# Optimal Ranking and Sequencing of Non-domestic Building Energy Retrofit Options for Greenhouse Gas Emissions Reduction

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## Declaration

This PhD thesis is my own original work and has not been submitted elsewhere in fulfilment of this or any other award.

**Abstract**

Whether it is based on current emissions data or future projections of further growth, the building sector currently represent the largest and singular most important contributor to greenhouse gas (GHG) emissions globally. This notion is also supported by the Intergovernmental Panel on Climate Change based on projection scenarios for 2030 that emissions from buildings will be responsible for about one-third of total global emissions. As such, improving the energy efficiency of buildings has become a top priority worldwide. A significant majority of buildings that exist now will still exist in 2030 and beyond; therefore the greatest energy savings and carbon footprint reductions can be made through retrofit of existing buildings. A wide range of retrofit options are readily available, but methods to identify optimal solutions for a particular abatement project still constitute a major technical challenge. Investments in building energy retrofit technologies usually involve 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 and resource-efficient design and retrofit have focused on the environmental merits of these options, emphasising a lifecycle approach to emissions reduction. Retrofit options available for energy savings have different performance characteristics and building stakeholders are required to establish an optimal solution, where competing objectives such as financial costs, energy consumption and environmental performance are taken into account. These key performance parameters cannot be easily quantified and compared by building stakeholders 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 performance indicators. 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 thesis presents a novel deterministic decision support system (DSS) for the evaluation of economically and environmentally optimal retrofit of non-domestic buildings. The DSS integrates the key variables of economic and net environmental benefits to produce optimal decisions. These variables are used within an optimisation scheme that consists of integrated modules for data input, sensitivity analysis and takes into account the use of a set of retrofit options that satisfies a range of criteria (environmental, demand, cost and resource constraints); hierarchical course of action; and the evaluations of 'best' case scenario based on marginal abatement cost methods and Pareto optimisation. The steps involved in the system development are presented and its usefulness is evaluated using case study applications. The results of the applications are analysed and presented, verifying the feasibility of the DSS, whilst encouraging further improvements and extensions. The usefulness of the DSS as a tool for policy formulation and developments that can trigger innovations in retrofit product development processes and sustainable business models are also discussed. The methodology developed provides stakeholders with an efficient and reliable decision process that is informed by both environmental and financial considerations. Overall, the development of the DSS which takes a whole-life $CO_2$ emission accounting framework and an economic assessment view-point, successfully demonstrates how value is delivered across different parts of the techno-economic system, especially as it pertains to financial gains, embodied and operational emissions reduction potential.

## Dedication

To my late dad, Hon. Yusuf Ibn-Mohammed, the man that I admire the most, whom I consider the special gift in my life and who in the 19 years that I had with him, gave me unconditional love, thought me a sense of duty and gave me reasons to keep working hard and to be selfless.

## Acknowledgement

Melody Beattie (1987), the author of *Codependent No More* wrote:

**"Gratitude unlocks the fullness of life. It turns what we have into enough, and more. It turns denial into acceptance, chaos to order, confusion to clarity. It can turn a meal into a feast, a house into a home and a stranger into a friend."**

It is on the premise of the above favourite quote of mine that I will like to express my glowing admiration and heartfelt appreciation to a number of people, especially my excellent advisory and supervision team who have made my PhD journey enchantingly magical. Right before I commence my PhD, a sparkle of fear beclouded my heart, not from self-doubt but from the uncertainties associated with the dreadful mileage of the doctoral research. As my heart falters, the gracefulness radiated by both Dr Simon Taylor and Dr Leticia Ozawa-Meida, my respective (former) first and second supervisors, during my interview for the research position buoyed up my confidence and strengthen my determination. Now that the journey is complete, I am wholly grateful for what you have both been to me. Your styles of supervision, persistent encouragement and outstanding support have inspired me to think more, dream more and learn more to explore my intellectual prowess. Thank you!

The news of Dr Taylor's move to Loughborough University was received by me with a mixed feeling. I was thrilled at the career advancement the move will bring him but the thought of losing a supervisor for whom I have struck a chord was disappointingly sad. However, he handed me over into the safe and competent hands of Dr Rick Greenough, who then effectively became my new first supervisor. Dr Rick was profoundly knowledgeable and astute as a supervisor. His constant encouragement, psychological reassurance, constructive instructions and useful guidance during the course of the research have been essential motivators in completing this task. Every comment during monthly meetings was law! Dr Rick's aura of tolerance, subtle approach to difficult research issues and high level patience and professionalism are few of the qualities I have found exceedingly motivating in the course of this research journey. Accordingly, I say a big thank you!

My external advisor, Dr Adolf Acquaye was a brick! His expertise, technical prowess and solid advice went a long way in shaping my understanding of certain critical and difficult concepts. His words of encouragements, immense support and professional guide when the going was tough were simply phenomenal. I cannot sufficiently quantify what values your basket of ideas has added to me. Thank you! My gratitude also goes to the team of Input-Output experts at the Stockholm Environment Institute, University of York, who put together the data for the original UK-MRIO-1 model used for the I-O analysis in this thesis. My profound appreciation also goes to Prof. John Barret, Head of Sustainability Research at LEEDS University and Dr Simon Rees of IESD, for thoroughly examining my thesis in their respective capacities as external and internal examiners.

Completing a PhD without adequate funding can be mind-boggling. I am therefore beholden to the management of the Institute of Energy and Sustainable Development (IESD) for the generous doctoral studentship award. I am also deeply grateful for the highest level and most prestigious National PhD Scholarship award fully funded under the auspices of the Petroleum Technology Development Fund Overseas Scholarship Scheme (PTDF OSS), Federal Republic of Nigeria. These generous scholarship schemes avail me the rare opportunity of a PhD pursuit in a distinguished and resourceful Institute like the IESD. Priceless research experience enjoyed and garnered while working on my PhD, frictionless and conducive clime to carry out my research within the IESD have enriched my career life and made my stint in the academic industry unarguably fascinating.

Switching career focus from an electrical and electronics engineering background into the new and evolving field of sustainable energy systems engineering was non-trivial! At some point, it felt like a career suicide, however a number of good-hearted people made the transition a smooth one by helping to focus my work and bringing it to fruition. To this end, I extend my gratitude to the following people: First, my appreciation goes to Dr James Parker for his unrelenting and pragmatic advice at all times. Thank you for polishing my thought process at the early and every stage of my research. I thank Dr Graeme Stuart for providing me with quality data and for rendering assistance in terms of manipulation of large volume data. His deftness in computer programming and advance use of Microsoft Excel never seizes to amaze me. Thank you for your time and attention. To Xingxing Zhang, I am indebted to your technical assistance in numerical modelling. My gratitude also goes to all the lecturers of the Institute who granted me unrestricted access into their lecture classes. To Farhan Faruk, I express my profound appreciation for his outstanding support during the daunting moments.

Many thanks also go to the former DMU energy manager, Mr Umakant Pancholi and the sustainability manager, Mr Karl Letten for their professional support, provision of quality data and tremendous assistance rendered during the course of this research. My profound thankfulness also goes to my bosom friend, Dr Khameel Mustapha, for whom I never lost my respect. I thank you especially for the countless brainstorming sessions and intellectual discussions. Those sessions served as signalling boards for my thought process and fired up fresh thinking in me. I also thank Chris Clark for rendering advice regarding my finances.

When I started out, it was all so daunting and chaotic with moments that range from moody and lonely periods, sleepless nights, missed lunches, funny dreams, unending brain racking to the fear of the unknowns. Surviving those chaotic moments of the frightening PhD journey requires the support from loved ones. The prayers, words of comfort, advice and support from my mum, siblings and friends gave me strength throughout the thick and thin of my programme. I am grateful to you all.

In life, when you meet some friends, they lighten up the spirit of life-long learning in you. Others make you swallow the humble pie with the breadth of their wit and their exemplary spiritual virtues. This doctoral work brought me in contact with friends that combine these traits and I say thank you to them all. Most importantly, I say a big thank you to Mohammed Bamba for tolerating my weaknesses and for being a wonderful flatmate. To Omar Khan, thanks for consistently powering the batteries to my faith at all times with spiritual food for thoughts. I appreciate every bit of my time spent with you. My profound gratitude also goes to Lukman Abolaji, Abdul Hakeem Lawal and Abdul Hakeem Bello for their indefatigable support during my emotion-ridden days.

I suffered a fatal heartbreak which plunge me into a state that feels I will never be capable of loving again. Thankfully, the pangs of love have become resurrected again with vigour when I met the love of my life –Tuta. You have stepped out of the blues to rekindle my feelings and reassure me psychologically. Your warm support has kept me strong to beat the hurdles and your trust serves as a magnificent stimulator of what I have achieved so far in my programme. Although, I am aware of the barrier between us in terms of cultural ambience and geographical boundaries, it is my hope that someday we will be together forever and ever. I sure cannot wait to see this dream come to reality.

Finally, my profound gratitude to Allah - The Most High, The Most Knowledgeable and The best of Writers- for His complete guidance throughout the research period and always. He guides my thoughts, shapes my reflection and directs my liveliness to that which is beneficial. He made easy the most difficult task and magnifies the most relevant thoughts. All praises belong to YOU.

*"As the island of knowledge grows, the surface that makes contact with mystery expands. When major theories are overturned, what we thought was certain knowledge gives way, and knowledge touches upon mystery differently. This newly uncovered mystery may be humbling and unsettling, but it is the cost of truth. Creative scientists, philosophers, and poets thrive at this shoreline."* ~ **W. Mark Richardson,**

*'A Skeptic's Sense of Wonder,' Science*

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## Abbreviations and acronyms used in this thesis

| |
|---|
| **ASHP: Air Source Heat Pump** |
| **ASHRAE: American Society of Heating, Refrigeration and Air-conditioning Engineers** |
| **BEMS: Building Energy Management System** |
| **BP: British Petroleum** |
| **BRE: Building Research Establishment** |
| **BREDEM: BRE Domestic Energy Model** |
| **BREEAM: Building Research Establishment Environmental Assessment Method** |
| **CASBEE: Comprehensive Assessment System for Building Environmental Efficiency** |
| **CCC: Committee for Climate Change** |
| **CHP: Combined Heat and Power** |
| **$CO_2$: Carbon dioxide** |
| **$CO_2e$: Carbon dioxide equivalent** |
| **CoP: Coefficient of Performance** |
| **DECC: Department of Energy and Climate Change** |
| **DEFRA: Department for the Environment, Food and Rural Affairs** |
| **DSS: Decision Support System** |
| **DTI: Department of Trade and Industry** |
| **EIA: Energy Information Association** |
| **EPC: Energy Performance Certificate** |
| **FIT: Feed-in Tariff** |
| **FP: Fuel Poverty** |
| **GHG: Greenhouse Gas** |
| **GSHP: Ground Source Heat Pump** |
| **GWP: Global Warming Potential** |
| **HEQ: High Quality Environmental standard** |
| **HM's Government: Her Majesty's Government** |
| **IEA: International Energy Agency** |
| **IPCC: Intergovernmental Panel on Climate Change** |
| **KPI: Key Performance Indicator** |
| **KWh: Kilowatt hour** |
| **LCC: Life Cycle Costing** |
| **LCEA: Life Cycle Energy Analysis** |
| **LCTP: Low Carbon Transition Plan** |
| **LEDs: Light Emitting Diodes** |
| **LEED: Leadership in Energy and Environmental Design** |
| **MACC: Marginal Abatement Cost Curve** |
| **MRIO: Multi Region Input Output** |
| **NPV: Net Present Value** |
| **OECD: Organisation for Economic Cooperation and Development** |

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| **PO: Pareto Optimisation** |
| **PIR: Passive Infrared** |
| **PV: Photovoltaic** |
| **RES: Renewable Energy Supply** |
| **RHI: Renewable Heat Incentives** |
| **RHO: Renewable Heat Obligation** |
| **SBCI: Sustainable Buildings and Climate Initiative** |
| **SIC: Standard Industrial Classification of economic activities** |
| **SPC: Shadow Price of Carbon** |
| **TFA: Total Floor Area** |
| **TRV: Thermostatic Radiator Valve** |
| **UK: United Kingdom** |
| **UNEP: United Nations Environmental Programme** |
| **UNFCCC: United Nations Framework Convention on Climate Change** |
| **USGBC: United State Green Building Council** |
| **VAT: Value Added Tax** |

## Glossary of key terms and definitions used in this thesis

| S/N | Term | Definition |
|---|---|---|
| **1.** | **Building Energy Management System (BEMS)** | These are powerful tool for energy management in buildings and not a substitute. It involves the installation of a system that is computer-controlled and integrates the energy-using services and facilities in a building. It allows the facilities to be centrally managed by controlling the energy-consuming equipment to reduce energy use while maintaining a comfortable environment |
| **2.** | **Carbon footprint (CF)** | This is a measure of the total amount of greenhouse gas (GHG) emissions that are directly and indirectly caused through the activities of an individual, organisation, event or product or is accumulated over the life stages of a product. It is expressed as a carbon dioxide equivalent |
| **3.** | **$CO_2$-eq** | This is the concentration of $CO_2$ that would cause the same level of radiative forcing as a given type and concentration of GHG |
| **4.** | **Direct emissions** | These are emissions from accruing from sources that are owned or controlled by an organisation. They are also called on-site or scope 1 emission |
| **5.** | **Direct Requirement Coefficient Matrix** | It is also called the Technology Matrix in input-output analysis and represents the matrix of direct deliveries required to produce a product per unit of the total output |
| **6.** | **Downstream emissions** | These relates to the emissions that accrue in the lifecycle of goods and services that are sold subsequent to sale by the reporting organisation. These include the emissions by customers enabled through the purchase of these goods and services. Downstream emissions are part of scope 3 emissions as defined by the GHG Protocol. |
| **7.** | **Embodied $CO_2$-eq** | This is the equivalent carbon dioxide discharged into the atmosphere due to the energy embodied in a particular product |
| **8.** | **Embodied $CO_2$-eq Intensity** | This is the embodied $CO_2$-eq of a product per unit output, measured in terms of £, $m^2$, kg etc. |
| **9.** | **Embodied Energy** | This is the measure of all energy input that goes into the production any given product. It includes energy used in extraction of raw materials, processing, manufacture, transportation, delivery on the site, constructions, renovation and maintenance, final knocking down as well as all the activities and processes along the supply chain |
| **10.** | **Emission factors** | This is the average emission rate of a given pollutant from a given source relative to the intensity of a specific process or activity |
| **11.** | **Energy and emission policies** | These are policy instruments developed to encourage the reduction of energy consumption, promote energy efficiency and conversion processes, renewable energy supplies, etc. and the reduction of discharge of emissions into the environment |
| **12.** | **Epistemology** | This refers to the extent to which reality can be known (i.e. the assumptions that are made regarding the nature of the knowledge of human and how such knowledge are obtained and understood) |
| **13.** | **Feed-in-Tariff (FiT)** | This is a grant scheme that was 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 energy generation technologies, with a view to reducing demand |

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| **14.** | **Greenhouse Gases** | These are gases in the atmosphere, both natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. They are responsible for the heating of the earth in what is known as the greenhouse effect. The most common GHGs include carbon dioxide ($CO_2$), methane (CH4), nitrous oxide ($N_2O$), hydro fluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride ($SF_6$) |
| **15.** | **Hybrid Embodied Energy Analysis** | The systematic integration of the specificity of process analysis with the completeness of input-output analysis. By combining the benefits of both process and input–output analysis, fundamental errors and limitations associated with each method can be eliminated, improving both accuracy and precision |
| **16.** | **Indirect emissions** | These are emissions that are a consequence of the operations of an organisation, but occur at sources not owned or controlled by the organisation. These include scope 2 and 3 emissions as defined by the GHG Protocol |
| **17.** | **Input-Output analysis** | The input-output approach to lifecycle assessment operates through the tracking of all economic transactions between different sectors within an economy and the consumers. It is an economic modelling method which facilitates the understanding of the interactions between economic sectors of a country, the producers and the final consumers |
| **18.** | **Input-Output tables** | These are tables in the form of matrix, which provides a complete picture of the flows of products and services in an economy for a given year, illustrating the relationship between producers and consumers and the interdependencies of industries. The tables are usually compiled by the national government |
| **19.** | **Interactions** | This is a phenomenon that arises when the GHG emission savings potential of a measure is reduced due to the fact that another measure has been previously implemented. It usually arise between different types of abatement measures that act on the same end use |
| **20.** | **Leontief Inverse Matrix** | This is the matrix of cumulative (direct and indirect) deliveries required to produce a product per unit of total output and it can be approximated by the power series approximation of the matrix of direct requirement coefficient |
| **21.** | **Life Cycle Assessment** | This is a well-established systematic approach used for the identification, quantification, and assessment of environmental impacts throughout the lifecycle of an activity, product or process |
| **22.** | **Marginal Abatement Cost Curve** | In simple terms, MAC expressed in cost per tonne of GHG emissions saved, is the additional cost of abating an additional tonne of GHG above what would be achieved in a 'business as usual' context. A MACC therefore is a graphical device that combines the MACs of available abatement projects to facilitate decision making. MACCs are a useful tool to identify options which deliver the most economically efficient reductions in GHG and prioritize mitigation options based on certain criteria |
| **23.** | **Midstream emissions** | These are indirect (scope 3) emissions associated with the activities of an organisation but not caused by suppliers (upstream) or customers (downstream). E.g. an employee commuting to and from the workplace |
| **24.** | **MRIO framework** | Multi Region Input-Output (MRIO) framework allows the estimation of the environmental loads (embodied emissions) and implications of consumption associated with international trade flows regarding GHG emissions |

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| | | associated with the options. The framework 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 |
| **25.** | **On-site emissions** | These forms of emissions are those from sources that are owned or controlled by a company or an organisation. They are also known as direct or Scope 1 emission |
| **26.** | **Ontology** | This phenomenon relates to the nature of reality regardless of human attempts to understand it |
| **27.** | **Overlap** | This is a form of interaction that comes into play when "like for like" abatement measures are used to actualise the same result under different circumstances. Overlap also arises when a measure cannot be implemented because another measure that is deemed to have a better cost-effectiveness has already been implemented |
| **28.** | **Pareto optimization** | It is also called Pareto efficiency or Pareto optimality and is named after Vilfredo Pareto. The concept is a state of allocation of resources in which it is impossible to make any one individual better off without making at least one individual worse off. It is employed when a solution is required in the midst of conflicting objectives where solutions are chosen such that there are reasonable trade-offs among different objectives. With the Pareto Optimisation scheme, rather than generating a single optimal solution, a myriad of solutions are generated that satisfy Pareto Optimality criterion. The criterion is such that a solution point P is accepted only if there are no solutions better than P with respect to all the objectives |
| **29.** | **Performance validation** | This involves the assessment of the performance aspects of a system with the view to ascertain how effective its mode of operation is; how well it performs its functions and to what extent is the knowledge base of the system accurate and complete |
| **30.** | **Process Analysis** | The measurement in physical terms of all the energy and material flow that goes into the manufacture of a product to produce a unit output and it's undertaken at an industrial level |
| **31.** | **Refurbishment** | This refers to the necessary modifications required on a building with the view to returning it to its original state |
| **32.** | **Retrofit** | This refers to the necessary actions that will improve energy and/or environmental performance of the building |
| **33.** | **Scope 1 emissions** | These are emissions that accrue from sources that are under the ownership or control of a company or an organisation that discharge emissions straight into the atmosphere. They are also referred to as direct or on-site emissions. |
| **34.** | **Scope 2 emissions** | These are emissions that stems from activities of an organisation through own consumption from generation of electricity, heating, cooling, or steam purchased. They are indirect emissions that are a consequence of an organisation's activities but which occur at sources they do not own or control |
| **35.** | **Scope 3 emissions** | This refers to an organization's indirect emissions that are a consequence of its actions, which occur at sources which they do not own or control and which are not classed as scope 2 emissions. Scope 3 emissions are categorised into upstream, midstream and downstream emissions |
| **36.** | **Subjective appraisal** | This involves gathering thoughts and opinions from potential users to measure the usefulness and usability of a system. It also includes establishing |

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| | | the extent to which a system addresses the requirements of its potential users and assessment of its ease of use |
| **37.** | **System Boundary** | This is defined as the interface between a product system and the environment or other product system |
| **38.** | **Technical verification** | This entails checking the "*black box*" of a system to get rid of programming errors and checking the extent to which the system has been built well; checking the accuracy of its outputs; and ascertaining whether the advice produced is sound or not |
| **39.** | **Renewable Heat Incentive** | This a grant scheme set up by the UK Government in 2011 to encourage the implementation and use of renewable heating. It covers renewable energy technologies such as ground source heat pumps, biomass heating and solar thermal systems |
| **40.** | **Total Embodied $CO_2$-eq Intensity** | This is the total sum of direct and indirect embodied $CO_2$-eq intensities |
| **41.** | **Upstream emissions** | These are emissions of a company that occur in the lifecycle of goods, services, materials, and fuels that are purchased up through receipt by the reporting company. These include the supplier's emissions and are part of scope 3 emissions as defined by the GHG Protocol. Upstream emissions of a product occur in the lifecycle stages prior to the purchase of the product |
| **42.** | **Use-phase emissions** | These are emissions associated with the use phase of a product or service, e.g. emissions discharged through the driving of a car |
| **43.** | **Validation** | This involves the formation of documented evidence which gives a high degree of satisfaction and assurance that a specific procedure or process will consistently yield results that meets its predetermined quality attributes and functional specifications |
| **44.** | **Voltage optimisation** | Also known as voltage correction, voltage regulation, voltage stabilisation or voltage reduction, is an electrical energy saving technique, in which a device is installed in series with the mains electricity supply to provide an optimum supply voltage for the site's equipment |

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# CHAPTER ONE: INTRODUCTION

## Chapter Overview

This chapter provides an overview of the key information related to this PhD research and its overall content. The thesis presents a robust methodological framework of a decision support system, based on a techno-economic evaluation methodology, to analyse a range of building energy retrofit options. Detailed steps involved in the system development are presented in the overall thesis and its usefulness is evaluated using a case study building. A summary of the main contributions to knowledge that this work makes to research and scholarship including the lists of peer reviewed publications as well as an outline of the overall thesis structure and organisation are also concisely presented in this chapter.

## 1.1 Background

Globally, more than 80% of primary energy demands are met through the burning of fossil fuels (EIA, 2013; BP, 2012; IEA, 2012) and current profiles reveals that the world remains highly dependent on fossil fuels, resulting in the emission of carbon dioxide ($CO_2$) and associated greenhouse gases (GHG). In the past 40 years, the world has witnessed a decline in its reserves of oil and gas (Bentley, 2002). This notion is supported by several energy experts and analysts, who have argued that globally, oil production has hit its peak–a situation where the highest long-term rate of extraction and depletion of fossil fuels is attained (Pearce, 2006), and is now falling (DTI, 2007). Although, billions of barrel of oil are unexploited in some regions, it is expected that as the price of oil rises and demand outstrips supply, these huge sources of fossil fuel will become economically exploitable (Pearce, 2006). For example, the US alone has a total of about 166.7 billion barrels of proved and undiscovered oil reserves (EIA,2013; CRS, 2009) while Alberta, Canada, still boasts of roughly 178 billion barrels of established oil reserves in oil sands (NEB, 2005).

Unfortunately, these scenarios do not present a solution to the depletion in fossil fuel reserves based on the prediction by the International Energy Association (2006) that from 2004 to 2030, primary energy demand at a global level will increase by 53%, yielding a 55% increase in global $CO_2$ emissions associated with energy. This suggests that fossil fuels will remain the key source of energy worldwide; accounting for 83% of the upsurge in energy demand. The IEA report concluded that these levels of consumption and dependency on non-renewable energy resources are unsustainable given the growing demand for energy and the likely reduction in the world's oil reserves (Figure 1.1). It is therefore clear that a great deal of attention is required regarding the way fossil fuels are being consumed.

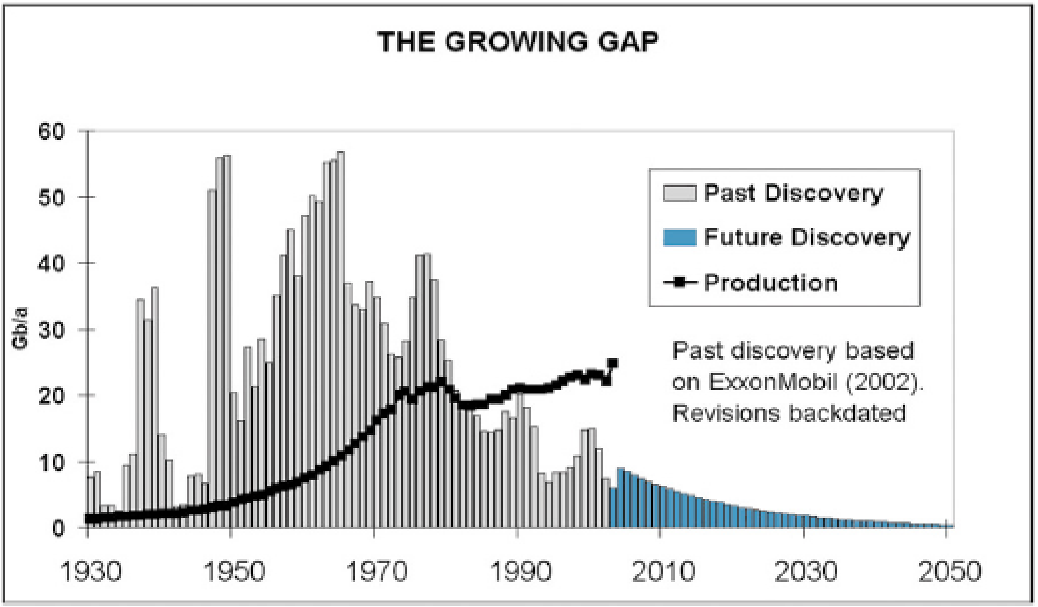



**Figure 1-1: Depletion of world's oil reserve (Chevron Oil, 2002 as cited by Lstiburek, 2009)**

The link between fossil fuel consumption and GHG emissions is well established. A multitude of different research has provided very strong evidence that anthropogenic emissions are the primary cause of climate change (IPCC, 2007a). More than two-thirds of the world's GHG emissions are attributed to the way energy is produced and consumed (DTI, 2007). As such, the supporting evidence and wider international recognition of the pernicious effect of climate change has precipitated legitimate concerns in the last decade and the need for a concerted effort towards mitigating GHG emissions continues to mount (IPCC, 2007a;UNFCCC, 2008). These issues have prompted the formulation of a range of international, regional and national energy and emissions policies (Jean-Baptiste and Ducroux 2003; Bazilian *et al.*, 2010), targeting energy intensive sectors of the economy (Noailly and Batrakova, 2010; Kanako, 2011).

In the UK, this policy agenda was formalised in the Climate Change Act (2008) which aims to build a low carbon economy by establishing a long-term framework to tackle climate change. Compared to the 1990 levels, the UK Government establishes a legally binding target, under the same act, to reduce its carbon dioxide emissions by at least 34% and 80% by 2020 and 2050 respectively. Intermediate legally binding five year carbon budgets that define emissions reduction paths are also set by the independent Committee on Climate Change (2008) under the same Act.

Analysis of the sources of global GHG emissions shows that emissions from the building sector currently constitute the single principal contributor, with nearly one-third of related global energy consumption taking place in buildings (UNEP-SBCI, 2008; IEA, 2009; USGBC, 2009). The sector is rated as the third highest emitter in the industrial sector only behind oil and gas and the chemical industry (IPCC, 2007). The Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC, 2007d), estimated that GHG emissions related to buildings attained 8.6 billion $tCO_2e$ in 2004, and suggested that this figure could almost double by 2030, reaching 15.6 billion $tCO_2e$ under high-growth scenarios.

The UK Carbon Plan (HM Government, 2011) has also identified the building industry as a priority sector of the economy where significant improvement in energy use and reduction in greenhouse gas (GHG) emissions can be achieved. This is because the building sector has the potential to deliver quick and significant reduction in GHG emissions at zero cost or net savings, using currently available technology and knowledge (IPCC, 2007; UNEP, 2007). The Committee on Climate Change (2008) predicts that in the UK, by 2020, there is a technical potential to cut down building-related emissions by almost 40 $MtCO_2$ (more than half of this figure would result from options with negative costs, with the rest achievable at a cost of < £40/$tCO_2$ ) through improvements in energy efficiency and changes in lifestyles. The sector is therefore central to low-cost climate mitigation worldwide (IEA, 2006; IPCC, 2007). As such, several energy policy frameworks, for example, the 2007 policy statement for target of zero carbon homes (DCLG, 2007a), have acknowledged the significance of lowering energy use in buildings. It requires all new domestic and non-domestic buildings to be 'carbon-neutral' by 2016 and 2019 respectively, and therefore these should not add further growth to $CO_2$ emissions (Energy Saving Trust, 2010; Zero Carbon Hub, 2009).

However, a significant majority of buildings that exist now or get built before the requirement for carbon-neutral buildings will still exist in 2050; therefore the greatest energy savings and carbon footprint reductions can be made through refurbishment. This suggests that only by adopting energy efficiency measures and renewable energy options to significantly improve the existing building stock can the building sector help the UK achieve its long term emission reduction targets of 80% compared to 1990 levels by 2050 (Energy Saving Trust, 2010; Caleb, 2008). These measures are intended to mitigate $CO_2$ emissions. It is estimated that the retrofits of existing buildings could save almost 15 times more $CO_2$ by 2050 compared to when they are demolished and replaced (Jowsey and Grant, 2009). Refurbishment lessens the time and cost associated with energy efficiency improvements of a building (Carbon Trust, 2009; Energy Saving Trust, 2010). Furthermore, either on a short-term or long-term basis, refurbishment can minimise energy use in buildings (Corus, 2010).

Against this backdrop, a reasonable question to ask is "what are the implications of this for the current research?" The answer to this important question is stated in Section 1.2.

## 1.2 Problem statement

Innovations and technological advances in the area of renewable energy technologies, energy efficiency and inducements to change behaviour have led to promising building energy retrofit solutions. However, these measures often lead to increased material and energy use for their production, contributing to an increase in embodied emissions. As such, recent trends towards resource efficient design have focused on the environmental merits of these measures, emphasising a lifecycle approach to emissions reduction. In practice, the implementation of all suitable measures is unlikely to be achieved in a single operation, due to financial costs, project timelines and other constraints. Additionally, the inclusion of embodied emissions in the analysis of retrofit measures always increases the overall emissions, though once they are included, a change in the approach taken to their production might result in a reduction. These effects can in turn affect the overall performance of a given measure when conducting retrofit decision analysis for prioritisation purposes. To this end, there is the need for a robust decision-making methodology with which optimal choices can be made regarding the prioritisation of the measures. Such a methodology will take into account multiple and sometimes competing objectives such as energy consumption, financial cost, environmental impact and the interactions of measures.

## 1.3 Research motivation

Across the globe, whether it is due to the depletion in fossil fuel reserves; or the need to pursue complete energy independence; or concerns about the pernicious effects of climate change; or the need to balance out international inequality about the impact of climate change on least influential countries; or even a desire to avert foreign ownership of a growing global market; the motives for cutting down on the growing demand for energy in order to reduce global $CO_2$ emissions related to energy, have become apparent and abundant. In the context of the current research, the motivation stems from a number of diverse but complementary observations that include the following:

### 1.3.1. The need to meet emissions reduction target

The over-arching motivation for this research emanates from the now widely-accepted need to significantly reduce emissions of $CO_2$ and associated GHGs linked mainly to the consumption of fossil fuels. This has led to challenging emissions reduction targets for the UK and the Government has since embarked on several ambitious reduction agendas. Despite the identified need and urgency, progress to date has been slow (DECC, 2009; Carbon Trust, 2008). Further technological innovations and research to underpin the mitigation of $CO_2$ is therefore pertinent.

### 1.3.2. The need for a cost-effective mitigation strategy

As national and international concern over climate change related issues becomes more prevalent, the need for the development of systems to support climate mitigation initiatives and policies becomes more apparent. Indeed, the effective management of energy and reduction of emissions in buildings involves the adoption of appropriate tools and methodological framework that support the strategic decision-making process of choosing measures, that are both economically viable and environmentally friendly (Doukas *et al.*, 2009).

Improving the efficiency and sustainability performance of a building is a complex problem due to difficulties associated with the assessment of the relative improvements in sustainability of one decision over another (Anastas and Zimmerman, 2003). Additionally, the future energy performances of buildings are difficult to predict during the design phase of a retrofit project when the capacity to make changes to retrofit project cost is greatest, but when adequate and detailed information regarding the final design is unavailable. Also, since the resources (project timelines, financial costs, etc.) to retrofit buildings are not unlimited, a dilemma as to how to apply limited project budgets when planning retrofit project is thus created. In order to address these issues and maximise the benefits of sustainable buildings, there is the need for a cost-effective mitigation strategy which will optimise initial decision making, regarding the retrofit of buildings. The development and appropriate use of such strategy 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.

### 1.3.3. Integration of embodied emissions

Embodied emissions are the lifecycle emissions of a product related to its production such as the emissions associated with a retrofit option. As the wider international recognition and global concern over energy use, material and resource utilization and the emissions of GHGs into the atmosphere continues to grow, embodied emissions associated with building energy retrofit options are becoming increasingly important as operational emissions of buildings fall, in response to regulations. Embodied emissions therefore constitute a key issue that is required to be tackled in the design stages of building retrofit projects.

In future, legislation (which places a price on carbon, using, for example, cap and trade schemes) and innovative technologies and knowledge will trigger aggressive operational emissions reductions while the large existing building stock will prompt major refurbishment and/or rebuild effort. This may further lead to increase in overall emissions and suggest that embodied emissions are likely to become one of the key metrics to be addressed in whole-life building emissions assessment. As such, future regulations may require embodied emissions to be considered by the installer in attempts to achieve the best-value retrofit plan. The development of a decision-making methodology which takes a whole-life environmental and economic assessment viewpoint can demonstrate how value is delivered across different parts of the techno-economic system; specifically on financial gains, embodied and operational emissions reduction potential.

### 1.3.4. Policy enhancements

In the past decade, there have been significant efforts towards designing, operating and maintaining energy efficient buildings. Improving energy efficiency in buildings and consequently reducing emissions is a complex and multifaceted problem because of the many variables and constraints that must be taken into account. Hence, efforts to improve building energy efficiency performance are focusing on specific actions and policies (such as development of energy management systems and audits to address operational energy use) without the adoption of holistic policy approaches mainly due to the problem's complexity.

The use of an improved decision-making approach may provide the basis to address these complexities and can be used to support policy initiatives towards emissions reduction in buildings. The development of such an approach could also play a role in improving policy discussions in the building sector and provide better insights (for instance through the creation of an efficient and standardised decision making process) when integrated with other top-down policy approaches.

## 1.4 Research aim and specific objectives

*The central aim of this research is to develop a robust decision-making methodology that will rank and sequence a range of intervention options for reducing greenhouse gas emissions. The intended output is the best-value approach to emissions saving in a non-domestic building, taking into accounts both operational and embodied emissions and the cost of each option.*

Allied to this central aim are the following **specific objectives**:

1. *Carry out a critical review of the relationship between embodied and operational emissions over the lifecycle of buildings, to verify and highlight the increasing importance of embodied emission in building emissions assessment.*
2. *Establish and formulate the suite of emissions saving options, including energy demand and supply interventions, which are feasible and capable, of achieving significant greenhouse gas (GHG) emissions reductions in non-domestic buildings.*
3. *Develop a robust decision-making methodology for the optimal ranking and sequencing of the identified and selected emissions saving options.*

   The following **sub-objectives** underpin the methodological development of the decision-making framework:

   - **i.** To analyse emissions saving refurbishment options in terms of their economics and emissions saving potentials with respect to base line operational energy consumption of a non-domestic building
   - **ii.** To compute the embodied emissions associated with each GHG abatement measure and evaluate how the balance between the embodied emissions of a measure and the corresponding operational emissions savings is affected by its implementation
   - **iii.** To identify and apply the appropriate investment appraisal techniques for the evaluation of the financial costs and payback periods of the retrofit intervention
   - **iv.** To establish the criteria that will be used for measuring the performance of the selected building retrofit intervention options
   - **v.** To illustrate how interactions and overlaps arise between emissions savings measures and suggest an appropriate approach on how they should be accounted for
   - **vi.** To assess the sensitivity of the costs to changes in policy, energy prices and discount factors
   - **vii.** To integrate the measures of financial costs, operational and embodied emissions into a robust method of ranking and sequencing building energy retrofit options according to the required criterion

4. *Develop the optimal retrofit pathway that will reduce greenhouse gas emissions in non-domestic buildings*
5. *Evaluate and validate the decision-making methodology*

## 1.5 Summary of major contributions

The contribution of the work undertaken by the researcher can be summarized as follows:

- Development of a novel unified decision support system for evaluation of economically and environmentally optimal retrofit of non-domestic buildings to enhance efficient and reliable investment decisions that are informed by both environmental and financial considerations
- Implementation of Pareto optimisation technique within the decision support system to address a mathematical error in the standard ranking criterion for measures that yields a negative cost within a marginal abatement cost framework
- Insight into the effects of interaction between building energy retrofit options, supported with mathematical formulations and analysis, through the use of interaction factor
- Novel application of economic input-output (EIO) model within a multi-region input-output (MRIO) structure to estimate the embodied emissions of a number of building energy retrofit options, providing insight into the UK consumption pattern and identifying policy, business and consumer triggers that will lead to emissions reduction strategies
- Novel mathematical proof and analysis of the relationship between operational and embodied emissions for a given retrofit option through the integration of both types of emissions and financial costs into a single model
- Novel extension of the marginal abatement cost curve to cover embodied emissions to frame policy initiatives and identify business and consumer triggers with the view to shaping future decisions towards holistic climate change mitigation strategies

Further detailed discussions of the above contributions are provided in Chapter seven.

## 1.6 List of publications

All the work presented in this thesis is the author's original work and has not been submitted elsewhere except in the under listed journal, conference and book chapter articles that stems from the current research in the three years it was carried out.

**Journal Publication List**

1. **Ibn-Mohammed, T.,** Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A. (2013). **Operational vs. embodied emissions in buildings - a review of current trends.** Energy and Buildings Vol.66 pp. 232–245.
   DOI: http://dx.doi.org/10.1016/j.enbuild.2013.07.026 *(Impact Factor: 2.679)*
2. **Ibn-Mohammed, T.,** Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A. (2014). **Integrating economic considerations with operational and embodied emissions**

**into a decision support system for the optimal ranking of non-domestic building retrofit options.** Buildings and Environment. Vol. 72 pp. 82–10.
DOI: http://dx.doi.org/10.1016/j.buildenv.2013.10.018 *(Impact Factor: 2.430)*

3. **Ibn-Mohammed, T.,** Greenough, R., Acquaye, A, Taylor, S., Ozawa-Meida, L. (2014). **Making an environmentally sustainable choice: why embodied emissions really matters.** Environmental Science and Technology *(Impact Factor: 5.257-Submitted: Under Review)*
4. **Ibn-Mohammed, T.,** Greenough, R., Acquaye, A., Taylor, S., Ozawa-Meida, L. (2014). **Development of a Decision Support System: Computed Optimised Building Retrofit Advice (COBRA) Software.** Decision Support Systems *(3-Star ABS Journal - Submitted: Under Review)*
5. **Ibn-Mohammed, T.,** Greenough, R., Ozawa-Meida, L., Taylor, S., Acquaye, A. (2014). **Design, Evaluation and Validation of a Computed Optimised Building Retrofit Advice (COBRA) Software.** Decision Support Systems *(3-Star ABS Journal -Submitted: Under Review)*

**Book Chapter**

1. **Ibn-Mohammed, T.,** Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A. (2013). **A decision support framework for evaluation of environmentally and economically optimal retrofit of non-domestic buildings.** Smart Innovation, Systems and Technologies. Vol. 22, pp. 209-227

**Conference Papers**

1. **Ibn-Mohammed, T**., Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A. (2013). **A Novel Decision Support System for the Optimal Ranking of Building Energy Refurbishment Options (Poster).** Engineering Sustainability '13 - Innovation and the Triple Bottom Line. David L. Lawrence Convention Centre, Pittsburgh. PA, USA (7th - 9th April, 2013)
2. **Ibn-Mohammed, T.,** Greenough, R., Taylor, S., Ozawa-Meida, L., Acquaye, A. (2012). **Optimal Ranking of Retrofit Options for Emissions Reduction options-A Review**. CIBSE- ASHRAE Conference on Sustainable Systems and Services for the 21$^{st}$ Century, Imperial College, London UK. (18th-19th April, 2012)
3. **Ibn-Mohammed, T.,** Greenough, R.M., Taylor, S., Ozawa-Meida, L. and Acquaye, A. (2012). **Foundation for a Decision Support Framework for Optimal Sequencing of Emissions Savings Refurbishment Options in Non-Domestic Buildings.** In: Laryea S, Agyepong SA, Leiringer R and Hughes W (Eds) Proc 4th West Africa Built

Environment Research (WABER) Conference, 24th-26th July 2012, Abuja, Nigeria, pp. 663-675

A list of awards, recognition and activities which stems from this research work is provided in Appendix E.

## 1.7 Thesis structure and organisation

The remainder of the thesis is structured into six chapters as follows. In Chapter 2, a review of the existing literature that is relevant to the current research is presented. The review presented in Chapter 2 provides the 'lens' through which the current study is viewed. Further information about other relevant studies is provided where necessary within the context of each chapter to buttress what is available in the extant literature and what is not.

The objective of Chapter 3 is to present and demonstrate the methodical framework adopted in achieving the objectives stated in Section 1.4. To this end, in Chapter 3, a detailed research methodology and the significance of the current research are presented.

Chapter 4 provides a rigorous description of the decision support system in terms of its underlying principles and components, including system structure, system requirements and system outputs. Chapter 4 also includes a detailed analysis of the design concepts, engineering principles and computational frameworks taken to achieve the identified research problems.

