh/year)**	**CO_2 saved (tCO2e/year)**	**% savings against baseline**
Switch off appliance (500 Units of PCs)	109.80	57.60	7%
180 Units PIR (Occupancy) sensors	152.47	79.99	9%
1 Unit Voltage optimisation	139.16	73.00	9%
976 Units of Efficient Lighting (LEDs)	350.54	183.89	22%
200 Units of Thermostatic Radiator Valve (TRVs)	179.80	33.01	4%
1 Unit of Building Energy Management System (BEMS)	242.32	91.94	11%
Energy awareness campaign (EAC)	46.12	16.38	2%
38kW$_e$ Combined Heat and Power (Micro CHP)	422.82	141.14	17%
400kW$_{th}$ Biomass Boiler	229.24	42.28	5%
250kW$_t$ Ground Source Heat Pump (GSHP)	380.77	21.45	3%
15kW$_p$ Micro Wind Turbine	16.24	8.52	1%
44kW$_p$, 400m^2 Photovoltaic System	34.79	18.25	2%
7m^2 Solar Hot Water	1.64	0.30	1%

Table 3: Estimated energy and CO_2 savings from options (N/A: Not Applicable)

Intervention option	Capital cost (£) {C}	Cost of energy saved (£)	NPV of energy saved (£) {E}	Net savings or Net Cost (£) {N} [C-E]	tCO_2e saved over 15 years {S}	Cumulative savings (tCO_2e)	£/tCO_2 saved {M} [N/S]	Ranking
NEGATIVE COST MEASURES								**Pareto**
LEDs	70000	35089	364211	-294212	2758.40	2758.40	N/A	1
Micro CHP	100000	28203	292741	-192742	2117.11	4875.51	N/A	2
TRVs	8000	17998	186813	-178813	495.17	5370.68	N/A	3
PIR sensors	5000	15262	158414	-153414	1199.79	6570.47	N/A	4
Voltage optimisation	22500	13930	144588	-122089	1095.03	7665.50	N/A	5
Switch off PCs	0	10991	114082	-114083	863.99	8529.49	N/A	6
BEMS	120000	17901	185808	-65809	1379.13	9908.62	N/A	7
EAC	3500	3204	33258	-29758	245.64	10154.26	N/A	8
POSITIVE COST MEASURES								**MAC**
Biomass Boiler	120000	8826	91611	28389	634.15	10788.41	44.77	9
Wind Turbine	60000	1625	16867	43133	127.75	10916.16	337.63	10
GSHP	300000	14659	152162	147838	321.78	11237.94	459.43	11
Photovoltaic	200000	3482	36142	163858	274.17	11512.11	598.02	12
Solar Hot Water	10000	63	653.92	9346	4.56	11516.67	2049.58	13

Table 4: Intervention options with their equivalent final demand in monetary terms

Intervention options	Physical Quantity	Unit Cost	Final Demand
1. PV System	400 m^2, 45kW_p	£300.00	£120,000.00
2. Solar Hot Water	7m^2	£850.00	£5,950.00
3. Micro Wind turbine	15kW_e	£2,500.00	£3,7500.00
4. Ground Source Heat Pumps	250kW_t	£1,000.00	£250,000.00
5. Biomass Boiler	400 kW_t	£200.00	£80,000.00
6. Micro CHP	38 kW_e	£1,200.00	£57,000.00
7. Voltage Optimisation	1 Unit	£18,000.00	£18,000.00
8. BEMS	1 Unit	£120,000.00	£120,000.00
9. Efficient Lighting (LEDs)	976 Units	£20.00	£19,520.00
10. Thermostatic Radiator Valves	200 Units	£15.00	£3,000.00
11. PIR (Occupancy) sensors	180 Units	£25.00	£4,500.00

Table 5: Estimated net emission savings from intervention options (N/A: Not Applicable)

Intervention option	Net savings or Net Cost (£) {N}	tCO_2e saved over 15 years {S}	Embodied emissions incurred (tCO_2e) {e}	Net Emissions savings (Net tCO_2e) {G=S-e}	Cumulative net savings (Net tCO_2e)	£/Net tCO_2 saved {C'_{eff}} [N/G]	Ranking
NEGATIVE COST MEASURES							**Pareto**
LEDs	-294212	2758.40	17	2741.40	2741.40	N/A	1
Micro CHP	-192742	2117.11	132	1985.11	4726.51	N/A	2
TRVs	-178813	495.17	4	491.17	5217.68	N/A	3
PIR sensors	-153414	1199.79	2	1197.79	6415.47	N/A	4
Voltage optimisation	-122089	1095.03	15	1080.03	7495.50	N/A	5
Switch off PCs	-114083	863.99	0	863.99	8359.49	N/A	6
BEMS	-65809	1379.13	101	1278.13	9637.62	N/A	7
EAC	-29758	245.64	0	245.64	9883.26	N/A	8
POSITIVE COST MEASURES							**MACC**
Biomass Boiler	28389	634.15	85	549.15	10432.41	51.70	9
Wind Turbine	43133	127.75	39	88.75	10521.16	486.01	10
Photovoltaic	163858	274.17	104	170.17	10691.33	962.91	11
GSHP	147838	321.78	258	63.78	10755.11	2317.94	12
Solar Hot Water	9346	4.56	6	-1.44	-	-	-

Table 6: Effect of Government incentives on renewable technologies-operational emissions only

Intervention option	Energy generated (kWh/yr)	Annual Savings (£)	NPV of Annual Savings (£)	Net savings (£)	CO_2 saved over 15 years (tCO_2e)	£/tCO_2 saved
Feed-in-Tariff [SCENARIO I-part of energy (50%) exported to grid]						
Photovoltaic	34789	*Generation*:4696.55 *Export*: 782.76 *Reduced bill*:1741.20 ***Total*:7220.51**	74946.42	125054	274.17	456.4
Micro CHP	193582 (Power) 229242 (Heat)	*Generation*:21294.05 *Export*: 4355.60 *Reduced bill*: 9688.79 Gas savings:8825.82 ***Total*: 44164.26**	458409.89	-358410	2117.11	-169.29
Wind Turbine	16235	*Generation*: 4123.68 *Export*: 365.29 *Reduced bill*: 812.56 ***Total*: 5301.53**	55028.07	4972	127.75	38.92
Feed-in-Tariff [SCENARIO II-All energy consumed on site]						
Photovoltaic	34789	*Generation*: 4696.95 *Reduced bill*: 3482 ***Total*:8178.35**	84890.55	115109	274.17	420.11
Micro CHP	193582	*Generation*:21294.05 *Reduced bill*: 19377.58 Gas savings:8825.82 ***Total*: 49497.45**	513766.60	-413767	2117.11	-195.44
Wind Turbine	16235	*Generation*: 4123.68 *Reduced bill*: 1625 ***Total*:5748.68**	59669.33	331	127.75	2.59
Renewable Heat Incentives (RHI)						
Biomass Boiler	229242	*Generation*: 11691.34 *Reduced bill*: 8826 ***Total*:20517.34**	212962.97	-92963	634.15	-146.6
GSHP	380770	*Generation*: 19485.57 *Reduced bill*: 14659 ***Total*:34144.57**	354419.34	-54419	321.78	-169.12
Solar Hot Water	1635	*Generation*: 145.47 *Reduced bill*: 63 ***Total*:208.47**	2163.85	7836	4.56	1718.45

Table 7: Effect of Government incentives on renewable technologies-operational emissions with embodied emissions

Intervention option	Energy generated (kWh/yr)	Annual Savings (£)	NPV of Annual Savings (£)	Net savings/ Net cost (£)	Net emissions saving (tCO_2e)	£/tCO_2 saved
Feed-in-Tariff [SCENARIO I-part of energy (50%) exported to grid]						
Photovoltaic	34789	*Generation*:4696.55 *Export*: 782.76 *Reduced bill*:1741.20 ***Total*:7220.51**	74946.42	125054	170	735.61
Micro CHP	193582 (Power) 229242 (Heat)	*Generation*:21294.05 *Export*: 4355.60 *Reduced bill*: 9688.79 Gas savings:8825.82 ***Total*: 44164.26**	458409.89	-358410	1985	-158.02
Wind Turbine	16235	*Generation*: 4123.68 *Export*: 365.29 *Reduced bill*: 812.56 ***Total*: 5301.53**	55028.07	4972	89	55.87
Feed-in-Tariff [SCENARIO II-All energy consumed on site]						
Photovoltaic	34789	*Generation*: 4696.95 *Reduced bill*: 3482 ***Total*:8178.35**	84890.55	115109	170	677.11
Micro CHP	193582	*Generation*:21294.05 *Reduced bill*: 19377.58 Gas savings:8825.82 ***Total*: 49497.45**	513766.60	-413767	1985	-182.43
Wind Turbine	16235	*Generation*: 4123.68 *Reduced bill*: 1625 ***Total*:5748.68**	59669.33	331	89	3.72
Renewable Heat Incentives (RHI)						
Biomass Boiler	229242	*Generation*: 11691.34 *Reduced bill*: 8826 ***Total*:20517.34**	212962.97	-92963	549	-123.87
GSHP	380770	*Generation*: 19485.57 *Reduced bill*: 14659 ***Total*:34144.57**	354419.34	-54419	63	525.55

Table 8: Sensitivity analysis for CO_2 abatement potential with different discount rates

Discount rate (%)	Cumulative NPV of energy saved over 15 years (£)	Cumulative Net Savings (£)
5	1777359	-758360
10	1302426	-283424
15	1001273	17727
20	800604	218396

Table 9: Initial assessment of interaction between measures based on interaction matrix

Second measures		First measures			
		Measure A	**Measure B**	**Measure C**	**Measure D**
	Measure A	–	AB	AC	AD
	Measure B	BA	–	BC	BD
	Measure C	CA	CB	–	CD
	Measure D	DA	DB	DC	–