In Chapter 5, details are provided about the extension of the decision support methodology to a case study building and other extended applications. Hence, Chapter 5 includes results, analysis and discussion that stems from the application of the decision support system.

In Chapter 6, the validation and evaluation results which complement the design and implementation of the decision support model are presented.

A summary of the conclusions from the numerous analyses carried out in the course of this research, original contribution to knowledge, limitations of the work and the direction of possible future extension of the work are presented in Chapter 7.

# CHAPTER TWO: LITERATURE REVIEW

## Chapter Overview

This chapter presents a review of existing literature, detailing the relevant background issues for this research. Literature review involves a paradox: an effective literature review cannot be undertaken unless a research problem is formulated, yet the literature search plays an essential role in helping to formulate the research problem. In the context of the present work, the approach taken to overcome this conundrum involves searching and reviewing the existing literature in the specific area of study (energy and sustainability in buildings), using it to develop the theoretical framework from which the current study emerges and using this to establish a conceptual framework which then becomes the basis of the current investigation. The chapter therefore establishes the link between what has already been studied and what the current research explores; and identifies current gaps in knowledge that this research seeks to fill.

## 2.1. Greenhouse gas emission reduction targets and goals

Empirical evidence regarding the depletion of the world‘s fossil fuel reserves due to increased energy consumption and the resultant increase in greenhouse gas (GHG) emissions have motivated the promulgation of a number of international treaties including the Kyoto Protocol. Increase in anthropogenic GHG has caused a rise in global average temperatures and triggered other climatic changes such as rise in sea levels, coastal line erosion, and desertification (IPCC, 2007). These treaties have been passed to help protect the global environment and promote environmental sustainability and it requires both industrialised and developing countries with market economies to reduce GHG emission on a global scale.

In the UK, the Government has demonstrated clear leadership by accepting relatively high burden-sharing responsibilities within the European Union (EU) under the Kyoto Protocol and has been the vanguard of policy development initiatives and diplomatic solutions (DECC, 2009). Based on the report provided by the Royal Commission on Environmental Pollution (RCEP) in 2000, the Government recommended that $CO_2$ emissions of the UK be cut down by 60%, of the then current level, by 2050, and has since increased the target figure to 80%. The transition of the UK to a low carbon economy as outlined in the White Paper: *UK Low Carbon Plan* and underpinned by the 2008 Climate Change Act is expected to be driven by maintaining secure energy supplies, maximising economic opportunities and more importantly cutting emissions from every sector including the decarbonisation of energy intensive sectors of the economy.

The range of approaches briefly described above clearly indicates that, as much as the setting of $CO_2$ emission reduction targets is informed by the scientific research on climate change, it is indisputably, also a political process. Given this notion, it is important to discuss the sources of these emissions and the potentials of meeting the emissions reduction targets, especially as it relates to the building sector, which is the focus of this research.

## 2.2. Global energy consumption and GHG emissions from buildings

An assessment of global emissions sources shows that the building sector is a major consumer of global primary energy supply and consequently a major contributor to global greenhouse gas (GHG) emissions and global environmental burden (Kolokotsa *et al.*, 2009). For instance, the report by the Intergovernmental Panel on Climate Change (IPCC, 1996) under its Working Group II, estimated that global $CO_2$ emissions from buildings (including residential, commercial, and institutional) are forecasted to grow from 6.9 Gt $CO_2$/year in 1990 to 6.9−10.6 Gt $CO_2$/year in 2010, 6.9−12.1 Gt $CO_2$/year in 2020, and 6.9−19.4 Gt $CO_2$/year in 2050. Similarly, the United Nations Environment Programme, UNEP (2005) broke down the environmental (including carbon) footprint of the building sector as follows: energy use constitute 40% of the total carbon footprint, raw materials use, 30% , solid waste and water use each constitute 25%, and the remaining 12% is attributed to land use. This trend may seem to be rising since Pérez-Lombard *et al.* (2008) also stated that global GHG emissions from buildings continue to rise at an annual rate of 1.5%. These estimations clearly indicate that buildings are key component in dealing with energy and climate problems.

The building sector represents a priority sector by the United Nations in terms of climate change mitigation since it is collectively responsible for 40% of the global energy consumption and one-third of global GHG emissions (UNEP-SBCI, 2008; IEA, 2009; USGBC, 2009). This sector also constitutes the largest emissions source in most developed and developing countries (ibid). For example, in China, the building sector currently accounts for 23% of its total energy use (Liang *et al.,* 2007) and its building footprint is increasing annually by about 2 billion $m^2$, almost double England's entire non-domestic building stock (Zhou *et al.,* 2007). At the same time, a large body of literature (IEA, 2006a; IPCC, 2007; UNEP, 2007), suggests that the building sector is central to low-cost climate change mitigation worldwide. Turmes (2005) suggested that the sector is often regarded as a 'goldmine' of GHG mitigation as it has more potential than any other sector (Figure 2-1) to deliver quick and deep cuts in GHG emissions at zero cost or net savings using innovative technologies and best practice knowledge that are currently available (IPCC, 2007b; UNEP, 2005).

Based on 80 studies carried out by the IPCC across 36 countries, the report suggests that 29% emissions reduction in forecasted baseline emissions by 2020 is realizable at net savings or zero cost, while further improvements could be achieved with relatively low investment levels. The building sector is therefore an integral element in the process of decarbonisation and represents one of the most essential areas where effective policy development is required to guide the move towards a sustainable and low carbon future.

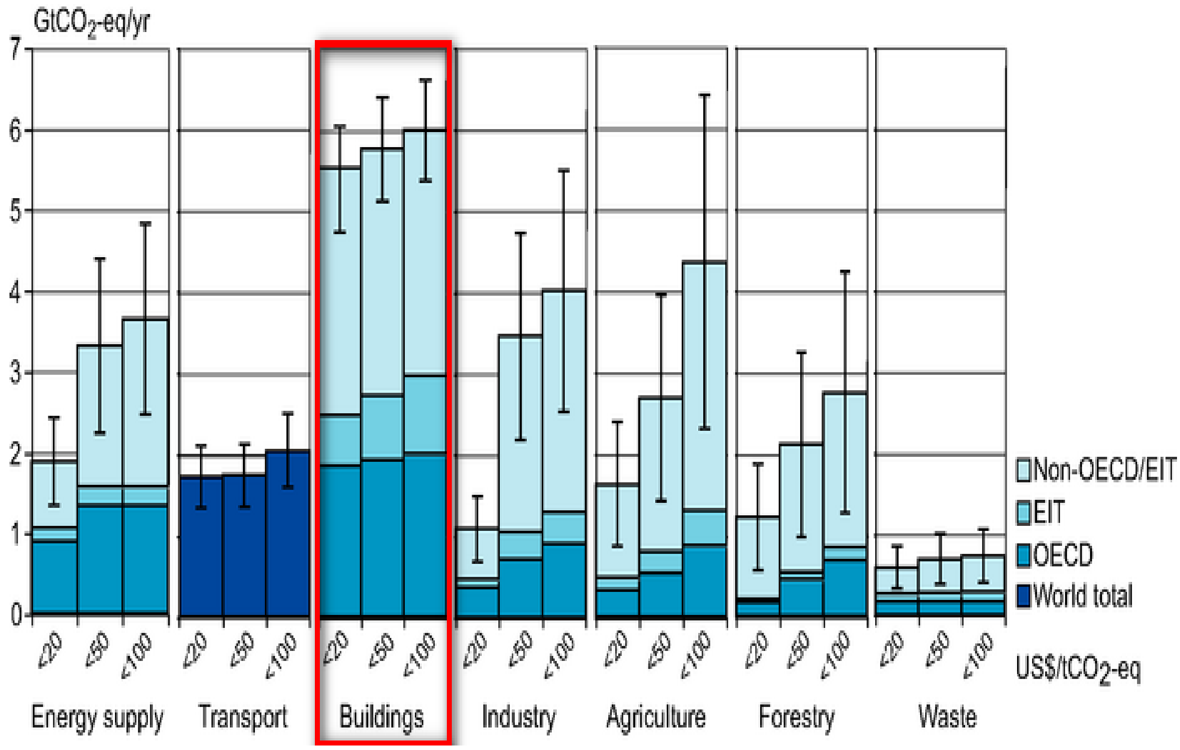



**Figure 2-1: Importance of building sector in emissions reduction (Source: IPCC AR-4)**

## 2.3. The UK energy consumption and GHG emissions from non-domestic buildings

In the UK, the building and construction sector represents an important economic sector. Historically it has contributed approximately 10% of GDP (CIC, 2007), but also accounts for approximately 50% of total emissions (Dowden, 2008), while contributing to acidification, eutrophication, smog and solid waste emissions (EIA, 2010). As such, the sector is one of the key target sectors for energy policy. This sector contributes nearly 47% of the UK's total emissions (17% from non-domestic buildings) – a figure which does not include construction or maintenance (Healey, 2009; Carbon Trust, 2008). In 2006, emissions resulting from buildings and industries were quantified and reported to be 400 $MtCO_2$, representing 70% of the UK's total $CO_2$ emissions (CCC, 2008). Within this, non-domestic buildings (public sector and commercial buildings) were responsible for around 78 $MtCO_2$, residential buildings accounted for 149 $MtCO_2$, and the rest of the industry accounted for the remaining 155 $MtCO_2$ (CCC, 2008).

Annual emissions from existing non-domestic buildings in the UK are estimated to be over 100 $MtCO_2$ (Caleb, 2008). Given this presentation of the UK emissions data, one might question the focus on non-domestic buildings. The answer is rooted in the reasons highlighted in the succeeding paragraphs.

Most research in the built and natural environment sector, for example, Rezaie *et al.* (2013); Kavgic *et al.* (2010) and Reeves *et al.* (2010) has focused on emissions reductions in the domestic sector, with relatively little research in the non-domestic sector. This is particularly so in the UK where the stock of 1.8 million non-domestic buildings is highly varied in size, form and function. Proposing carbon-saving solutions in such a diverse group of buildings is non-trivial (Jenkins *et al.*, 2009). These buildings use around 300TWh of energy a year (equivalent to the entire primary energy supply of Switzerland (IEA, 2006)); predominantly for heating, ventilation and lighting (Figure 2-2).

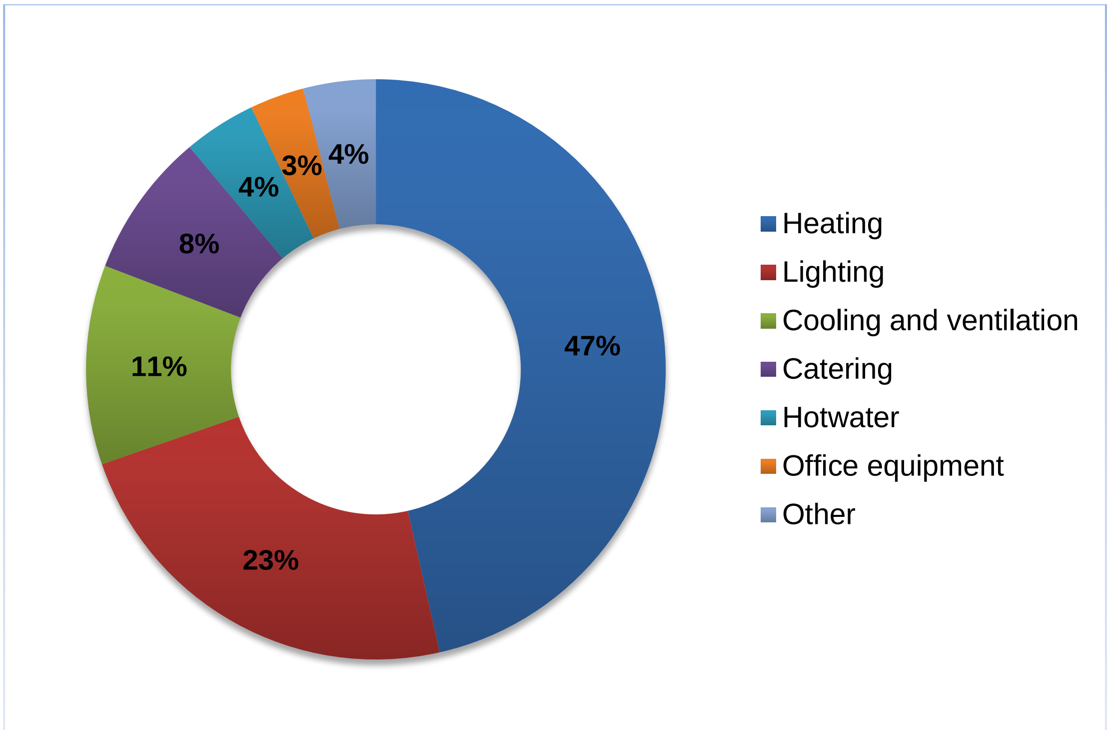



**Figure 2-2: $CO_2$ emissions of non-domestic buildings in the UK based on end use {100% = 106$MtCO_2$} [Source: DECC, 2009]**

Despite these levels of emissions, multiple studies such as Taylor *et al.* (2010), McKinsey (2008), CCC (2008) and IPCC (2007) have all shown that the potential for $CO_2$ emissions reduction from non-domestic buildings is enormous, much of which is cost-effective based on the application of low-cost technologies and solutions which are available today. The Carbon Trust has identified an emissions reduction potential of 37Mt $CO_2$, while the Committee on

Climate Change has identified a potential of about 34Mt $CO_2$ for non-domestic buildings, of which 13.5Mt $CO_2$ could be achieved at a cost of less than £40/t$CO_2$ (Caleb, 2008). Through the reduction of emissions from non-domestic buildings, financial benefits to the tune of £4.5bn (cumulative to 2020), with a possibility of further $CO_2$ reductions of about 70−75% at no net cost could be reached (Carbon Trust, 2008). Despite the huge potential for emissions reductions and the associated financial benefits, $CO_2$ emissions from non-domestic buildings have persisted at a roughly constant rate in the past twenty years as illustrated in Figure 2-3 (Carbon Trust, 2008).

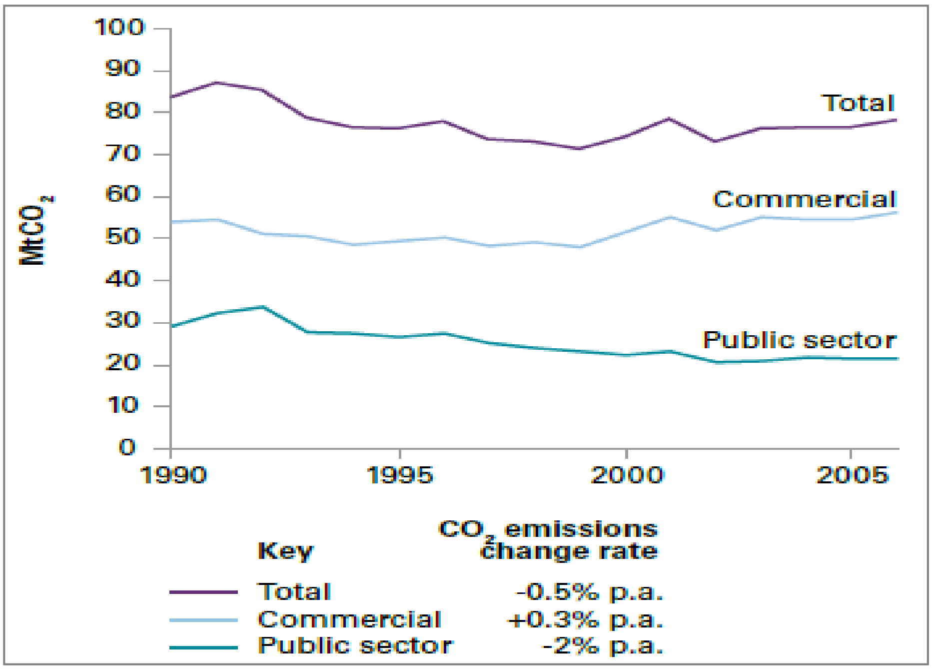



**Figure 2-3: Historical trend of $CO_2$ emissions from non-domestic buildings (public sector and commercial buildings only) between 1990 and 2006 (Source: Carbon Trust, 2008)**

The preceding section has established the relevance of the current study by highlighting the global and national trends in energy use and GHG emissions. It was argued that since there are substantial emissions arising from the building sector, there exists a significant opportunity for emissions reduction. A focus in this research is on analysing the emission reductions that can be realised with the aid of a range of intervention options including renewable energy technologies, energy efficiency measures and inducements to change behaviour. This takes into account both embodied and operational emissions and the cost of each option. To this end, the succeeding sections look at how energy is consumed in buildings and the resulting emissions, from a lifecycle perspective. This is important, as it is vital to understand the flow of energy usage from the activities, processes and products involved in the lifecycle of buildings with the view to meet national and global emissions reduction targets.

## 2.4. Contextual evaluations of energy and emissions in buildings

Lifecycle emissions assessment (LCEA) is a well-established systematic approach used for the identification, quantification and assessment of the associated environmental impacts throughout the lifecycle of an activity, product or process (ISO, 2006a; Elcock, 2007). LCEA considers emissions discharged into the atmosphere due to the use of materials from 'cradle to grave' (i.e. from the extraction of raw material through to manufacturing and processing, transportation, end use, disposal and end of life scenarios). Through the adoption of LCEA approach, environmental impacts can be taken into consideration in design and implementation decisions with the view to identify potential environmental impact hot spots; compare different features of specific products or processes, and to establish baseline of information on an entire system for certain processes based on current or predicted practices (Elcock, 2007; Ally and Pryor, 2007).

The LCEA approach has inspired a great deal of interest and has developed quickly since the 1990s. It is increasingly being used to aid efficient decision during product design and development in several other sectors (Jeswani *et al.*, 2010; Finnveden *et al.*, 2009), and has led to increased standardisation, integration and harmonisation, which has resulted in a wide range of standards with international recognition (Finnveden *et al.*, 2009). Specifically, ISO 14040 describes the general principles while ISO 14044 offers guidance for practitioners (ISO, 2006a; ISO, 2006b). With respect to a building, lifecycle energy assessment entails tracking of all energy inputs in its lifecycle. The system level boundaries of these assessments include the energy use associated with different phases of a product (e.g. building) as discussed in Section 2.4.2 to 2.4.4. Before discussing lifecycle emissions in buildings, it is important to set out some definitions and differentiate between certain key terms as presented in Section 2.4.1.

### 2.4.1. Distinction between energy and carbon

The terms *energy* and *carbon* (both of which are used many times in this thesis) are often interchanged inappropriately in the context of embodied and operational emissions because carbon is closely related to energy. In order to avoid misinterpretation of these terms in this thesis, a clear distinction is established between them. In the case of *carbon*, the proportion of *carbon* emissions associated with the use of *energy* varies, depending on the fuel mix. For instance, *energy* derived from fossil fuel will yield emissions high in *carbon* content, but on-site renewable *energy* will generally yield emissions with low *carbon* content. As such, operational *energy* and *carbon* are approximately proportional for a particular fuel mix and thus their usage is often interchanged informally (Engin and Frances, 2010).

On the other hand, no direct relationship exists between embodied *energy* and embodied *carbon*. This stems from the fact that processes involved in material production and processing can both emit and sequester carbon. This is particularly the case with cement where about half of its embodied *carbon* is emitted due to an inherent chemical process that bears no relationship with *energy* use. This is in contrast to timber where carbon is sequestered during its growth (Smith, 2008). It is therefore important that the distinction between *carbon* and *energy* be maintained when describing the embodied impact of a product as opposed to the operational impacts. A summary of the differences between the two terms is presented in Table 2-1.

**Table 2-1: Distinction between energy and carbon (Engin and Frances, 2010)**

| | **Embodied** | **Operational** |
|---|---|---|
| **Energy** | Energy used for:<br>• The extraction raw material resources<br>• The processing of material<br>• The assemblage of product components<br>• The transportation between each phase<br>• Construction of the product<br>• Repair and maintenance<br>• The final deconstruction and disposal | • The operation of building (through processes like heating/cooling, lighting, ventilation, etc.)<br>• Appliance use |
| **Carbon** | Carbon resulting from:<br>• Embodied energy use, each energy expenditure has its own mix of fuel types<br>• Chemical reactions<br>• Sequestration (carbon absorbed) | Carbon emitted through:<br>• Operational energy use in a whole building based on a mix of fuel types |

### 2.4.2. Definition and interpretation of embodied energy

Energy is required not only for use in a building through activities and processes including heating, cooling, lighting and operating appliances, but also used to create the building elements (bricks, steel, glazing, etc.) and to use them in construction. Buildings and building products are constructed using different types of materials throughout their lifecycle (Dixit *et al,* 2012). The lifecycle stages of buildings consist of the extraction of raw materials, transportation, manufacturing, assemblage, installation, disassembly, dismantling and decomposition. The energy consumed during production (i.e. energy expended in conversion and transport of raw material), may be termed the 'embodied energy', 'virtual energy', 'embedded energy' or 'hidden energy' of the material.

Reddy and Jagadish (2003), define the embodied energy associated with a building as "*the total energy associated with its production – that is for raw materials extraction, processing and manufacturing as required, transportation to site before putting them together as a single entity*". Miller (2001) suggests that the concept of 'embodied energy' is open to several definitions and interpretations and estimated values that are already published are found to be quite ambiguous. For instance, Crowther (1999) puts the definition of embodied energy as "*the total energy needed for the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy that is required to manufacture the materials and components of the buildings*."

Treloar *et al.* (2001) described embodied energy as the "*energy required to provide a product (both directly and indirectly) through all processes upstream*". Similarly, Ramesh *et al.* (2010), defines embodied energy as "*the energy utilised during manufacturing phase of the building or building product".* It is the energy associated with all the materials utilised during construction and installations, and energy expended when the building is under renovation. Energy content of materials refers to the energy used for the extraction of raw materials (e.g. excavation), manufacturing and transportation to the building construction site.

Another interpretation provided by Bousted and Hancock (as cited by Langston and Langston, 2008) is, *"Embodied energy is the energy demanded by the construction plus all the necessary upstream processes for materials such as mining, refining, manufacturing, transportation, erection and the like..."* Also, a broader definition, given by Ding (2004) is *"embodied energy comprises the energy consumed during the extraction and processing of raw materials, transportation of the original raw materials, manufacturing of building materials and components and energy use for various processes during the construction and demolition of the building."* Finally, a comprehensive description put forward by Hammond and Jones (2008), states that "*The embodied energy of a building material can be taken as the total primary energy consumed (carbon released) over its life cycle. This would normally include (at least) extraction, manufacturing and transportation. Ideally, the boundaries would be set from the extraction of raw materials (including fuels) until the end of the products lifetime (including energy from manufacturing, transport, energy to manufacture capital equipment, heating and lighting of factory, maintenance, disposal...etc.), known as 'Cradle-to-Grave'".*

The definitions highlighted above represent differences of opinion regarding the establishment of system boundaries for embodied emissions analysis. Typically, embodied emissions are calculated as a function of emissions per unit of product material, component or system. For instance embodied energy results are expressed in different units including megajoules (MJ) or gigajoules (GJ) per unit mass (kg or tonne) or area ($m^2$).

### 2.4.3. Forms of embodied emissions

Embodied emissions may be categorised into two parts namely initial and recurring embodied emissions. The initial embodied emissions of a building are the emissions incurred for initial construction of the building (Chen *et al.,* 2001; Ramesh *et al.*, 2010). It entails the emissions associated with the extraction of raw materials, their processing, manufacturing, transportation to site, and final construction. Initial embodied emission are further categorised into two parts namely *direct emissions* and *indirect emissions*. Direct emissions are those related to construction activities whether on-site or off-site (in the case of prefabrication), whereas indirect emissions are those related to the *manufacturing* of building components (such as doors and windows) and *processing* of building materials (such as cement), which takes place in factories and processing plants.

Different proportions and forms of materials are used for the construction of a building. In some instances, some of these materials may have a life span that is less than that of the building itself. As a result, they may be due for replacement during the life of the building. In addition to this, buildings require routine maintenance (i.e. replacing parts with shorter life span or replacements carried out for reasons other than wear). The collective emissions associated with such repairs and replacements need to be accounted for across the lifecycle of a building (Ramesh *et al.,* 2010). These are termed *recurring embodied emissions* in buildings and therefore represents the emissions associated with the energy consumed during maintenance, repair, restoration, refurbishment or replacement of materials, components or systems across the lifecycle of the building (Treloar, 1998; Ding, 2004; Chen *et al.,* 2000; Ramesh *et al.,* 2010).

### 2.4.4. Total lifecycle emissions in buildings

Emissions from buildings are classified by life cycle stages; namely embodied, operational, disposal and recycling after end of life use (Cole and Kernan, 1996; Hubermanand *and* Pearlmutter, 2008). Whereas, operational emissions are associated with the energy required to run a building by operating processes such as heating and cooling, lighting and appliances; embodied emissions of a building is the emissions associated with the energy consumed by all the processes associated with its production, i.e. energy used to create the building products, build it and demolish it (Reddy *et al.,* 2003; Yang *et al.*, 2005; Ramesh *et al.*, 2010). Emissions associated with demolitions are those that relates to the energy required for the demolition of the building; the transportation of the waste material to recycling plants and/or landfill sites at the end of the buildings' lifespan (Ramesh *et al*., 2010). The total lifecycle emissions of a building is therefore the sum of its embodied emissions, operational emissions, emissions associated with maintenance and replacement of materials and components as well as emissions accrued from the recycling of the building materials after demolition (Yang *et al*., 2005; Ramesh *et al*., 2010). A pictorial representation of lifecycle emissions in building is shown in Figure 2-4.

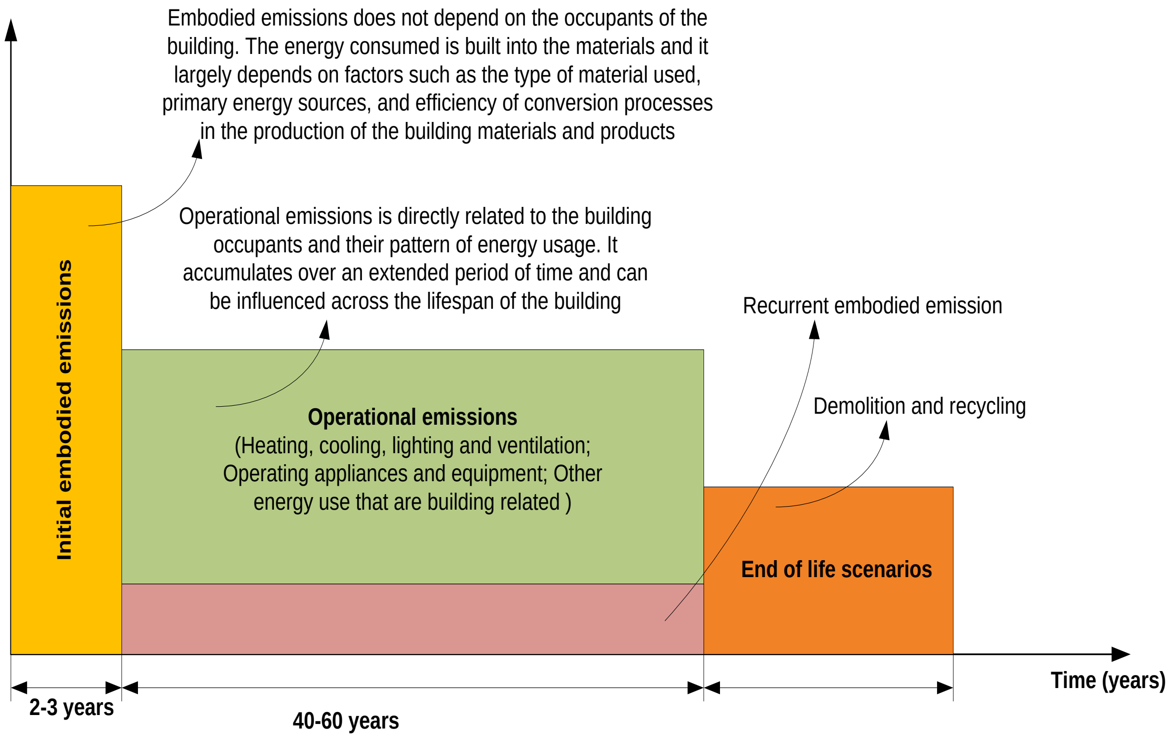



**Figure 2-4: Lifecycle emissions components of a typical building**

## 2.5. Relationship of operational emissions to embodied emissions in buildings

In this section, exploration of the varying proportion of embodied emissions as compared to operational emissions across different buildings is presented. This is done to verify and highlight the increasing proportion of embodied emissions that is one consequence of efforts to decrease operational emissions.

### 2.5.1. Distinction between operational energy and embodied energy

Operational energy includes all activities associated with the use of energy in a building across its lifecycle. It is the energy expended in maintaining the indoor environment of a building within the desired range (Chen *et al.,* 2000). Operational energy is the energy required for the maintenance of day-to-day activities and comfort conditions of buildings through operating processes and activities such as heating, cooling, lighting and appliances, ventilation and air conditioning (Ramesh *et al.,* 2010). Whereas, operational energy consumption depends on the occupants, embodied energy does not depend upon occupancy. Instead, the energy is built into the materials and it largely depends on the material type used, primary sources of energy, and conversion process efficiency of the production of building materials and products (Ramesh *et al.,* 2010).

Operational energy accumulates over time and can be influenced across the effective lifespan of the building (Milne and Reardon, 2005; Dixit *et al.*, 2010). On the other hand, almost all embodied energy is incurred once, at the initial construction phase of a building (the rest being during maintenance, renovation and demolition). Operational energy can be reduced through the use of energy efficient appliances, renewable energy technologies and improved materials for insulation (Ding, 2004; Sartori and Hestnes, 2007; Nassen *et al.,* 2007). Embodied energy can be reduced either through optimisation of building fabric to reduce material use or through intelligent specification and selection of materials with a lower embodied carbon and energy intensity (Dixit *et al.*, 2010; Acquaye, 2010).

### 2.5.2. Previous estimates of embodied emissions in buildings

In the past, some have assumed that the embodied emission associated with a building was small compared to the emissions associated with operating the building across its lifecycle. For instance, the relationship between operational and embodied emissions for a typical office building, as modelled by Cole and Kernan (1996) and depicted in Figure 2-5, demonstrates that embodied emissions are very small compared to the operational emissions. The data plotted in the figure represent average operational energy consumption pattern under a given climatic conditions based on the assumption that the building envelopes are maintained at conventional levels with energy efficient equipment. As indicated, the initial embodied emission over a time frame of 50 years is 4.82 $GJ/m^2$.

On the other hand, the recurring embodied emissions rises from zero when the building was built to completion, to an aggregate value of 6.44 $GJ/m^2$ by the 50th year. The operational emissions eclipse both the initial and recurring embodied emissions at a total figure of 70.28 $GJ/m^2$ representing just more than 85% of the total lifecycle emissions at the expiration of the 50-year time frame. This relationship shows that about 4–9% of 50 years lifecycle energy demand is embodied emissions and this has led some practitioners and researchers to arrive at the conclusion that embodied emission is relatively small and that for a given building, it will be surpassed by the operational energy consumption at the early stage of the life of the building.

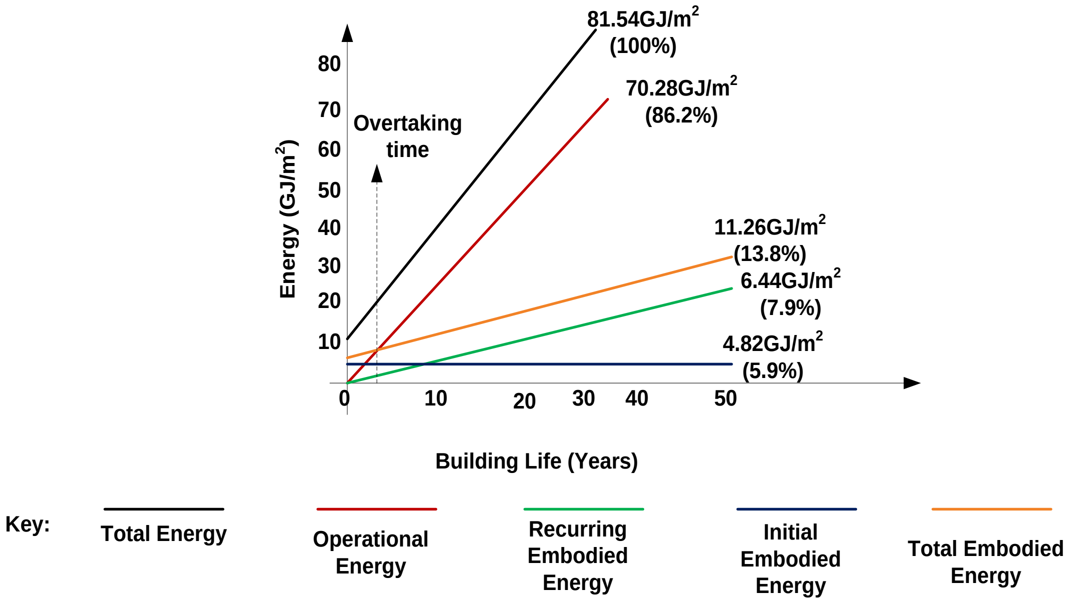



**Figure 2-5: Energy use components during 50-year lifecycle of typical non-domestic building**

For instance, in 1991, the UK Building Research Establishment (BRE) estimated that the operational energy consumption of a standard 3–bed detached house would surpass embodied energy within 2–5 years (SHG, 1999). Supposing the life span of the house before it requires any form of major refurbishment is 60 years (the minimum span as specified for new buildings by the BRE), the operational energy would outstrip the embodied energy by a margin in the range of 12–30. This implies that even with an 'overtaking time' of maximum of 5 years and a life span of 60 years, embodied energy constitutes just roughly 10% of the energy consumption across the lifespan of the building.

Assuming the time taken for operational emissions to overtake embodied emissions were reduced and the lifespan of the building is increased to 100 years, the operational energy consumption would be 40-50 times more important as compared with embodied energy (i.e. about 2–2.5% of total lifecycle energy consumption of the building will be attributed to embodied energy). This analysis will seem to indicate that in order to minimise the consumption of energy across the life span of a building, achieving a reduction in operational energy is far more important and effective as compared to minimising embodied energy. However, this conclusion may not be entirely accurate as recent development and studies, elaborated below have shown.

### 2.5.3. Present day embodied emissions estimates

Traditionally, the inclusion of embodied $CO_2$ emissions in lifecycle emissions assessment of buildings has been considered optional because they were deemed to be of insignificant magnitude when compared with operational $CO_2$ emissions. As such, considerable effort has gone into reducing buildings' operational emissions by improving energy efficiency within the building envelope. Moreover, with the advent of more energy efficient appliances, more effective insulation materials, improvements in building fabric design, reduced air permeability, low energy lighting, heat recovery systems, benign sources of renewable energy, etc., the potential for reducing operational energy consumption has increased (Gustavsson and Joelsson, 2010). This has led to an increase in the relative proportion of $CO_2$ emissions embodied within buildings, so that their contribution to total lifecycle emissions has become more significant. Hence, embodied emissions has become of great interest in sustainable architecture and building design and current emphasis have focused on its inclusion in building energy analysis in order to reduce total lifecycle emissions (Ding, 2004; Nassen *et al.*, 2007; Lee and White, 2008; Smith and Fieldson, 2008; Dixit *et al.,* 2010; Engin and Frances, 2010).

### 2.5.4. Comparison of embodied and operational building emissions in other countries

Contemporary research which details the proportion of embodied versus operational emissions in different buildings has shown that embodied emissions can actually be higher than operational emissions. Many studies have estimated varying proportions of embodied emissions to total lifecycle emissions. The differences are mainly due to the differences in the type of building being assessed, the use of the building, the type of building materials used, construction methods employed, geographic differences, etc. Sartori and Hestnes (2007) reviewed 60 case studies from different countries, and reported that the embodied emissions could be responsible for 2–38% and 9–46% of the total lifecycle emissions for a conventional building and low energy building respectively. Similarly, Ramesh *et al.* (2010) carried out a critical review of analyses of building lifecycle emissions (including both residential and office buildings) from 73 case studies across 13 countries, and concluded that embodied emissions accounted for 10–20%.

Based on the research carried out by the Commonwealth Scientific and Industrial Research Organisation (CSIRO, 2006) it was reported that in Australia, an average dwelling contains about 1000 GJ of energy embodied in the materials used for its construction. This is equivalent to approximately 15 years of normal operational energy consumption. For a dwelling whose lifespan is 100 years, this is more than 10% of the energy consumed across its life span (Milne and Reardon, 2005). The research concludes that as the energy efficiency of buildings improves, the embodied energy associated with them will approach 50% of the lifetime energy consumption. Pullen (2000) also stated that the embodied energy associated with a building constitutes a very significant portion of the lifecycle energy consumption when compared to operational energy consumption. Ding (2004) reported that about 75% of the total energy embodied in buildings accrue from the off-site production of the building and its associated components and this share of energy is increasing at a gradual pace because of increased use of materials whose energy intensity are very high (Sartori and Hestnes, 2007; Langston and Langston, 2008).

Based on the work of Crawford and Treloar (2003), the embodied energy associated with a building in Australia is 20–50 times the annual operational energy required by the building. Webster (2004) estimates a global-warming potential (GWP) of 2–22% attributable to embodied emissions, based on 3 different building types, over a 50 year life, in the US and in Montreal. Athena (2007) estimated 9–12% of 60 year lifecycle energy demand is embodied energy. Thormark (2002) carried out a lifecycle energy analysis of a low energy building in Sweden and reported that for a building with a lifespan of 50 years, embodied energy represents 45% of the total energy required with a 35–40% recycling potential of the embodied energy. BuildCarbonNeutral (2007) stated that equivalent $CO_2$ is 13–18% over a 66 year life span. Engin and Francis (2010) conducted lifecycle energy analysis of buildings based on the implementation of five different intervention options ranging across baseline (i.e. do nothing scenario), energy efficiency, clean power, refurbishment and rebuild. They concluded that embodied carbon is 11–50% of 60 year life-cycle emissions. The lower and upper limit of the range represents embodied carbon for baseline and rebuild respectively.

In his analysis of lifecycle emissions, Thormark (2007) asserts that for a low energy house, embodied emissions could range between 40–60% of total lifecycle emissions. Huberman and Pearlmutter (2008) also reported that the embodied energy associated with buildings that are situated in a climatically responsive area like the Negev desert part of Israel is 60% of the total lifecycle energy across a 50 year life span. With respect to hot region, Plank (2008) concluded that embodied emissions represent approximately 10% of the total lifecycle emissions. Nebel *et al.* (2006) also agree with this notion when they concluded that the amount of embodied emissions in total lifecycle emissions of buildings depends on geographic location and the characteristics of the climate at a given location. In hot regions, embodied emissions represent a relatively low percentage of total lifecycle emissions; however, this may not be the case for cold region due to the relatively lower operational emissions associated with the latter. In the case of conventional buildings in developing countries, the associated embodied energy can be significantly large compared to the operational energy, as the latter is reasonably low (IPCC, 2007a).

### 2.5.5. Comparison of embodied emissions to operational emissions in UK buildings

In the UK, Lee and White (2008) reported that embodied energy is 3–35% of 100 year lifecycle energy demand, where the lower and upper limit of the range represents embodied carbon for baseline and retrofit respectively. Eaton and Amato (2005) found a much larger percentage of the total carbon emissions attributable to what the materials embodied. They reported that embodied carbon is 37–43% of 60 year lifecycle carbon emissions. Smith and Fieldson (2008), estimate that up to 80% of the life-cycle carbon emissions are embodied carbon. For a one-storey non-domestic building in the UK, Yohanis and Norton (2002) reported that the embodied energy initially incurred (i.e. excluding the recurrent and end-of-life contributions) by an office building could be as high as 67% of the operational energy consumption across a 25 year time scale. Hamilton-MacLaren *et al.*, (2009) reported that less than one-fifth of the whole-life emissions in buildings can be attributed to embodied emissions. He further stated that, as energy efficiency for new buildings improves towards attaining the zero carbon targets in 2016 (2019 for non-domestic buildings), with a corresponding increase in building refurbishment rates, embodied emissions will assume an increasing proportion, attaining 100% of the lifetime energy use and emissions.