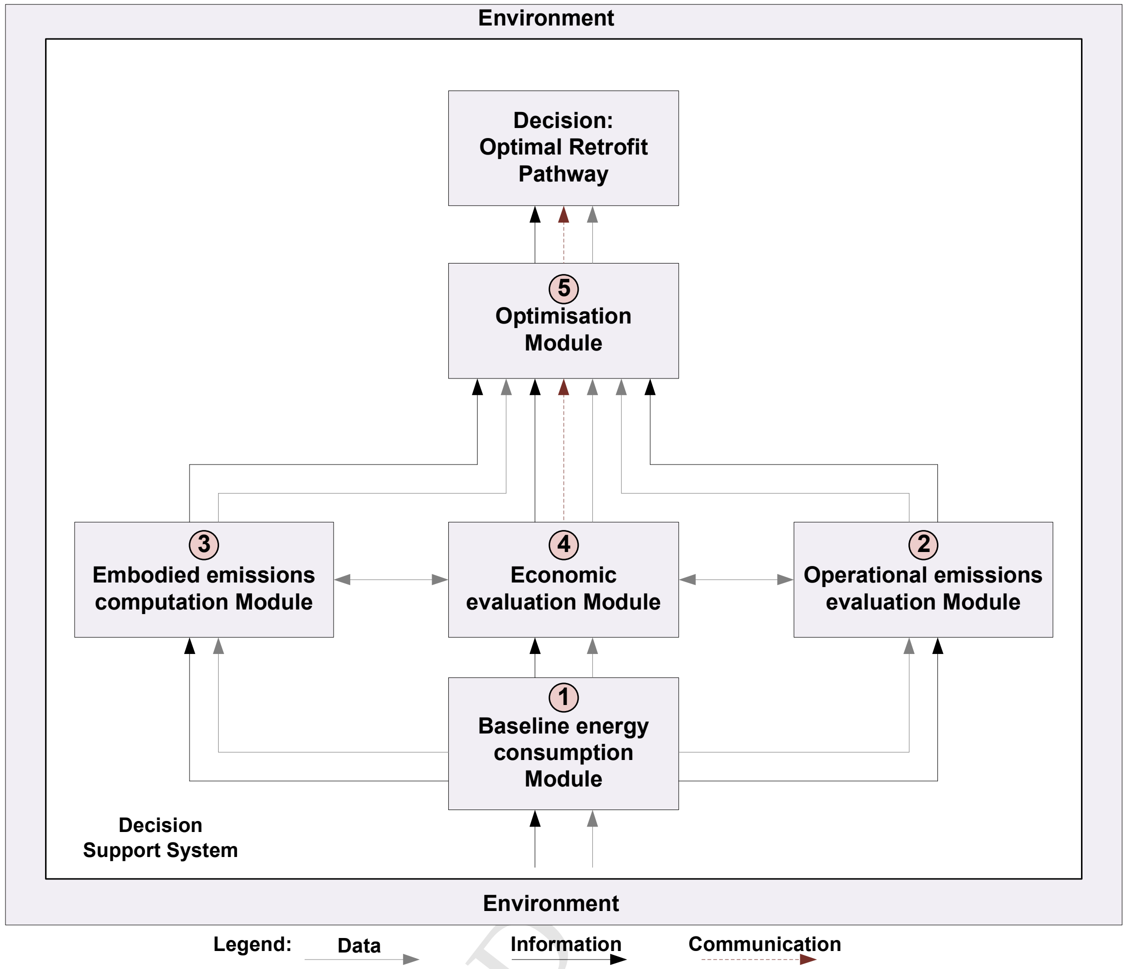


Figure 1: Decision support system modules

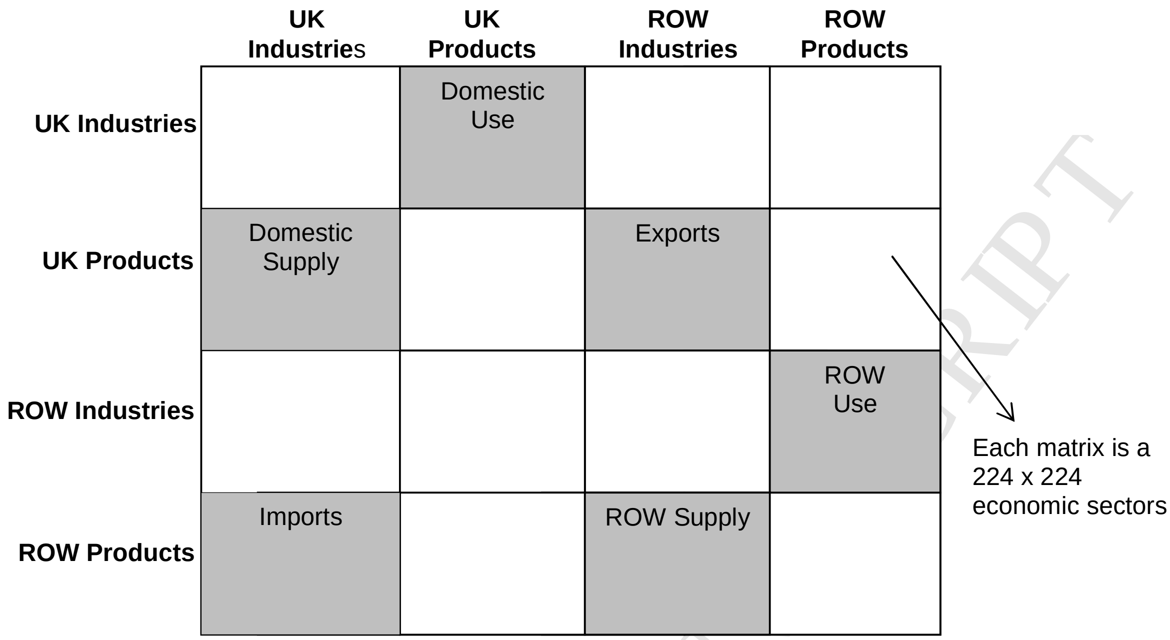
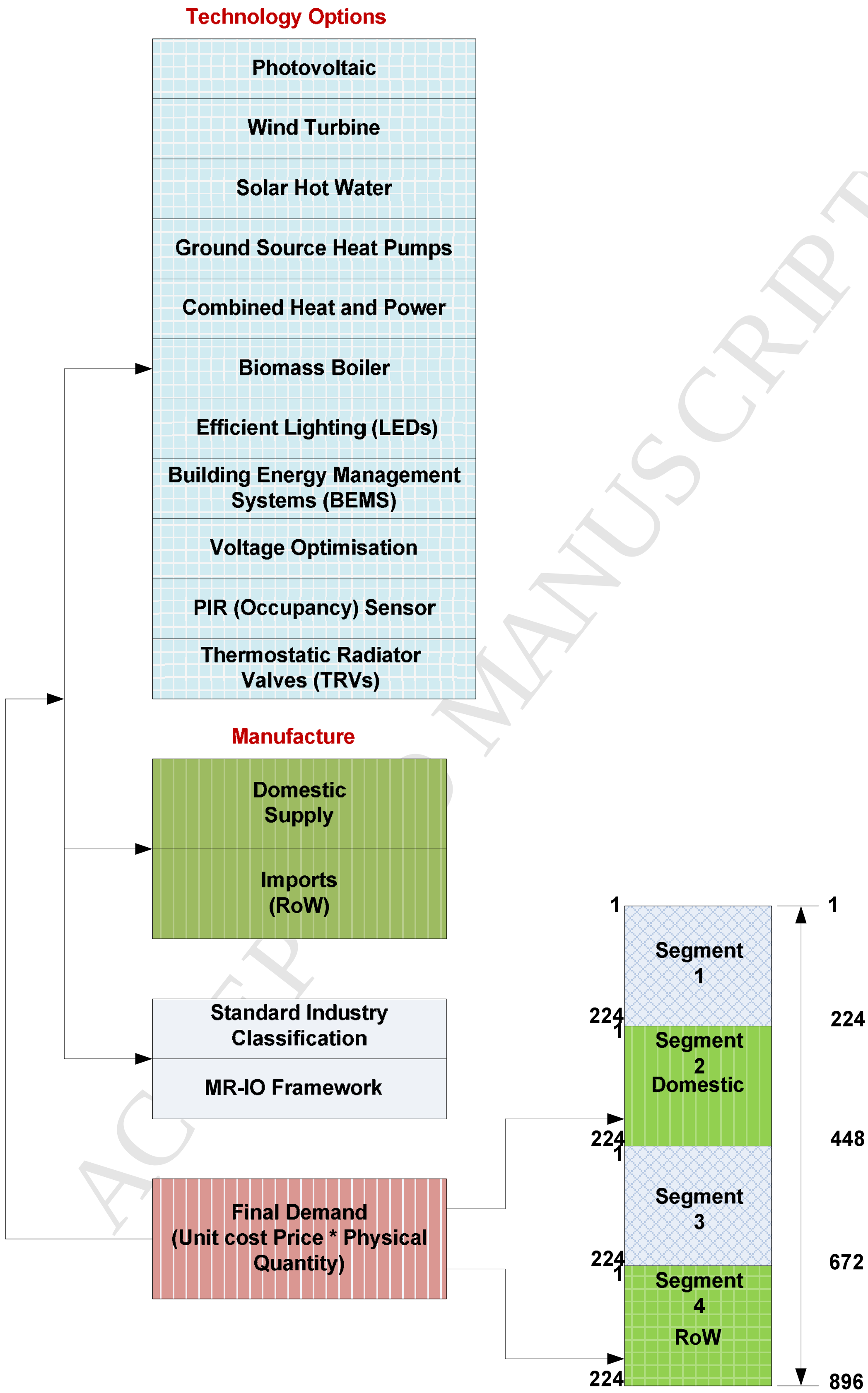


Figure 2: Illustration of two-region (UK and Rest of the World) Multi-Region Input–Output (MRIO) framework



Technology Options
Photovoltaic
Wind Turbine
Solar Hot Water
Ground Source Heat Pumps
Combined Heat and Power
Biomass Boiler
Efficient Lighting (LEDs)
Building Energy Management Systems (BEMS)
Voltage Optimisation
PIR (Occupancy) Sensor
Thermostatic Radiator Valves (TRVs)
Manufacture
Domestic Supply
Imports (RoW)
Standard Industry Classification
MR-IO Framework
Final Demand (Unit cost Price * Physical Quantity)
1
Segment 1
224
1
Segment 2 Domestic
224
1
Segment 3
224
1
Segment 4 RoW
224
1
224
448
672
896

Figure 3: Evaluation of embodied emissions using E-E I–O Method, within a MRIO framework.

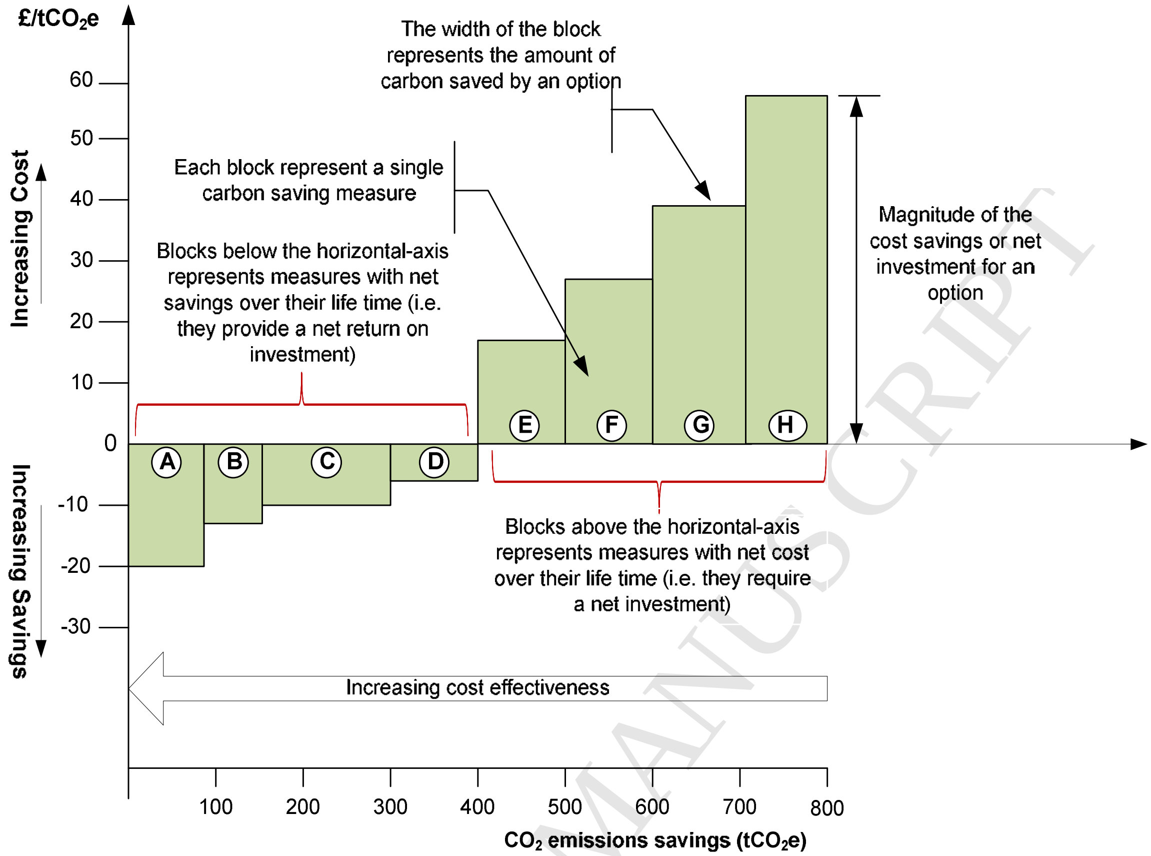


Figure 4: Illustrative MAC curve for CO_2 abatement options

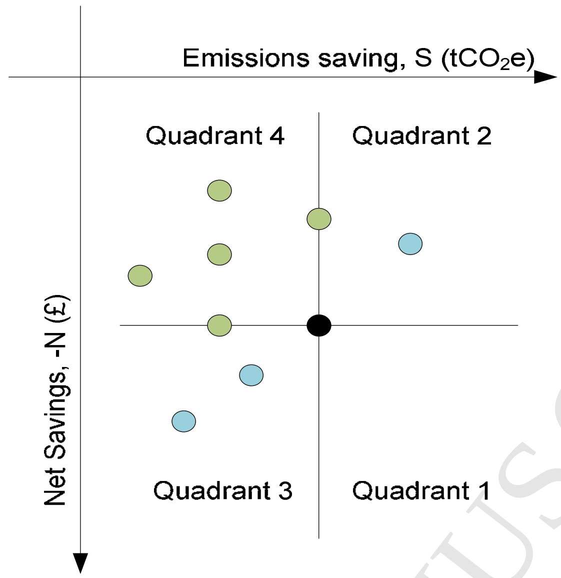


Figure 5: Plotting of Pareto front for emissions reduction measures (adapted from Taylor [37])