A recent energy assessment of the British Land's Commercial City Office building reported a carbon footprint of 197,000 $tCO_2e$ over a 60-year lifecycle, which is equivalent to 98 years' worth of the building's operational energy consumption (CIBSE, 2010). The split between embodied and operational carbon is 42:58 (CIBSE, 2010). But according to Battle (2010), if the grid were decarbonized from 0.5 $kgCO_2e/kWh$ in 2010 to 0.1 $kgCO_2e/kWh$ in 2030 and 0.2 $kgCO_2e/kWh$ in 2050 (as recommended by the Committee on Climate Change, 2008), the split between embodied and operational carbon would change to 68:32. This increase in embodied carbon content from 42% to 68% suggests that in the future, building developers may need to place more importance on their choice of building material. Figure 2-6 summarises the most frequently cited research comparing embodied emissions and operational emissions over the total lifecycle of buildings.

| Country | Author | Relationship between embodied and operational emissions in different buildings |
|---|---|---|
| UK | Lee & White (2008) | Embodied energy is **3-35%** of 100 year life-cycle energy demand |
| | Yohanis & Norton(2002) | Embodied energy is **67%**of operational energy over a 25year period |
| | Eaton & Amaton (2005) | Embodied carbon is **37-43%**of 60 year life-cycle carbon |
| | Smith & Fieldson (2008) | Up to **80%** of life-cycle carbon emission is embodied carbon |
| | CIBSE (2010) | Embodied carbon is **42-68%**of 60 year life-cycle carbon |
| US & Canada | Engin& Francis (2010) | Embodied energy is **11-50%** of 60 year life-cycle carbon |
| | Webster (2004) | Embodied energy is **2-22%**of 50 year life-cycle energy demand |
| | Athena (2007) | Embodied energy is **9-12%**of 60 year life-cycle energy demand |
| | Build Carbon Neutral (2007) | Embodied energy is **13-18%**of 66 year life-cycle energy demand |
| Australia | CSIRO (2006) | Over **10%**of 100 year life-cycle energy demand is embodied carbon |
| Sweden | Thormark (2002) | Embodied emission is **45%** of 50 years life-cycle emissions |
| Israel | Huberman &Pearlmutter (2008) | Embodied emission is **60%** of 50 years life span |

**Key:**

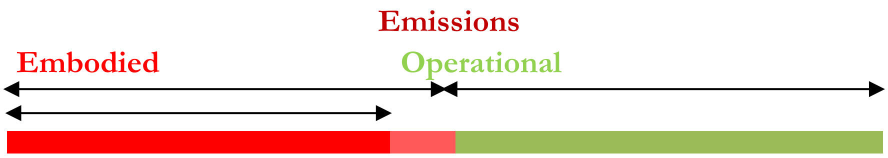



**Figure 2-6: Variation of embodied and operational building emissions**

### 2.5.6. Observations on the trends concerning embodied emissions estimations

From the foregoing analysis, a trend that may be observed is the increasing proportion of embodied energy that is one consequence of efforts to decrease operational energy demand. As such, global efforts to minimise energy consumption in buildings can only be achieved by considering the energy embodied in buildings. The importance of embodied energy when making decisions regarding carbon reduction strategies should therefore be acknowledged and treated with utmost seriousness. This suggests that the performance characteristics of buildings should be calibrated in terms of both operational and embodied emissions by accounting for all energy consumption from cradle-to-grave (i.e. from the extraction of raw materials through to materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling) (Treolar *et al.,* 2001; Langston and Langston, 2008; Acquaye, 2010). This will promote greater mitigation efforts and facilitate informed decision making regarding energy-efficient building design and construction.

Another theme in the literature is the variability in the proportion of embodied emissions across the cited studies and within them. Most of the authors conveyed their results as a range (as indicated by the deep red and light red color in the key in Figure 2-6), which shows the sensitivity of the results for embodied and operational emissions to a host of variables such as the lifespan of the building, the types of materials used and differences in calculation methods. The range also illustrates variations in results which depend on different methods employed in computing embodied energy and carbon emissions related to each of the materials. Langston and Langston (2008) concluded that while measurement of operational emissions is straightforward, estimating embodied emissions is more complex. Furthermore, there is no method available to estimate embodied emissions with the required level of accuracy and consistency that is currently accepted generally (Crowther, 1999; Miller, 2001; Battle, 2010) and because of this, wide variations in estimated results are inevitable.

### 2.5.7. Embodied emissions of energy generation technologies

Necessary modifications and actions are required to improve the overall energy and/or environmental performance of buildings with the view to return them to their original state. These set of actions that are most appropriate for retrofitting buildings to mitigate GHG emissions including low carbon technologies such as renewable energy generation technologies and energy efficiency measures are widely available today. As such, there is an expectation that substantial savings in greenhouse gas (GHG) emissions can be achieved in the refurbishment and operation of buildings through the application of these low carbon technologies. An extensive discussion regarding the performance of low carbon retrofits technologies in terms of their operational emissions savings potentials is provided by Hinnells (2008). Current focus on these technologies to reduce operational energy requirements has led to the neglect of embodied energy. This may result in obscuring the actual or net environmental gain for a given technology.

This is because as benefits from operational emissions reduction are achieved through the implementation of the low carbon technologies, embodied emissions associated with these solutions will become increasingly important in making further progress.

Understanding the actual lifecycle environmental gains is therefore necessary if a holistic effort in achieving sustainable built environment is to be attained. This prompted a review of the embodied emissions associated with some selected energy technologies. Peng *et al.* (2013) provided an exhaustive review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Varun *et al.* (2009) carried out energy, economics and environmental impacts of renewable energy systems and highlight the significance of embodied emissions. Similarly, Monahan and Powell (2011) carried out a comparison of the energy and carbon implications of new systems of energy provision in new build housing in the UK based on three criteria namely energy use, consequential emissions of $CO_2$, and annual running costs. They concluded that ground source heat pumps have the highest annual primary energy demand, $CO_2$ emission and annual running costs over the 20 year period considered. The homes with active solar technologies provided most benefit across all three evaluation criteria (ibid). This suggests that even though there is still significant variation and uncertainty regarding the evaluation of operational performance and environmental impact of low carbon generation technologies, they can offer substantial emission savings compared to fossil fuel alternatives when installed in suitable locations. A summary the most frequently cited research that illustrate the magnitude of embodied emissions associated with some energy technologies is presented in Table 2-2.

**Table 2-2: Embodied emissions associated with some selected low carbon technologies**

| **Authors (year)** | **Location** | **Low carbon technology assessed** | **Methodology** | **Estimated embodied energy or emissions** | **Energy payback period (years)** |
|---|---|---|---|---|---|
| Crawford and Treloar (2004) | Australia | Electric-boosted solar hot water | Input-output based hybrid | 34.47GJ | 5 |
| Crawford and Treloar (2004) | Australia | Gas-boosted solar hot water | Input-output based hybrid | 43.66 GJ | 2.5 |
| Kalogirou (2009) | Cyprus | Thermosiphon solar hot water | Process-based | 6.95 GJ | 1.7 (electricity back-up)<br>2.2 (diesel back-up) |
| Radhi (2010) | United Arab Emirate (UAE) | Façade-integrated 1m² photovoltaic (PV) systems | Process-based | 1450 kWh | 12-13 years depending on orientation. When reduction in operational |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | energy are considered, payback period is 3-3.2 years |
| Bakers and Waber (2004) | Sydney, Australia | 1m² PV systems | Process-based | 1060 kWh | 8-11 years |
| Alsema (2000) | - | Multi-crystalline silicon (mc-Si) PV system | Process-based | 4.2 GJ (module only); 5.4 GJ (module with frame (Al) supports and inverter) | 3.2 years |
| Alsema (2000) | - | Single-crystalline silicon (sc-Si) PV system | Process-based | 5.7 GJ (module only); 6.9 GJ (module with frame (Al) supports and inverter) | Not available |
| Alsema (2000) | - | Thin film | Process-based | 1.2 GJ (module only); 2.4 GJ (module with frame (Al) supports and inverter) | 2.7 years |
| Bankier and Gale (2006) | - | Multi-crystalline silicon (mc-Si) PV system | Process-based | 6.4 GJ (module with frame, supports, inverter and human labour) | 3.8 years |
| Bankier and Gale (2006) | - | Single-crystalline silicon (sc-Si) PV system | Process-based | 7.9 GJ (module with frame, supports, inverter and human labour) | Not available |
| Bankier and Gale (2006) | - | Thin film | Process-based | 3.4 GJ (module with frame, supports, inverter and human labour) | 3.8 years |
| Marimuthu and Kirubakaran (2013) | India | 1.65 MW wind turbine<br><br>25kW solar PV system | <br><br>Process-based | 3,392 MW<br><br>66.96 MW | 1.12 years<br><br>1.6 years |
| Nawaz and Tiwari (2006) | India | 1.2 kWp PV system | Process-based | 6.16 GJ/m² (open field installation, with Balance of System (BOS) at 11% efficiency )<br><br>4.97 GJ/m² | 16.44 years<br><br>13.26 years |

| | | | | | |
|---|---|---|---|---|---|
| | | | | (rooftop installation, with Balance of System (BOS) at 11% efficiency ) | |
| Kato and Murata (1998) | - | PV system (mono-Si module)<br><br>PV system (multi-Si module) | Process-based | 11.67 GJ/m²<br><br>3.38 GJ/m² | Not available |
| Knapp and Jester (2001) | - | PV system (multi-Si module) | Process-based | 8.05 GJ/m² | Not available |
| Laleman *et al.* (2011) | - | PV system (multi-Si module) | Process-based | 3.51 GJ/m² | Not available |
| Genchia *et al.* (2002) | Japan | Ground source heat pump | Process-based | 0.68 Gt $CO_2e$ with 87% of the $CO_2$ emissions resulting from the digging process | 1.7 years |
| Bush *et al.* (2014) | United Kingdom | 2 kWp micro wind turbine @ 10m/s wind speed | Integrated hybrid input-output | 7.7 t $CO_2e$ | 2 years |
| Monahan and Powell (2011) | United Kingdom | Ground source heat pump<br><br>Heating controls | Process-based | 38.6 t $CO_2e$<br><br>35.2 t $CO_2e$ | Not available |
| US DoE (2012) | United State | LED lightings | Process-based | 3.89GJ | Not available |
| Gazis and Harrison (2011) | United Kingdom | 24 kWp micro CHP | Process-based | Embodied energy (1606 GJ) over 15 years<br><br>Carbon emissions (90 $tCO_2e$) over 15 years | 1.32 - 2.32 years<br><br>0.75 - 1.35 years |
| Battisti and Corrado (2005) | - | Multi-Si PV module | Process-based | 5.15 GJ/m² | 2.7 years |
| Alsema and Nieuwlaar (2000) | - | Multi-Si PV module | Process-based | 4.60 GJ/m² | 2.7 years |
| Pacca *et al.* (2007) | - | Multi-Si PV module | Process-based | 4.32 GJ/m² | 3.2 years |

NB: Authors such as Nawaz and Tiwari (2006) reported their estimated embodied emissions value in kWh. The values were converted into joules using 1kWh =3.6MJ

## 2.6. Consideration of embodied emissions in building energy conservation decisions

The preceding section highlighted the increasing importance of embodied emissions in lifecycle emissions assessment of buildings. Given that a sustainable building is one whose construction is based on design for energy and material efficiency, intelligent material selection, deployment of energy efficiency measures and integration of renewable energy systems (RES) and cogeneration technologies; the key questions therefore are "*how much energy has been embodied in assembling the building, how does it compare with operational energy throughout the building's lifecycle and how can both be reduced?*"

Based on the entire carbon footprint of any form of construction project, embodied emissions constitute about 13–18% (UNEP, 2007). More than 40% of the energy generated in the UK is consumed to meet the operational requirement of building users (Carbon Trust, 2008). These statistics explain the justification for initiatives and regulations that focus on increasing energy efficiencies to curtail operational emissions discharge. Such regulations do not take into consideration the entire formation of the building which takes into account other important lifecycle stages including maintenance, dismantling and other building-related embodied emissions (Brummer and Pienaar, 2008).

Part L of the UK Building Regulations reflects the fact that more energy is utilised in the operation of a building than in constructing it (Rawlinson and Weight, 2007). This is also reflected in most policies focusing on the building sector, which have concentrated historically on promotion of operational energy efficiency and the implementation of renewable energy technologies, but have neglected embodied emissions associated with the building. For instance, the 2007 Energy White Paper for UK (DTI, 2007) which sets out the energy policy framework from 2007 to 2020 reported the need to reduce total energy consumption by optimising energy efficiency to reduce operational energy use. However, the White Paper overlooked the significant energy reductions that can be achieved by considering embodied emissions. This is a significant omission, given the acknowledged importance of lifecycle emissions appraisal in evidence-based decision making (Kenny *et al.,* 2010).

## 2.7. Significance of embodied energy in building emissions assessment

Embodied energy analysis has been identified as an important part of lifecycle energy assessment (Crawford, 2005) and is used for the estimation of environmental impacts that are energy-related, such as the $CO_2$ emissions associated with a product such as building. Consideration of embodied emissions in lifecycle emissions analysis of buildings is important for several reasons:

(i) Construction/refurbishment projects are energy-intensive (UNEP 2008; HM Government, 2010). For example, between 5 and 6% of the total $CO_2$ emissions of the UK is attributed to the industry sector responsible for construction materials alone (Rawlinson and Weight, 2007). Regarding new construction and renovation activities in the UK, each year, the embodied emissions from both forms of activities are collectively responsible for about 10% of the total $CO_2$ emissions (DTI, 2007; HM Government, 2010). Within this, roughly half is used in the extraction and manufacturing of raw materials and half is utilised for transportation (DTI, 2007). Similarly, for domestic and non-domestic buildings, the total embodied energy of construction materials added up to about 70 $MtCO_2$ in 2003. This constitutes approximately 13% of the total UK $CO_2$ emissions quantified and reported, including transport of materials (Lazarus, 2005). These statistics show that building designers can in fact influence the carbon footprint associated with buildings if alternative materials with lower embodied emissions exist (Brummer and Pienaar, 2008).

(ii) In building construction/refurbishment projects, savings derived from embodied $CO_2$ emissions can achieve considerable reductions that would take many years to achieve through operational emissions saving alone (Acquaye, 2010; Dixit *et al.,* 2010; Rawlinson and Weight, 2007).

(iii) Operational emissions reductions depend on the performance characteristics of a given building. This performance, however, could be lost through management systems that are sub-optimal or through an accelerated refurbishment cycles (i.e. the rate at which a building is refurbished over its lifespan) (Rawlinson and Weight, 2007). Building design with shorter lives and retrofit/refurbishment cycles may increase lifetime emissions. This impact can only be reflected when embodied emissions are considered in lifecycle building emissions analysis (ibid).

(iv) Embodied emissions appraisals take into consideration the utilisation of low-carbon energy sources (e.g. hydro-electricity) and the use of materials that are recycled such as plasterboards and steel. The embodied energy of a building can therefore be minimised by selection of appropriate materials.

(v) The energy expended to produce complex, lightweight building components is often higher as compared with that used in traditional construction approaches. However, this fact is often neglected when high-performance components are specified for low-carbon buildings (Brummer and Pienaar, 2008). It is only by considering the impact of embodied energy that such a fact can emerge and it can assist in emissions reduction strategies.

### 2.7.1. Labelling

Eco-labelling of products provides useful information about the environmental credentials of products to consumers and it has been employed, within a lifecycle emissions assessment framework, to evaluate the environmental merit of such products (Wan, 2008; Fernandez, 2006). "*An 'Eco-label' is a label which identifies the overall environmental performance of a product or service within a specific/service category based on lifecycle considerations*" (Ball, 2002). Since embodied emissions associated with products (e.g. building materials), and energy reduction levels are the key environmental performance indicators upon which eco-labelling scheme is based (Gelder, 1999; Lenox and Ehrenfeld, 1995), consideration of embodied energy will further enhance eco-labelling standards, which will in turn encourage the use of materials with low embodied energy content. Some progress was made in this regard, where bodies such as the UK Eco-labelling Board have indicated serious concerns regarding the energy embodied in materials used for the construction of building (Chulsukon *et al.,* 2002).

### 2.7.2. Building assessment

Green building appraisal systems including BREEAM, HQE, CASBEE, VERDE, BEPAC, LEED and Green Globe have recognised the importance of embodied emissions (Dixit *et al.*, 2012). This is so as embodied emissions have been included in green building energy assessment framework based on two key performance indicators, namely, material consumption reductions and use of materials that are locally available (Sinou and Kyvelou, 2006). This recognition will facilitate the prioritisation of selection of environmentally-friendly products with low embodied emissions. This could yield greater energy consumption savings with a corresponding decrease in $CO_2$ emissions due to energy expended for material productions (Acquaye, 2010; Dixit *et al,* 2012). For instance, Atkinson (1996) established that the savings in energy consumption derived through environmental preference could be as high as 20 %. On the other hand, Thormark (2006) found a decrease of 17% based on selection of material with lower embodied emissions and an increase of roughly 6% in embodied energy estimates, based on the choice of materials with higher embodied emissions. Therefore, for building professionals involved in decision-making, selecting environmentally friendly materials for design consideration requires identification and specification of materials or products with low embodied energy content (Fernandez, 2006).

## 2.8. Difficulties and challenges in estimating embodied emissions

The concept of embodied energy and $CO_2$ emissions analysis, albeit with significant variations in methodological approach, is used to estimate the energy and the resulting $CO_2$

emissions from materials used in the construction industry (Acquaye, 2010). As shown in the foregoing analysis, it is clear that the inclusion of embodied energy in lifecycle building energy assessment is important. For years, the concept of embodied energy has been an integral part of the debate towards a sustainable future, but despite all the advantages of its inclusion in lifecycle emission analysis of buildings, there is currently little incentive to integrate the calculation of embodied emissions in construction decision making (Hamilton-MacLaren *et al.*, 2009). The reasons are partly due to challenges associated with methodological framework, the focus of regulations on operational energy and carbon, the lack of appropriate legislation and a lack of interest in the impacts of embodied energy by the public and industry stakeholders (Hamilton-MacLaren *et al.*, 2009; Rawlinson and Weight, 2007).

Additionally, the long period of time and the demanding data collection procedures that are required for the quantification of embodied emissions make it difficult. This is particularly so because the tracking of raw material from their original sources requires data that are reliable based on the manufacturing processes and supply chains (Engin and Frances, 2010). Due to the time-consuming requirement and the variation in accuracy of embodied energy calculation results, their adoption in the decision-making process when conducting building energy assessment and performance analysis has to a very large extent been restricted.

### 2.8.1. Data quality

The complexity and uncertainty associated with the estimation of embodied energy and the associated $CO_2$ emissions is made worse by problems with data collection, variations in technology manufacturing processes, as well as the number, diversity and interactions of processing steps (Acquaye, 2010). Additionally, there is a lack of reliable information about embodied energy in products, and this affects both embodied emissions calculations and the decisions based on them (Fernandez, 2006; Pears, 1996).

Variations in calculation results of embodied emissions hinder the process of selecting environmentally friendly materials (Pears, 1996; Davies, 2001). Such comparisons may be invalid if they are based on data with different energy values (Atkinson, 1996; Pullen, 1996). Pacca and Horvath (2002) also noted that uncertainties in embodied energy analysis can also come into play through problems such as economic boundary and methodological constraints, which also affect decision making. Published results of embodied emissions are inconsistent and in many cases the results are not comparable due to differences in calculation procedures, age of data and a host of other factors as detailed in Dixit *et al.,* (2010). Results also vary between countries due to the specific energy mix and transformation processes as well as manufacturing technologies (ibid).

### 2.8.2. Complexity of analysis

Another major challenge in embodied carbon emissions calculations is that many variables (e.g. primary energy sources, manufacturing process, lifespan of products, chemical processes, transport fuel type and the extent of waste or recycling) affect the carbon intensity of products (Engin and Frances, 2010). However, the carbon intensity of some products, for example aluminium, cement and glass, are considerably higher than others, so it might not be absolutely essential to compute the total carbon footprint associated with a project, due to the fact that most individual components will have impacts that are negligible and provide limited opportunities for emission mitigation purposes (Rawlinson and Weight, 2007).

For the case of a building, computation of its embodied emissions based on lifecycle assessment framework is not straightforward as highlighted by Dixit *et al,* (2012); Ramesh *et al.* (2010); Khasreen *et al.* (2009); Nebel and Gifford (2007). This is particularly so, as buildings are highly varied in size, form, and function. They are complex and have a unique nature. Hence, their design and construction often involves bringing together a wide range of manufactured materials and products. Tracking material flows, products and all the processes involved in the construction of a building with a view to evaluating its total lifecycle emission is non-trivial due to non-uniformity of the systems boundary of buildings.

When compared to other products, the life spans of buildings are much greater. As such, substantial effort, in terms collection of data, analysis and interpretation is required in order to track and assess lifecycle emissions. Given that buildings undergo changes including alteration, extension, retrofit and refurbishment, due to their dynamic nature, and are characterised with maintenance and replacements activities, the process of data collection for lifecycle emissions assessment is made even more difficult (Ramesh *et al.,* 2010; Nebel and Gifford, 2007). Unlike other manufactured products, the standardisation of processes involved in the construction of building is limited, making the collection of data a difficult task (Dixit *et al.,* 2012).

Behavioural influences and the complex interplay, in terms of different motivations of key stakeholders, involved in a building's delivery process also further compound the problem (Ramesh *et al.,* 2010; Nebel and Gifford, 2007). The lack of up-to-date data regarding energy and environmental impacts of building materials and components makes the calibration of buildings difficult with respect to their embodied energy content, within a lifecycle assessment framework (Ramesh *et al.,* 2010).

Due to these challenges which stem from diverse and inconsistent datasets as well as complexity of analysis, there is no method available to estimate embodied emissions with the required level of accuracy and consistency that is currently accepted generally (Acquaye, 2010), although a general framework exists in the ISO 14000 series of standards. As a result, wide discrepancies in embodied emissions measurement results are unavoidable, because of various other factors responsible for inconsistency and disparity in embodied energy results which are well detailed in Dixit *et al.* (2010) and Hamilton-MacLaren *et al.* (2009). However, in the pursuit of near zero-carbon buildings, the inclusion of embodied emissions is becoming increasingly important, as operational emissions associated with buildings fall in response to new regulations.

The UK Carbon Plan (HM Government, 2011) has provided new definitions of useful benchmarks in the traded/non-traded price of carbon[1]. These benchmarks reflect the global cost of the damage caused by a tonne of carbon over its lifetime, and have been used to appraise proposals and policy initiatives. Additionally the UK Government has recently established a mandatory carbon reporting scheme for companies. These new schemes indicate that embodied emissions are likely to become one of the standard metrics to be addressed in lifecycle emissions assessment of buildings. Its inclusion in the decision-making process is therefore necessary.

## 2.9. Benefits of considering embodied emissions

If, as suggested above, embodied emissions become a target for emissions reduction, it will become necessary for traditional construction companies to quantify and report the emissions associated with their projects. This will potentially allow the emissions of the sector as a whole to be evaluated and allow a more accurate apportioning of responsibilities for the overall emissions of the country (Hamilton-MacLaren *et al.*, 2009). In addition, the reporting of the embodied carbon footprint of a project will give building engineers the opportunity to present, alongside existing operational emissions measures, a more holistic view of the environmental impact of completed projects (Rawlinson and Weight, 2007). Consideration of embodied emissions will also assist in putting operational emissions savings in context and may facilitate improvement initiatives with a positive emissions reduction profile (ibid).

At a macro-level, the consideration of embodied and operational emissions will add to relevant information and data required to build an energy economy that takes both indirect and direct emissions contributions into consideration (Dixit *et al.,* 2010). This will also facilitate the

[1]A short term traded price of carbon of **£25 in 2020, with a range of £14–£31.** A short term non-traded price of carbon of **£60 per tonne CO2e in 2020, with a range of +/- 50% (i.e. central value of £60, with a range of £30–£90).**

development of a robust (i.e. relatively accurate and complete) and reliable embodied emissions databank. Such a databank would also assist in deriving guidelines that could be developed into standard protocols that will be accepted globally (Dixit *et al.,* 2012). Such improvements in embodied energy data for a carbon index (i.e. a numerical scale based on carbon for comparing different variables with one another) will enable building analysts to be able to group buildings by their embodied energy ratings (Brummer and Pienaar, 2008).

A methodology for grouping buildings with respect to their embodied carbon emissions is illustrated by Acquaye *et al.* (2011). This approach will allow clients to gain an understanding of the carbon impact of their completed projects. It will also allow for specifications, where environmental impacts and ease of implementation are taken into account. This will in turn promote demands to create market transformations in energy-intensive sectors of the supply chain (Rawlinson and Weight, 2007). In addition, accounting for embodied energy will ensure that construction companies use recycled and recyclable construction materials, foster an appreciation and acknowledgement of the impact of strategies such as renewable energy technologies (Brummer and Pienaar, 2008) and create demand for products with low-carbon processes (Rawlinson and Weight, 2007).

Increased awareness of the embodied emissions content of materials used for the construction of buildings may promote not only the fabrication and development of materials with low embodied emission, but also improve the chances of building designers using them with a view to reducing energy consumption and the resulting $CO_2$ emissions (Ding, 2004). Knowledge of the carbon footprint associated with construction/refurbishment projects may also help promote "loose-fit, long-life fit-outs" to be commissioned, reversing the tendency towards shorter refurbishment cycles (Rawlinson and Weight, 2007).

In addition to the benefit to the environment, consideration of embodied emissions at the design stage of construction/refurbishment projects will enable significant contributions to sustainable development of the nation's building stock. As Tiwari (2001) puts it, the results of embodied emissions are vital for national and global strategic plans towards a sustainable future, since the building material production industries accounts for 20% of global energy consumption.

The increasing importance of embodied emissions is discussed in preceding Sections (2.4 to 2.9). Since the embodied emissions estimates of selected building energy retrofit options is of interest in the current work, it is important to review the current approaches taken to the computation of embodied emissions. This is required so as to identify an appropriate approach in the context of the current research. A review of the approaches is detailed in Section 2.10.

## 2.10. Embodied emission analysis framework and methodologies

Broadly speaking, there are three main methodological approaches taken to the computation of embodied emissions, namely: **Process-based, Input/Output-based and Hybrid.** Each of these is briefly discussed in the next sub sections.

### 2.10.1. Process-based

The process-based approach for embodied emissions analysis is one of the most commonly used methods. It utilises process flows to systematically gather data and calculate known environmental inputs and outputs. At an industrial level, process-based analysis is undertaken by measuring the input and output of energy and materials during all the processes and activities involved in the manufacturing of a product (Acquaye, 2010). The estimation process works backward in the upstream of main process by starting with the material as a final product (Figure 2-7), taking into consideration all the potential forms of inputs related to direct energy or the contribution of sequestered energy by each material (ibid).

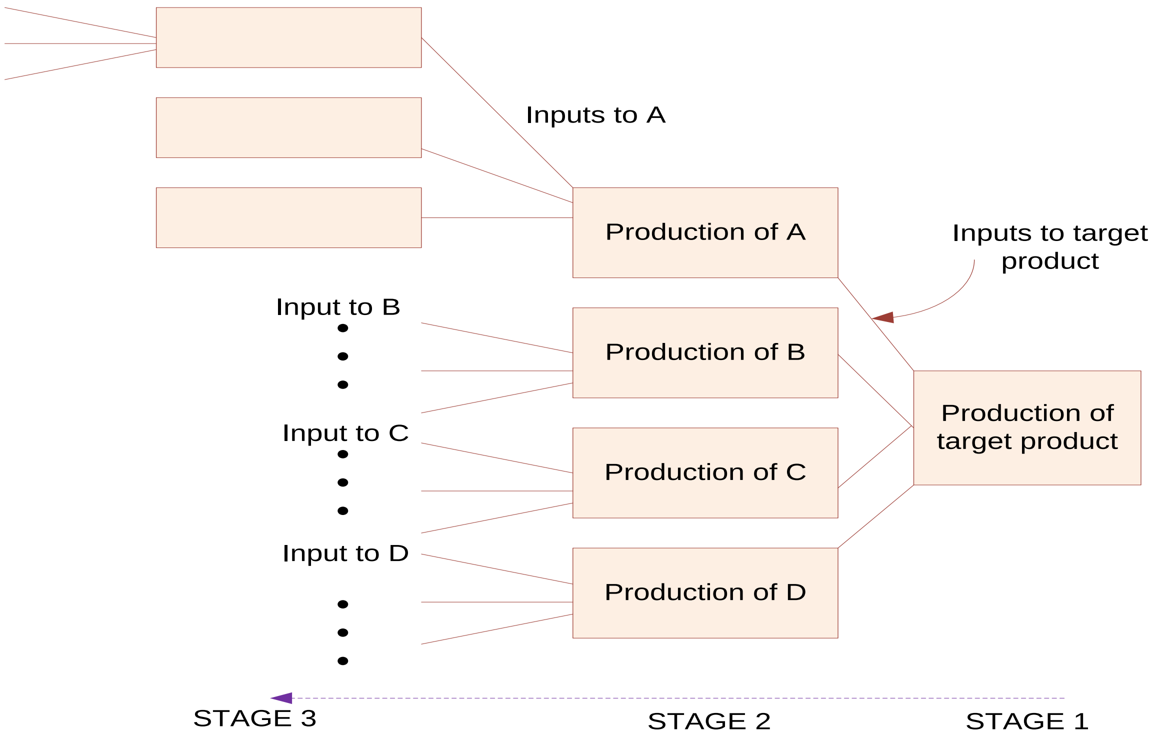



**Figure 2-7: Diagrammatic illustration of the process-based approach**

The total energy consumed during the manufacture of the product, directly and indirectly, per unit output of the product, is described as the process energy intensity, normally expressed as energy per unit mass (e.g. GJ/kg) for that particular product. The embodied energy of a product is therefore evaluated by multiplying the energy intensity by the quantity of materials used in tonnes. Process-based analysis is more suitable for adoption in instances where the flows of a range of goods and services for specific processes, products, or chains of manufacturing are easy to trace and track at a physical level. Essentially, the process-based approach is employed to gain an understanding of the "cradle to grave" environmental impacts associated with specific products.

With the use of specific and basic primary and secondary process data, the process-based approach can be adopted to achieve high-precision results for defined products (Wiedmann, 2010). The approach is limited to the flows of product under consideration, where the energy consumed along the supply chain up to and including the manufacturing of a product is estimated and energy intensity established (Acquaye and Duffy, 2011). In practice, all the many energy inputs involved in the manufacturing processes of a product cannot be estimated in this manner.

Process analysis is generally time consuming to carry out because all the energy inputs that go into the production of a product are numerous and therefore almost impossible to determine with accuracy due to circular relationship and boundary problems (Acquaye, 2010). A system boundary (i.e. "the interface or the border between a product system and the environment or other product system", as explained in ISO 14040) is therefore set, leading to the truncation of some of the energy inputs and resulting in errors of unknown size in embodied emissions estimates (Dixit *et al.*, 2013). The degree of the incompleteness and inaccuracy posed by setting a system boundary varies subject to the type of product or process under consideration and how thorough the study is, but it can be as high as 50% or more (Lenzen *et al.,* 2002). Process analysis also relies on the availability of data from manufacturers, who may not be willing to supply the information unless required by law. An alternative has been suggested in the form of the input-output approach.

### 2.10.2. The input-output based

The input-output (I-O) approach to lifecycle assessment operates through the tracking of all economic transactions between different sectors within an economy and the consumers. It is an economic modelling method which facilitates the understanding of the interactions between economic sectors of a country, the producers and the final consumers (Wiedmann, 2010). A general I-O model records the flows of resources (products and services) from each industrial sector considered as a producer to each of the other sectors considered as consumers (Miller and Blair, 2009).

As an example, the construction industry utilises fabricated metal products, machinery and equipment, electricity and gas etc. to construct houses. This implies that when a house is built, the demands for metal products, electricity and gas, machineries etc. are affected. This shows that outputs from one industry become inputs to another industry. The I–O concept is illustrated in Figure 2-8.

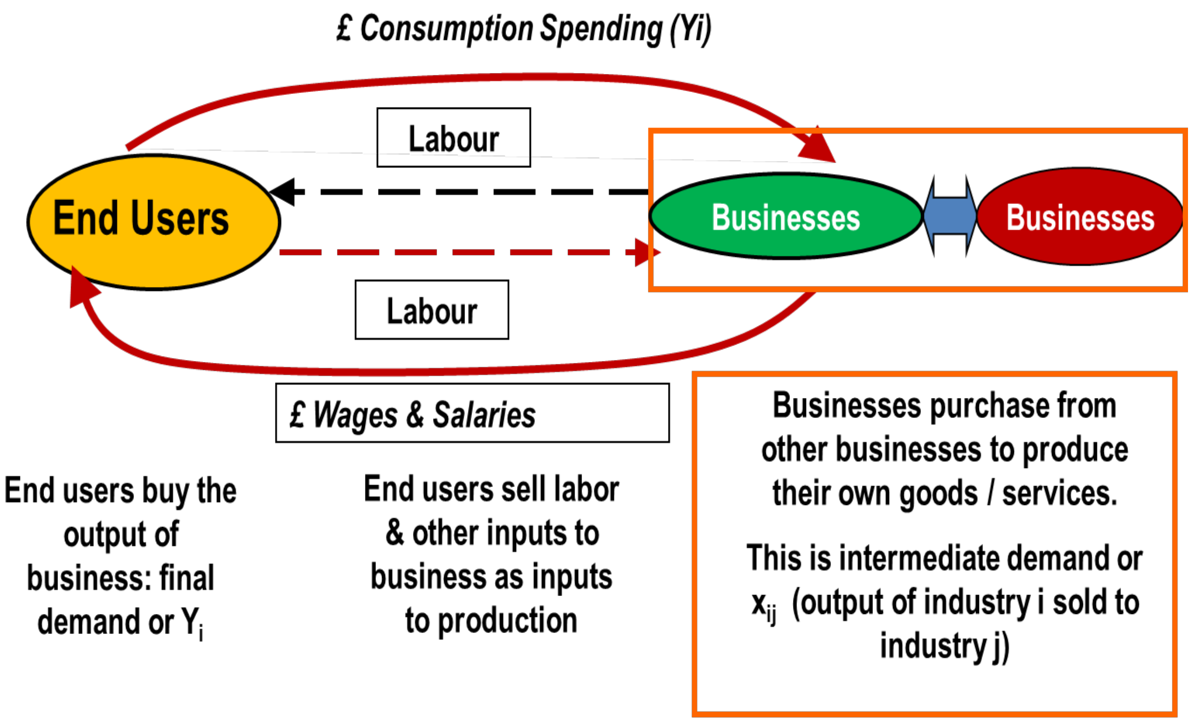



**Figure 2-8: Diagrammatic illustration of the framework for I–O based analysis**

An I-O model is therefore a matrix representation of all economic (production and consumption) activities taking place within a country, region or multi-region. With process-based approach, the flows of material and energy are expressed in physical quantities, but with input-output analysis, flows are expressed in monetary terms. The I-O process utilises cash flow within different sectors of a given industry. The data are organised into an input-output table which is usually compiled by the national government. The table gives a full description of the trading activities happening in a national economy. It shows how products from producers are being sold to final consumers for their use or to contribute to further production in other sectors of an industry (Nielsen and Wiedmann, 2001). Essentially, the I-O table is an economic map which shows how the economy is broken down into various sectors and the inter-relationships between all the economic sectors (Acquaye, 2010). The number of sectors within an industry and their respective definitions vary from region to region.

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 every sector of the economy (row) required to produce total output of each industry sector (column) also expressed in £. The main data used in I-O analysis in this research are the UK input-output table. The general I-O methodology has been well documented in literature (Lenzen *et al.,* 2003; Ten Raa, 2007; Miller and Blair, 2009). The method offers comprehensiveness and completeness because it captures nearly the entire system boundary (Dixit *et al.,* 2010), by taking into account the entire activities along the chain of supply of a product including those accrued by indirect suppliers, allowing the tracking of the complete range of inputs to a process, thus avoids systems boundary issues that characterises the process-based approach (Sousa e Silva, 2001; Acquaye and Duffy, 2010).

The I-O approach has been used in many applications. For instance, the concept has been applied to environmental impact assessment (Lenzen *et al.*, 2003; Mattila, 2010; Yang and Suh, 2011), ecological and industrial systems (Bailey *et al.,* 2008), waste management (Nakamura and Kondo, 2006), energy and embodied energy analysis (Park and Heo*,* 2007; Acquaye and Duffy, 2010), carbon footprint analysis (Wiedmann *et al.,* 2010), material flow analysis (Hawkins *et al.,* 2006), and energy systems (Crawford and Treloar, 2004; Crawford, 2009). The use of the I-O approach in energy and environmental research studies has several advantages, such as being inexpensive to carry out and the fact that the analysis can be completed within a short period of time as well as minimising cut-off error and system boundary incompleteness, some of the major drawbacks of a process-based approach (Acquaye and Duffy, 2010).

By linking environmental information (e.g. GHG emissions) with economic data (e.g. financial transactions) to each sector, an environmental burden (i.e. carbon footprint) can be determined. This characterises the environmental impact of an additional £1 of output from each industry. Similar to tracking cash flow from the time of production to the period of final consumption, an environmentally extended input-output model allows tracking of the flow of environmental impacts along both the supply and production chains. Given that each step in the production process yields an environmental burden, a lifecycle inventory of impacts of production and consumption carbon footprints is produced (Wiedmann, 2010).

Despite the fact that the I-O method has the ability to cover an infinite number of production steps in an elegant manner as described above, the method suffer from a number of well-recognised limitations that are well-documented in literatures, including proportionality assumption, homogeneity assumption, conversion of economic quantities into physical quantities (Dixit *et al.,* 2012; Acquaye and Duffy, 2010; Pullen, 2007; Nielsen and Wiedmann, 2001; Treloar *et al.* 2001; Pullen, 2000).

I-O tables are generated at the national level, and domestic productions of imports are usually assumed during modelling. In open economies, this can lead to considerable errors (Weber and Mathews, 2007). Additionally, in the I-O method, the supply network can be artificially bounded based on the dataset employed for the analysis and does not take other factors such as important business processes and geographic location into consideration. In Chapter four (Sections 4.4.3 and 4.9), the approaches used to overcome some of the identified limitations are discussed. A comparison between process-based and I–O based methods is presented in Table 2-3.

**Table 2-3: A comparison between process and I–O based approaches to lifecycle assessment**

| Method | Advantages | Disadvantages |
|---|---|---|
| **Process** | Provides detailed analysis of related to specific products, processes, or manufacturing chains of goods and services whose flows are easy to track at the physical level | Lack of quality data in most cases |
| | Offers more reliable comparison of products | Truncation error due to subjective system boundary |
| | Allows easier identification of process improvements | Uncertainties in data collected |
| | | Time and cost intensive |
| | | Requires a great deal of data and specific information about the manufacturing of the target product |
| | | |
| **Input-Output** | Comprehensive system boundary defined as whole economy | Errors in converting economic data to physical quantities |
| | Publicly available data | Data is usually aggregated |
| | Results can be reproduced | Uncertainties in data collected |
| | Suitable for aggregated nationwide problems. | Identification of process improvements is difficult |
| | | Changes in price levels over time affects results |
| | | Homogeneity and proportionality assumptions (i.e. Physical flows are assumed proportional to monetary values) |
| | | Change in the structure of the economy or change in technology adopted for producing goods and services can affect results |

### 2.10.3. Hybrid analysis

Combining the accuracy and specificity of process-based approach together with the extended system boundary completeness of the I-O method in what has become collectively known as 'hybrid analysis' can produce results that has the benefits of both approaches in terms detail and comprehensiveness (Suh *et al.,* 2004; Suh and Huppes, 2005; Mattila *et al.,* 2010; Acquaye, 2010; Wiedmann *et al.,* 2011). By integrating the benefits of both process and I-O analysis, fundamental errors and limitations associated with each method can be eliminated, improving accuracy and precisions (ibid). Guinée *et al.* (2001) and all the researchers listed here also recommended the use of the hybrid approach as a procedure for filling data gaps. In the section that follows, a review of embodied emissions of international trade flows is presented

## 2.11. Embodied emissions of international trade flows

Possessing knowledge of how much energy is needed to produce building energy retrofit intervention options and their associated emissions can prove useful in assessing the overall environmental impacts of buildings. This knowledge can in effect assist consumers, businesses and even regulators to make informed choices regarding the environmental consequences of different choices. Countries all over the world depend on one another through imports and exports of manufactured goods and services as well as biophysical resources. As such, many countries, due to mounting pressure to cut down on their overall emissions, are increasingly interested in establishing the extent and the origin of the environmental implications of their imports and dependencies (Peters and Hertwich, 2008).

Consumption of energy results into environmental impacts in two different ways. The first way relates to direct environmental impacts resulting from consumption when consumers directly burn fossil fuels and the second pertains to significant environmental impacts that arise indirectly in the production of consumable goods. When production occurs in the same country as consumption, then it is relatively easy to formulate government policy to regulate environmental impacts. However, increasing competition from imported products has led to a large share of production occurring in a different country to consumption. The production of goods and services is becoming increasingly global with countries depending on each other in terms of export and import. For instance, in 2001, the production of commodities traded internationally was responsible for about 22% of global $CO_2$ emissions (Hertwich and Peter, 2010). As such, regulating the resulting emissions embodied in international trade is becoming critical to stem global emissions levels. Due to increased globalization of production networks, there is increasing interest in the effects of trade on the environment (Copeland and Taylor, 2003; Jayadevappa and Chhatre, 2000)

In the UK, for example, there has been a recent shift in production of a range of building retrofit options to overseas markets, and although this has, to a certain extent, led to reductions in GHG emissions occurring on the UK territory, in reality, the consumption of materials has grown and global GHG emissions has risen as the needs are met through imports For instance Barrett *et al.* (2013) reported that the UK territorial-based emissions indicated a 19% reduction between 1990-2008, whereas, consumption-based emissions show a 20% increase during the same period and is driven by GHG embodied in imported products. This assertion is supported by a consumption-based perspective to GHG reporting (Larsen and Hertwich, 2009; Kanemoto *et al.,* 2013). Given this imbalance in the UK emissions pattern, it is pertinent to understand the energy systems, consumption and emissions patterns of the UK industry especially as it relates to retrofit decisions and highlight implications for policy formulation and development. This can trigger innovations in product development processes and sustainable business models.

Emissions embodied in trade (as a result of importation of products and services from producing countries) have the ability to create imbalance in emissions pattern of countries (Munksgaard and Pedersen, 2001). This exporting of emissions through international trade flows therefore has the ability to nullify the effectiveness of emissions reduction strategies and this can undermine environmental policies of individual countries, especially as it relates to global $CO_2$ emissions (Peters and Hertwich, 2008). This is largely due to the fact that international trade flows has an impact on national $CO_2$ emissions since the production of goods for exportation, with high $CO_2$ emissions intensity, is charged to the national $CO_2$ inventory (Munksgaard and Pedersen, 2001). On the other hand, the embodied emissions associated with the importation of goods are charged to the $CO_2$ accounts in foreign producer countries (ibid).

It follows that open economies facing the challenge of meeting national $CO_2$ emissions reduction targets but saddled with the burden of possessing a large net export of $CO_2$ intensive goods will have to put in additional effort to reduce domestic $CO_2$ emissions (Munksgaard and Pedersen, 2001). The embodiment of $CO_2$ in international trade flows has therefore triggered the debate regarding the sharing of responsibilities between producer and consumer when accounting for $CO_2$ emissions in open economies (i.e. which of the producer or the consumer should take responsibilities for the $CO_2$ emitted) (Rodrigues and Domingos, 2007); Lenzen *et al.,* 2007; Munksgaard and Pedersen, 2001). Particularly, members from countries where their exporting industries have high emissions intensity have argued that the countries that import emissions-intensive goods should bear the responsibility, and the consequent penalties

(Kanemoto *et al.,* 2012). This implies that international trade flows and leakage of $CO_2$ plays an increasingly important function when debating $CO_2$ emissions at a global level.

Getting around the debate above with the view to solving the associated environmental problems requires the use of generally acceptable indicators to assess the severity of the problems and to observe improvement and progress towards resolving the problem (Rodrigues and Domingos, 2007). The definitions of quantities or indicators describing the emissions embodied in international trade flows, and their measurement, must be adequately robust before global policy can be formulated regarding emissions reduction (Kanemoto *et al*, 2012). To this end researchers including Rodrigues and Domingos (2007) and Lenzen *et al.* (2007) among others have introduced an indicator, namely environmental responsibility. This environmental responsibility as defined by Rodrigues and Domingos (2007) is the average between the upstream embodied emissions of final demand at the domestic level (i.e. consumer responsibility) and the downstream embodied emissions of domestic primary inputs (i.e. producer responsibility). Similarly, Lenzen *et al.* (2007) suggested that when an economic flow crosses a sector, there exist a fraction of sector-specific embodied emissions in the upstream that are retained by that sector. This retained upstream emission is termed "producer responsibility". On the other hand, the part of the upstream embodied emissions reaching domestic final demand is considered to be "consumer responsibility".

If the production and consumption of goods and services happened in the same country, it might be relatively straightforward for government to come up with policies that can be used to regulate environmental impacts. However, competition from imported products has significantly increased over the years and this has led to a large share of production happening in a different country to consumption (Hertwich and Peter, 2010). To this end, the regulation of the resulting emissions embodied in international trade flows is becoming critical to curtail global $CO_2$ emissions levels (Wiedmann *et al.,* 2011; Hertwich and Peter, 2010). This in turn has led to an increased interest on the effects of international trade flows on the environment due to an increase in production networks at the global level as demonstrated by Copeland and Taylor (2003), Jayadevappa and Chhatre (2000) among others.

To gain a deeper understanding of the wider impacts of sustainability relating to consumption, in the hopes of promoting and implementing sustainable consumption and production policies, there is the need to track the entire lifecycle impacts of goods and services across international supply chains (Wiedmann *et al.,* 2011). The use of MRIO methodological framework as described in Section 4.4.3 and demonstrated in Section 4.9.5 can be used to achieve this. MRIO databases are a well-established and suitable foundation for analyses of global sustainability issues, addressing a wide range of policy and sustainable business models. This stems from the fact that environmentally extended MRIO analysis has witnessed a significant increase in methodological progress, quality and quantity of underlying data and relevant applications for policy development (Lenzen *et al.,* 2013; Kanemoto *et al.,* 2012; Hoekstra, 2010; Peters and Hertwich, 2009; Tukker *et al.,* 2009; Wiedmann *et al.,* 2007).

The use of EIO model, within an MRIO framework can be used to estimate the environmental loads and emissions implications of consumption associated with some selected building energy retrofit options. This will allow comparison of emissions results associated with products manufactured in the UK and the rest of the world (ROW). The aim is to facilitate better understanding of the UK consumption pattern and identify policy, business and consumer triggers that will lead to an overall emissions reduction while enhancing the UK's roles as a global climate change policy development and initiatives for emissions reduction. As an example, the knowledge of the comparison between products manufactured in the UK and the ROW can be used in policy analysis to ascertain the environmental impacts of international trade flows between different countries with the view to understand the consequences that the relocation of a given industrial sector within the UK to the rest of the world has on emissions. For instance, if the embodied emissions associated with the manufacturing of a given retrofit option is much higher than when manufactured in the UK, then from a production-based perspective to GHG reporting it will appear better if the manufacturing of such an option is carried out in the UK rather than importing them from any other part of the world.

Furthermore, the use of the MRIO framework can allow countries to form bilateral collaborations with other countries they indirectly import emissions from in order to effectively address emissions embodied in trade. A detailed breakdown of world MRIO data can help shed light into such an analysis. This in turn can help in the formulation of policies such as border leveling (i.e. leveling carbon costs at the border, equalizing the associated costs of carbon with international participants) (Barrett *et al.,* 2012) and encourage countries to adopt a consumption-based approach to national emissions accounting rather than a production-based perspective. This has implications for global environmental policies as discussed in Chapter five, Section 5.11.2.

Sections 2.2 through to 2.11 have focused extensively on the sources of emissions in buildings, both operational and embodied emissions, laying the foundations for this research.

Also embedded in the sections above is the computational framework for embodied emissions. Another key aspect of this research is economics and optimisation, which seeks to highlight the financial attractiveness and cost optimality of emissions savings retrofit options. To this end, it is important to review these aspects and is the focus of the next Sections (2.12 to 2.14).

## 2.12. Criteria for energy efficiency and management decision support in buildings

Broadly speaking, the criteria for the management of energy efficiency in a retrofitted building or new building can be categorized as quantitative or qualitative and are broken down into the types as depicted in Figure 2-9.

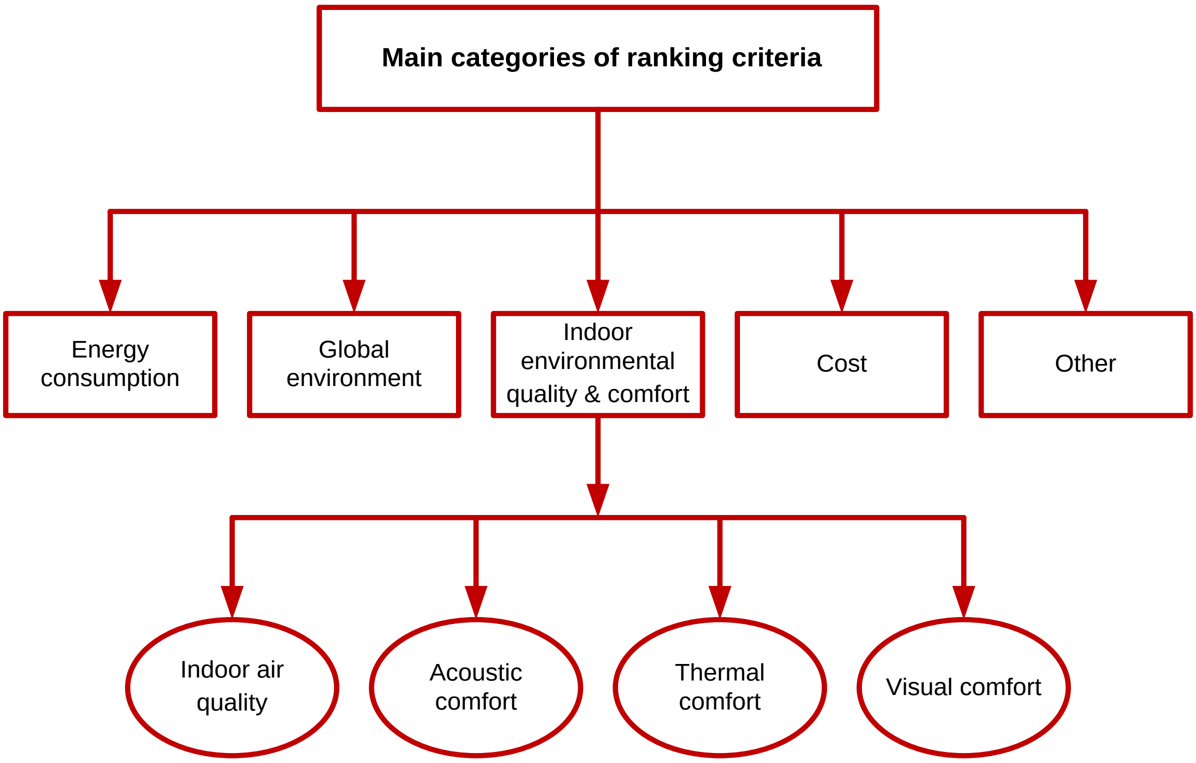



**Figure 2-9: The key criteria for environmental quality and energy efficiency in the building sector (Kolokotsa *et al.,* 2009)**

Given the above criteria, the ones that are related to this research are energy use (primary or delivered), costs, and global environment. Table 2-4 gives a summary of the indices which have been used in relation to the three aforementioned criteria.

**Table 2-4: Summary of the main criteria categories**

| Criteria main category | Indices | Author (s) |
|---|---|---|
| | ●Normalized yearly energy consumption for lighting and heating (kWh/m$^2$) | Rey, 2004; Zhu, 2006 |
| | ●Heating and cooling load for buildings that are conditioned | Bouchlaghem, 2000 |
| | ●Annual electricity use (kWh/m$^2$) | Chen *et al.,* 2006 |
| | ●Embodied energy (Joule/ m$^2$) | Chen *et al.,* 2006 |

| | | |
|---|---|---|
| **Energy use** | ●Energy and time consumption index (ETI) | Chen *et al.,* 2006 |
| | ●Energy savings through retrofitting expressed as: $\left[1 - \frac{\text{Energy}}{\text{Energy baseline}}\right]\%$ | Gholap and Khan, 2007 |
| **Costs** | ● Direct costs and initial investment costs | Rosenfeld and Shohet, 1999 |
| | ● Economic life span | ibid |
| | ● Annual on-going maintenance charges | Rosenfeld and Shohet, 1999; Rey, 2004 |
| | ● Annual on-going charges | Rey, 2004 |
| | ● Net present value (NPV) of the investment in energy | Toke and Taylor, 2007 |
| | ● Internal rate of return (IRR) of the energy investment | Toke and Taylor, 2007 |
| | ● Cost of conserved energy (CCE) | Martinaitis *et al.,* 2004 |
| | ● Life cycle cost (LCC) | Wang *et al.,* 2005 |
| | ●Energy savings by retrofitting expressed by: $\left[1 - \frac{\text{Energy}}{\text{Energy baseline}}\right]\%$ | Gholap and Khan, 2007 |
| | ● Savings to investment ratio (SIR) given by: $\frac{\text{Present value of the total life time energy saving}}{\text{investment cost}}$ | Gorgolewski,1995 |
| | ● Profitability Index (PI) given by: $\frac{\text{Present value of future cash flows}}{\text{investment cost}}$ | Gorgolewski,1995 |
| **Global environment** | ● Annual emissions GWP- global warming potential in ($kgCO_2eq/m^2$) | Rey, 2004 |
| | ● Global warming emissions reduction potential | Alanne, 2004 |
| | ● Lifecycle environmental impact | Wang *et al.,* 2005 |
| | ● Acidification potential in $kgSO_2eq/m^2$ | Rey 2004; Alanne *et al.,* 2007 |
| | ● Water use | Alanne *et al.,* 2007 |

Some of the criteria highlighted above are incompatible and it is practically unfeasible to obtain a global and inclusive solution to satisfy all the listed criteria at the same time (Kolokotsa *et al.*, 2009). As a result, many frameworks for decision support are employed in both the design and operational stages and even refurbishment stage, with the view to attain a solution that will satisfy a range of criteria based on the priorities of the users or owners of buildings. In the context of this research, what is required is a criterion that has a unique attribute which relates cost to $CO_2$ emissions savings potential (i.e. a criterion which shows the relationship between the marginal quantities of $CO_2$ reduced and the related marginal costs per unit of $CO_2$ abated), with a focus on building energy retrofit options. The quest to establish this criterion prompted a thorough review of marginal abatement cost (MAC) concepts where such a criterion is employed, as discussed in the next section.

## 2.13. Marginal abatement cost curve (MACC)

The use of Marginal Abatement Cost (MAC) curves is a standard policy approach for appraising and indicating emissions abatement potential and associated costs (Kesicki and Strachan, 2011). They are also widely employed in the economics of the environment as well as domestic and international policy on climate change for the assessment of costs associated with $CO_2$ emissions reduction (Kesicki, 2013). In combination with a marginal damage function, MACCs are used for the analysis of static and inter-temporal cost-benefits to appraise an optimal level of environmental discharge and to show the prioritisation of certain emissions policies under uncertainty (ibid). Essentially, MACCs are employed to prioritise the $CO_2$ emissions reduction options of an abatement project (i.e. a project to reduce net GHG emissions) based on a set of criteria.

The MAC expressed in cost per tonne of GHG emissions saved, is the additional cost of abating an additional tonne of GHG above what would be achieved in a 'business as usual' context. A MACC is a graphical device that combines the MACs of available abatement projects to facilitate decision making. A MACC therefore shows the connection between the marginal quantity of $CO_2$ reduced and the related marginal costs per unit of $CO_2$ saved through the application of a range of abatement options into the energy system, replacing parts of the baseline emissions (Kesicki and Strachan, 2011; Morthorst, 1994). The cost curve illustrates the abatement options for $CO_2$ emissions reduction by considering a range of technologies and the costs associated to them. The associated costs are computed using conventional investment appraisal techniques such as net present value (NPV) or internal rate of return (IRR).

In MACC, emissions reduction options are ranked according to their cost effectiveness or cost of $CO_2$ abatement (i.e. cost per unit of $CO_2$ saved). The cost-effectiveness for each emissions reduction option is computed using the relation (Toke and Taylor, 2007):

$$\mathrm{C_{eff}}\ (£/\mathrm{tCO_2}) = \frac{\text{Cost of energy saving}(£/\mathrm{kWh})}{\mathrm{CO_2}\ \text{savings made}\ (\mathrm{tCO_2/kWh})} \qquad (2.1)$$

Equation 2.1 can also be written as:

$$\mathrm{C_{eff}} = \frac{\text{Total Investment Cost}\ (£) - \text{NPV of the cost of enery saved}\ (£)}{\mathrm{CO_2}\ \text{saved per year}\ (\mathrm{tCO_2e}) \times \text{Number of years}} \qquad (2.2)$$

Equations 2.1 and 2.2 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 2.2, if the total investment cost is greater than the net present value of the cost of energy saved, it indicates that the intervention option under consideration reduces emissions but incurs a positive cost. Similarly, if the NPV of the financial savings in energy cost exceeds the investment cost, this indicates that the intervention option under consideration reduces emissions and save money.

As an example, assuming that the capital cost of implementing an abatement measure is £35,000 and the NPV of the annual energy savings is £20,000. If the total $CO_2$ abatement resulting from the implementation of the measure is 1,200t $CO_2$, by applying Equation 2.2, we have, for a single year:

$$\text{Cost of } CO_2 \text{ abatement} = \frac{\pounds 35{,}000 - \pounds 20{,}000}{1{,}200tCO_2} = \frac{15000}{1{,}200} = \pounds 12.5/tCO_2$$

The calculation above is repeated for all the measures being considered. Some measures (e.g. options A-D in Figure 2-10) have negative costs (i.e. the NPV of the financial savings in energy cost exceeds the capital cost), so that their implementation produces a net gain/savings over the time frame considered (i.e. the measures reduce emissions and save money). Some other measures, for example, options E-H in Figure 2-10, shows positive costs (as in the example above); which means that they do not pay back their investment even if they do save $CO_2$ (i.e. the measures reduces emissions but incur a positive cost).

Given a basket of emissions-saving 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 (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. To generate a true marginal cost curve for the investment, the blocks are lined up from the one with the lowest marginal abatement cost on the negative portion (i.e. left hand side) of the curve to the largest on the positive portion (i.e. right hand side) of the curve and the optimal result is achieved through the implementation of the measures in an orderly fashion from left to right. The entire breadth of the blocks represents the total GHG emissions reductions realizable. The MACC curve therefore allows different abatement options under consideration to be compared in terms of their cost-effectiveness relative to their $CO_2$ emissions reduction potential. As shown in Figure 2-10, option A is considered the most economically attractive option, indicating lower capital costs and a considerable $CO_2$ reduction with reference to the baseline. This is then followed by the analysis of the MACC results, from which the most interesting mitigation options can then be chosen by the decision and policy makers.

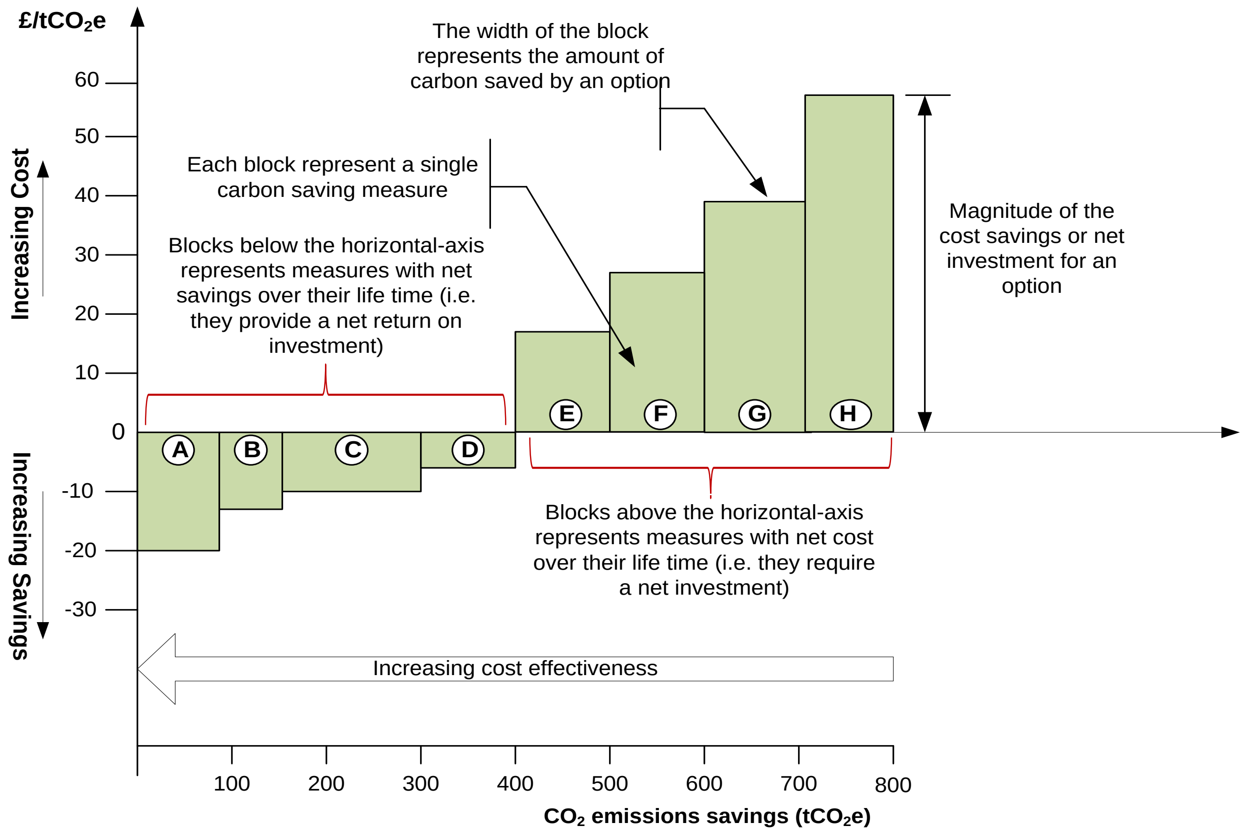



**Figure 2-10: Illustrative MAC curve for $CO_2$ abatement options**

Given an emissions reductions target, the MACC can be used to identify the best abatement strategies to be considered for implementation with the aim of achieving the set target in a cost-effective and efficient manner. As illustrated in Figure 2-10, if the desired $CO_2$ emissions reduction target is say 400 $tCO_2e$, then the optimal pathway to accomplish those reductions would be to carry out the implementation of options A–D. Likewise, if the emissions reduction target were 700 $tCO_2e$, then the implementation options E–G and so on would also be considered. Essentially, by disaggregating an existing emission reduction development with comparison to a baseline, the intervention options (or categories of abatement projects) A to H, exhausts the targeted reduction potential. In doing so, it is possible to identify the most cost-effective reduction option (A) to the least cost-effective one (H). This information might then be employed in the formulation of cost-effective strategies, and consequently in the implementation of these strategies.

MACCs such as the one illustrated in Figure 2-10 are used in many GHG emissions policy briefs. They have been applied to several sectors such as higher education (SQW Energy, 2009), waste management (Hogg *et al.*, 2008), transportation (Spencer and Pittini, 2008), and many more sectors. With respect to buildings, the UK and the US are two particular countries which have adopted MACCs for macro-analysis of their respective building stocks. In particular, the UK Government has adopted the use of MACC for shaping its climate change policies. For example, an extensive use of MACC was demonstrated in the UK Low Carbon Transition Plan (HM Government, 2009) and the carbon valuation approaches by the Department of Energy and Climate Change (DECC, 2009). The Committee on Climate Change which provides autonomous advice to the UK Government and Parliament on GHG emissions reductions strategies have also employed MACCs. Similarly, based on the Global Carbon Finance (GLOCAF) model (CCC, 2008, p.162), the DECC predict the financial and economic flows between various world regions within a MACC framework.

## 2.14. Weaknesses concerning the use of MACC

Despite the wide usage of MACC as a policy tool for climate change mitigation strategies, the method has certain weaknesses. A carefully selected, but not exhaustive, list of recent work on the subject includes: the studies by Kesicki and Strachan (2011) on the methodological shortcomings of MACCs leading to biased decision making; Kesicki and Ekins (2012) on the inability of MACCs to handle interactions and interdependencies within the wider energy system; Fischer and Morgenstern (2005) on the wide range of estimates in MACC results; and Taylor (2012) on the flaw associated with the standard ranking criterion for negative-cost options (i.e. those options that produce a return on investment).

### 2.14.1. Flaw in the ranking criteria for negative-cost measures

Of all the weaknesses identified, the one that has the highest distortion to the 'physical outlook' (i.e. the separation of the MACC regimes into negative and positive regimes) of the concept of MACC is the one associated with the standard metric (i.e. cost per unit of $CO_2$ saved) upon which negative-cost measures are ranked. This is illustrated with an example below using the data in Table 2-5.

**Table 2-5: Comparison of two abatement options illustrating a flaw in mathematical formula for cost-effectiveness**

| Abatement options | Option A | Option B |
|---|---|---|
| Net cost of $CO_2$ emissions saved (£) | -200 | -100 |
| $CO_2$ reduction ($tCO_2$) | 20 | 4 |
| Cost of abatement (£/$tCO_2$) | -10 | -25 |

Supposing the net costs (i.e. the difference between the initial capital and the net present value (NPV) of the cost of energy saved) and the corresponding operational emissions savings over the lifespan of an abatement option A, are -£200 and 20 $tCO_2e$ respectively as shown in Table 2-4. This yields a £/$tCO_2e$ savings of -£10/$tCO_2e$ (i.e. -£200/20$tCO_2e$). Also, supposing option B has a net cost of -£100 and saves 4 $tCO_2e$ across its lifespan, so that £/$tCO_2e$ saved is -£25/$tCO_2e$. From this example, it is clear that option A should ordinarily be the preferred option in that both the economic net benefit and the $CO_2$ emissions savings are higher compared to option B. However, the $CO_2$ reduction criterion (i.e.£/$tCO_2e$) as stated in Equation 2.1 leads to incorrect ranking and consequently a faulty decision, namely the selection of option B. This flaw is quite significant because wrong ranking implies a potential failure to achieve the optimal result in terms of emissions savings.

All measures with a negative cost-effectiveness can be safely ranked before those with a positive cost-effectiveness, but the mathematical flaw prevents a relative ranking from being assigned to these negative-cost measures. For energy efficiency options with economic net benefits, the concept leads to wrong priorities. In particular, a meaningful comparison between heat-based and electricity-based options is not possible, as Taylor (2012) shows. For instance, consider two $CO_2$ abatement options, one heat-based (gas) and the other electricity-based. If both options yield a negative cost of -£300 and save 20kWh of energy/year. For simplicity, let the $CO_2$ emissions factor (cf in kg $CO_2$ /kWh) of gas equal 1 and that of electricity equal 3 (since in actual sense, cf of electricity is thrice that of gas, in the UK, for example). Also assume cost of gas equals cost of electricity for illustration sake. Therefore $CO_2$ savings will be 20kg $CO_2$ /year for the heat-based (gas) option and 60kg $CO_2$ /year for electricity-based option. So, based on the standard ranking criterion ($C_{eff}$), the cost-effectiveness is -£15/ $kgCO_2e$ for gas (i.e. -£300/20) and is -£/5 $kgCO_2e$ (i.e. -£300/60). The ranking criterion prioritises the heat-based option (-£15/ $kgCO_2e$) over the electricity-based option (-£5/$kgCO_2e$) which is a faulty decision based on the inherent flaw in the ranking criteria. The decision is faulty because the only difference between the two cases is the amount of $CO_2$ saved, and the ranking process suggests that the one that saves less $CO_2$ is more cost-effective.

Kesicki and Ekins (2011) provided a list of recommendations to be considered, for MAC curves to realise their potential as decision support tools for policy and decision makers. In effect, the technique of MACC can still be used for shaping climate change mitigation strategies, provided certain critical weaknesses are addressed.

### 2.14.2. Description of the anomaly with ranking criteria, $C_{eff}$ (£/t$CO_2$e)

A comprehensive analysis, including numerical examples, detailed explanation and mathematical proofs showing that no ranking criterion in the form of a figure of merit exists for negative-cost measures is provided by Taylor (2012). A brief analysis, based on the work of Taylor (2012), regarding the ranking anomaly identified is presented in this section. As earlier stated that the standard ranking criterion $\boldsymbol{C_{eff}}$, defined in Equation (2.1) works correctly when a measure returns a positive cost, it is now obvious that there is a mathematical flaw with the criterion when a measure returns a negative net cost. This anomaly is illustrated by Taylor (2012) in the form of a surface plot of standard metric $(\boldsymbol{C_{eff}})$ as a function of net cost $(\boldsymbol{N})$ and potential emissions saving $(\boldsymbol{S})$ as shown in Figure 2-11.

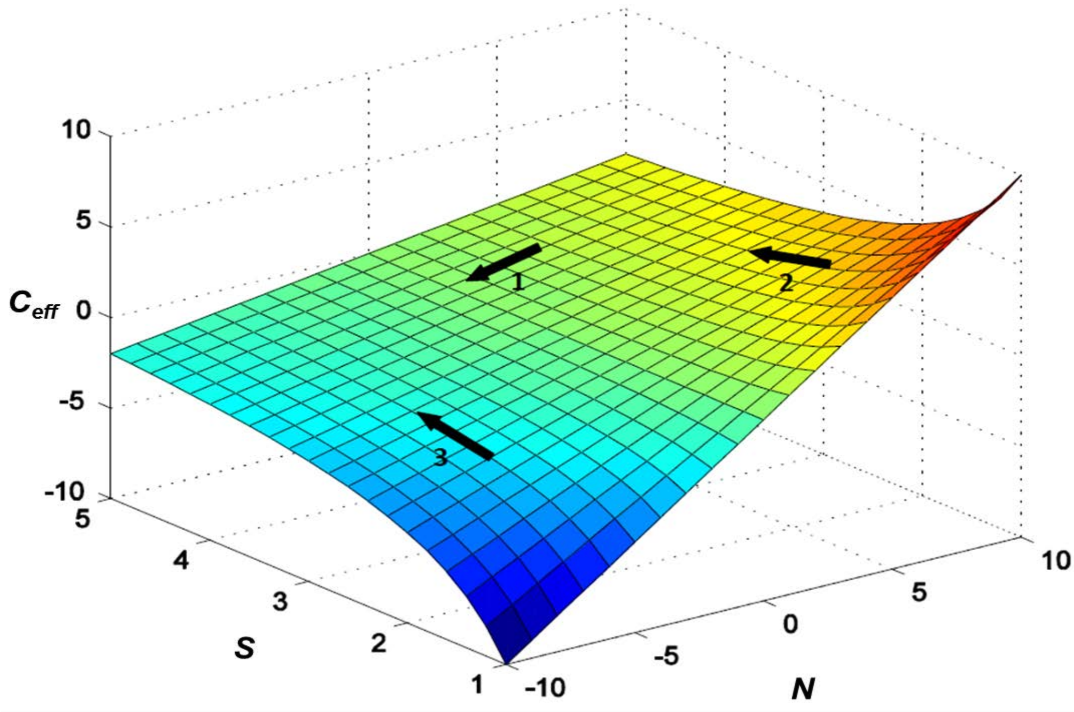



**Figure 2-11: Surface plot of standard metric $C_{eff}$ as a function of net cost N and potential emissions saving S (adapted from Taylor, 2012)**

As shown in Figure 2-11, the alteration in the way $\boldsymbol{C_{eff}}$ reacts to the emissions saving $(\boldsymbol{S})$ when there is a change in sign (i.e. from + to – and vice-versa) of net cost $(\boldsymbol{N})$ is as a result of its functional form. For instance, the function behaves accurately when there is a reduction in net cost $(\boldsymbol{N})$ with emissions savings $(\boldsymbol{S})$ kept constant, producing a decrease in $\boldsymbol{C_{eff}}$ as indicated by the arrow labelled 1. Similarly, when $\boldsymbol{N} > 0$, which implies a positive net cost, the function also exhibits normal behaviour– an increment in the potential emissions saving $(\boldsymbol{S})$ always yields a decrement in $\boldsymbol{C_{eff}}$ as indicated by the arrow labelled 2, facing the downward direction in a similar fashion as arrow 1. It then follows that if the function exhibit a correct behaviour, an increase in $(\boldsymbol{S})$ would also cause a decrease in $\boldsymbol{C_{eff}}$ when $< 0$ , thereby making the arrow labelled 3, points downhill in a similar manner as the arrow labelled 2. But as depicted in Figure 2-11, the arrow labelled 3 is pointing towards an upward direction, which implies that, an increment in the potential emissions saving $(\boldsymbol{S})$ causes an increment and not a decrement, in $\boldsymbol{C_{eff}}$.

As concluded by Taylor (2012), rectifying the mathematical flaw cannot be achieved by introducing minor modifications such as disregarding negative signs in the calculation procedure. The fact is that the function is basically flawed when the option under consideration is one with a negative cost. Taylor (2012) further submitted that the criterion required is such that when used in the negative $\boldsymbol{N}$ domain behaves in a similar way as the arrows labelled 1 and 2 and that this prerequisite for the accurate gradient in the standard ranking criteria is a fundamental requirement that must be satisfied.

### 2.14.3. Interaction and overlaps between measures

Potential emissions saving from individual measures and their respective cost-effectiveness are usually considered in isolation (i.e. stand-alone) within the framework of a MAC curve. This is entirely accurate for the sole aim of ranking the measures. A drawback, however, is that, in reality, measures are implemented in combination with one another and the individual abatement potential of each measures cannot be summed up, since such simple algebraic adding up significantly over-estimates the total emission savings due to ***interactions*** and ***overlaps*** between certain measures. ***Interactions*** involve a scenario whereby the GHG emission savings potential of a measure is reduced due to the fact that another measure has been previously implemented. This implies that interaction usually arise between different types of abatement measures that act on the same end use (e.g. the concurrent application of wall insulation, efficient systems and controls for heating), although it can also occur between different end uses (CCC, 2008).

As an example, emission savings from a more efficient boiler is reduced if wall insulation is carried out first. This is so, because when boiler efficiency is increased, the resulting emissions saving depend on the consumption, implying that a higher consumption translates into a higher saving. But gas consumption is directly proportional to the rate of heat loss, so that the reduction of heat loss through the insulation of the building walls means that the consumption, and therefore the emissions saving will be reduced. As such, the savings attributed to the efficient boiler and to insulation will depend on the order in which they are implemented, although, the effect of the two together is independent of the order. Similarly, improvement in electrical efficiency of appliances means less heat is provided to supplement the work of the boiler. So again the gas consumption is affected by the change, making a boiler efficiency improvement interact with the appliance efficiency measure.

*Overlaps* is a form of interaction that comes into play when "like for like" abatement measures are used to actualise the same result under different circumstances (CCC, 2008). It could happen in parallel as in the case of cavity wall insulation and external insulation and also arise with "like for like" abatement measures with varying efficiency levels (e.g. the replacement of existing window glazing with double or triple glazing). Overlap also arises when a measure cannot be implemented because another measure that is deemed to have a better cost-effectiveness has already been implemented. For instance, if a micro CHP system has been implemented then the subsequent introduction of solar water heating system might not be cost-effective. Therefore, in estimating the GHG emissions saving potential of a range of abatement options, interactions and overlaps between measures must be taken into consideration. Significant double-counting and over estimation of the overall abatement potential derived from an abatement project might result if interactions between measures failed to be taken into account (Kesicki and Strachan, 2011; Morthorst, 1994).

## 2.15. Alternative ranking approach for negative cost measures-Pareto optimality

Despite the anomaly described in Section 2.14.1 and 2.14.2, alternative approaches for ranking negative cost measures exist. One of such methods is the use of Pareto principles within a multi-objective optimisation framework as presented by Taylor (2012). Since the mathematical theorem of Pareto optimisation technique is well-covered in the literature (for instance Pavan and Todeschini, 2008), only a brief description and its application in addressing the ranking anomaly with the negative cost side of MACC is presented, for the sake of brevity.

Pareto optimisation is employed when a solution is required in the midst of conflicting objectives where solutions are chosen such that there are reasonable trade-offs among different objectives (Pavan and Todeschini, 2008). Within the Pareto optimisation scheme, rather than generating a single optimal solution, a myriad of solutions are generated that satisfy the Pareto optimality criterion. Named after Vilfredo Pareto, the principle is such that, if for two alternatives $\boldsymbol{x}$ and $\boldsymbol{y}$ are to be ranked, based on a criterion f, such that $\boldsymbol{f_{xi}} \geq \boldsymbol{f_{yi}}$ for all the conditions $(\boldsymbol{1} \leq \boldsymbol{i} \leq \boldsymbol{p})$, with a minimum of at least one inequality, then it is said that alternative $\boldsymbol{x}$ dominates $\boldsymbol{y}$.

For a given range of alternatives, those that are not dominated by some other alternatives are referred to Pareto Optimal (PO) points. A range of PO points are termed the Pareto frontier (Pavan and Todeschini, 2008). Given a set of plotted points based on certain criteria, the technique of Pareto optimality prioritises the superior PO points over the PO points that are inferior based on a particular criterion. Figure 2-12 illustrates a criterion space with two dimensions.

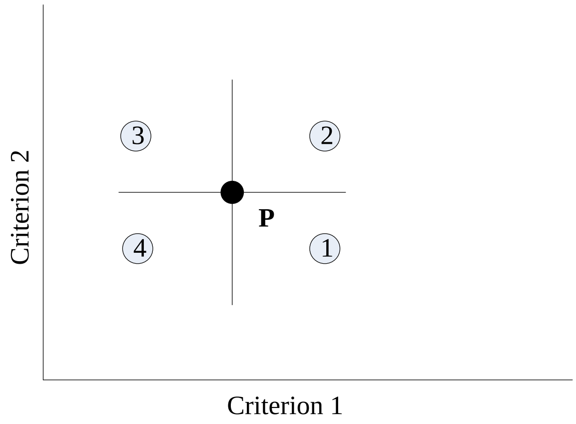



**Figure 2-12: Graphical illustration of the 4 quadrants, based on a two-dimension criterion space with respect to point P (Pavan and Todeschini, 2008)**

As an example, in Figure 2-12, the space surrounding the point P is subdivided into four quadrants. Given two criteria $f_1$ and $f_2$, both of which are to be maximised, from a Pareto optimisation perspective, the points plotted in the second quadrant are superior to point P whereas the points plotted in the fourth quadrant are inferior to point P. A point is said to be Pareto optimal when it is superior to all other points compared to it. It follows that the criterion is such that a solution point P is accepted only if there are no solutions better than P with respect to all the objectives. In the context of ranking negative cost measures, Taylor (2012) proposed plotting emissions reduction measures as points on the x-y plane with x and y given by the criterion values - emissions saving ($tCO_2e$) and net cost savings (£). The points in the Pareto frontier of this initial set are ranked first. These ranked first points are then removed and the points in the Pareto frontier for the remaining set are ranked second. The process is repeated until all the points have been ranked.

It is important to state however that other Pareto-based approaches other than the method of non-dominated ranking described above are possible, but in this thesis the method described will be referred to as "Pareto ranking" for simplicity.

### 2.16. Need for the inclusion of embodied emissions in MACC

In spite of the popularity of MACCs as a standard policy instrument for assessing climate change mitigation economics (Kesicki and Strachan, 2011), their usage tend to only consider operational emissions saving potentials of the options under consideration but neglect the embodied emissions associated with the options. Although, the policy framework within the UK Low Carbon Transition Plan (DECC, 2009) provided useful definitions of benchmarks which shows the global cost of the damage a tonne of carbon causes over its lifetime, there is no policy instrument that integrates embodied emissions with operational emissions for the purpose of climate change mitigation. This omission is possibly due to some of the difficulties of calculating embodied emissions highlighted in Section 2.8.

However, extending the use of MACCs in a way which integrates financial considerations with both embodied and operational emissions into a single model should, in principle, facilitate a more holistic view of the environmental impact of emissions abatement options. This extension to the use of MACCs is one of the key objectives which the current research seeks to address and the methodological approach taken is provided in detail in Section 4.14.

### 2.17. Decision support systems

The term 'decision support system' (DSS) is a context-free expression (De Kock, 2003) which may mean different thing to different people. Turban (1993) as cited by De Kock (2003) asserts that there is no universally accepted model or definition of DSS, because many different theories and approaches have been proposed in this broad field. Because there are numerous working DSS theories, DSS can be defined and classified in many ways. DSSs are "*computer-based tools that can be employed to support decision making that are complex and for problem solving"* (Shim *et al.*, 2002). They are interactive systems that are able to process and produce information and, in some situations they can even promote understanding related to a given application field with a view to obtaining worthwhile assistance in resolving problems that are complex and ill-defined (Georgilakis, 2006). Essentially, DSSs are used to gather, process, analyse and present data from different sources in order to make sound decisions or construct strategies from the analysis. They are intended to provide evidence to aid decision making.

DSSs differ in their scope, the decisions they support and their targeted users (Mallach, 1994). For instance, they have been developed to provide evidence for GHG emissions assessment and the identification of carbon hot-spots in product supply chains (SCEnAT, 2011; CCaLC, 2010). They have also been developed for agricultural production (Jones *et al*, 1998), forest management (Kangas and Kangas, 2005), nuclear emergency (Papamichail and French, 2005), water use policy (Recio *et al.,* 2005), waste water management (Turon *et al.,* 2007), housing evaluation (Natividade-Jesus *et al.*, 2007), medical diagnosis (Fitzgerald *et al.,* 2008), wholesale electricity market (Sueyoshi and Tadiparthi, 2008), pollution control (Vlachokostas *et al.,* 2009), green supply chain network design (Wang *et al.,*2011) and many other purposes.

### 2.17.1. Review of decision support systems in the building sector

With respect to the building sector, which is the focus of this research, there is a complex interplay of policy information and decision pathways between building users, building designers and regulatory authorities. This stems from the fact that policy information from the regulatory authority, for example, can trigger actions that can affect building users and designers regarding emissions reduction targets. As such, the sustainability performance of a building can become a complex problem due to the overlapping nature of the multiple and sometimes competing constraints such as energy consumption, financial costs, environmental impact and the influence of regulation from national authorities. To this end, various decision support tools have been developed to support and advice building stakeholders and property owners regarding retrofit decisions for emissions reduction in buildings (Kumbaroglu and Maslener, 2011).

Some selected, but evidently not complete, examples of current work on the subject include studies by Costa *et al.* (2012), Hong *et al.* (2012), Chidiac *et al.* (2011), Yin and Menzel (2011), Diakaki *et al.* (2010), Loh *et al.* (2010), Juan *et al.* (2010), Doukas *et al.* (2009), Guggemos and Horvath (2006), etc. These studies focused on development of DSSs based on a number of variables and techniques for energy consumption and energy efficiency improvements in buildings. Diakaki *et al.* (2010), for instance, developed a decision model based on a multi-objective optimisation for the improvements of energy efficiency in buildings. The model was constructed to allow for the consideration of a potentially infinite number of alternative options according to a range of criteria. However, the model yielded no optimal solution because of the competition between the set of criteria involved. Chidiac *et al.* (2011) also developed a decision-making tool for screening and selection of cost-effective energy saving retrofit options for typical office buildings in Canada. Their methodology assesses the profitability of an energy-efficient measure but did not account for the environmental merits of the options.

Similarly, Doukas *et al.* (2009) identified the need for intervention and further evaluation of measures that save energy in an existing building using an innovative decision support model, based on the systematic integration of data generated by a Building Energy Management System. Consequently, the energy efficiency of the building is quantified and measures that possess the potential to save energy are proposed, including various options for retrofit. The proposed solutions are then evaluated using investment appraisal techniques but economic parameters such as discount factor are assumed to be constant, ignoring the uncertainty associated with such factors.

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 DSS highlighted above have only focused on economics and operational emissions savings potentials of the retrofit options, with a view to enhancing the decision making of building stakeholders.

Section 2.5 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 retrofit options, emphasising a lifecycle approach to emissions reduction. Currently, 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.

Building stakeholders (e.g. energy managers) cannot easily 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. Gaps therefore exist in the field of DSSs for emissions reduction in buildings. To effectively manage the reduction of lifecycle environmental impacts, it is necessary to link financial cost with both operational and embodied emissions.

As a result of increased global awareness of sustainable design and the strong relationship between global warming and $CO_2$ emissions, the role of new, improved and integrated DSS models to evaluate whole-life economic and net (embodied and operational) emissions savings is crucial, as this can play an important function in the early stages of the design process for retrofit projects. To this end, there is a need for a comprehensive techno-economic evaluation methodology that takes into account the aforementioned crucial factors in the environmental and economic analysis of retrofit options for buildings. Such a methodology, which the current research seeks to develop, provides stakeholders with an efficient and reliable decision process that is informed by both environmental and financial considerations.