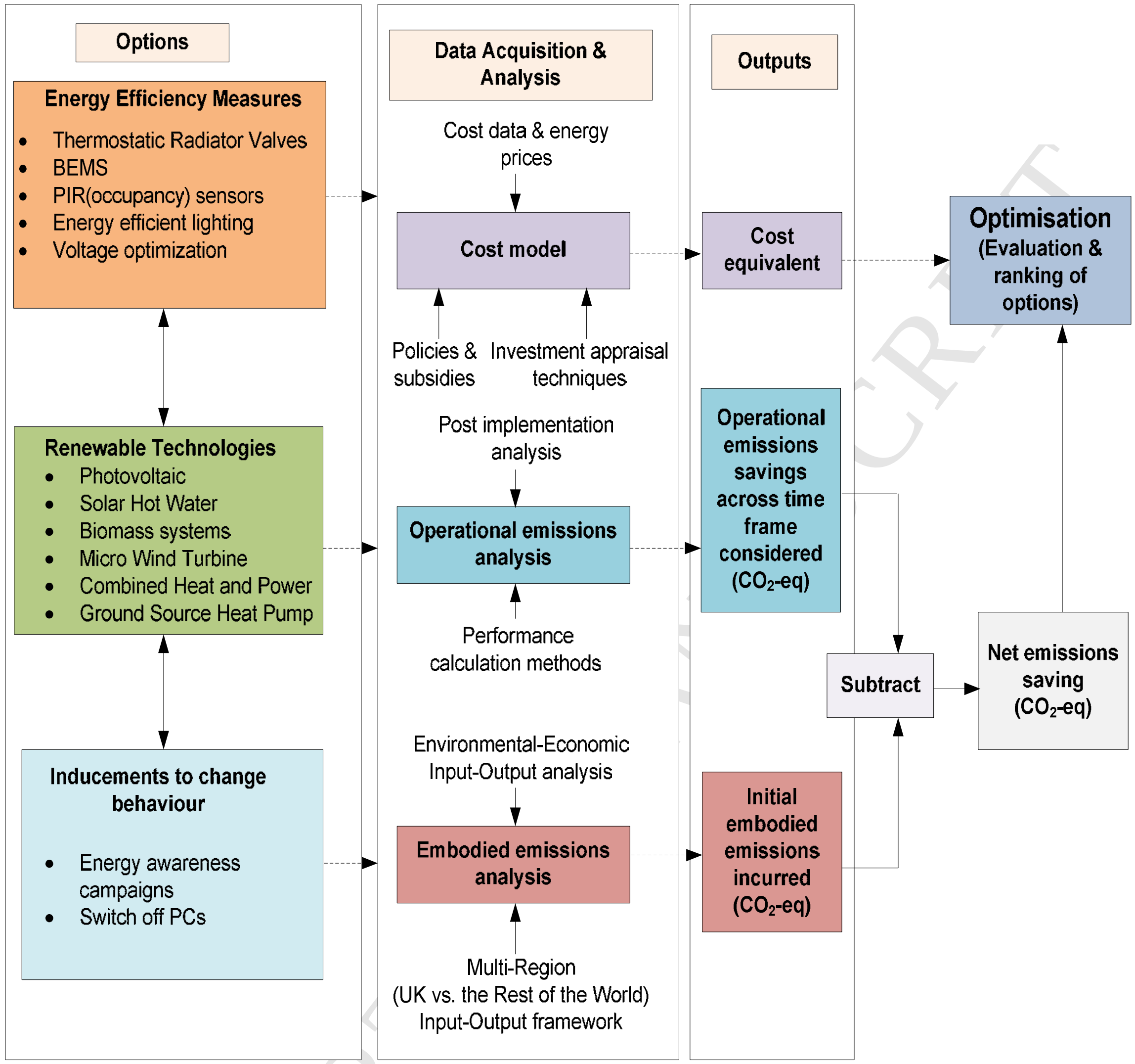


Figure 6: Data flow diagram: integrating embodied emissions into MACC

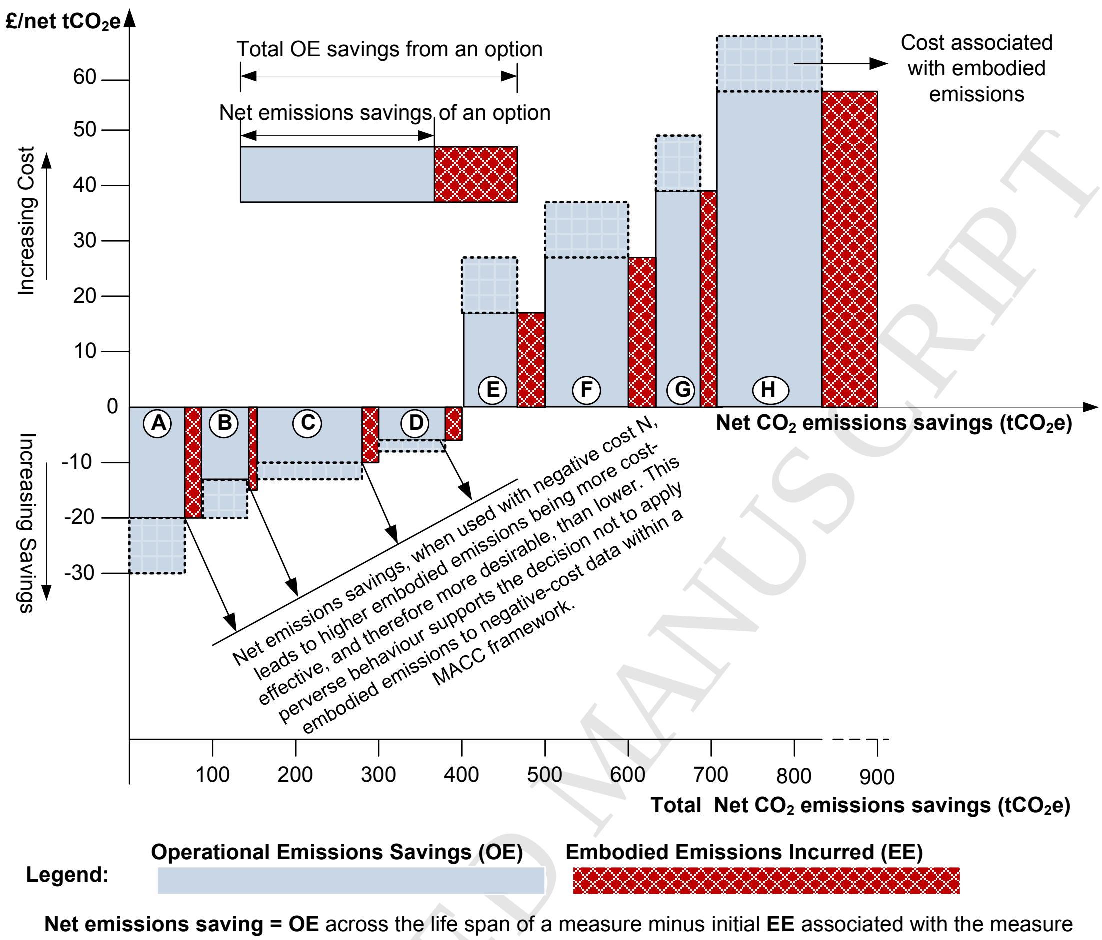


Figure 7: MACC curve integrating economic considerations with operational and embodied emissions (Positive cost measures only)

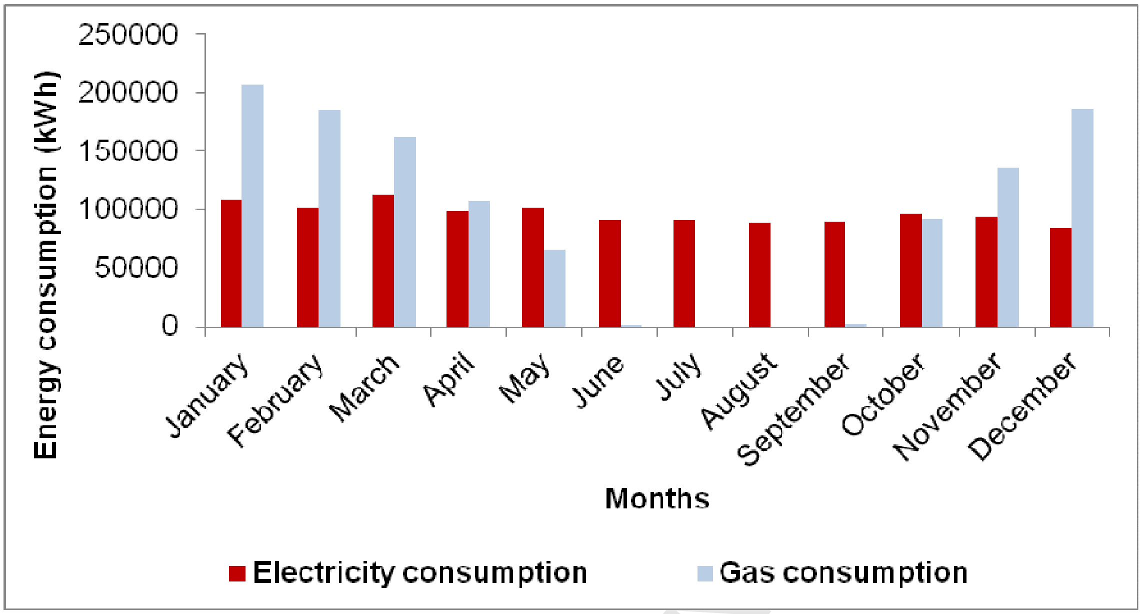


Figure 8: Baseline annual electricity and gas consumption for the Queens Building