## 2.18. Chapter summary

This chapter has established the key theories and concepts which this research explores and has identified gaps in knowledge that the current research seek to address. The key conclusions are as follows.

- It is increasingly important to recognize the significance of embodied emissions when considering GHG emissions reduction options or strategies. The need to standardize the performance characteristics of buildings with respect to both embodied and operational emissions in order to reduce total lifecycle emissions is also highlighted. This suggests that embodied emissions analysis results can serve as a standard indicator of $CO_2$ emissions and could be used as a benchmarking standard for environmental impacts of buildings.
- Underlying limitations of the MACC approach and the points to be aware of, such as effects of macroeconomic assumptions, interdependencies of measures and the mathematical flaw associated with the ranking of cost-effective options were highlighted. The resulting ranking based on MACC sometimes favours abatement options that produce low emissions savings when the measure has a negative cost. It was established that the result is unreliable and it suggests that the use of the concept of cost-effectiveness, quoted in £/t$CO_2$ or equivalent, for ranking negative-cost measures is invalid. An alternative ranking approach is required.
- 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 and resource efficient design and retrofit have resulted in a focus on the environmental merit of retrofit options, with emphasis on a lifecycle approach, gaps therefore exists in the field of DSS for emissions reduction in buildings.

The implications of these conclusions for the research questions devised for the current study are discussed in Chapter 3.

# CHAPTER THREE: RESEARCH METHODOLOGY

## Chapter overview

In Chapter two, it was revealed that a number of studies have been carried out into the development of decision support systems to aid and advise building owners with respect to retrofitting decisions for energy conservation. However, existing research has generally focused on two performance indicators, namely financial costs related to energy savings, and operational emissions savings potential. Researchers have tended to neglect the environmental merit (i.e. embodied emissions) of retrofit options as part of an integrated approach to emissions reduction. It is also observed from the surveyed literature, that the ranking of negative cost measures according to their cost-effectiveness (measured in £/t$CO_2$ or equivalent) within a MACC framework is mathematically flawed. This suggests the need for a different ranking approach. The objective of this chapter therefore is to describe the framework used to address these problems. The chapter presents the methodological framework adopted to meet the research objectives stated in Section 1.4.

## 3.1. Introduction

In order to put the current chapter into perspective, it is important to describe what a piece of research entails. Kumar (2011) defines research as a way of thinking which involves a critical and thorough examination of the several aspects of a field of study, by understanding and establishing guiding principles that forms the basis of a particular procedure, with the overall aim of formulating and testing new theories and knowledge, to further advance a given field of study. Research therefore involves an empirical examination or a systematic investigation to find answers to key questions.

Trochim and Donnelly (2007) suggest that all forms of research are based on assumptions regarding the way the world is perceived and how an understanding of it can be derived. These assumptions are governed by various entities including the research field of study (Trauth, 2001), the phenomenon under investigation (Remenyi *et al.*, 1998) and to some extent, the character and point of view of the individual conducting the research (Fielden, 2003). Undertaking a research study in the hopes of finding answers to a question(s) suggests that the research process is carried out within well-established frameworks in the context of a set of philosophies (Kumar, 2011) adopting steps, methods and techniques that are well articulated and suitable in the context of the overall research philosophy (Knight and Cross, 2012), and have been verified for their validity and reliability (Kumar, 2011).

In the present study, the overall contextual framework of the research project is underpinned by the use of the Contextual Construct Model, developed by Knight and Cross (2012), where the research point of view, research philosophy, research methodology, and research design and validation are considered as an integrated whole as depicted in Figure 3-1. Each block in the figure is explained in the succeeding sections as they relate to the current research.

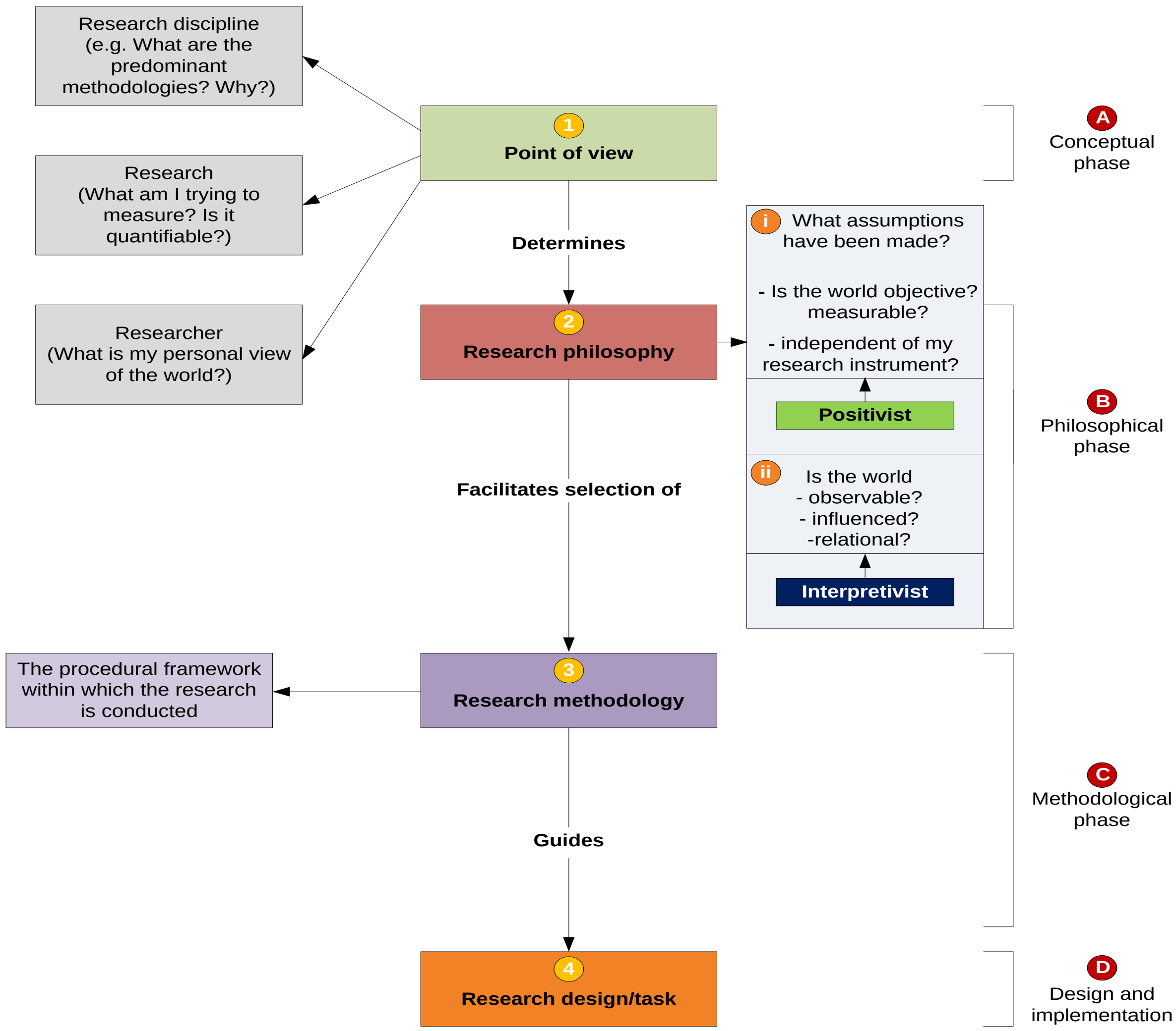



**Figure 3-1: Contextual construct model (adapted from Knight and Cross, 2012)**

## 3.2. Conceptual phase

This is the stage in a research endeavour where the point of view is established. It involves the identification of the exact and particular phenomenon that the researcher intend to explore, and the context with which the exploration will take place (Knight and Cross, 2012). The main drivers of research methods are therefore the research topic and the set of research questions for which answers are sought (Remenyi *et al.*, 1998). Gaining an understanding of what is already known is a prerequisite to gaining an appreciable knowledge of what is new (Trauth, 2001). As such, the next most important step in the conceptual phase is the identification of the research field and context within which the research will be conducted. This then allows extant literature and theories before the current research to be studied (Webster and Watson, 2002) and thereby form a robust theoretical basis regarding the investigation of the phenomenon.

In the context of the present work, the research field area (energy and sustainability in buildings) and the associated discipline were identified. This was done to establish the boundaries of the investigation by developing a schema of the phenomena of the research. Figure 3-2 gives a schematic representation of the various component phenomena identified at the early stage of the current research. The schema was developed to ascertain whether the research phenomenon possesses a diverse range of characteristics or a group of phenomena that have either convergent or divergent features.

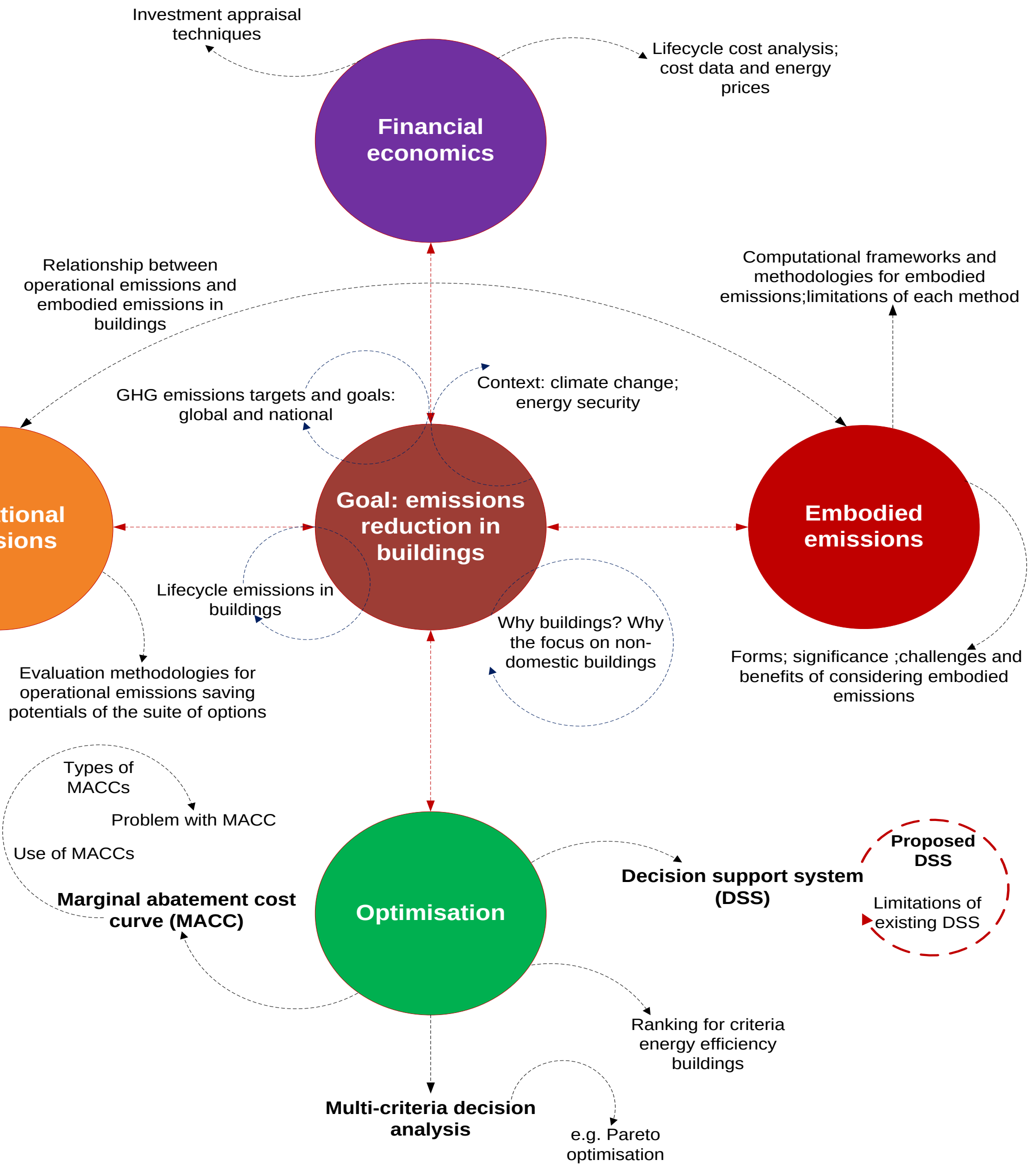



**Figure 3-2: Component phenomena of the current research**

As indicated, the nature of the phenomena and the numerous interactions amongst the individual entities of the entire phenomena were established to be relatively complex, thereby requiring a multi-disciplinary approach to theory search and literature review. To this end, a state-of-the-art literature review, detailed in Chapter two, was conducted using the schema in Figure 3-2 as a guide. The themes garnered while studying the key characteristics of the phenomena under investigation then formed the basis of a sound theoretical framework which underpinned the current research.

The theoretical framework was developed by sorting the information gathered under identified themes and theories, highlighting agreements and disagreements between different authors. This then led to identification of the unanswered questions or gaps in knowledge, verifying what is already known whilst ascertaining past errors and limitations. These identified theories and issues, which are embedded in the ***theoretical framework***, are then adopted to establish a ***conceptual framework***, which then becomes the basis of the current investigation.

Given a developed conceptual framework which establishes and identifies the phenomena being investigated, basic conceptual questions as to whether the phenomenon under consideration can be observed or quantified or defined are then asked. The answers to this set of important questions then form the basis of the problem to be examined in this research, and therefore assist in formulating the actual research questions established for the study. This increasing understanding of the phenomena under investigation then helps in developing other aspects of the research.

### 3.2.1. Research questions

The conceptualisation and articulation of the research questions helps put the research scope into focus (Kari, 2004; Heinstrom, 2003). Knight and Cross (2012) stated that the formulation of the research question assists in:

- Determining the key features of the phenomenon under investigation
- Identifying relevant literature required to fully explore the research problem;
- Identifying the context of the research, as well as areas of synergy across different fields of study;
- Determining a target user-audience (where appropriate);
- Identifying data type and gathering procedures

In the context of the current research, based upon the findings from the review of literature in Chapter two, the formulation of a problem statement (stated in Section 1.2) and the challenges facing the building sector, the research questions that this thesis seek to address emerged and are described in the succeeding paragraphs.

Given the research aim of developing a novel and robust decision-making methodology that will rank and sequence a range of intervention options for reducing greenhouse gas emissions in a non-domestic building, taking into account both operational and embodied emissions and the cost of each option; the **main research question** is therefore:

***How can a set of retrofit intervention options be prioritised for optimal cost effectiveness in reducing greenhouse gas emissions in non-domestic buildings, taking into account operational and embodied emissions as well as cost?***

Judging from the main research question stated above, it seems clear that a set of building energy interventions, including renewable energy technologies, energy efficiency measures and inducements to change behaviour, have to be identified and evaluated for their suitability in the context of the current research. This therefore led to the **first sub-question:**

1. ***What building energy interventions are feasible and capable of achieving significant greenhouse gas emission reductions in non-domestic buildings?***

Given the identification and evaluation of the set of emissions saving options, the challenge to reduce building energy consumption is to find effective strategies to implement these options. It is well known that significant emissions reductions are possible from applying low carbon retrofit interventions to existing buildings. The choice of retrofit intervention options includes evaluation of applicability, reduction in energy consumption, environmental impact and the cost. To develop energy efficiency strategies for existing buildings, there is the need for decision support to evaluate whole-life economic and net emissions gain of each option. Against this backdrop, the **second sub-question** is outlined as**:**

2. ***What decision-making methodology is suitable for the ranking of the identified building energy retrofit intervention options?***

Within the desired decision-making methodology, it is imperative to gain insight into emissions saving retrofitting technologies in the context of operational emissions savings potential, embodied emissions incurred and the associated financial cost. This therefore led to the exploration of the following **sub-research questions**:

i. **What is the effect, in terms of economics, emissions saving potential and environmental merit, of the identified retrofit intervention options?**

ii. **What economic techniques should be used to determine the financial costs and payback periods of the retrofit intervention options?**

iii. **How should embodied emissions be taken into account in an assessment of the performance of building energy retrofit options?**

Once the effects listed above are assessed and evaluated, the next research task is to establish the criteria for assessing the key performance indicators (regarding operational performance and environmental merit) of the options. Hence the next **sub-research question**:

iv. **What criteria should be used for measuring the performance of building energy retrofit intervention options?**

Potential emissions saving from individual measures and their respective cost-effectiveness are usually considered in isolation (i.e. stand-alone) when assessing building energy retrofit options. However, in practice, measures are implemented in combination and the individual emissions saving from measures cannot be added up, since such simple algebraic adding up significantly over-estimates the total GHG emission savings due to interactions and overlaps between certain measures. The next obvious **sub-research question** therefore is:

v. **How do interactions and overlaps arise between measures and how should they be accounted for?**

Given that retrofit intervention options are influenced by factors such as energy prices, discount factors and government incentives such as Feed-in-Tariff (FiT) and Renewable Heat Incentives (RHI), it is important to assess the sensitivity of the cost of each retrofit option to the aforementioned factors. Hence the next **sub-research question:**

vi. **How sensitive are the costs to changes in policy, energy prices and discount factors?**

Since the overall aim is to integrate the three variables of operational emissions, embodied emissions and financial costs into a single decision support model, the next **sub-research question** is:

vii. **How should the measures of both embodied and operational emissions and financial costs be combined into a robust way of ranking retrofit options according to the required criteria?**

Once all the **sub-research questions** have been answered, the final **sub-question** is:

3. *How can an optimal retrofit pathway for reducing greenhouse gas emissions in non-domestic buildings be identified?*

Addressing these questions will enable this research to make an original contribution to knowledge by extending and deepening knowledge of the field of decision support systems for building retrofit advice; and by integrating the three variables of embodied emissions, operational emissions, and cost. In doing so, it is intended that economically and environmentally optimal retrofit pathways towards decarbonisation of the non-domestic building stock will be established and the outcome of this research will provide valuable guidance when planning future retrofit projects.

### 3.3. Research philosophy and paradigms

Given the research questions highlighted in Section 3.2.1, the next challenge is to understand what constitutes a valid set of answers to them, and how the answers are arrived at through scientific investigation. To address these issues, it is important to establish the philosophical stance that underpins the current research. This is vital, as it helps in the determination of which approach best suits either: (i) the phenomena to be investigated; or (ii) the aim of the research as to whether it entails theory building, testing or extension (Knight and Cross, 2012). The philosophical stance adopted influences which methods will yield acceptable evidence in response to the research questions.

Generally speaking, any research approach is guided by two key philosophical phenomena known as **epistemology** and **ontology**. Whereas epistemology refers to the extent to which reality can be known (i.e. the assumptions that are made regarding the nature of the knowledge of humans and how such knowledge is obtained and understood), ontology relates to the nature of reality regardless of human attempts to understand it. Epistemological and ontological stances have typically been categorised by academic researchers into separate research paradigms, which are a set of generally accepted perspectives and basic beliefs about a particular discipline at a given time (Creswell, 2007).

There are two distinct paradigms that form the basis of a research process, one known as the **positivism** and the other **social-constructivism.** At an epistemological level, **positivism** (also known as the systematic, scientific, deductive, or quantitative approach) is a paradigm that is associated with scientific research, entailing a belief "that reality is objective and can be described or measured based on methods that are not dependent on the researcher" (Knight and Cross, 2012). This implies that all knowledge must be such that logical inference can be drawn from a set of basic facts that are observable (Easterbrook *et al.,* 2007). The approach involves a methodology to rigorously test prior hypotheses, typically using quantitative methods. On the other hand, **social-constructivism** (also known as ethnographic, ecological, naturalistic, inductive, qualitative or interpretivist approach) is a common paradigm in social research. It emphasises the subjective nature of reality and sees the construction of meaning as being situation and context specific, and favours qualitative methods (Knight and Cross, 2012; Creswell, 2007). It rejects the idea that scientific knowledge can be isolated from its human context (Easterbrook *et al.,* 2007).

### 3.3.1. Research philosophy and paradigm used in this research

In the context of the current research, a distinct post-positivist approach, known as **pragmatism**, which does not fit easily within the paradigm of positivism or social-constructivism, has been employed as the philosophical viewpoint to guide this study. This paradigm breaks the traditional association between worldview and methodology (Creswell, 2007) and acknowledges the fact that all knowledge is approximate and inadequate, and its value is influenced by the methods with which it was derived (ibid) whilst supporting the notion that knowledge is judged based on its usefulness in solving practical problems (Easterbrook *et al.,* 2007).

Taking a pragmatic stance allows the researcher to employ whatever research method elucidates the research problem. Essentially, pragmatism applies an engineering method to research where practical knowledge is appreciated more than abstract knowledge, and uses any proper method to obtain it (Easterbrook *et al.,* 2007). A pragmatic stance is less dogmatic than both positivist and constructivist approach (ibid) and strongly favours mixed research methods which combine both qualitative and quantitative methods to elucidate on the issue under study (Creswell, 2007). In this way, pragmatism, as a research philosophy, more or less needs a pluralistic approach to its methodology because it embraces both the merits of positivism and the recognised prejudice of social-constructivism.

To this end, a mixed mode strategy that takes a pragmatic stance, known as ***sequential explanatory strategy*** (Easterbrook *et al.,* 2007) is adopted in this research. Based on the strategy, quantitative data are collected and analysed followed by qualitative data collection and analysis. The overall aim is to allow the use of results gathered from qualitative analysis to assist in the explanation and interpretation of findings from the quantitative study, providing a rich tapestry of research approach which may not be feasible if the research had taken an absolute positivist or social-constructivist approach. Figure 3-3 illustrates how the current research took a pragmatic, pluralistic approach to the issue at hand.

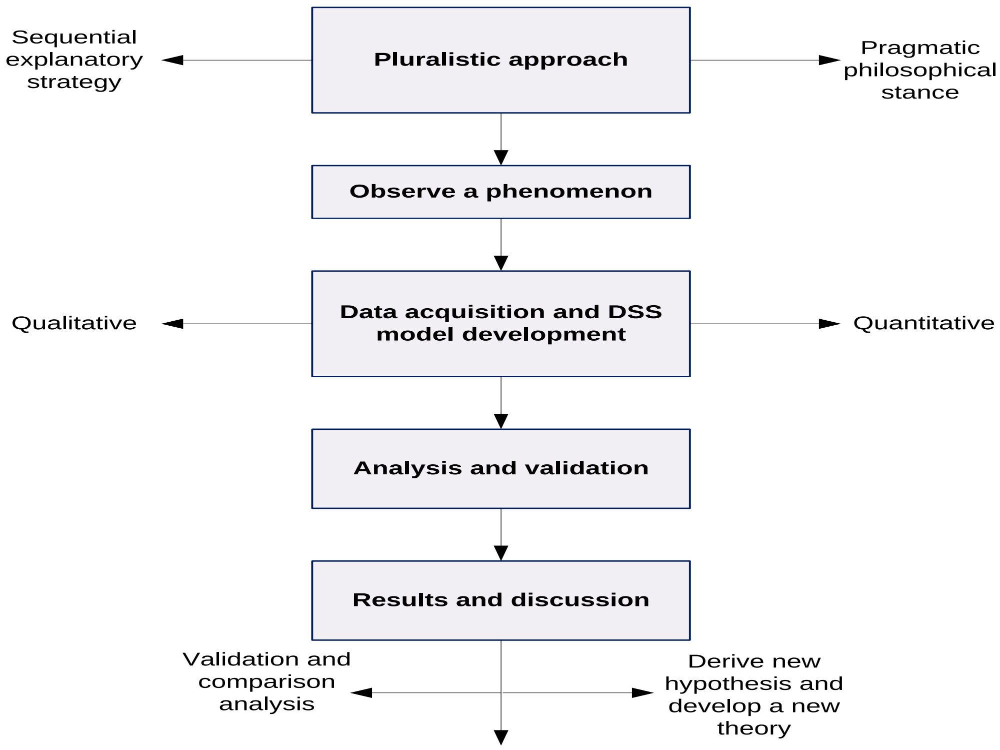



**Figure 3-3: Philosophical stance taken in the current research**

The distinct issues and research questions which the current study seeks to address have led to the methods being employed. Notwithstanding the over-arching pragmatist stance employed, the philosophical assumptions underlying this research can be conveniently explained with reference to the research paradigms highlighted above. The decision support methodology, which entails the development of a quantitative energy model for the evaluation of economically and environmentally optimal retrofit of non-domestic buildings, is informed by an ontology and epistemology that fits with the post-positivist paradigm. This is because the reality of the situation at hand (energy use, operational and embodied emissions, financial cost, etc.) is seen as objective and independent of the researcher. It is therefore possible to gain appreciable knowledge of this situation but restricted by limits in theoretical understanding or lack of supporting data.

The qualitative component of the sequential explanatory strategy explores the views, perceptions, experiences, feelings and beliefs of the potential users (e.g. energy managers, sustainability manager, environmentalist etc.) of the decision support model by conducting interviews to evaluate the DSS model that is created. This is important as it is believed that the respondents (i.e. potential users) are the best judges of whether or not the research findings have been able to reflect their opinions and feelings accurately. However, the reality of this situation is not observer-independent, due to the essentially involved role on the part of the researcher, influencing both views and action of the potential users, making a post-positivist framework not completely appropriate. Instead, the current research was informed by a paradigm that is positioned somewhere between post-positivism and social-constructivism, recognising the views expressed by the potential users and allied professionals as subjective and context-dependent.

### 3.4. Research methodology

The research philosophy described in Section 3.3 enhances the understanding of the overall research and it provides the basis for the selection of appropriate methodologies or strategies within the field of study, by which the phenomena of the current study will be investigated. At a functioning level, a methodology is the framework which provides the step by step procedures within which the research is conducted (Remenyi *et al.*, 1998). It involves the use of specific methods to collect adequate and representative evidence of a problem (Buckley *et al.*, 1976 as cited by Knight and Cross, 2012); develop appropriate ways to analyse and interpret the data collected (Fielden, 2003) and show the validity of any findings (Amaratunga *et al.*, 2002).

In the context of the present thesis, the methodology comprises two approaches. The first approach relates to the quantitative study where key issues of interest such as operational emissions savings, embodied emissions incurred and the financial cost of the retrofit intervention options are quantified through the development of a decision support system. The second approach, which involves a qualitative approach based on interviews with potential users, evaluates the decision support system by examining the attitudes of potential users to the overall output of the tool. The aim of this strategy is to adopt qualitative results with a view to explaining and interpreting the findings from the quantitative energy model, which then allows both technical viability and wider acceptability to be explored, providing an answer to the main research question.

In order to address the gap in literature highlighted in Chapter two, it is necessary to use a procedural framework through which the phenomenon underpinning the current research can be considered. Figure 3-4 provides a summary of the overall research methodological framework taken to achieve the research objectives. As shown, the overall idea is to provide a foundation for the development of a best-value retrofit approach to emissions saving in a non-domestic building. This requires the integration of economic considerations with operational and embodied emissions into a decision support system for the optimal ranking of building energy retrofit options, whilst taking into account the problems and limitations highlighted in Chapter two.

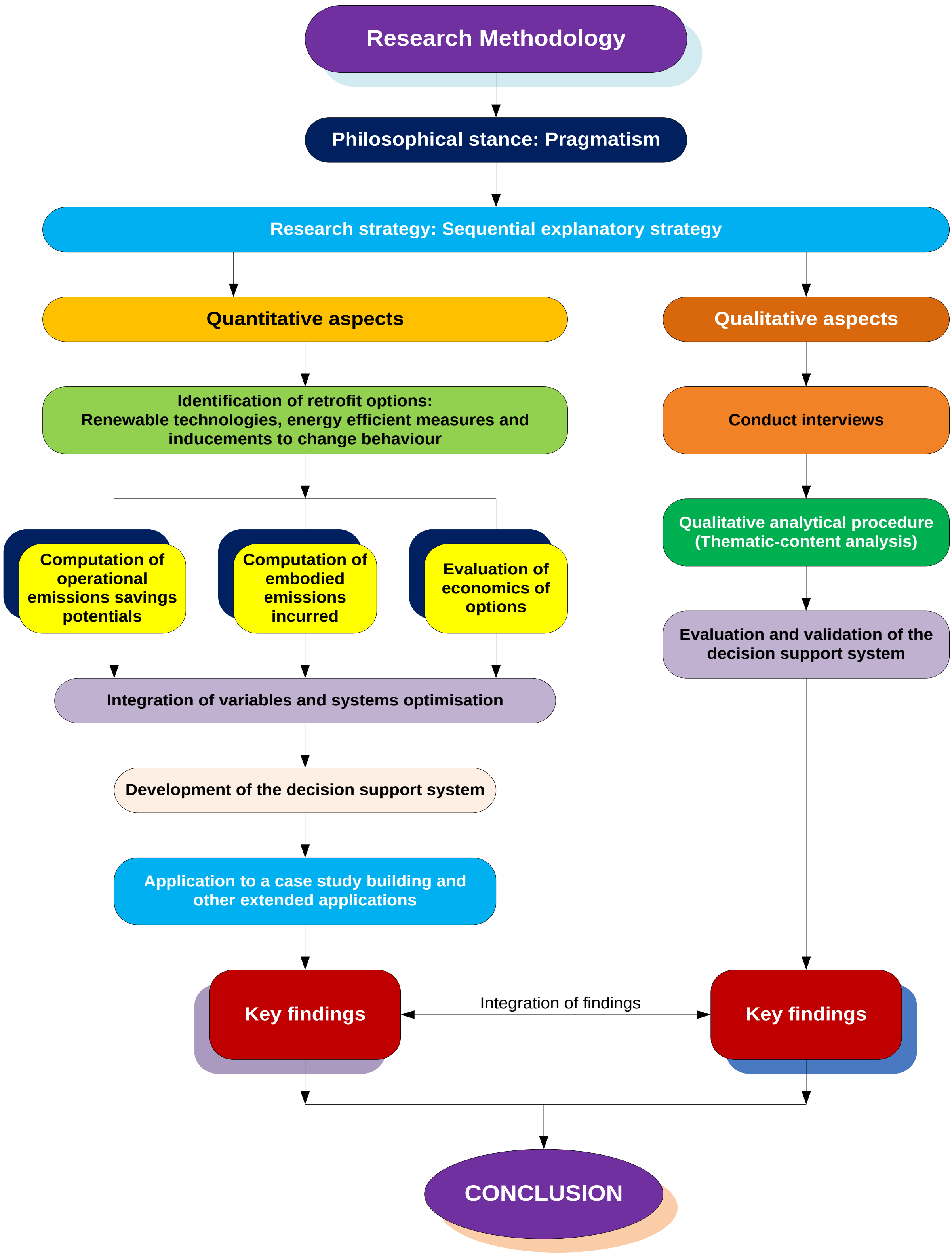



**Figure 3-4: Research method-procedural framework**

## *3.5.* Empirical validity

For an empirical work to be satisfactory as a scientific contribution to knowledge, the conclusions drawn from the study must be validated (Amaratunga *et al.,* 2002). Ascertaining validity is a key part of a research as it is the quality upon which a research is adjudged effective, reliable, and – in some cases – generalizable (Easterbrook *et al.,* 2007). The criteria by which a research's validity is judged depend on its philosophical stance. There are four criteria for validity (Knight and Cross, 2012; Kumar, 2011; Yin, 2009; Creswell, 2007; Easterbrook, 2007):

i. ***Construct validity*** pertains to whether the theoretical constructs are interpreted and measured accurately. It is identified through the accurate design and use of data collection techniques for the specific concepts under investigation
ii. ***Internal validity*** pertains to the study design, and most importantly it establishes whether the results realised are in tune with the data used. It is required for demonstrating any causal relationships in which certain conditions are believed to lead to other conditions.
iii. ***External validity*** pertains to whether claims for the generality of the results are justified. It is the degree to which the findings of the research can be generalised.
iv. ***Reliability*** pertains to whether the study produces similar results if other researchers repeat the procedure (i.e. the degree to which the research can be repeated, with the same results).

To ensure that research findings are reliable and credible, a research design should seek to address specific validity threats (Maxwell, 2005). Through the explicit acknowledgment of the validity threat, the researchers demonstrate that they are conscious of the potential flaws and have adopted appropriate steps to lessen their effects (Easterbrook *et al.,* 2007). In the context of the current research, validity threats and the approaches used to mitigate them are described for each study in Chapter six (Section 6.3).

### 3.6. Research design and structure

Drawing a fine distinction between where research methodology ends and where research design starts, from a conceptual point of view, is a difficult proposition (Knight and Cross, 2012). The concepts are interrelated as they drive one another at various stages of the research process and they mean different things when used by different authors. The final phase of the process of research involves the design and implementation. It is regarded as the 'blueprint' or the 'rules of engagement' of the research process and involves planning the entire research work from initiation to the end. It is distinct from the research methodology, which involves the overall procedural strategies used in investigating the phenomena of the research.

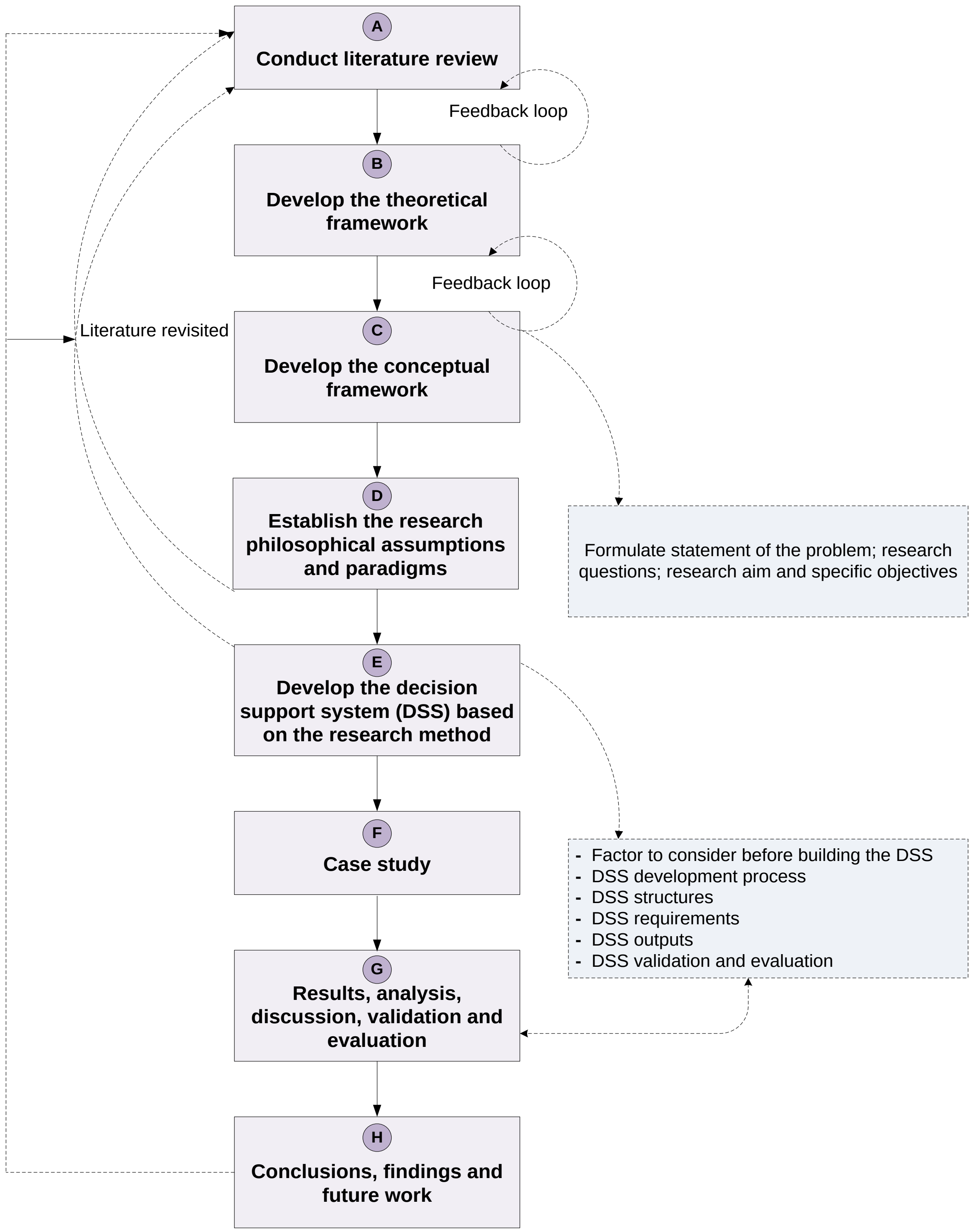



**Figure 3-5: Research design and structure**

The methodological strategies identified in this research were implemented based on the specific research activities illustrated in Figure 3-5, which adopts a holistic and cyclical approach (as adopted by Knight and Cross, 2012) to the tasks associated with the research work. The entire project is contextually driven, making it *holistic* and its *cyclical* nature stems from the fact that each research activity builds on the knowledge garnered in previous activity(s); provides feedback effects and loops that can help improve the previous and future activity(s) further; and incrementally adds, in an iterative manner, to the intricacy of the entire research project. As indicated, the literature review represents a key repetitive component of the research that helps in establishing the knowledge base of the research object and context. Further details of each block in Figure 3-5 is already presented as part of the overall structure and organisation of the thesis in Chapter one (Section 1.7).

### 3.7. DSS evaluation and validation methods

A DSS exists to augment the decision maker's capabilities of gaining an understanding of a problem that requires strategic decision with the view to choosing option(s) that is/are sound. Since the decision makers are human, it is important not only to assess the technicalities involved in designing and constructing the DSS and its overall performance but to also ascertain the views of the potential users and allied professionals.

Generally speaking, evaluation is usually carried out in the hopes of *verifying* and *validating* a DSS (Papamichail and French, 2005). The terms *'verify'* and *'validate'* are often wrongly interchanged in the context of evaluation of DSS. Whereas *verification* pertains to checking if the actual model constructed is indeed a representation of what it is constructed for, *validation* relates to checking that the model actually represents the concept being modelled and that it is sufficient for the goals of the task of which it is a part (Miser and Quade, 1998). A short but interesting definition put forward by O'Keefe *et al.* (1987) is: *verification* is constructing the system right; *validation* is constructing the right system. This suggests that *verification* is an element of *validation*; a system that has not been constructed in the right way is not likely to be the right system (O'Keefe and Preece, 1996). These distinctions between verification and validation are similar to the ones between efficiency and effectiveness or usability and usefulness.

*Verification* has to do with logical correctness of the DSS, but a knowledge base may be logically correct without being *valid*. Hence, *validation* has to do with how well a model conforms to what is being modelled (De Kock, 2003). *Validation* is concerned with attributes such as data inputs, knowledge base (i.e. concepts and relations), reasoning (i.e. strategies) and results (i.e. conclusions). Both *verification* and *validation* of a DSS are closely related to maintenance and learning (ibid).

There are several different approaches to the evaluation of a DSS. In the context of the current research best practice approaches have been identified from the literature and involve the following assessment levels (Papamichail and French, 2005):

i. **Technical verification**: checking the "*black box*" to get rid of programming errors and checking the extent to which the system has been built well; checking the accuracy of its outputs; and ascertaining whether the advice produced is sound or not.

ii. **Performance validation:** this involves the assessment of the performance aspects of the system with the view to ascertain how effective its mode of operation is; how well it performs its functions and to what extent is the knowledge base of the system accurate and complete.

iii. **Subjective appraisal:** this involves gathering thoughts and opinions from potential users to measure the usefulness and usability of the system. It also includes establishing the extent to which the system addresses the requirements of its potential users and assessment of its ease of use.

In testing and evaluating a system, norms are needed to test the actual behaviour of the system. Three kinds of norms exist (De Kock, 2003) namely: (a) *theoretical norms*, which is described by the normative decision theory; (b) *empirical norms*, which include norms such as those prescribed by the system model for solving a problem and (c) *subjective norms* which entails the qualitative assessment of the system performance, either by the users or experts. Whereas, *theoretical* and *empirical* norms *validate* the system, *subjective* norms *evaluate* the system. Since an integral component of the evaluation process is to measure the perceived utility of the DSS from the perspective of the intended users, a set of well-established criteria was used as a framework has shown in Figure 3-6.

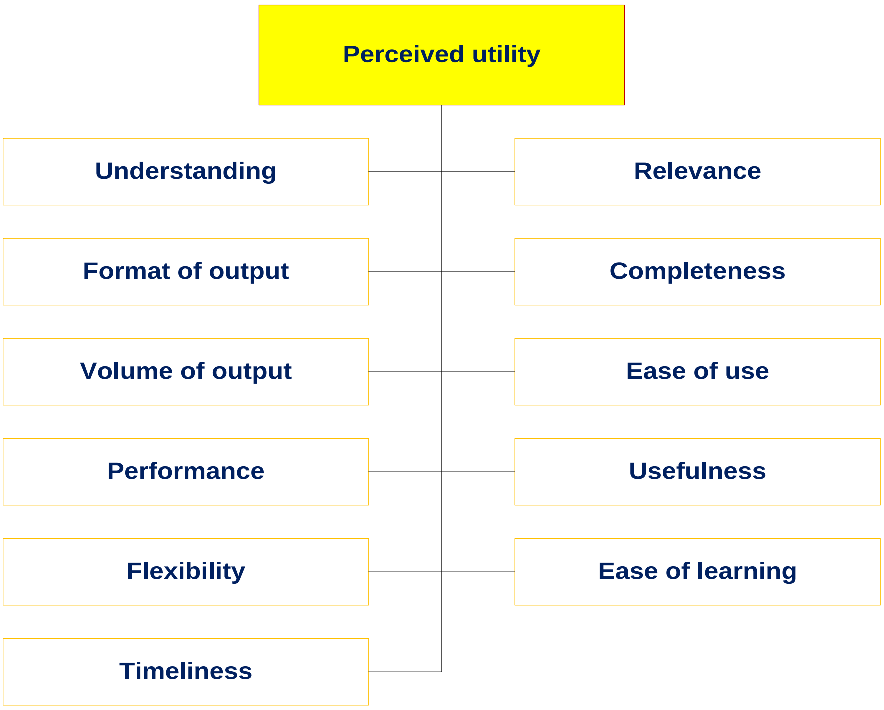



**Figure 3-6: Criteria for DSS evaluation (Papamichail and French, 2005)**

These criteria as defined by Bailey and Pearson (1983) and cited by Papamichail and French (2005) are given below:

- **Perceived utility:** this puts the judgement of the potential users into perspective regarding the DSS's usefulness
- **Understanding of the system:** the level of understanding or comprehension from the point-of-view of the user regarding the functions provided by the DSS
- **Relevance:** this measures the extent to which the needs or requirements of the user and the capabilities of the DSS are met
- **Completeness:** the level of detail associated with information content the DSS's output.
- **Output format:** the pattern of design, layout and structural display of the content of the system's output
- **Volume of output:** the quantity of the processed information generated by the DSS for onward use by the user
- **Ease of use:** the level of effort the potential user will put in to gain mastery of the use the tools and functionalities that come with the system.
- **Ease of learning:** a measure of how simple or difficult it is to learn how to use the DSS
- **Timeliness**: a function of how readily available is the final output of a system at any given time
- **System's adaptability/flexibility:** the measures the ability of the system to respond to new rules, conditions, demands, or situations for a given input
- **Performance:** this measures the capability of a system to assist a decision maker in accomplishing a task within time, cost and technical performance objectives
- **Usefulness:** the degree to which the DSS contributes to the improvement of the performance of the users

The results of the subjective assessment based on the above criteria are presented in Chapter six (Section 6.6).

### 3.7.1. Software validation and testing methods

Validity denotes relevance, meaningfulness and correctness and two types of validations of DSS exist namely, content and construct related validity. Whereas, content validation judges each item in the system for its presumed relevance to the property being measured, construct validation refers to the validation of the model including its knowledge base, reasoning strategies and analytical relationships. During a DSS evaluation process, three types of faults may be encountered (De Kock, 2003): (a) *factual faults*–faults due assertions does not correctly represent the facts; (b) *inferential faults,* where a certain rule does not correctly represent the domain knowledge and the result produced represent an incorrect output produced by the system and (c) *control faults*, in which the rules are correct, but have undesirable control behaviour. Against this backdrop, it is important to check the logical correctness of the knowledge base of the system under consideration. This can be achieved by a three-step validation procedure including the running of the program; identification of faults; and modification of the program (rules and control strategies). The details of the validation are provided in Section 6.3.

### 3.8. Chapter summary

The overall research design and methodology used have been presented. These comprise two inter-related studies:

1. A quantitative energy study, for which a decision support model is to be developed to quantify energy use and rank a range of building energy retrofit options in terms of operational emissions saving potential, embodied emissions incurred and the financial cost
2. An approach to the evaluation of the DSS through interviews.

Developing the DSS requires an extensive number of decisions and assumptions to be made, as part of the overall development process. Chapter four explains in more depth these underlying assumptions, principles and approaches used to develop the DSS in terms of structure and systems requirements, with the model results and evaluations reported in Chapters five and six respectively.

# CHAPTER FOUR: DESIGN OF THE DECISION SUPPORT SYSTEM

## Chapter overview

This chapter presents a detailed analytical study devoted to the design concepts, engineering principles, methodological and computational framework as well as the rationale underpinning the development of a Decision Support System (DSS) which seeks to fill the gaps identified in Chapter two.

## 4.1. Introduction

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) (De Benedetto and Klemeš, 2009; Joshua, 2010). The reduction of emissions in buildings poses a difficult challenge, as it involves a complex interplay of information and decision pathways between the building users, building designers, cost data and energy prices and regulatory authorities as depicted in Figure 4-1.

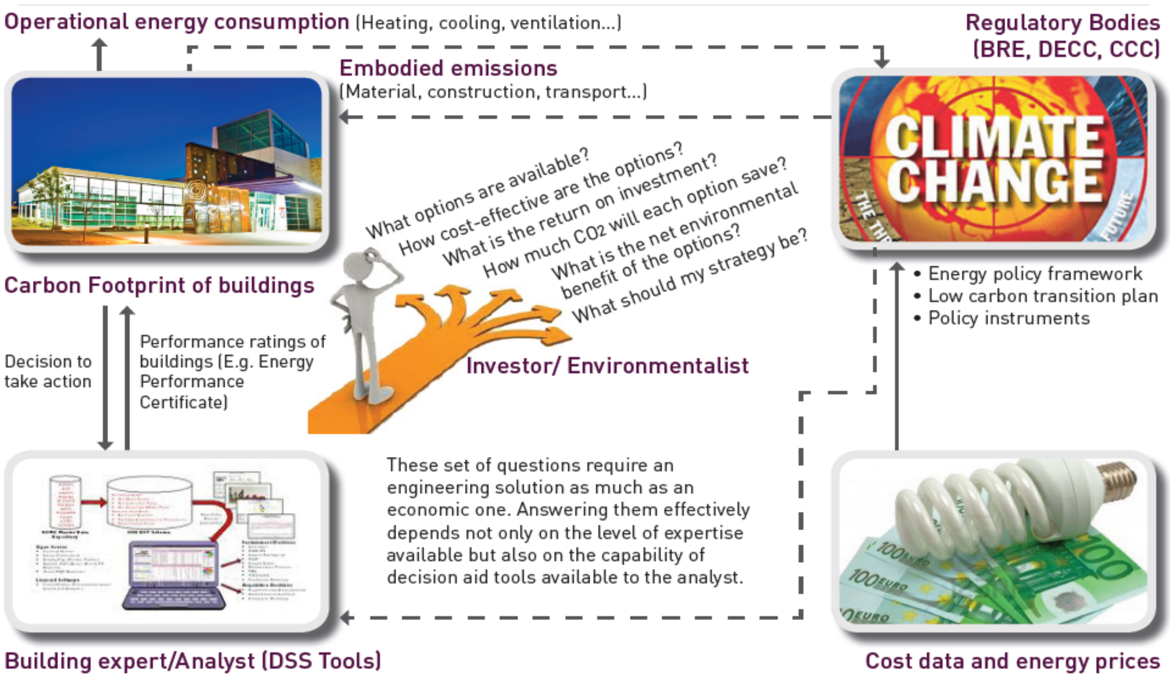



**Figure 4-1: Interplay of information and decision pathways between buildings and regulatory authorities (own conceptualisation)**

This stems from the fact that information from the regulatory authority (e.g. putting a cap on emissions or using results from energy performance certificates to appraise buildings) can trigger actions that can prompt building users and designers regarding emissions reduction targets. As such, the sustainability performance of a building can become a complex problem due to the overlapping nature of the multiple and sometimes competing constraints such as energy consumption, financial costs, environmental impact and the influence of regulation from national authorities.

Against this backdrop, for every refurbishment/retrofit project relating to non-domestic buildings, the following questions might be asked:

- What options are applicable to reduce building emissions now and in the future?
- How cost effective are these options? What will be the return on investment?
- How much $CO_2$ emissions will each option abate?
- What is the net emissions reduction of the options?
- What is the best combination of options and what should the strategy be?"

These questions will be considered in a different way by an investor and an environmentalist. The sole desire of the investor is to realise a high financial savings and generate favourable economic return, whereas the environmentalist may 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 challenge therefore is to develop such a robust decision support methodology to establish the combination of measures that can create synergy effects, generate cost benefits, and lead to the optimal investment level and better results (regarding cost and environmental performance), while also taking into account the interdependencies of measures.

## 4.2. The decision-making/modelling processes of a DSS

Generally speaking, a decision problem involves a situation whereby an individual or an organisation must choose from a given set of alternative courses of action without any prior knowledge of which choice(s) is/are the best one(s). A decision process or a decision support modelling framework can therefore be decomposed into three phases as depicted in Figure 4-2. As shown, the first is the ***intelligence phase*** where the problem is identified and structured. It involves the establishment of the aim of the decision, the acknowledgment of the decision problem that requires solution, the identification and analysis regarding cause and effect interactions for the decision circumstances and the recognition of the performance indicators and criteria for decision (Pavan and Todeschini, 2008; Turban *et al.,* 2001).

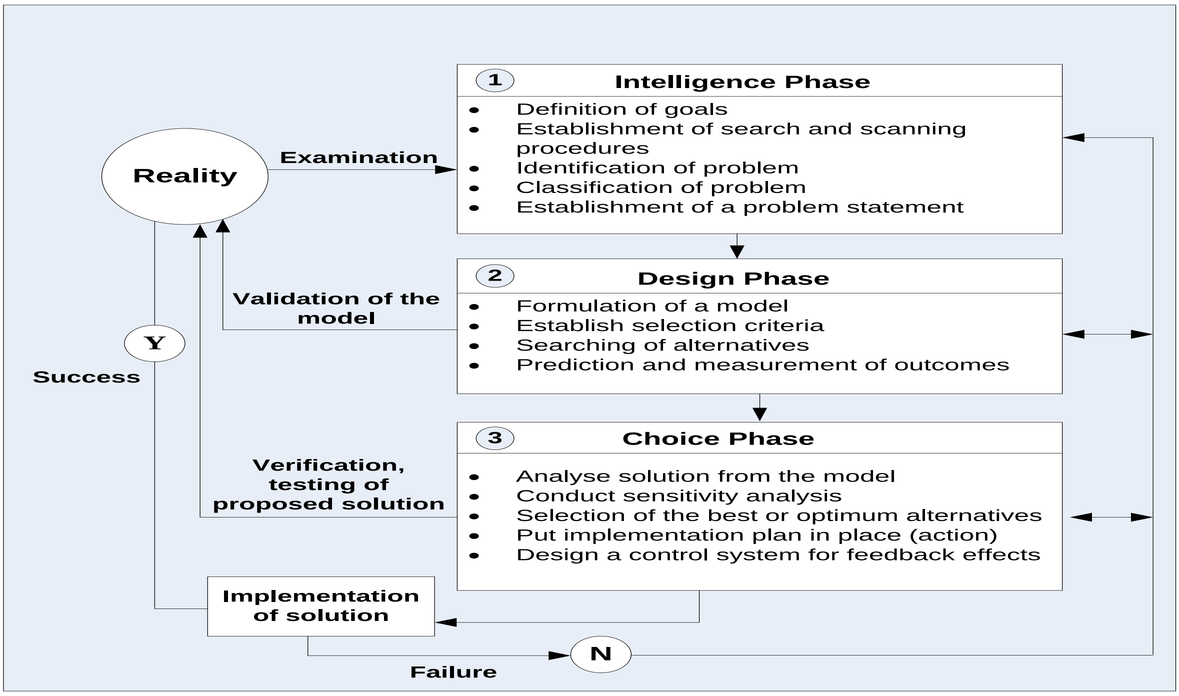



**Figure 4-2: The modelling process of a decision support system (Turban et al., 2001)**

The ***design phase*** or ***use phase*** comes next and is where the actual model development commences. It involves the development of models to ascertain the preferences of the decision makers. In this phase, some goals which are to be traded off are established to enable comparison between different actions in a logical, efficient and unprejudiced way (Pavan and Todeschini, 2008). Finally, the ***choice phase*** is where the plans of actions are developed, because the analysis itself does not unravel the final decision. The final phase is where a set of solutions are checked whether positive conclusions outweighs possible losses. In summary, the purpose of a decision process is to effectively produce information regarding the problem based on data availability; to efficiently establish solutions; and to facilitate an understanding of the decision phenomenon (Pavan and Todeschini, 2008; Shim *et al.*, 2002). The decision modelling framework and concepts described above are applied to the current research problem. In the subsection that follows, details are provided regarding the processes involved in the development of a decision support system.

### 4.2.1. Decision support system development process

Developing a decision support system is a complex procedure which requires various factors to be considered before the software design commences. Mallach (1994) suggested a number of factors to be considered before starting to design a DSS, including:

- Determination of the aim of the DSS regarding the decision being made and the outputs it must produce

- Determination of external sources, if any, that the DSS will communicate with and establish any data flows to and from these sources
- Determination of internal data files needed. It should be ascertained if the data in these files are obtained from external data sources and if it is, the external sources should be specified and determination of the major processes in the DSS

Gaining an understanding of the above considerations will facilitate the understanding of the DSS as a system. A development process for a classical DSS, including all activities necessary for the construction of a DSS is depicted in Figure 4-3. These steps form the guiding principles which the current research adopted in the development of the DSS for the specific purpose it was designed for.

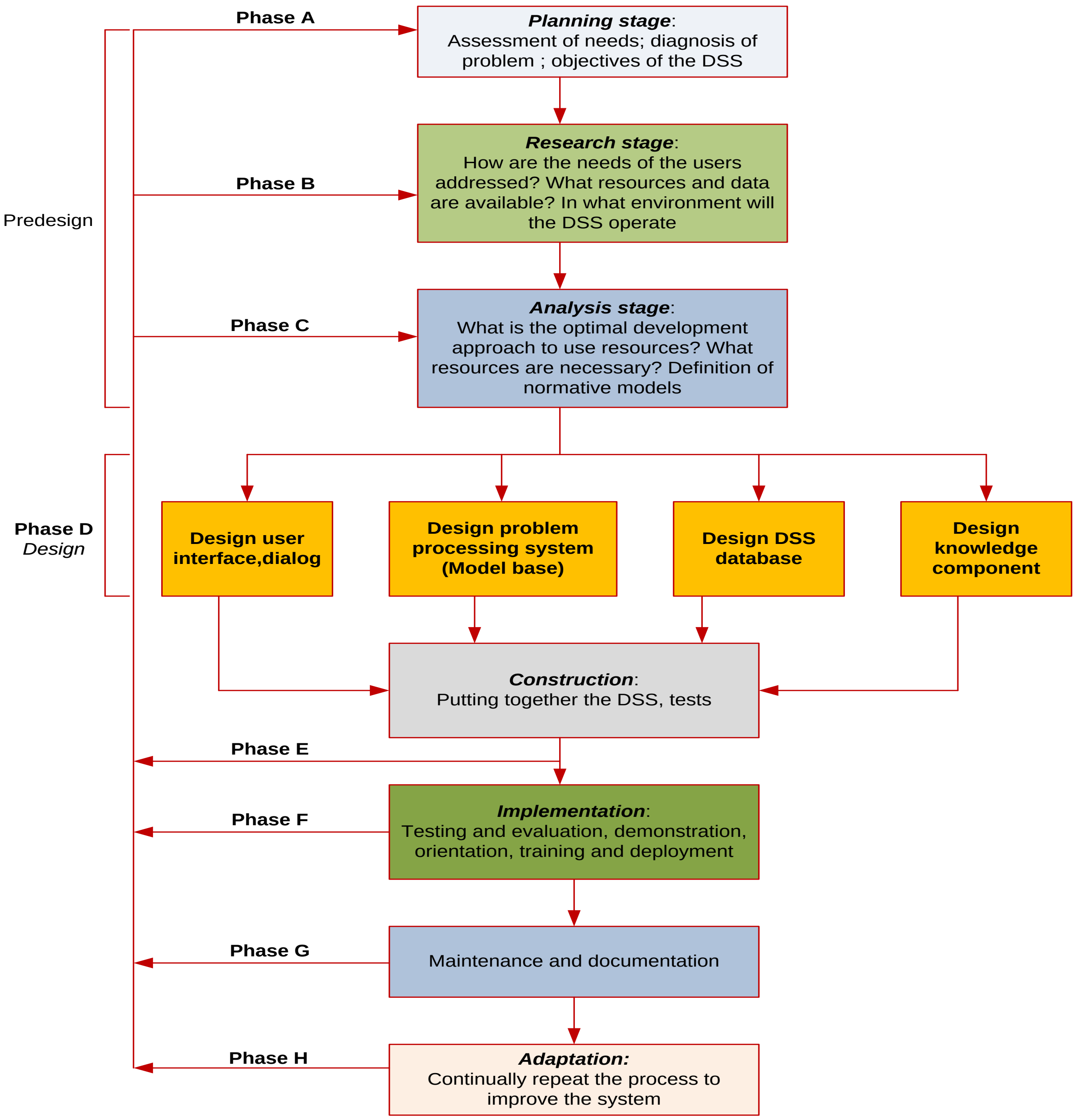



**Figure 4-3: The development process of a DSS (Source: Turban, 1995)**

### 4.2.2. Decision support approach to improve a building's sustainability

The sustainability of a building could be improved if the necessary and vital requirements that are optimum for the overall functioning of building are met. This could be enhanced through the use of decision support framework with steps illustrated in Figure 4-4 and includes (Kolokotsa *et al.*, 2009):

- Identifying the overall aim of decision making, ancillary objectives and the various criteria or key performance indicators (i.e. objective function and performance measurement) for comparative analysis
- Identifying the set of alternative building energy retrofit strategies or options;
- Appraising each strategy and/or option performance with respect to the defined criteria and performance indicators
- Weighting of criteria or objectives; evaluation and assessment of the general performance
- Appraising and ranking of options as well as conducting sensitivity analysis

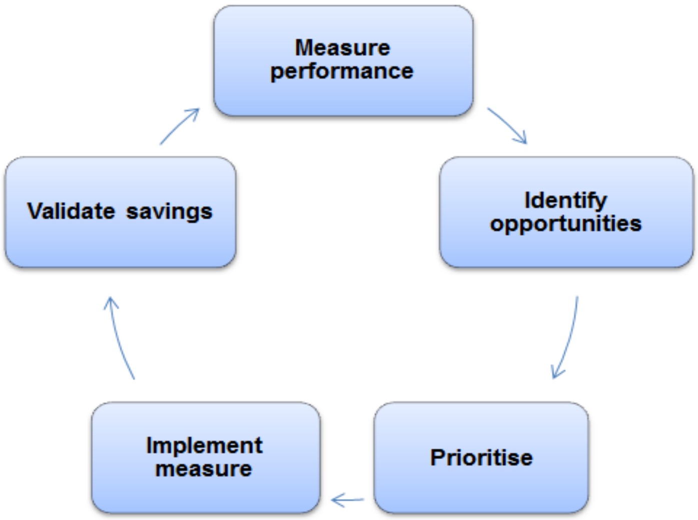



**Figure 4-4: Steps to choosing right options in building performance analysis (Kolokotsa *et al.,* 2009).**

## 4.3. Research scope

The scope of this research is limited to the development of a robust a decision support framework for evaluation of economically and environmentally optimal retrofit of non-domestic buildings, based on ranking principles derived from marginal abatement cost (MAC) principles and Pareto methods as described in later sections of this Chapter. It is a research endeavour that employed the power of these optimisation methods together with operational and embodied emissions evaluation approaches, to investigate how both forms of emissions and cost can be integrated into a single model. The intended overall output is to provide decision makers (e.g. energy managers) with an efficient and reliable process that is informed both by environmental and financial considerations. To this end, the current research does not cover the issue of uncertainties in the computation of embodied emissions. This is because embodied emissions results vary, due to various factors highlighted in Section 2.8. Also, the assessment of the intervention options is based purely on economics and operational emissions saving potential and does not consider implementation issues.

## 4.4. Design of the DSS – definition, basic structure and components

The design and methodological framework for the current DSS is shown in Figure 4-5 and is composed of 5 modules carrying out the following functions: $(i)$ computation of the baseline energy (gas and electricity) consumption of the building to establish a benchmark for future comparison; $(ii)$ identification of technically feasible low carbon intervention measures and computation of their potential energy and $CO_2$ savings; $(iii)$ computation of the embodied emissions related to each low carbon intervention measure. This will allow the net emissions of an option to be evaluated. 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; $(iv)$ economic evaluation of investment and operating costs using an appropriate investment appraisal technique; $(v)$ optimisation, integrating financial cost and operational and embodied emissions to produce a ranking of the retrofit options.

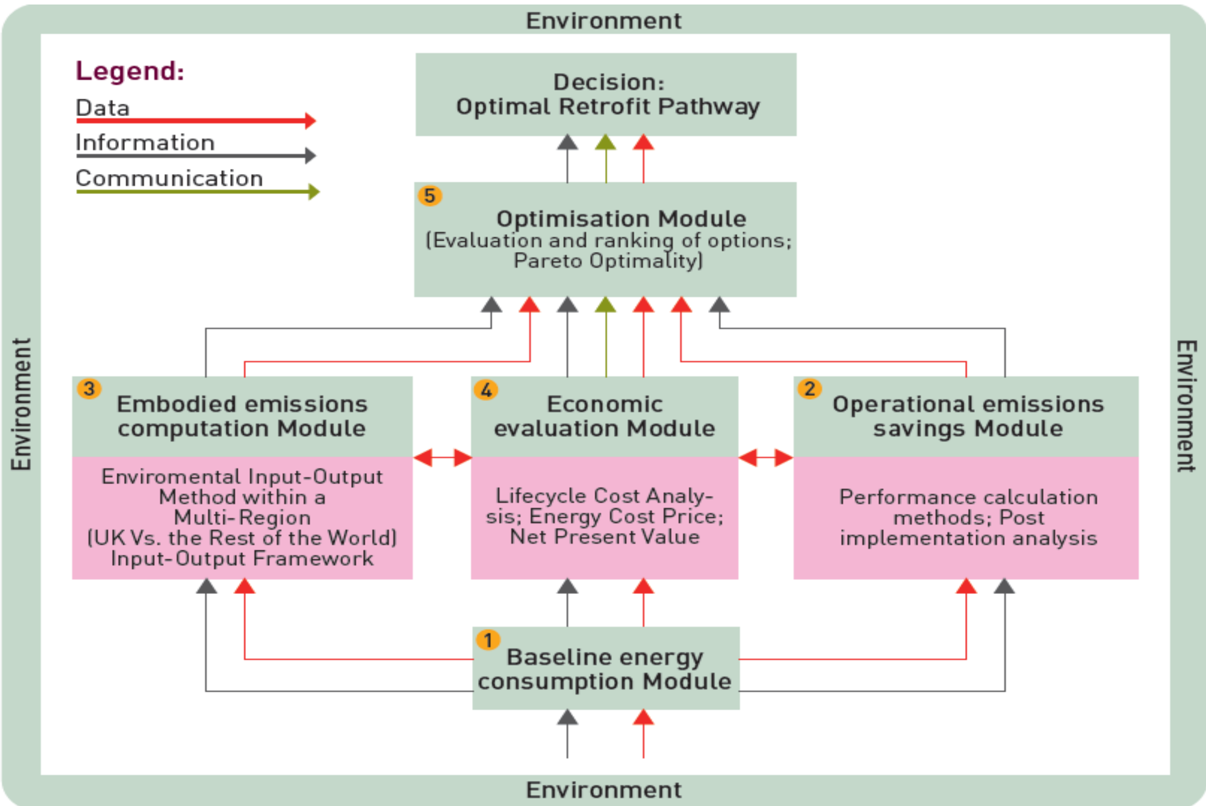



Figure 4-5: The decision support system architecture and modules

The overall structure of the DSS in terms of its logical flow with some level of details is illustrated in Figure 4-6. The development of the DSS structure is based on a techno-economic evaluation methodology for energy retrofit of buildings which integrates economic (cost) and net emissions (embodied and operational emissions) cost or benefit parameters within an optimization scheme. In the subsections (4.4.1 to 4.4.5) that follow, a brief description of each module is presented.

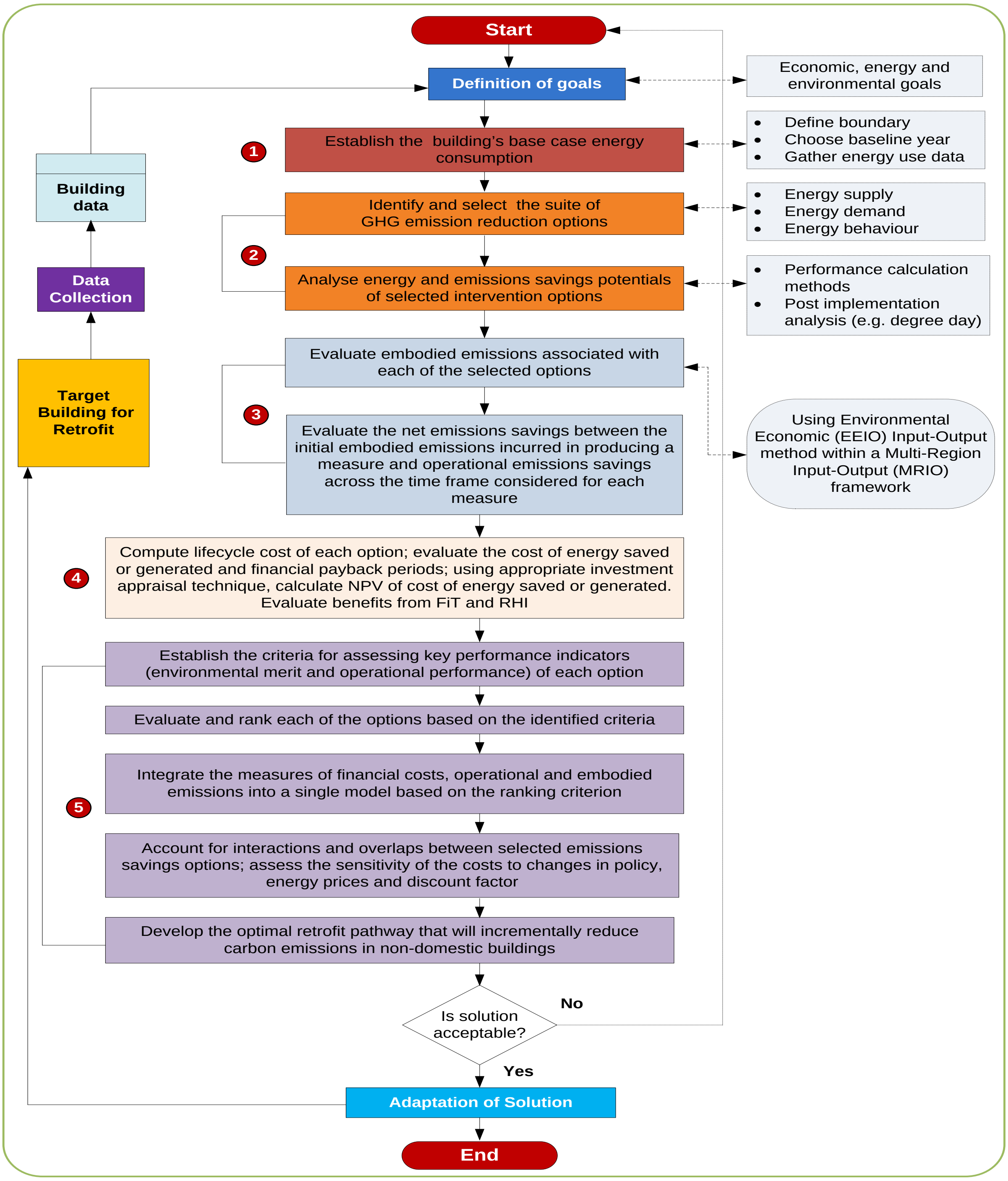



**Figure 4-6: Flowchart showing the logic of the decision support system.**

### 4.4.1. Module 1 - baseline energy consumption

This involves the establishment of the base line (the 'do nothing' option) for energy (gas and electricity) consumption of the building through evaluation of the energy systems characteristics and the patterns of energy use. It entails the measurement of energy use and energy intensity of the target building at a suitable 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 (Carbon Trust, 2011).

The building (detailed characteristics of the case study building presented in Section 5.2) in its present form including its associated operational energy consumption and $CO_2$ emissions as well as running costs forms the baseline for comparative emissions 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.

### 4.4.2. Module 2 - operational emissions savings

The energy saving predictions from each measure are based on performance calculation methods using standard algorithms for low carbon energy sources (Building Regulation, 2006; RETScreen, 2005; London Renewables, 2004) and post-implementation evaluation using appropriate energy data analysis techniques (e.g. degree day analysis) (Stuart, 2011; Carbon Trust, 2010). The chosen evaluation method for a measure depends 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. Savings from BEMS, voltage optimisation are based on post implementation evaluation using degree day analysis. Savings from other measures such as LEDs are based on derived performance calculation methods.

### 4.4.3. Module 3 - embodied emissions incurred

Embodied emissions related to each of the established and formulated building energy interventions are evaluated. This will allow for the evaluation of the net emission gain in terms of the embodied emissions of a low carbon intervention measure and the corresponding operational emissions savings after its implementation. Net emissions savings in this context is the difference between the operational emissions savings of a measure across the time period considered and initial embodied emissions incurred in the production of the measure. With known estimated value of associated embodied emissions of a retrofit option, the emission payback period can be estimated.

As discussed in Section 2.10, there are three possible options namely process-based, input-output-based and hybrid-based available for the calculation of embodied emissions. Process-based or hybrid approaches, using established LCA database could have been used. However, integrating detailed process-based embodied energy calculations of all the retrofit options considered within DSS will be extremely time-consuming. Besides, the overall aim of the DSS is not to evaluate the embodied emissions of the retrofit options with the highest level of accuracy but to provide rough estimates. To this end, the Environmental-Economic Input-Output (EIO) approach within a multi-regional input-output (MRIO) is adopted within the overall DSS to estimate the embodied emissions of the retrofit options under consideration based on the following reasons:

- It takes a system-wide view of embodied energy analysis
- It allows for multi-regional input-output (MRIO) analysis of embodied emissions
- Availability of robust , highly disaggregated, two-region (UK and the Rest-of-the-World) MRIO dataset
- Availability of cost information pertaining to the retrofit options
- Ease of implementation within the overall framework of the DSS

In Section 2.10.2, a number of well-recognised limitations regarding the use of EIO methodology were highlighted. Therefore the method utilised for the estimation of embodied emissions associated with each intervention option under consideration is underpinned by the use of EIO methodology (Acquaye and Duffy, 2010; Wiedmann *et al.* 2010; Lenzen *et al.* 2003) which is based on the two-region (UK and the Rest-of-the-World) Multi-Regional Input-Output (MRIO) methodological framework (Kanemoto *et al.*, 2012; Kanemoto *et al.*, 2011; Wiedmann *et al.* 2010; Wiedmann, 2009; Turnera *et al.,* 2007). Due to data availability issues (McGregor *et al.,* 2008), import assumptions (Hertwich and Peter, 2010) and for the purpose of simplicity (Turner *et al.* 2007), MRIO frameworks are usually presented as a 2-region model. Such two regional models have been applied in a wide range of studies including Peters and Hertwich (2004); Yu *et al.,* (2010); Acquaye *et al.*, (2014) and forms the basis for adopting such approach in this thesis.

Problems with high levels of aggregation in industry and commodity classifications are resolved in this research by using highly disaggregated input-output tables within an MRIO framework to minimize this aggregation error. Also, the error with the assumption of domestic production of imports is theoretically resolved using MRIO models through the use of dissimilar technology for dissimilar regions (i.e., countries). The application of MRIO framework makes it 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 (Wiedmann *et al.* ,2013; Hertwich and Peter, 2010; Wiedmann *et al,* 2007). The development of the MRIO framework reflects the fact that production of goods and services is becoming increasingly global. For instance, in 2001, the production of commodities traded internationally was responsible for about 22% of global $CO_2$ emissions (Hertwich and Peter, 2010). To this end, researchers, including Wiedmann *et al.* (2010); Wiedmann *et al.* (2010); Lenzen *et al.* (2010); Wiedmann (2009a); Wiedmann (2009b); Druckman and Jackson (2009); Andrew *et al.* (2009) have adopted MRIO to represent global aspects of consumptions, including trade between different countries. The manner in which the EIO is applied within a MRIO framework in the current work is described in Section 4.9.

#### 4.4.4. Module 4 - economic evaluations

The financial costs/benefits of each low carbon retrofit intervention option are evaluated using an investment appraisal technique based on the calculation of net present value. The abatement costs (i.e. the additional cost of abating an additional tonne of GHG above what would be achieved in a 'business as usual' context) 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.

#### 4.4.5. Module 5 - performance criteria evaluation and optimisation

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 $CO_2e$ (£/$tCO_2e$) is calculated. This value represents the cost-effectiveness. All the options under consideration are then ranked based on this criterion to produce an optimal output. Given the ranking anomaly with negative cost measures (i.e. low carbon investment options which reduce emissions and saves money) highlighted in Section 2.14, there is a need for an alternative ranking approach. Furthermore, economic considerations are integrated with operational emissions savings and embodied emissions incurred. These variables are used within an optimisation scheme (Figure 4-7) that consists of integrated modules for data input, sensitivity analysis and ranking based on appropriate optimisation methods. The methodological approach takes into account the use of selected carbon abatement technologies that will satisfy a range of criteria (environmental, demand, cost and resource constraints); treatment of uncertainty; hierarchical course of action; and the evaluation of 'best' case scenario.

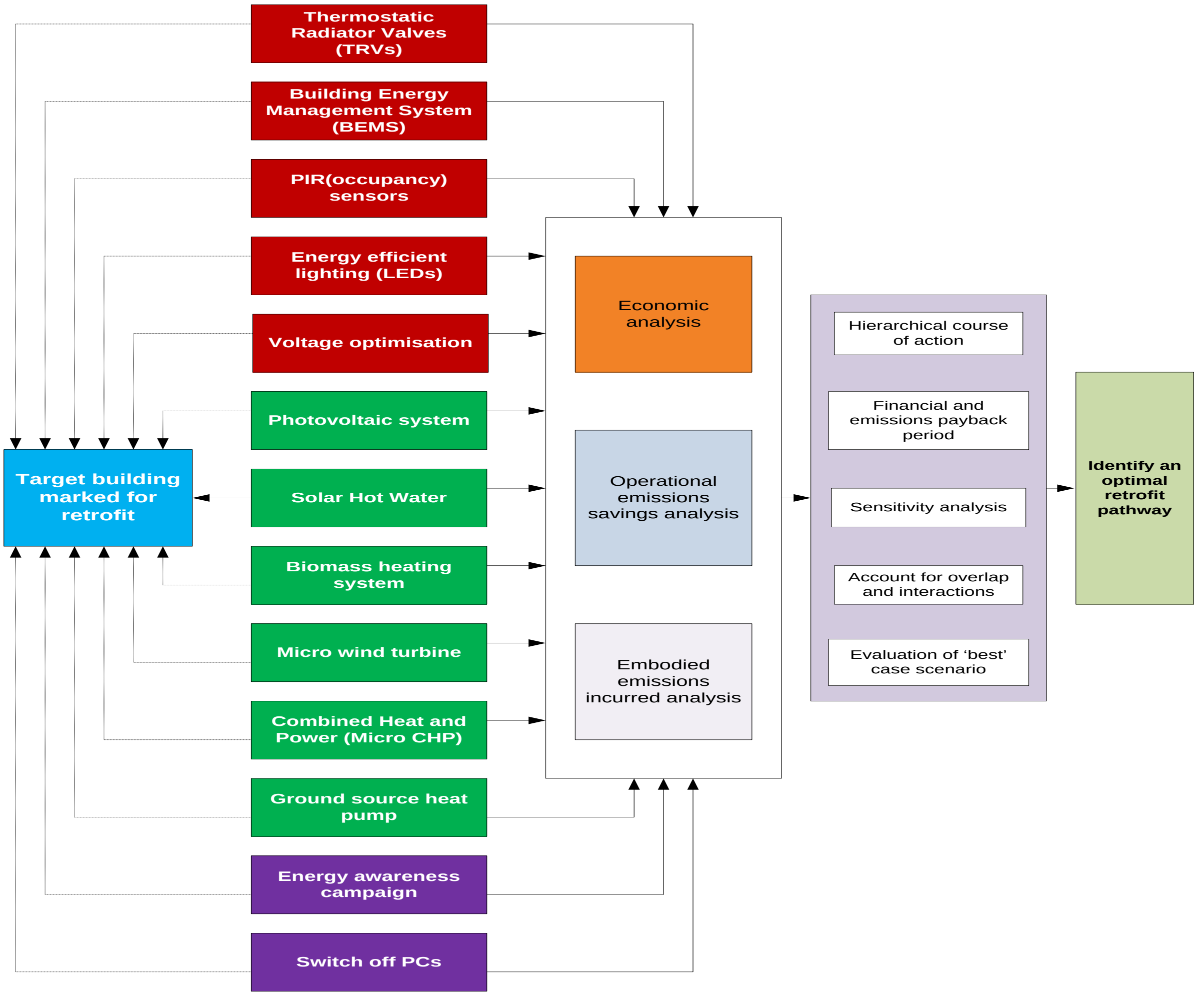



**Figure 4-7: Decision support system: option specification and optimisation scheme**

The output of the DSS will give an indication of financial benefits (fuel savings and $CO_2$ emission reductions) and the environmental merit of the measures across the time period considered. This will indicate the scenarios where measures that lead to net emissions reduction also save money, and will put into perspective measures where the investment cost cannot be recovered. This will in turn allow trade-offs between various refurbishment options to be identified and communicated, and ensure decisions that are informed both by environmental and financial considerations.

## 4.5. Selection criteria for GHG emissions reduction options within the DSS

The overall aim is 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 renewable energy generation technologies, energy efficiency measures, and inducements to change behaviour which was generated through detailed analysis of completed retrofit projects (Figure 4-8), e.g. Tarbase Project (Jenkins *et al.*, 2009a). The initial long list of retrofit options was further pruned following discussions with the energy manager of the case building.

The options considered within the model as indicated in Figure 4-7 are those that are: **(i)** feasible and capable of significant emissions reductions in non-domestic buildings based on the existence of well-established performance calculation algorithms; **(ii)** available in the market, technically proven and in existence over an extended period of time; **(iii)** considered acceptable for providing the amount of energy demand and deemed the most likely options that decision makers (e.g. energy managers) will prioritise; **(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 minimum wind velocity of approximately 6m/s on site is not guaranteed, may not necessarily consider wind turbine as an option. London Renewables (2004) and DECC (2013) highlight the major implementation issues that must be taken into consideration before the adoption of each technology.

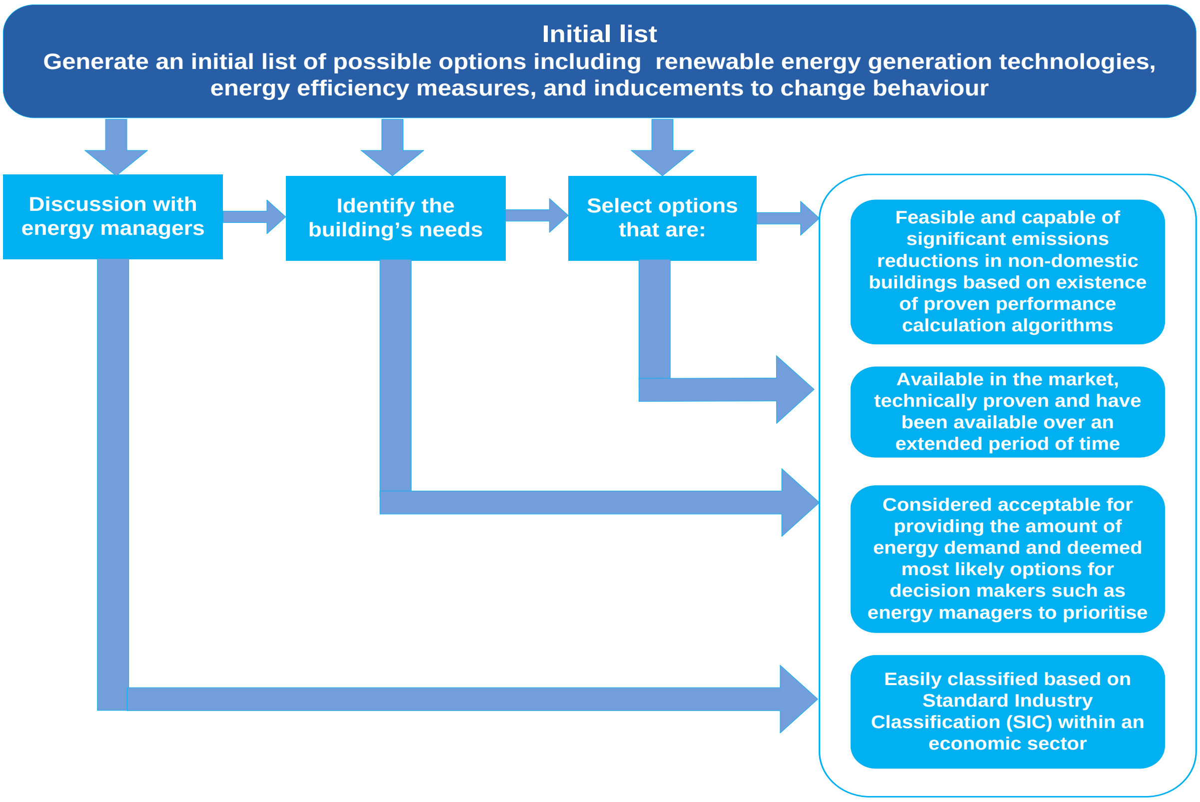



**Figure 4-8: Criteria for selection of GHG emissions reduction options**

### 4.5.1. Rationale for excluding some retrofit measures within the DSS

Although the basis for the selection of retrofit options within the DSS is summarised in Figure 4-8, the retrofit options that are included in the DSS are only a subset of the possible methods for improving energy performance of a building and they are chosen due to their suitability to the DSS process. The DSS model does not currently consider passive measures like wall insulation and double/triple glazing of windows in terms of their emissions savings potential because they are deemed not suitable for this process given that they are highly building specific. Such estimates require detailed thermal modelling and simulation of building fabrics. However, the DSS can evaluate the embodied emissions associated with these options. 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.

Furthermore, 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 related issues important for decision makers and stakeholders, is very often almost impossible. This is due to differences in algorithms and performance calculation procedures, data requirements and data formats for each option. However, the DSS can be further developed to capture technologies such as absorption cooling, ground cooling and other options with proven performance calculation methods.