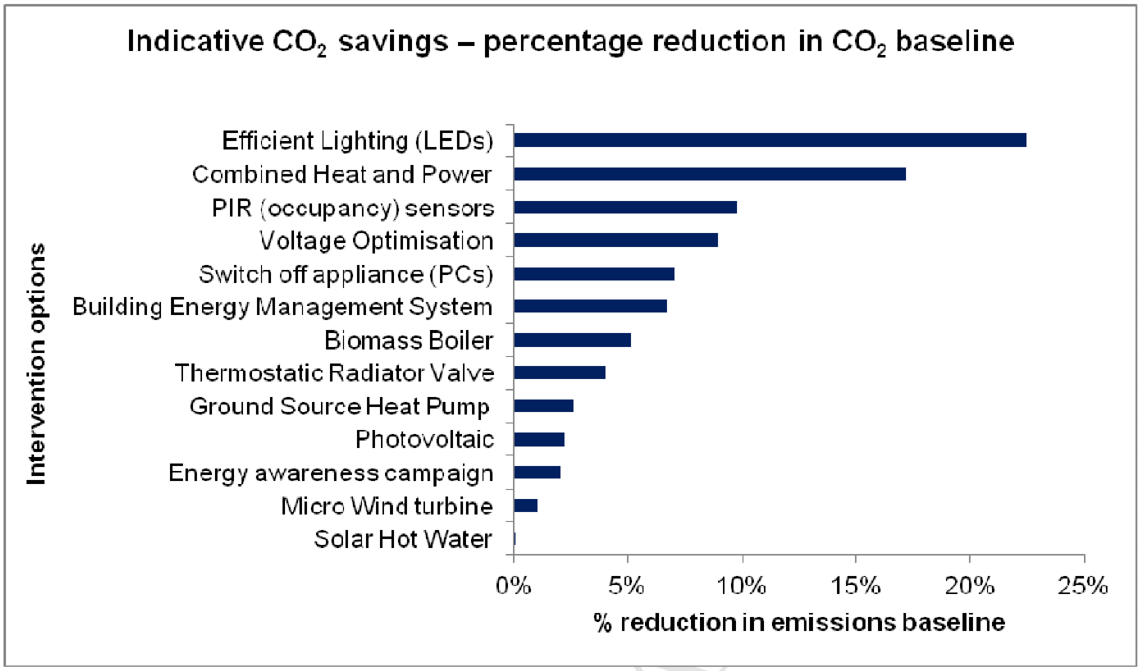


Figure 9: Indicative CO_2 savings – percentage reduction in CO_2 baseline

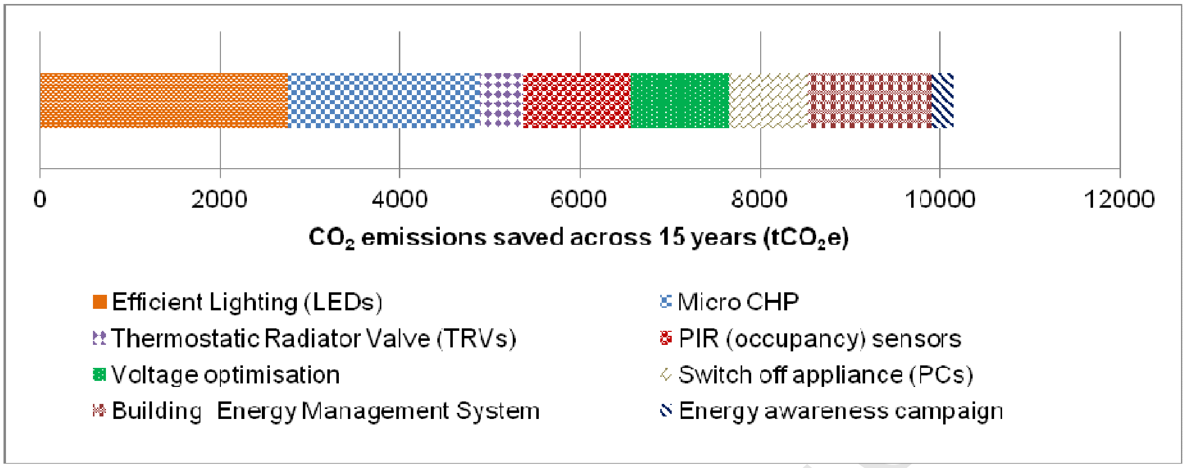


Figure 10a: Pareto ranking of negative cost measures (As a function of operational emissions only)

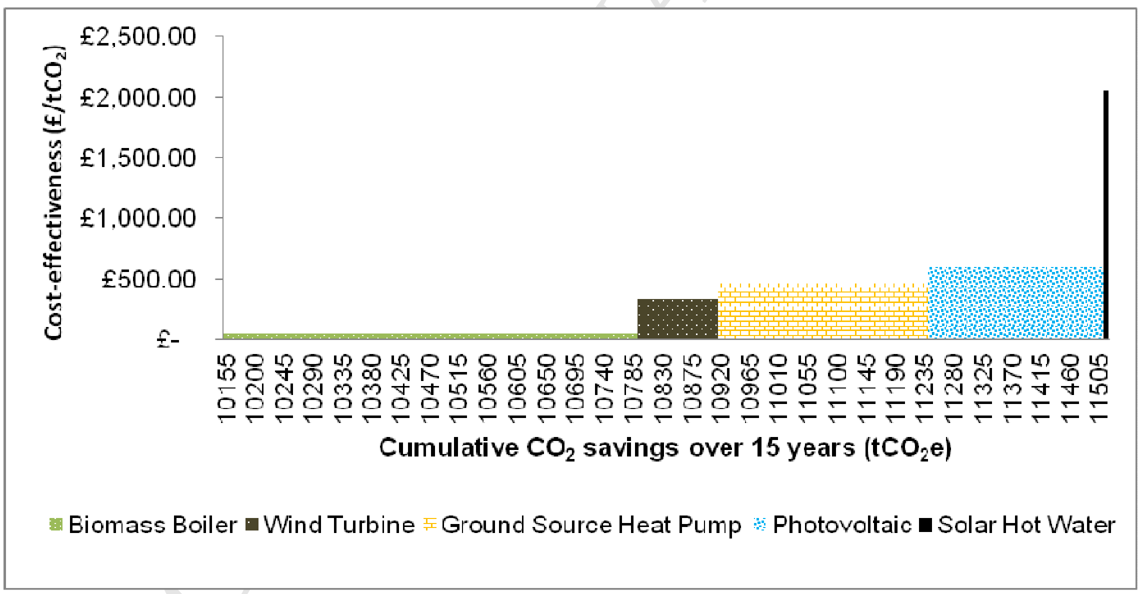


Figure 10b: MACC for positive cost low carbon intervention options (operational emissions only)