## 4.6. Development of the DSS into a practical software

The overall decision support system presented in this thesis was developed into practical software based on Microsoft Excel and Microsoft Visual Studio (C#) application packages. Microsoft Excel was used for handling the database aspect of the DSS for the embodied emissions evaluations. Microsoft Excel was adopted because it is an easily accessible spread sheet program with instinctive design and layout as well as its ease of use as a prototyping tool. Additionally, Microsoft Excel offers a great deal of customisation based on macros and Visual Studio add-ons. Microsoft Visual Studio, an Integrated Development Environment (IDE) was used to code the overall intelligence behind the DSS. Visual Studio provides multi support functionalities which make coding easier and reliable. With the use of Visual Studio, software creation, debugging and deployment are greatly simplified because of its several new and improved features that support software development processes. The final software is named COBRA – Computed Optimised Building Retrofit Advice.

The overall operation of the DSS is set up such that the use of embodied emissions can be switched in and out of the DSS so as to allow its use solely for operational emissions evaluations (the most likely case in the first instance) and to allow immediate comparison with the effects of including embodied emissions. In the Sections (4.7 to 4.14) that follow, elaborate description of the modular components described in Sections 4.4.1 to 4.4.5 and the underlying mathematical and computational frameworks as well as assumptions as adopted within the DSS are presented.

## 4.7. Module 1-base line evaluation

In this module, the energy consumption is converted into carbon footprint by multiplying with appropriate greenhouse gas emissions factors. The baseline energy consumption of a building is computed using:

$$\mathrm{BE} = (\mathrm{EC} \times \mathrm{F_e}) + (\mathrm{GC} \times \mathrm{F_g}) \tag{4.1}$$

Where:

BE = Base line emissions ($kgCO_2e$/year)

EC = Electricity consumption (kWh/year)

GC = Gas consumption (kWh/year)

$F_e$ = GHG emission factor ($kgCO_2e/kWh$), for electricity

$F_g$ = GHG emission factor ($kgCO_2e/kWh$), for gas

### 4.8. Module 2-evaluation of operational emissions saving potentials of options

The algorithms and the mathematical approaches taken to the evaluation of the potential operational emissions savings from a range of building energy retrofit intervention options including, renewable technologies, energy efficiency measures and inducements to change behaviour are presented in this section. Where necessary, detailed flowchart, showing the calculation procedures for some selected retrofit options are provided in the Appendix. This is to maintain conciseness and the flow of the overall thesis since the calculation procedures are not an integral part of the thesis but are supplementary information relevant to the main DSS development process.

#### 4.8.1. Photovoltaic system

Solar Photovoltaic (PV) modules convert solar energy from the sun into DC electricity and can be integrated into buildings. They are not directly related to any specific fabric elements of a building or service and therefore allow for flexibility in their sizing, subject to certain constraints (e.g. available surface area of roof or facade). Different types exist, including monocrystalline, polycrystalline, hybrid and thin-film with differing efficiency and longevity. Electricity generation can meet the demand and any additional can be exported. The performance calculation method used within the overall DSS to estimate potential emissions savings from PV systems is shown in the flow chart in Figures A-1a and A-1b in Appendix A.

#### 4.8.2. Micro wind turbine

Micro wind turbines are also not directly related to any specific fabric elements of a building or service. As such, they allow for practical flexibility in their sizing, subject to certain constraints (e.g. visual impact) and can generate renewable electricity for buildings if installed in optimum locations. The performance of a micro wind turbine is influenced greatly by the availability of wind resources, including wind velocity and rate of occurrence. Further brief description of wind technology and the flowchart for the performance calculation methods adopted within the DSS are detailed in Figure A-2 in Appendix A.

#### 4.8.3. Solar hot water system

These are renewable energy technologies that are explicitly designed for the purpose of capturing energy from sunlight and transform it to useful heat for applications such as water heating for provision of hot water for domestic purposes, swimming pools and under floor heating. Further brief description of solar thermal systems and the flowchart for the performance calculation methods adopted within the DSS are detailed in Figures A-3a and A-3b in Appendix A.

### 4.8.4. Ground source heat pump

Given that 46% of the sun's energy is absorbed by the earth (NRCan, 2002), providing on-site earth energy in large quantities and preventing the need for transportation of energy over long distance in contrast to other sources of energy (NRCan, 2002), the energy can be put into use for heating and cooling a building. Further brief description of ground source heat pump technology and the flowchart for the performance calculation methods adopted within the DSS are detailed in Figures A-4a and A-4b in Appendix A.

### 4.8.5. Micro combined heat and power

Micro combined heat and power (CHP), also called "cogeneration" is a renewable energy generation mechanism that involves the simultaneous production of two or more types of usable energy from a single energy source. Further brief description of micro CHP technology and the flowchart for the performance calculation methods adopted within the DSS are detailed in Figures A-5a and A-5b in Appendix A.

### 4.8.6. Biomass Heating

Biomass heating system is a solid fuel which serves as an alternative to the conventional fossil fuels. It involves the burning of organic or plant matter including agricultural residues wood chips, or even urban waste) to produce heat. Further brief description of biomass heating system technology and the flowchart detailing the performance calculation methods adopted within the DSS are presented in Figure A-6 in Appendix A.

### 4.8.7. Efficient lighting (LEDs)

In commercial buildings, about 20-45% of energy consumption is from lighting (Carbon Trust, 2008). Significant energy savings can be realized with a minimal capital investment from energy-saving lighting systems including low energy, LED and high frequency lightings. LEDs typically have a long lifetime and will need less frequent replacement than many other lighting types (Carbon Trust, 2012). The flowchart detailing the performance calculation methods for LED installations are presented in Figures A-7a and A-7b in Appendix A.

### 4.8.8. Passive infrared (occupancy) sensor

Passive Infrared (PIR) sensors are microelectronic devices that measure infrared (IR) light radiating from objects within their spectrum. PIR sensor installations ensure that lighting only comes on when required, and most importantly that lighting is switched off when an area is vacated. High quality PIR sensors are a cost effective solution for commercial and domestic end users in reducing energy consumption and carbon footprints. Savings start as soon as the sensors are installed. The flowchart detailing the performance calculation methods for passive infrared (occupancy) sensor installations are presented in Figures A-8a and A-8b in Appendix A.

### 4.8.9. Building Energy Management System

Building Energy Management Systems (BEMS) are powerful tool for energy management and not a substitute (Connor and Butler, 2010). They are computer-controlled installations that integrate the energy-using services and facilities in a building. Further information on theory of BEMS is provided in Appendix A9. Energy savings from the installation of BEMS could be considerable, but information about such prospective energy-savings benefits varies. Over the past decades, research studies conducted have revealed a wide range of energy savings for BEMS. The savings vary from none to more than 30% (ibid). Few case-specific data are available but summary discussions in literature (e.g. Brambley *et al.*, 2005) reports average energy savings between 5 and 15% of overall building energy consumption. Based on the experience of some energy experts and systems integrators, commercial buildings that have HVAC systems with boilers and chillers report an overall energy use reduction between 18 to 20% (Kamm, 2007). The Energy Institute (2011) reported an average energy saving of 20% from the installation of BEMS. Similarly, a recent installation of Trend BEMS in an Italian supermarket chain saw energy consumption reduced by 26% over the first eight months (MBS, 2013).

In the context of the current study, one year gas and electricity half-hourly data of the case study building were analyzed using degree day (i.e. a summation over an extended period of time, of the difference between a reference or base temperature and the temperature of the surrounding) approach (Stuart, 2011), before and after the installation of BEMS, to ascertain its potential energy savings as compared to the baseline energy consumption. Figure 4-9 and 4-10 shows the results of the forecast versus actual electricity consumption and the annual cumulative electricity savings respectively. As shown in Figure 4-10, annual electricity savings from BEMS is estimated to be about 135 MWh/year, representing approximately 12% of the case building's baseline electricity consumption.

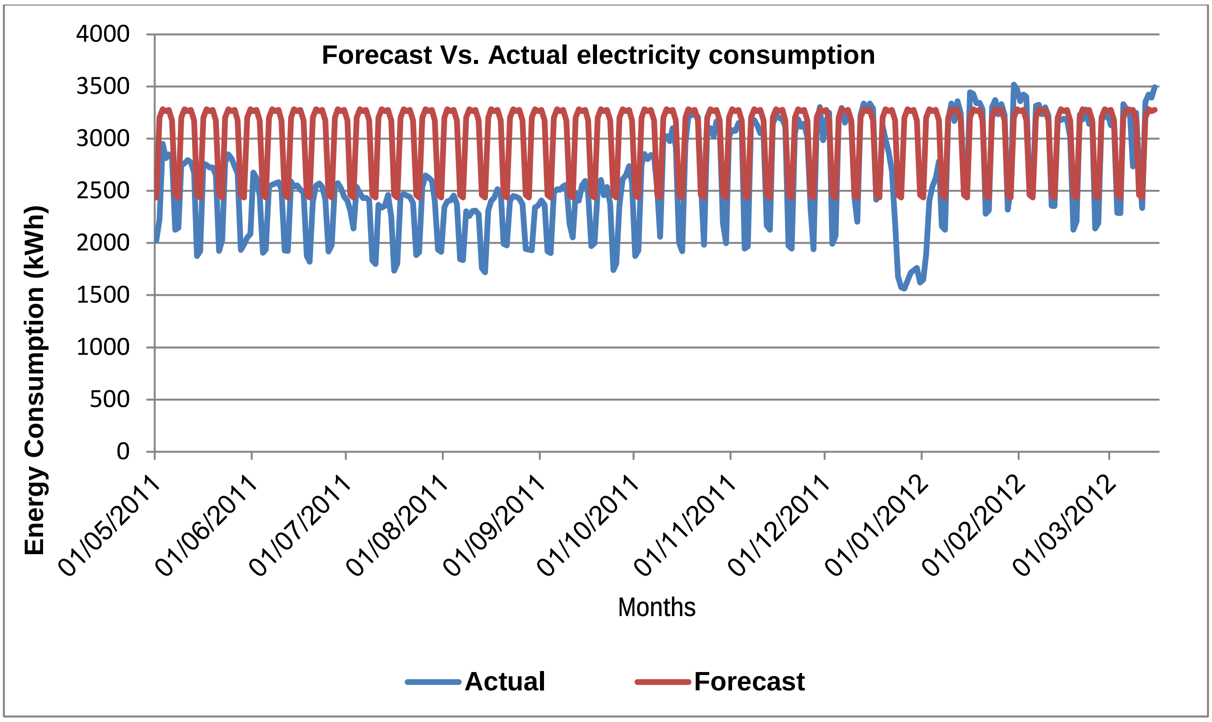



**Figure 4-9: Forecast vs. actual electricity consumption of the case building**

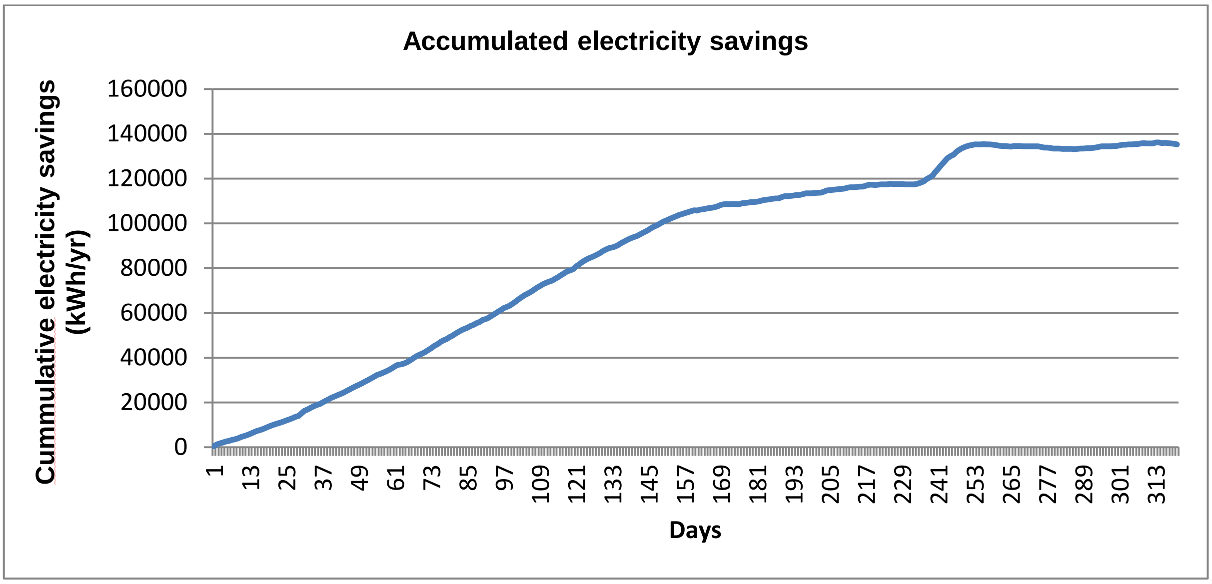



**Figure 4-10: Cumulative savings from electricity consumption due to BEMS installations**

Similarly, Figures 4-11 and 4-12 shows the results of the forecast versus actual gas consumption and the annual cumulative gas savings respectively. As shown in Figure 4-12, annual gas savings from BEMS is estimated to be about 98 MWh/year, which represents about 9% of the case building's baseline gas consumption. This suggests that the total energy (gas and electricity) savings from BEMS is about 21% – a figure that is representative of most reported energy saving estimates from BEMS.

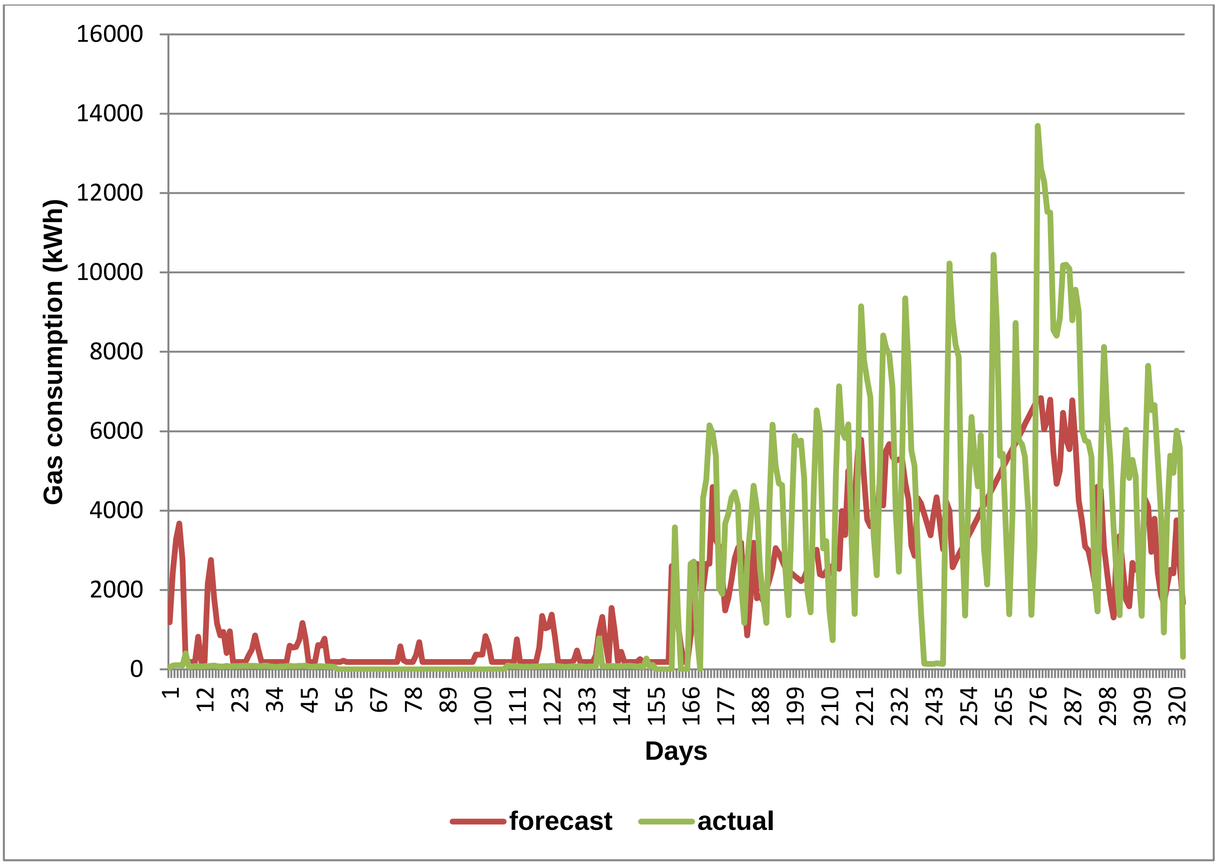



Figure 4-11: Forecast vs. actual gas consumption

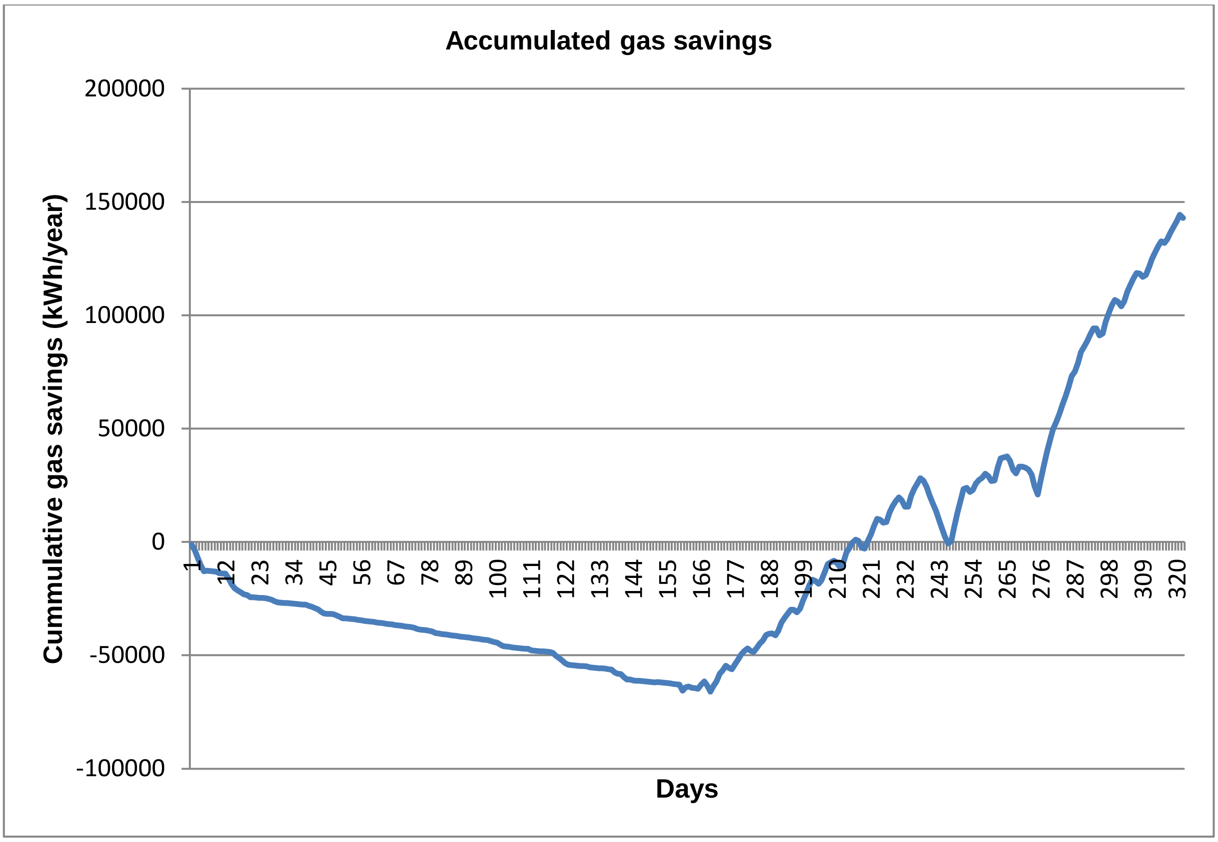



Figure 4-12: Cumulative savings from gas consumption due to BEMS installations

These estimated percentage savings forms the basis of the algorithm used in the flowchart shown in Figure 4-13 as part of the overall emissions savings from BEMS within the decision support system.

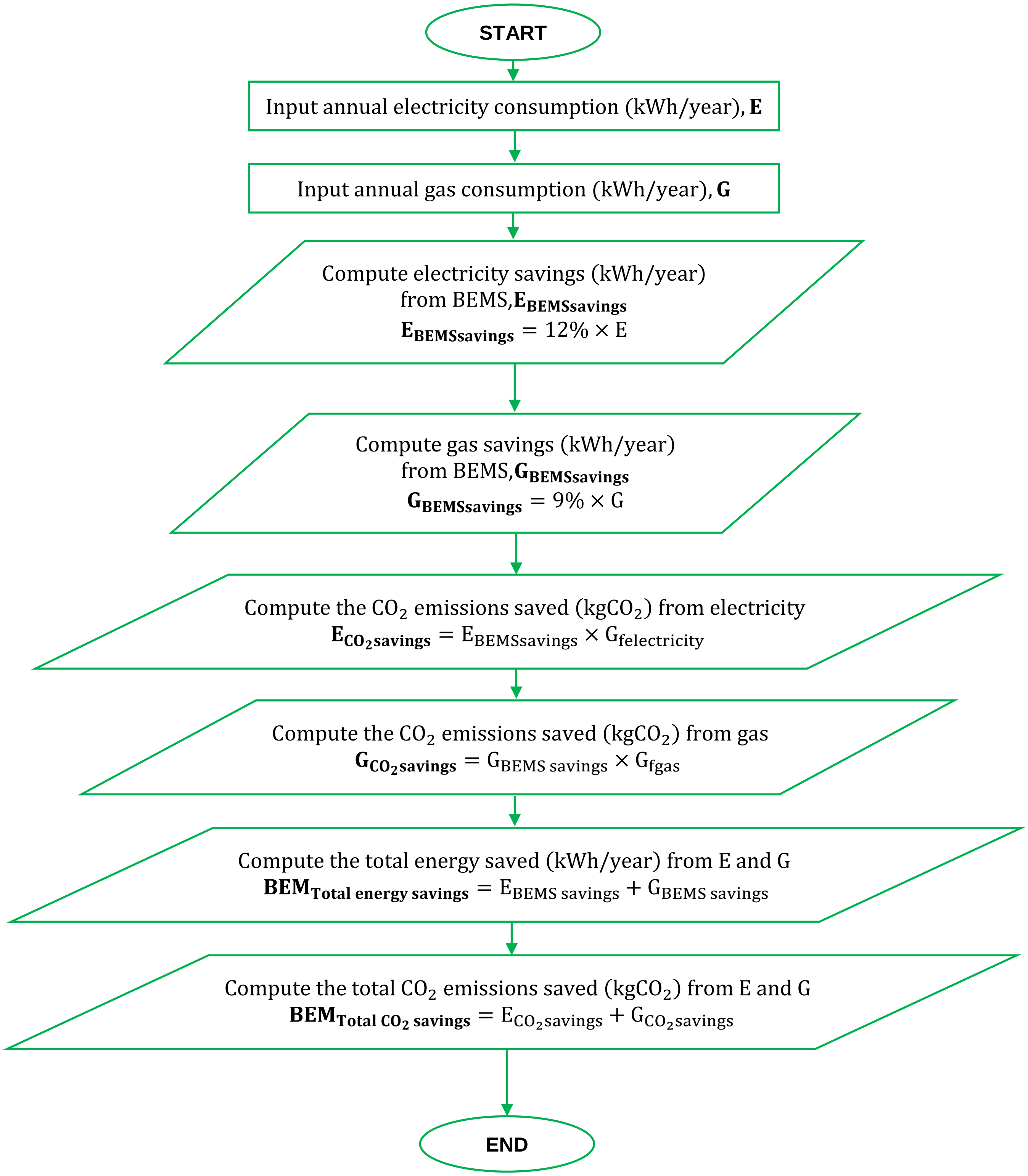



**Figure 4-13: Performance calculation method for BEMS**

### 4.8.10. Voltage optimisation

Voltage optimisation (also known as voltage correction, voltage regulation, voltage stabilisation or voltage reduction) is an electrical energy saving method which involves the installation of a device in series with the electricity mains supply to produce an optimum voltage for the building's facilities and equipment (Power star, 2010). The technique is employed to reduce the difference between the initial voltage supplied and the optimal voltage required by a piece of electrical equipment, thereby reducing loss of energy. Although it is usually not considered the main solution but an integral part of an energy reduction plan (Simmonds, 2011), voltage optimisation is considered as a proven, cost-effective and efficient way to achieving energy and $CO_2$ emissions savings targets. Further details on the theory of voltage optimisation are provided in Appendix A10.

In the context of the current research, the performance analysis approach described in Section 4.8.9 for the estimation of the electricity savings components from BEMS was adopted to estimate the potential energy savings from the implementation of voltage optimisation. This was found to be about 139 MWh/year, representing approximately 12% of electricity savings from the case building's baseline energy consumption. This estimated percentage savings therefore forms the basis of the algorithm used in the flowchart shown in Figure 4-14 as part of the overall emissions savings from voltage optimisation within the decision support system.

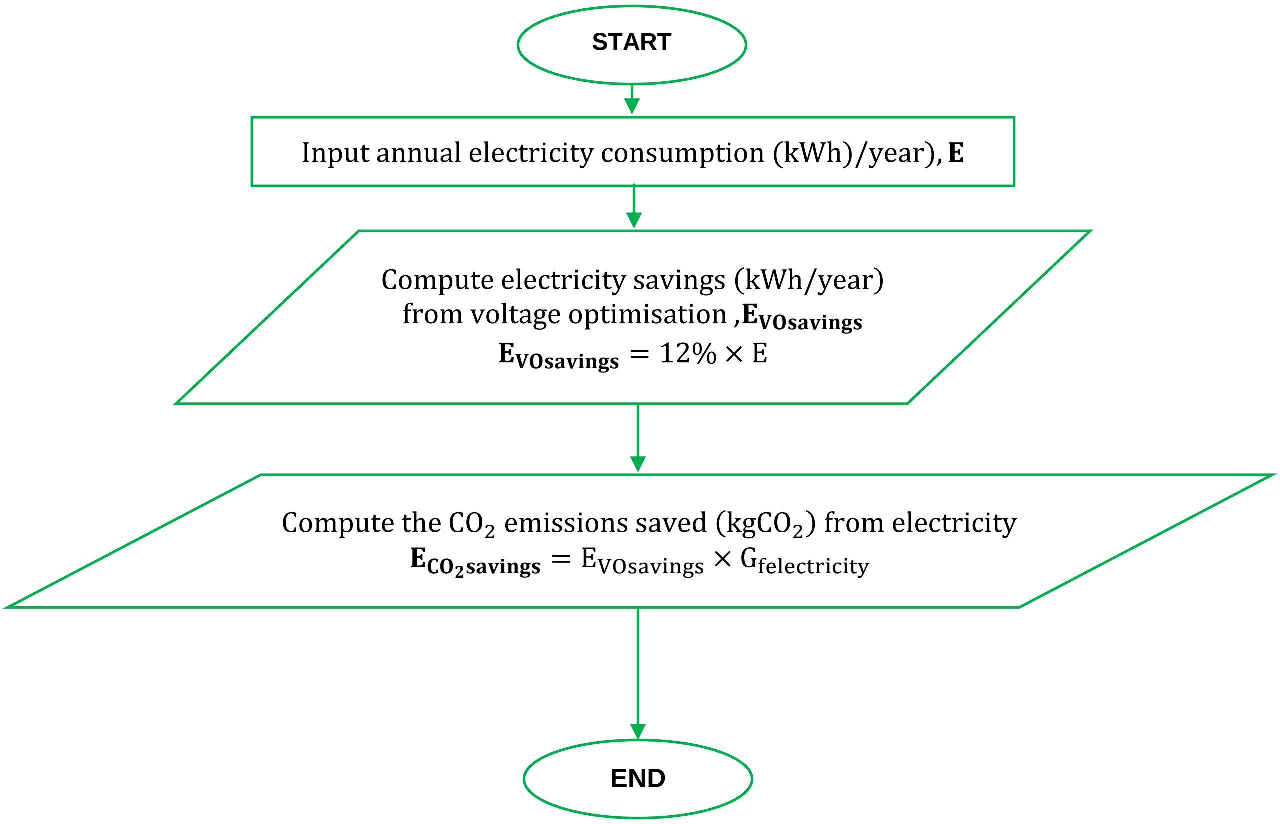



**Figure 4-14: Performance calculation method for voltage optimisation**

### 4.8.11. Thermostatic radiator valves

A thermostatic radiator valve (TRV) is an electromechanical device that is used for controlling a room's temperature as hot water flows through a radiator. A TRV does not control the boiler itself; instead, it just reduces flow of water through the radiator it is installed on when the temperature rises beyond a certain setting. They are installed on radiators on an individual basis and allow the temperature of a room to be varied, with some degree of flexibility. TRVs can be set to any desired level by the user- a lower setting utilises less energy resulting in lower gas bills.

Based upon the fact that TRVs possess the ability to regulate temperature for individual rooms, they are often considered an environmental choice and it has been estimated by the Energy Saving Trust (2010) that TRVs can save 45kg of carbon per year (i.e. 160kg $CO_2e$/year, which is about 900kWh of gas savings per year). Based on this fact, the performance calculation method within the overall DSS framework for estimating the operational emissions saving potentials of TRVs is shown in Figure 4-15. As shown, the user supplies the number of TRVs installed, from which the potential savings are evaluated.

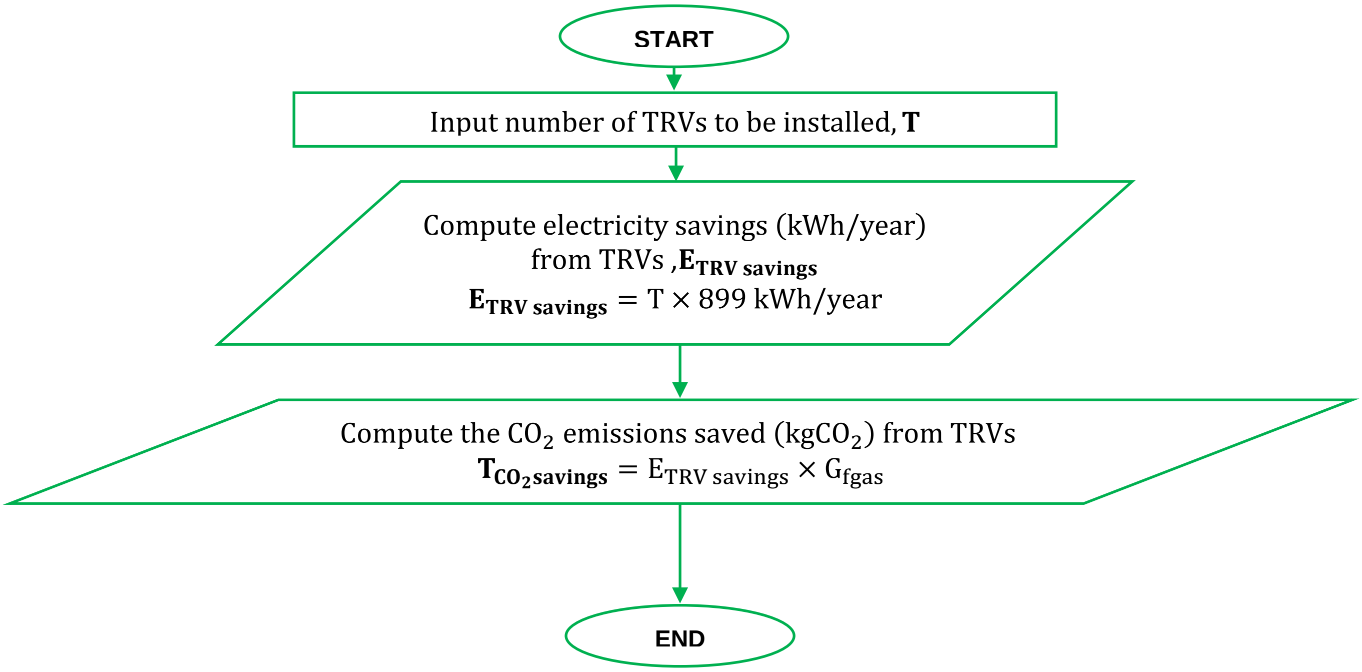



**Figure 4-15: Performance calculation method for thermostatic radiator valves (TRVs)**

### 4.8.12. Switch off PCs

The approach taken to the approximate energy savings from switching off PCs involves the instigation of actual weekend switch off of 500 accessible computers in the case building. The case building has a high electricity base load, averaging 100kWh and remains constant at most times including night, weekends, public holidays, term-time and vacation periods as shown in Figure 4-16.


**Figure 4-16: Case building base load– 1st September, 2010 to 15th October, 2010**

The switch-off in the weekend (16th-17th October, 2010) carried out in the hopes of understanding the base load and the impact of PCs on that load, yielded a clear reduction in the base load of 20kWh (from 100kWh to 80kWh, i.e. a 20% reduction in electrical base load) as depicted in Figure 4-17. Results from detailed analysis of energy consumption based on one year data with the corresponding energy savings estimates from the switch-off promotion data are presented in Brown *et al.* (2012).

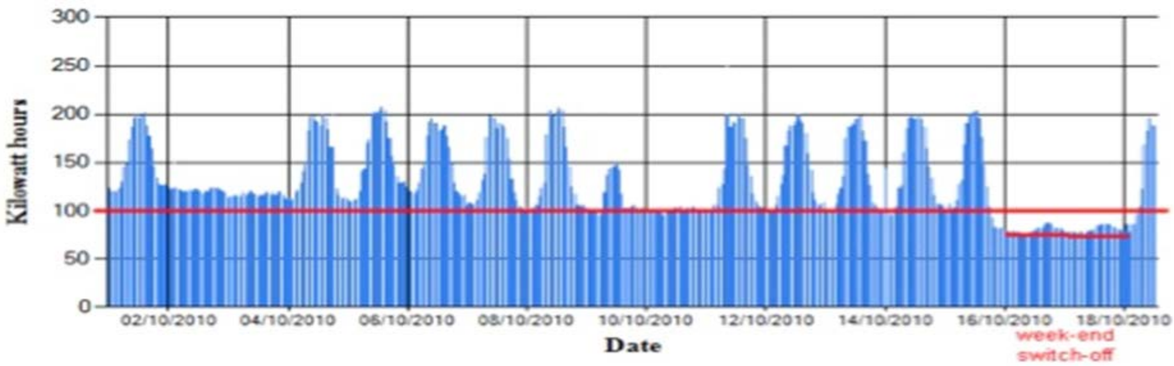



**Figure 4-17: Case building base load– 16th October, 2010 to 18th October, 2010**

The total base load consumption for weekends is not considerably lower, when day and night time consumption is taken into consideration. However, the total consumption for all nights in a week only, sum up to a substantial proportion of the total yearly consumption. The total weeknight and weekend consumption, taking into account daytime yielded a slightly greater amount of energy savings (Brown *et al.*, 2012). By extrapolation to a weeknight campaign, the resulting total electricity saving from a switch-off campaign yielded an annual electricity savings of 110 MWh/year which is about 9.2% of the case building electricity consumption. However, a total weekend switch-off campaign has the potential to save around 12.7% (ibid). This estimated electricity energy savings therefore forms the basis of the calculation procedure illustrated in the flowchart shown in Figure 4-18 as part of the overall estimated emissions savings from switching off PCs within the decision support system.

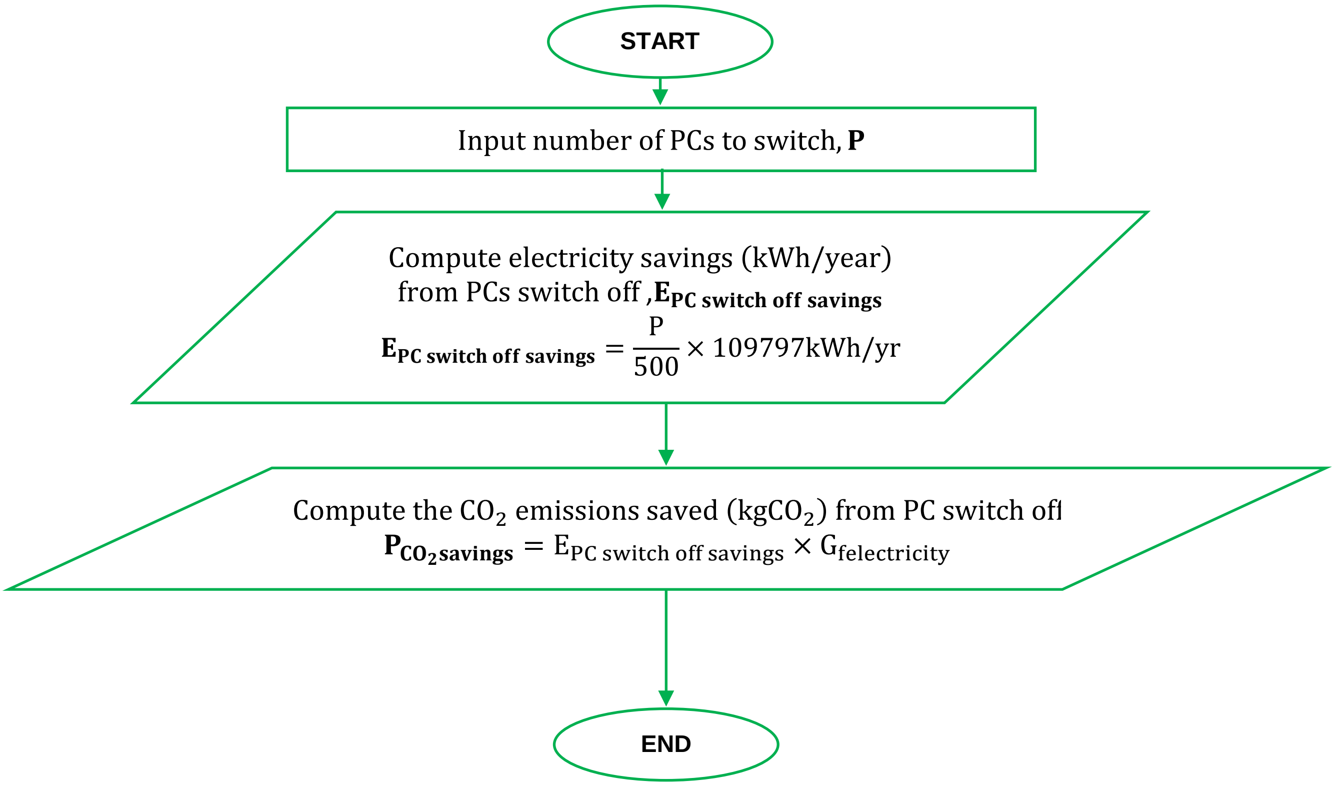



**Figure 4-18: Performance calculation method for PCs switch off**

### 4.8.13. Energy awareness campaign

The assumed performance calculation methods for estimating savings derived from energy awareness campaign is presented in the flowchart in Figure A-10 in Appendix A11.

## 4.9. Module 3-evaluation of initial embodied emissions incurred by options

In this section, details are provided regarding the methodological approach for the evaluation of the initial embodied emissions associated with each of the identified building energy retrofit intervention measures. In the subsections that follow, a detailed description of the underlying methodologies stated in Section 4.4.3 are presented.

### 4.9.1. General input/output (I-O) model

This section describes how the EIO and MRIO methodologies fit into the overall framework of the present DSS. As stated in Section 4.4.3, the calculation of embodied emissions requires an analysis of international trade flow of emissions. The following sections show how this is implemented in the present work. In Chapter two (Section 2.10.2) it was stated that the I-O process utilises economic data of cash flow among various sectors of industry. Barrett and

Scott (2012), Miller and Blair (2009), Ten Raa (2007) etc. provides a comprehensive and easy to understand introduction on the application of I-O method for embodied emissions calculation. The total output of an economy, $x$ can be expressed as the sum of intermediate consumption, $Ax$, and final consumption, $y$:

$$\underline{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y} \quad (4.2)$$

The element $A$ in the Equation 4.2 is the direct requirement matrix of the economy (Miller and Blair, 2009). Matrix $\boldsymbol{I}$ is the identity matrix and $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ the **Leontief Inverse matrix**, named after Wassily Leontief, who developed the I-O analysis framework. He won a Nobel Prize in 1973 in recognition of his achievement. Equation 4.2 represents the basic I-O relationship and can be generalised for an open economy to include imports from other countries or regions (Weber and Mathews, 2007; Wiedmann *et al.,* 2011; Acquaye *et al.,* 2010) as detailed in Section 4.9.2, from which further developments in the methodology are applied in this thesis.

### 4.9.2. Multi-Region Input-Output (MRIO) model

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 (Hertwich and Peter, 2010). It therefore gives an account of the global supply chains of products consumed. The application of MRIO model for estimation of greenhouse gas emissions provides the following advantages (Wiedmann *et al,* 2007; Hertwich and Peter, 2010):

- The MRIO framework is globally closed and sectorally deeply disaggregated. As such, using a model with such a high disaggregation of sectors will facilitate international supply chains tracking and produce more accurate results
- MRIO framework is in tune with current United Nations Accounting Standards (UNAS, 2003). Developing the MRIO framework in conjunction with the current normalization of the carbon footprint methodology has the capacity to strengthen and provide credibility to a footprint accounting standards
- Implementing an MRIO will assist in overcoming uncertainties in energy or emissions intensities of imported goods and services. This is achievable, since links from all international trade, including direct and indirect, are potentially accounted for. This will further add to the accuracy and comprehensiveness of emissions associated with international trade.

- MRIO framework combines, in a robust way, the matrices of domestic or local technical coefficient with the matrices of import from numerous countries or regions into one big coefficient matrix. This has the overall influence of capturing the supply chains associated with trade between all the participating trading partners as well as provide feedback pathways and effects.