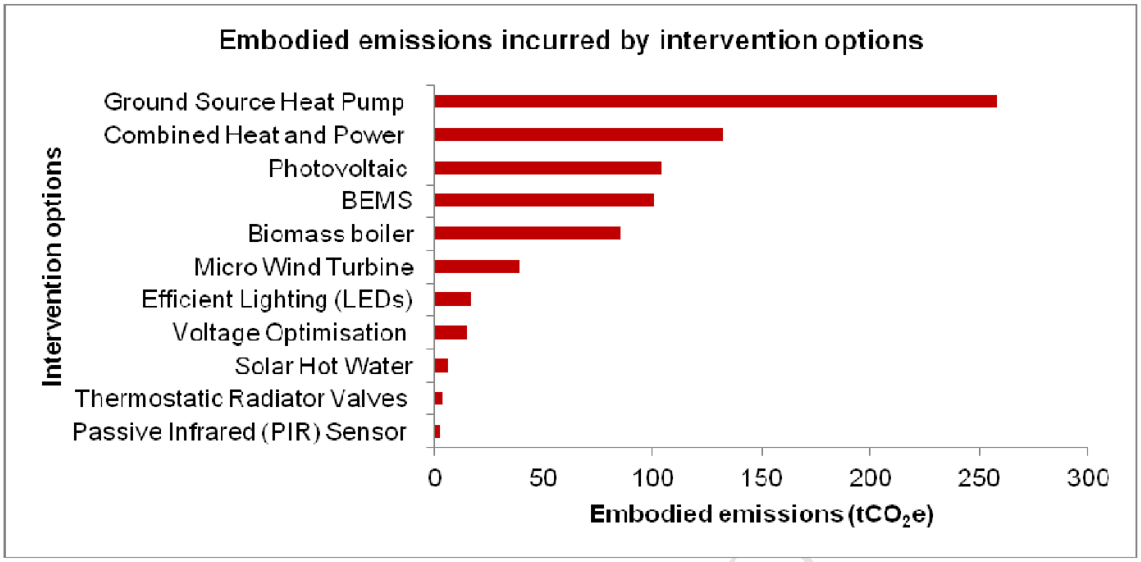


Figure 11: Embodied emissions incurred by the intervention options under consideration

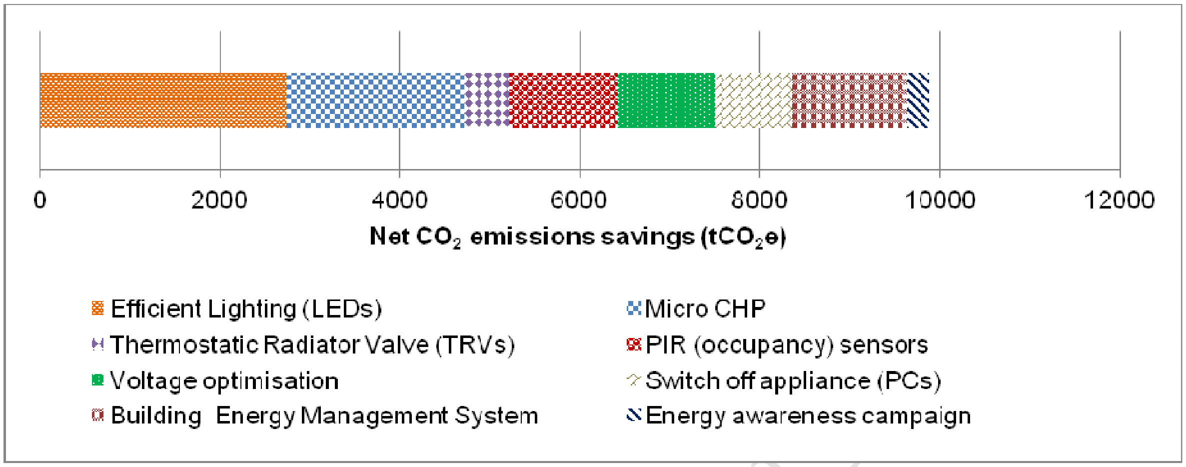


Figure 12a: Graphical representation of the Pareto ranking of negative cost measures (As a function of net emissions savings)

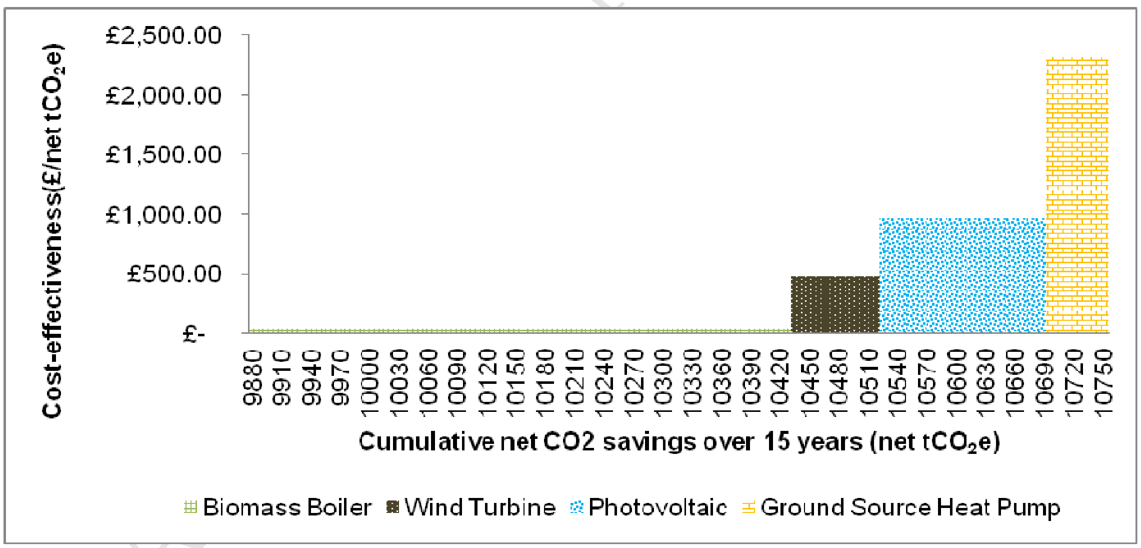


Figure 12b: MACC for positive cost measures (as a function of net emissions savings)

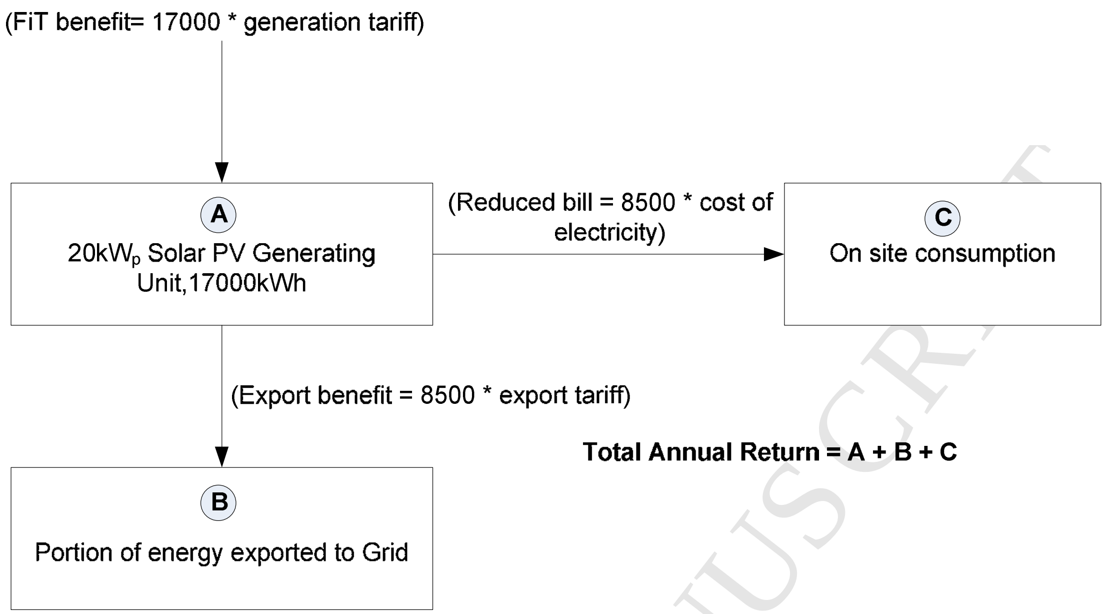


Figure 13: Illustration of total annual return for a solar PV installation

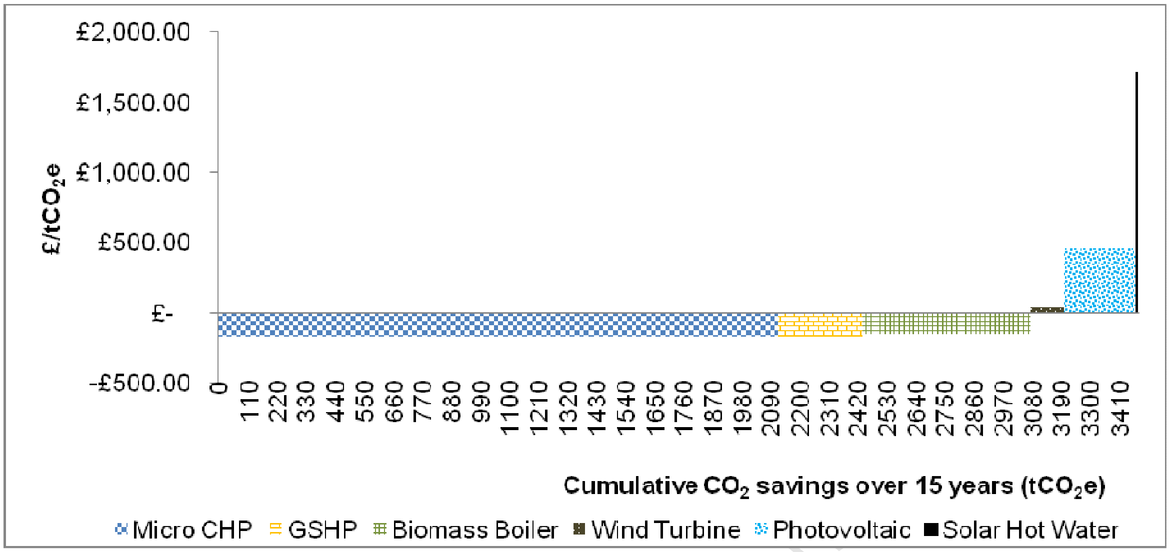


Figure 14: MACC for operational emissions savings from renewable technologies with consideration of FiT and RHI when 50% of energy generated exported to the grid

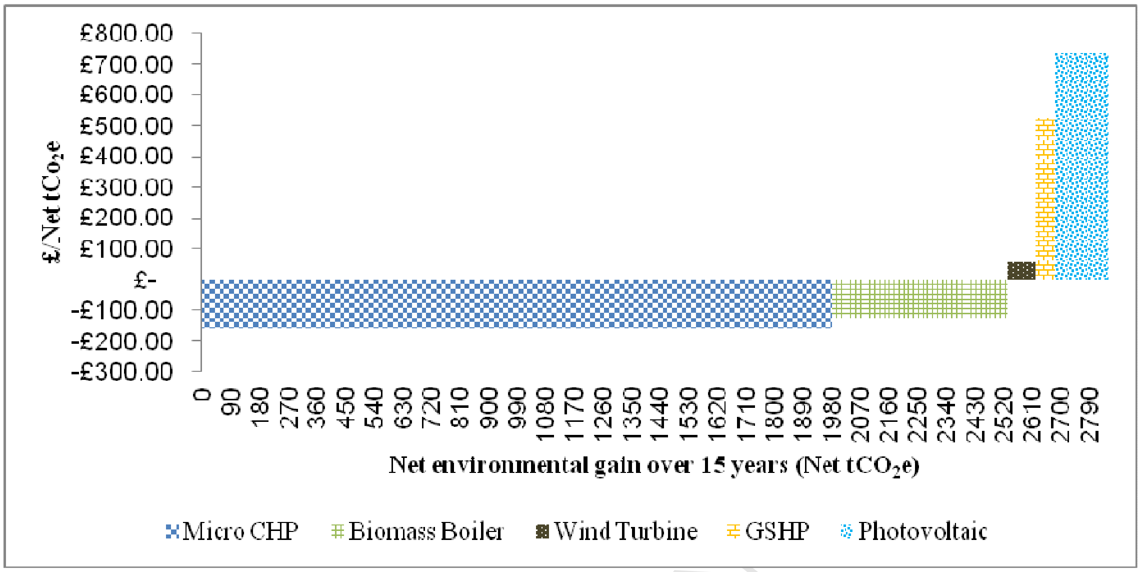


Figure 15: MACC for net emissions savings from renewable technologies with consideration of FiT and RHI when 50% of energy generated exported to the grid

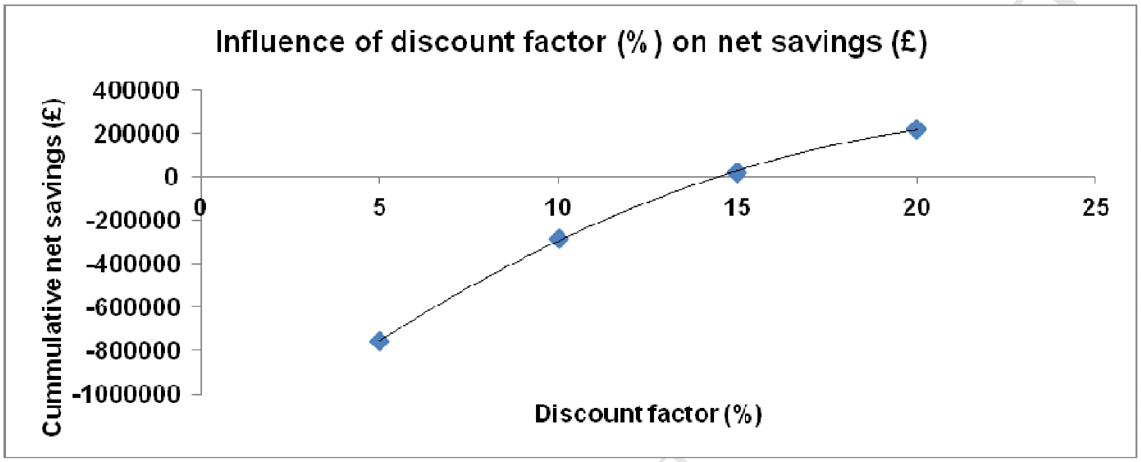


Figure 16: Sensitivity analysis-Influence of discount factor on net-savings

Highlight:

- A DSS based on optimal ranking of building energy retrofit options is presented
- The framework integrates economic and net emissions benefits into a single model
- The output produce optimal decisions based on MACC methods and Pareto optimisation
- The DSS provides stakeholders with efficient and reliable decision-making process
- Final decision is informed by both environmental and financial considerations