There are two major types of dataset required for MRIO models namely, input-output tables for individual region and the corresponding environmental emissions database. In this study, the 2-region MRIO data expanded upon by Wiedmann *et al.* (2010) to include MRIO tables split between the UK and Rest-of-the-World (ROW) were used. Unit cost (£/unit; example £/$kW_p$) of the abatement options under consideration are obtained from various sources which include: SPON's Architects and Builders Price Book (2011); SPON's Mechanical and Electrical Services Price Book (2011); CESMM3 Price Database (2011); costing information from: Salix Finance, Carbon Trust, department for communities and local government, DCLG (2008), manufacturers; a range of publicly available cost information on retrofit projects as well as reliable cost information from energy managers.

### 4.9.3. Application of the MRIO model within the DSS

The MRIO model used in environmental EIO analysis can be presented as a 2-region model; see for instance McGregor *et al.* (2008) who used a two-region MRIO model to enumerate embodied $CO_2$ emissions in inter-regional trade flows between the rest of the UK and Scotland. In this thesis, the Supply and Use format within a two-region (UK and the Rest of the World, ROW) I-O framework is adopted (See (Wiedmann *et al.,* 2011)). As reported by EUROSTAT (2008), the advantages of Supply and Use tables as an integral part of the national accounts lies in the fact that it has a stronger level of detail which ensures that there is a higher degree of homogeneity of the individual product and therefore better possibilities for determining categories of uses and consequently the environmental impacts. Additionally, it allows for the splitting of emissions as a result of using supply chain inputs either sourced from the UK or from the ROW. The methodology encompassing this MRIO approach and developed within the EIO methodology is presented below. Following on from defining the technical coefficient matrix $\boldsymbol{A}$, the I-O system in this thesis is setup as a MRIO system $(\mathrm{A_{io}})$ presented in the Supply and Use format as shown in Figure 4-19.

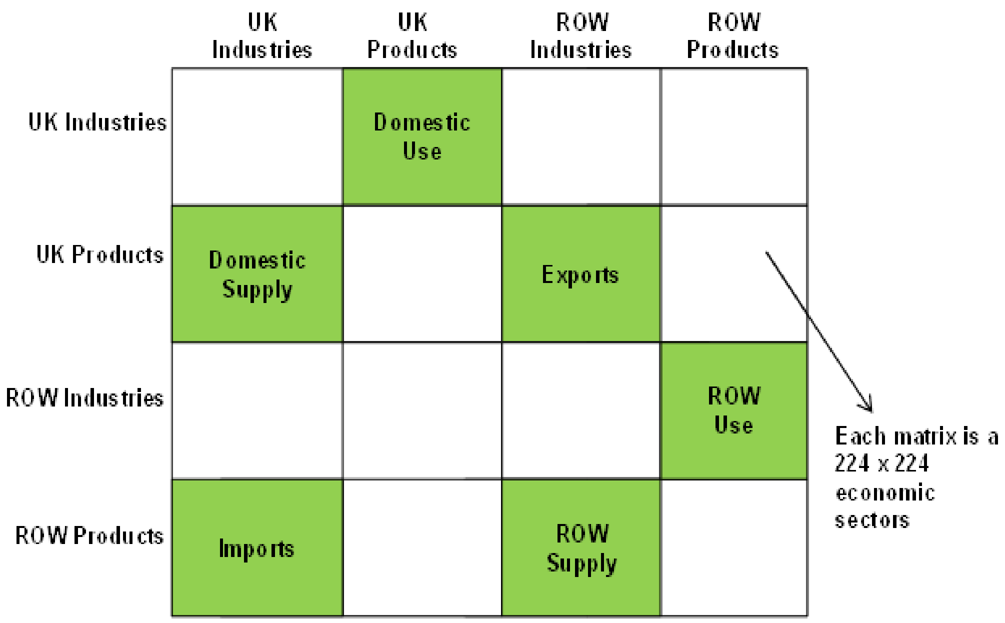



**Figure 4-19: Framework for MRIO in the Supply and Use format (Kanemoto *et al.,* 2011)**

In matrix representation, Figure 4-19 becomes:

$$A_{io} = \begin{bmatrix} 0 & \boldsymbol{A}_{(UK),U} & 0 & 0 \\ \boldsymbol{A}_{(UK),S} & 0 & \boldsymbol{A}_{(UK),EXP} & 0 \\ 0 & 0 & 0 & \boldsymbol{A}_{(ROW),U} \\ \boldsymbol{A}_{(UK),IMP} & 0 & \boldsymbol{A}_{(ROW),S} & 0 \end{bmatrix} \quad (4.3)$$

Where $A_{io}$ becomes the 2-region (UK and ROW) MRIO technical coefficient matrix. This includes the respective technical coefficient matrices for UK Domestic Use, $\boldsymbol{A}_{(UK)U}$, UK Domestic Supply, $\boldsymbol{A}_{(UK)S}$, UK Export to ROW, $\boldsymbol{A}_{(UK)EXP}$, ROW Use, $\boldsymbol{A}_{(ROW)U}$, UK Imports from ROW, $\boldsymbol{A}_{(UK)IMP}$ and ROW Supply to ROW, $\boldsymbol{A}_{(ROW)S}$. All of the individual $\boldsymbol{A}$ matrices are of dimensions $224\, x\, 224$; hence, both $A_{io}$ and $\boldsymbol{I}$ (the Identity Matrix) have a dimension $896\, x\, 896$.

The Technical Coefficient Matrix for UK Imports from ROW, $\boldsymbol{A}_{(UK)IMP}$ , for example, is defined as:

$$\boldsymbol{A}_{(UK)IMP} = \left[\frac{q_{ij}^{(ROW,UK)}}{x_j}\right] \quad (4.4)$$

Where: $q_{ij}^{(ROW,UK)}$ represents elements of UK imports input-output table from the ROW region representing the input of product $(i)$ from ROW into the industry $(j)$ of the UK while $x_j$ represents the total output of UK industry, $(j)$.

Given that requirements of supply chain inputs needed for the production of a given retrofit intervention option can be as a result of domestic (or UK) supplies or ROW supplies, the final demand matrix can be presented as shown below:

$$\boldsymbol{y} = \begin{bmatrix} \underline{y}_{(UK,UK)} & \underline{y}_{(UK,ROW)} \\ \underline{y}_{(ROW,UK)} & \underline{y}_{(ROW,ROW)} \end{bmatrix} \tag{4.5}$$

Where: $\underline{y}_{(UK,UK)}$ and $\underline{y}_{(ROW,ROW)}$ represents UK final demand for UK products and ROW final demand for ROW products respectively. Likewise, $\underline{y}_{(UK,ROW)}$ and $\underline{y}_{(ROW,UK)}$ represents ROW final demand for UK products and UK final demand for ROW products respectively. Indeed, by interconnecting the domestic and ROW input-output tables into a 2-region MRIO table, the model is able to capture all indirect upstream requirement that are needed to produce all the individual supply chain inputs either from resources from the UK or from outside the UK (that is ROW). In this study, it is assumed that the UK demand for products produced in the UK or from the rest of the world, hence $\underline{y}_{(UK,ROW)}$ and $\underline{y}_{(ROW,ROW)}$ are set to zero and the final demand matrix becomes a column matrix (dimension $896\ x\ 1$):

$$\underline{y} = \begin{bmatrix} \underline{y}_{(UK,UK)} \\ \underline{y}_{(ROW,UK)} \end{bmatrix} \tag{4.6}$$

Following on from the basic I-O equation, the total (direct and indirect) requirements needed by an industry to produce a given final demand using the MRIO model become:

$$\underline{x} = \left( [I] - \begin{bmatrix} 0 & \boldsymbol{A}_{(UK),U} & 0 & 0 \\ \boldsymbol{A}_{(UK),S} & 0 & \boldsymbol{A}_{(UK),EXP} & 0 \\ 0 & 0 & 0 & \boldsymbol{A}_{(ROW),U} \\ \boldsymbol{A}_{(UK),IMP} & 0 & \boldsymbol{A}_{(ROW),S} & 0 \end{bmatrix} \right)^{-1} \cdot \begin{bmatrix} \underline{y}_{(UK,UK)} \\ \underline{y}_{(ROW,UK)} \end{bmatrix} \tag{4.7}$$

This forms the basis of an environmentally extended MRIO model applied within the DSS.

### 4.9.4. Environmentally extended MRIO Model

Input-Output framework can be extended to an Environmental Input-Output (EIO) methodology to generate results which can be used in the embodied emissions calculations of products. By adding environmental information, such as GHG emissions, to each sector, an environmental burden (a "footprint") can be assigned to the financial transactions associated with the purchase of a product. This characterises the environmental impact of an additional unit cost of output from each industry.

Let $\mathbf{E} = \{\mathbf{e_{kj}}\}$ be the vector of environmental effect or environmental extension matrix (i.e. the total emissions (6 GHGs) emitted to produce the total output of each industry); **X** be the total output. The EIO methodology can therefore be defined in a generalised form as:

$$\underline{E} = \boldsymbol{E_{io}} \cdot \underline{x} = \boldsymbol{E_{io}} \cdot (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y} \qquad (4.8)$$

Where $\boldsymbol{E_{io}}$ is the direct emissions intensity (kg $CO_2$-eq/£) of the I-O industries.

Let the total (direct and indirect) emissions intensities be $\mathrm{T_{IM}} = \boldsymbol{E_{io}}.(\mathrm{I} - \mathrm{A})^{-1}$, measured in (kg $CO_2$-eq/£). It then follows that

$$\mathrm{E} = \mathrm{T_{IM}}.\underline{y} \qquad (4.9)$$

Hence total lifecycle emissions, E, ($kgCO_2e$) from a product is given by the matrix multiplication of

$$\text{Total (direct and indirect) emissions intensities matrix } (\mathrm{KgCO_2e/£}) \times \text{Final demand (£) for that product} \qquad (4.10)$$

The final demand given in monetary quantities (£) is calculated by multiplying the physical quantity in which a low carbon intervention 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 $(n \; x \; 1)$ as shown in Equation 4.6. Figure 4-20 illustrates a summary of the environmentally extended EIO methodology.

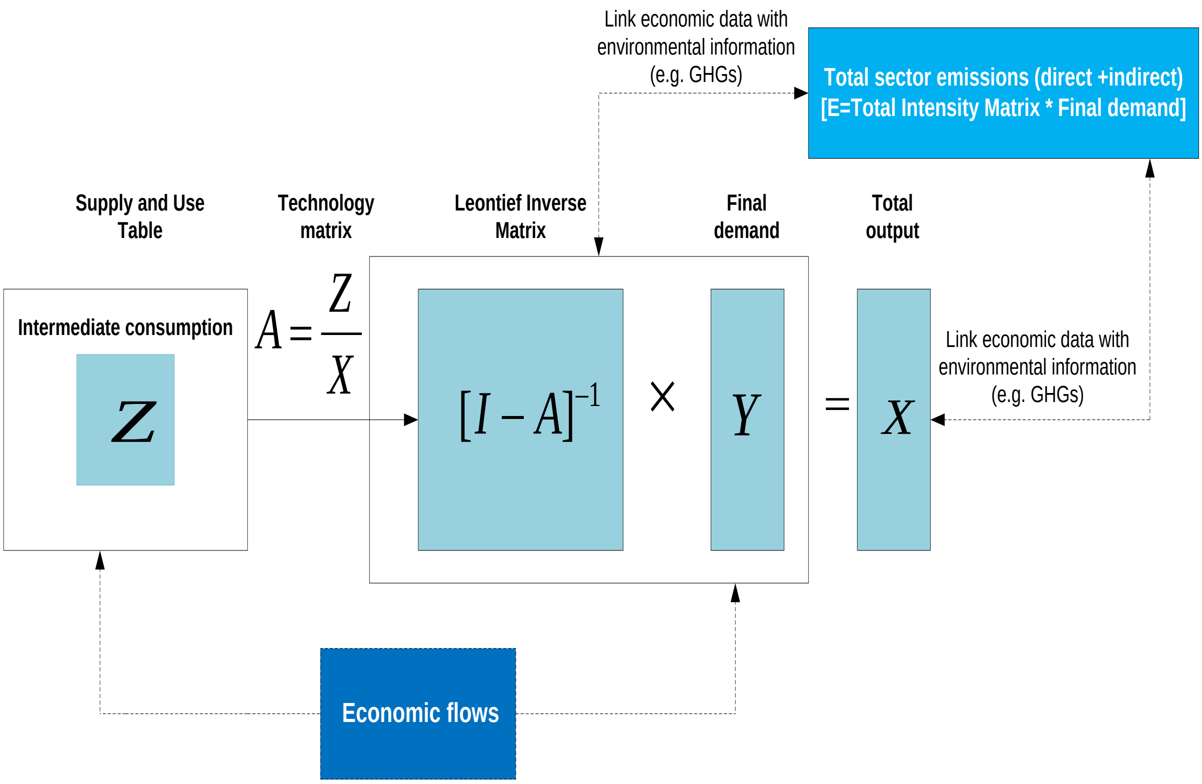



**Figure 4-20: Generalised environmentally extended input-output framework**

By extending the principles described above within a MRIO framework, the matrix $\boldsymbol{E_{io}}$ expressed in terms of the MRIO Supply and Use structure becomes:

$$\boldsymbol{E_{io}} = \begin{bmatrix} \hat{E}_{UK} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \hat{E}_{ROW} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{4.11}$$

Where $\hat{E}_{UK}$ and $\hat{E}_{ROW}$ are respectively the diagonalised direct emissions intensity (Sector emissions in kg $CO_2$-eq per total output in £) of each industrial sector in the UK and the ROW. Hence, the environmental-extended MRIO methodology takes the following form, where the matrix $(\underline{EE})$ describes the total embodied emissions:

$$\begin{bmatrix} \hat{E}_{UK} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \hat{E}_{ROW} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \left( [I] - \begin{bmatrix} 0 & \boldsymbol{A}_{(UK),U} & 0 & 0 \\ \boldsymbol{A}_{(UK),S} & 0 & \boldsymbol{A}_{(UK),EXP} & 0 \\ 0 & 0 & 0 & \boldsymbol{A}_{(ROW),U} \\ \boldsymbol{A}_{(UK),IMP} & 0 & \boldsymbol{A}_{(ROW),S} & 0 \end{bmatrix} \right)^{-1} \cdot \begin{bmatrix} \underline{y}_{UK,UK} \\ \underline{y}_{ROW,UK} \end{bmatrix} \tag{4.12}$$

This environmentally extended MRIO methodology described above forms the basis for calculating the embodied emissions associated with all intervention options considered in the overall decision support system.

### 4.9.5. Implementation of the environmentally extended MRIO model within the DSS

The abatement options under consideration are unified into a comprehensive 2-region (UK and Rest of the World) MRIO framework presented in Figure 4-19 and executed in Figure 4-21. 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 4-19 which consists of 4 segments with each containing $224 \times 224$ 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 $896 \times 896$ matrix.

Following on from Equation 4.6, the final demand for a given intervention option is also constructed using the same principle. As shown previously, assuming a UK demand, the Final

Demand matrix takes the form of a $896 \times 1$ matrix. If the $896$ rows in the Final Demand matrix are segmented to conform to the Supply and Use structure, Segment 1 (row 1-224) and Segment 3 (row 449 to 672) are 0 because they match the UK and ROW industries respectively. The intervention options are categorized either as produced domestically in the UK or imported from the ROW and are appropriately recorded as demand for UK products (Segment 2 or row 225 to 448) or demand for ROW products (Segment 4 or row 673 to 896). This is done using the appropriate economic sector according to the Standard Industry Classification (SIC) for the UK. Table 4-1 shows the intervention option under consideration, their standard industry classification and location of manufacture.

**Table 4-1: Standard Industry Classification and location of manufacture of options**

| **Retrofit option** | **Sector ID** | **Standard Industry Classification and Sector Description (SIC 2003 mapped with SIC 2007)** | **Location identifier in (S&U) table** | **Final Demand Location** |
|---|---|---|---|---|
| Photovoltaic | 137 | Electronic valves and tubes and other electronic components | B364 | Domestic |
| | | | B812 | ROW |
| Wind turbine | 126 | Machinery for the production and use of mechanical power, except aircraft, vehicle and cycle engines | B353 | Domestic |
| | | | B801 | ROW |
| Solar Hot Water | 127 | Other general purpose machinery | B354 | Domestic |
| | | | B802 | ROW |
| Combined Heat and Power (Micro CHP) | 163 | Steam and hot water supply | B390 | Domestic |
| | | | B838 | ROW |
| Ground Source Heat Pump | 126 | Machinery for the production and use of mechanical power, except aircraft, vehicle and cycle engines | B353 | Domestic |
| | | | B801 | ROW |
| Voltage optimisation | 134 | Electric motors, generators and transformers; manufacture of electricity distribution and control apparatus | B361 | Domestic |
| | | | B809 | ROW |
| Efficient lighting (LEDs) | 137 | Electronic valves and tubes and other electronic components | B364 | Domestic |
| | | | B812 | ROW |
| BEMS | 134 | Electric motors, generators and transformers; manufacture of electricity distribution and control apparatus | B361 | Domestic |
| | | | B809 | ROW |
| Biomass boiler | 122 | Tanks, reservoirs and containers of metal; manufacture of central heating radiators and boilers; manufacture of steam generators | B349 | Domestic |
| | | | B797 | ROW |
| Thermostatic Radiator Valves | 126 | Machinery for the production and use of mechanical power, except aircraft, vehicle and cycle engines | B353 | Domestic |
| | | | B801 | ROW |
| Passive Infrared (PIR) Sensors | 140 | Medical, precision and optical instruments, watches and clocks | B367 | Domestic |
| | | | B815 | ROW |

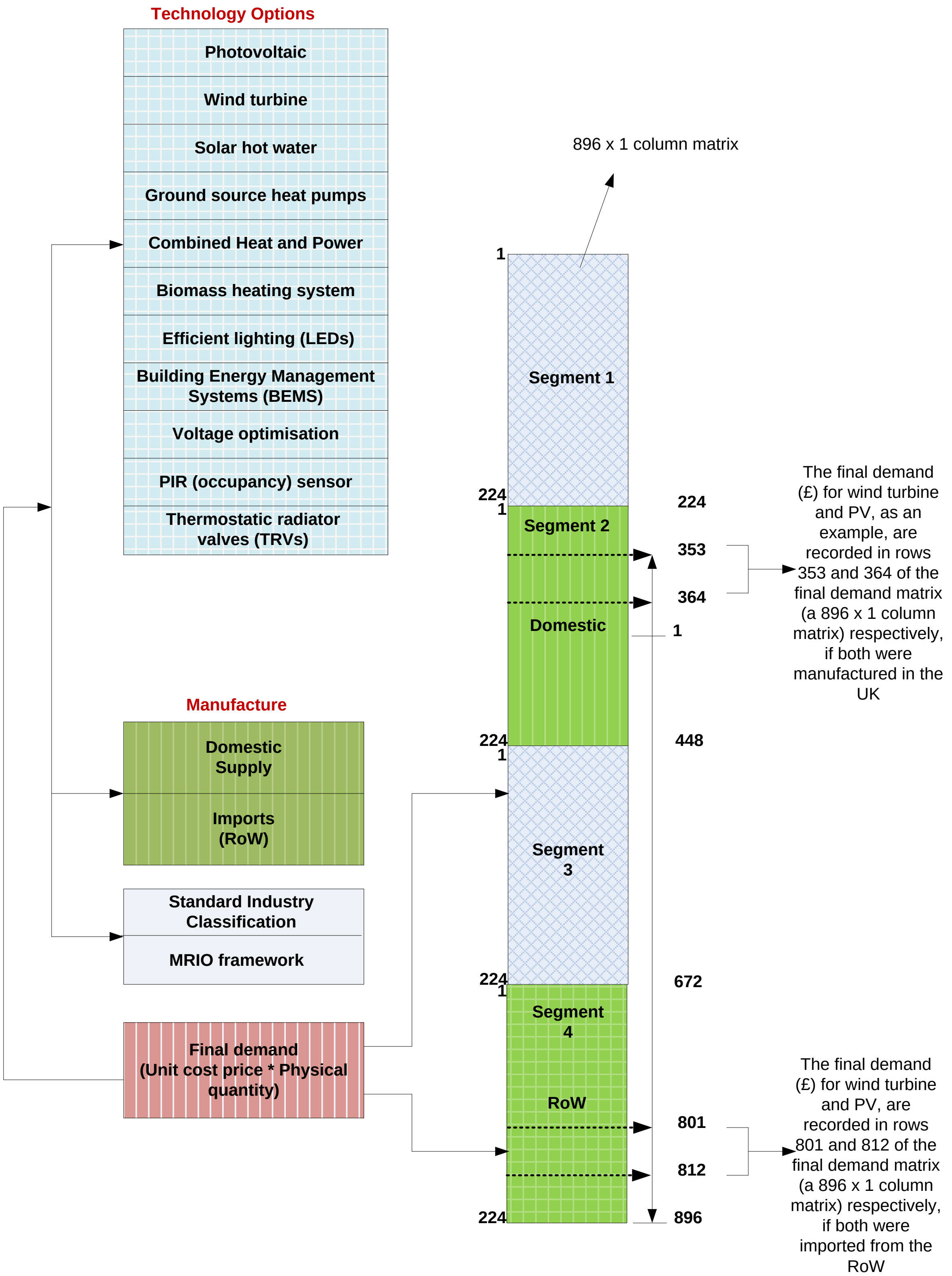



**Figure 4-21: Evaluation of embodied emissions using EIO within a MRIO Framework in the DSS**

As an example, assuming the embodied emissions of a $15\text{kW}_\text{e}$ micro wind turbine at $£2{,}500/\text{kW}_\text{e}$ is to be evaluated. The final demand, $\underline{\boldsymbol{y}}$, is equivalent to: $15\text{kW}_\text{e} \times £2{,}500/\text{kW}_\text{e} = £37{,}500$. Using the UK SIC, wind turbines are classified under *machinery for the production* *and use of mechanical power, except aircraft, vehicle and cycle engines.* This corresponds to sector 126 in the format of the supply and use (S&U) table used for this analysis. If the wind turbines were manufactured in the UK (i.e. domestic), then the demand for UK produced wind turbines corresponding to £37,500 is recorded in the final demand matrix (an 896 x 1 column matrix) corresponding to row 353 in the format of the supply and use as illustrated in Figure 4-21. On the other hand, if the wind turbine were manufactured outside the UK (i.e. imported from the RoW), then the final demand of £37,500 is recorded in the final demand matrix corresponding to row 801. The matrix multiplication of the total (direct and indirect) emissions intensities matrix (TIM) and final demand ($\underline{\boldsymbol{y}}$) is then carried out to obtain the embodied emissions associated with the wind turbine. The procedure is repeated for all the low carbon intervention options under consideration in this thesis.

### 4.9.6. Limitations of the evaluation approach to embodied emissions

There are certain limitations arising from the method used in the calculation of embodied emissions within the DSS which may culminate into uncertainties. For instance, heterogeneity of products within industry classification, which negates the proportionality and homogeneity assumptions (Acquaye *et al,* 2010) still, constitutes a problem in the EIO model. A large number of the 224 industrial sectors captured in the Supply and Use table consist of diverse products. Even the standard industry classifications (SIC) codes are quite broad, in that the SIC group, for example, sector 126-*machinery for the production and use of mechanical power, except aircraft, vehicle and cycle engines*, does not consist of homogeneous products produced from identical inputs and processes as in the case of wind turbines and Ground Source Heat Pump which are classified under the same sector 126. EIO method considers the environmental impacts of the total product mix in a given sector, resulting into potential errors from sector aggregation.

In EIO analysis, a physical quantity (e.g. GJ, kWh, $m^2$, $kW_p$ etc.) is required to be converted into economic quantity such as energy tariffs (e.g. £/$kW_p$). It follows that embodied emissions becomes dependent on unit cost and consequently, embodied emissions increases when unit cost also increases. However, several studies including Miller and Blair (2009); Acquaye (2010); Pullen (2000) and Treloar *et al.* (2001) reports that national average energy tariffs, for instance, are not representative across all industries since prices differ due to negotiated energy tariffs in certain industries. To this end, the use of average energy tariffs in the computation of embodied emissions reduces the accuracy of results.

In principle, the process-based approach to evaluation of embodied emissions can be adopted to carry out comparison of various types of a particular product. However, the approach cannot produce equally confident estimates in all comparisons (Acquaye, 2010; Dixit *et al*., 2010). In comparing different processes, products or materials, the complete range of both direct and indirect use of material resources and impacts are vital (Lave *et al.,* 1995). For instance, the differences due to indirect environmental impacts of different PIR sensors are probably infinitesimal, so that if a constricted systems boundary is drawn around the comparison, it will be appropriate. In contrast, comparing a monocrystalline (single-crystalline) PV module with amorphous silicon PV modules cannot be performed with confidence by making use of a narrow system boundary, since different production processes and raw materials are utilised.

The EIO method used within the present DSS focuses on the quantification of the complete range of both direct and indirect effects and their corresponding environmental consequences in terms of embodied emissions. The method is best suited for comparing aggregate, disparate processes or products and cannot differentiate between dissimilar forms of the same product types, but it provides the advantages of tracking all the complete direct as well as indirect implications of a processes, products or materials (Dixit *et al*., 2010; Wiedmann, 2010; Lave *et al.,* 1995). So if a potential user the current DSS wishes to undertake an analysis to determine which form of a PV module (or any other product) has better environmental credentials then the DSS would not be useful. The inability of EIO approach adopted within the DSS to address detailed comparisons is not an intrinsic limitation. With more detailed and far-reaching data, such as those from a process-based approach, and a two-step methodology, known as hybrid-based approach (Nielsen and Wiedmann, 2001; Mattila *et al.,* 2010; Acquaye, 2010) which integrates process and I-O approach, can yield credible results that has the advantages of both in terms of detail and completeness as well as accuracy and precision.

The monetary transactions and environmental impacts associated with both domestic and imports of products are captured in the current DSS model based on the MRIO framework. However, researchers such as Machado *et al*., (2001); Lenzen (1998); Battjes *et al.,* (1998) and Kondo *et al. (*1998) have all carried out EIO analysis within a MRIO framework under the common assumption that imported commodities are manufactured using similar technology as that of the domestic economy. Lenzen *et al.* (2004) used the term "autonomous regions" to describe the importation assumption while Stromman and Gauteplass (2004) described it as "mirrored economy" and both of them agreed that the assumption minimises the requirements for data collection, but may lead to potential errors (Hertwich and Peter, 2010) for embodied emissions associated with imports in situations where the participating countries have different technologies for manufacturing processes and energy mix (Lenzen *et al.,* 2004; Hertwich and Peter, 2010).

In this thesis, a 2-region MRIO IO model interlinking the UK and the Rest of the World (ROW) was adopted. Aggregation of the other entire world countries into a single region is a limitation as there are technology differences between different countries. Additionally, in instances where the UK is an importer, distinct supply chains between country of production and the UK cannot be established. As efforts are been made to build a global MRIO model with distinct country specific data (Lenzen *et al.,* 2013), this research can be extended in the future to overcome the data issue and limitations.

The data employed to build a MRIO framework for a variety of regions is likely to emerge from differing time periods. As such, adjustments to take into account the effect of inflation are required to make the data consistent for a given base year. The I-O data used in this research was for the baseline year of 2008. To adjust for inflation, the easiest approach is to use the Consumer Price Index (CPI) in each country (Peters and Hertwich, 2004). Ideally, in the context of this research, the 2008 unit prices for the intervention options can be used in the analysis to deflate the current prices to 2008 prices by using the CPI. However, this was not done because in instances where the intervention options are imported, a CPI for the Rest of the World would seem quite ambiguous to calculate, since a two region model was adopted. Additionally, even if it were possible to calculate the CPI, it is still likely to introduce other errors. This stems from the fact that CPI is an aggregated index, while price changes are likely to be different in each of the I-O sectors (Hertwich and Peter, 2010). Further, the CPI also varies depending on the base year used and the method of indexing applied (ibid). Accordingly, these issues are difficult to resolve and the errors will be bigger for a large CPI especially when there is a big difference in base years.

Other identifiable sources of error for Input-Output calculations include varying energy and materials prices; assumptions related to future energy costs and variation in years between the I-O model and cost data; and methods of data collection as reported by Pullen (2007). The age of the data also constitute a major source of error. For instance, the published 2008 input-output data for the UK is based on 2004-2006 data and published Leontief tables for the UK are based on 1995 data (Office for National Statistics, 2009). As technology changes over time, the use of older data may culminate into less accurate values. Input-Output tables are published periodically while energy prices changes irregularly because they are dependent on economics forces. As such, I-O tables for a given period of time may not match current energy prices. Because I-O tables are produced periodically, it is assumed that the technology matrix for each industry (i.e. the production mix ratios of supply chain input required by an industry to produce a unit output) remains the same between the periods it takes to produce the I-O tables. As such, it is also assumed that changes to energy prices do not affect an industry's technology matrix for the period of time it takes to produce an I-O table. Nevertheless, further research into dynamic I-O analysis can shed more light on the subject.

Despite these limitations, the methodology provides standardised, uniform and faster way of calculating reasonable embodied emissions estimates for the intervention options captured within the DSS (Crawford, 2008). The inexpensive nature of the analysis is another major merit because an EIO analysis can be completed within a short period of time without additional data, once the transaction matrix is available (Lave *et al.,* 1995).

### 4.9.7. Estimation of energy payback period

The Energy Pay Back Period (EPBP) can be described as the time in years taken for an energy-producing or energy-saving system to produce the amount of energy that will be consumed by the system across its lifespan, including disposal and end of life scenarios. In order to evaluate the EPBP of an energy-producing system using a simple approach, it is important to have knowledge of the embodied energy as well as energy output (e.g. kWh) from the system per year. The EPBP can then be evaluated by dividing the embodied energy by the annual energy output. The value obtained gives an estimate of how long it will take before energy investment is compensated by the energy generated. It can be mathematically expressed as:

$$\text{EPBP} = \frac{\text{Embodied emissions } (\text{tCO}_2\text{e})}{\text{Emissions savings } (\text{tCO}_2\text{e/year})} \tag{4.13}$$

By extension, the Embodied $CO_2$ ($ECO_2e$) emissions per year of a given system with a life span of *x* years can be calculated as:

$$\text{Embodied CO}_2 \text{ emissions per year} = \frac{\text{Embodied emissions } (\text{tCO}_2\text{e})}{\text{Lifetime of system (years)}} \tag{4.14}$$

## 4.10. Module 4-economics evaluations

This section describes the assessment of the cost or benefit of each low carbon retrofit intervention option under consideration within the DSS.

### 4.10.1. Computation of cost of energy saved/generated

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: (i) energy saved or energy generated (kWh) per annum by the option; (ii) equivalent $CO_2$ saved per annum by an option as a function of the base case building energy consumption; (iii) total investment cost of the option; (iv) cost of energy (gas and electricity).

From the above data, the cost of energy saved or generated (£) per annum is calculated. This is given as:

$$\text{Energy saved or generated (kWh)} \times \text{cost of energy(£/kWh)} \qquad (4.15)$$

The cost of energy is the cost of gas and electricity associated with an option. Finally, the effect of Government's incentives and tariffs such as Feed-in-Tariff (FiT) and Renewable Heat Incentives (RHI) on a number of renewable energy technologies are evaluated.

### 4.10.2. Net Present Value (NPV) of cost of energy saved/generated

To calculate the cost-effectiveness (i.e. abatement cost of a tonne of $CO_2$), the Net Present Value (NPV) of the abatement project, which measures the profitability or the cost of the project, must be known. In capital budgeting, the NPV concept is used to analyse the extent to which an investment or project is profitable. It denotes the discrepancy between the present value of the future cash flows derived from an investment and the amount invested. This allows cash flows happening over a wide time frame to be considered at their value at today's prices. The present value of the expected cash flows is calculated by discounting them at the specified rate of return. A positive NPV implies that the project or investment is profitable and a negative NPV suggests that the investments costs are greater than the expected benefits.

In the current DSS, the Net Present Value (NPV) of the cost of energy saved or generated is calculated by discounting all future savings to their equivalent present value using the formula (Gorgolewski, 1995):

$$\mathrm{NPV} = \mathrm{C}\left[\frac{1-(1+\mathrm{r})^{-\mathrm{n}}}{\mathrm{r}}\right] \qquad (4.16)$$

Equation 4.16 gives the net present value, $\boldsymbol{NPV}$, for an annual energy saving, $\boldsymbol{C}$, occurring for $n$ number of years with a real discount rate of $\boldsymbol{r}$. The main concern with the calculation of NPV is the careful selection of an appropriate discount rate. The discount rate is defined as the minimum level of return on investment that an organisation deems acceptable. It is used in calculating the NPV, and can have significant consequences on the cost-effectiveness of abatement projects. Figure 4-22 gives an illustration and details regarding the effects of discount rate on cost-effectiveness are discussed in Section 4.15.

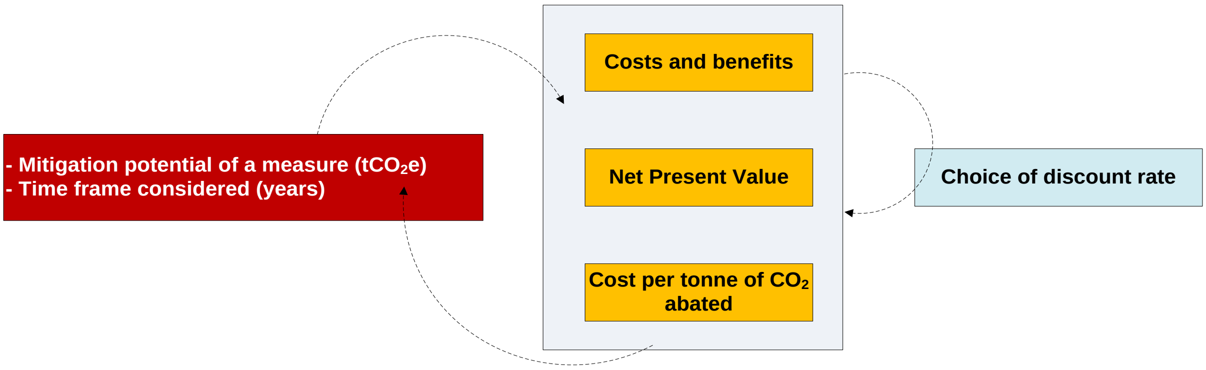



**Figure 4-22: Relationship between economic data and mitigation potential**

## 4.11. Module 5 - system optimisation, performance criteria evaluation and ranking

The viability of retrofit options are usually evaluated using the concept of cost-effectiveness, measured in pounds per tonne of $CO_2$ or equivalent as detailed in Chapter two (Section 2.13). The criterion is used to identify the economically most efficient way to fulfil the objective by comparing the relative costs and emissions saving potentials of different retrofit options. However, in Section 2.14.1, a fundamental flaw about the ranking criterion was identified and the need for an alternative ranking approach was highlighted.

Given the formula for computing the cost-effectiveness of a measure (Equations 2.1 and 2.2, [see Chapter 2 pp. 49]), 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, since it is a division of two positive numbers. 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. It therefore follows that if all the positive-cost options are compared with each other; the option with the least value of $C_{eff}$ yields the smallest financial expenditure per tonne of $CO_2$ abated, and therefore represents the optimal value. However, if an option yields a negative cost, representing a profit or net financial return on investment, the scenario changes. It then follows that a smaller $C_{eff}$ (i.e. a more negative value of $C_{eff}$) is realised by a higher financial gain, which is the goal that is desired, or by a reduction in the potential emissions savings, which is the direct opposite of what is anticipated.

This implies that the measure with the lowest numerical value $C_{eff}$ does not necessarily represent the best option. For abatement options with economic net benefits, the concept leads to wrong priorities. A numerical example is provided in Section 2.14.1. It then follows that the standard cost-effectiveness criterion, measured in £/$tCO_2e$, 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. The Pareto ranking technique adopted by Taylor (2012) as briefly described in Section 2.15 is implemented in an automated manner within the present DSS to address the problem as discussed in Section 4.11.1.

### 4.11.1. Implementation of Pareto ranking technique within the DSS

In the context of the current study, the two criteria to be maximised are (i) an improved emissions performance, which matches a larger (i.e. more positive) value of S, and (ii) a better economic gain, corresponding to a lesser (i.e. more negative) value of N. Therefore, in Pareto language, a measure, say, $X$ dominates measure $Y$ if:

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

This implies that, if the negative net cost (N) or the emissions saving potential (S) of X is better as compared to that of Y and the other is not worse off. Consider a fictitious plot of N against S as shown in Figure 4-23 for a given set of measures with negative cost. The option designated by the black point is superior (i.e. dominates) to all the options denoted by green points in the fourth quadrant, as well as those on the border demarcated by the dotted lines. The same point is neither superior nor inferior to the blue points in the second and third quadrants. It follows that if points existed in the first quadrant, together with those on the boundaries represented by dotted lines, the black point itself would also become inferior (i.e. dominated). For the set of measures in Figure 4-23, the Pareto front includes the black and blue points.

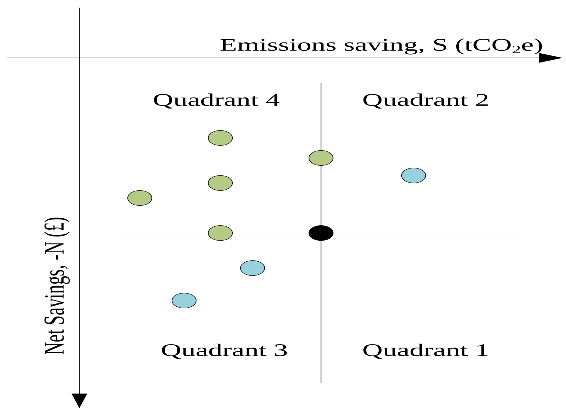



**Figure 4-23: Plotting of Pareto front for emissions reduction measures (Taylor,2012)**

So, by applying Pareto optimisation to the problem at hand, the following procedure as described by Taylor (2012) 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 (Pareto-optimal) when plotted as in Figure 4-23 – and are ranked first. The Pareto front are the measures that possess both combinations of more negative cost (-N) and high emissions savings potential (S) which makes them superior to the rest, allowing them to be rightly prioritised. It is to be noted that (i) the approach is not capable of differentiating between the measures and constitute the Pareto front – the ranking must be carried out simultaneously; (ii) It is not the case that every option captured within the Pareto frontier dominates all the options that are lower-ranked. The first-ranked measures comprising the front 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 steps listed above are applied to the measures that yield a profit until all measures are accounted for, it will lead to a clear ranking order that is fair and identify measures that are incorrectly ranked (although without specifying a cost-effectiveness), making it consistent with profit-maximizing behavior. In the context of the current DSS, the procedures described above are automatically implemented based on the logic described in the flow chart as shown in Figure 4-24.

As indicated in Figure 4-24, once the computation of the necessary parameters including the net costs $(\boldsymbol{N})$ and emissions saving potential $(\boldsymbol{S})$ of each measure under consideration are supplied, the DSS automatically identifies those measures with negative net cost $(-\boldsymbol{N})$ and their corresponding emissions saving potential $(\boldsymbol{S})$. It is to be noted that net cost is the difference between the capital cost of measure and the net present value (NPV) of the cost of energy saved by that measure. The identified measures are stored as a dimensional array of numbers in a "matrix X" where each row of the matrix is a mix of $\boldsymbol{N}\,(-\boldsymbol{n_1}, -\boldsymbol{n_2}, -\boldsymbol{n_3}, \ldots -\boldsymbol{n_f})$ and $\boldsymbol{S}(\boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}, \ldots \boldsymbol{s_f})$ for the negative cost measures. The $\boldsymbol{N}$ elements of "Matrix X" are sorted in ascending order of the costs $N$ (i.e. from the most negative $\boldsymbol{N}$). An empty "Matrix Q" which stores the sorted negative cost options is created. "Matrix Q" and "Matrix X" are initialized with counters $\boldsymbol{j}$ and $\boldsymbol{k}$ respectively. Whereas, counter $\boldsymbol{j}$ keeps track of the already sorted negative cost options based on the ranking criteria, counter $\boldsymbol{k}$ keeps record of the remaining options left to be ranked.

The next step as indicated by the decision box is where all options are compared simultaneously in terms of net savings $(-\boldsymbol{N})$ and emissions saving$(\boldsymbol{S})$. This is where the principle of dominance comes into play. An option with the most negative cost $(-\boldsymbol{N})$ and most positive emissions saving $(\boldsymbol{S})$ is said to dominate all other options when comparison is carried out. A measure dominates another measure if the first element (i.e. net savings) in "Matrix X" ≥ the net saving of the last element in "Matrix Q" and if its emissions saving in "Matrix X" is ≥ the emissions saving of the last element of "Matrix Q":

$$X_{k+1}(N) > Q_j(N)$$

$$\text{and}$$

$$X_{k+1}(S) > Q_j(S)$$

If the conditions above are satisfied, then the counter k is incremented accordingly and the dominant element is listed in the "Matrix Q". Otherwise, an additional condition which checks for situations where the net saving $(-\boldsymbol{N})$ of two options are exactly the same but the amount of emissions saving $(\boldsymbol{S})$ is different:

$$\text{Is } X_{k+1}(N) = Q_j(N)$$

$$\text{and}$$

$$X_{k+1}(S) \geq Q_j(S)$$

If the above condition is met, the measure with higher emissions saving will be given priority and ranked ahead. The procedure is continued, ensuring that all elements in "Matrix X" and consistently checked for dominance and are populated in an ordered fashion in "Matrix Q" leading to proper ranking of the options in terms of lower net cost and higher emissions saving. In situations where there is no clear cut dominance between a pair of consecutive ranked options, i.e.:

$net\ saving\ of\ option\ \boldsymbol{x} \leq net\ saving\ of\ option\ \boldsymbol{y}\ emissions\ saved\ by\ option\ \boldsymbol{x} \geq emissions\ saved\ by\ option\ \boldsymbol{y}$ or vice versa, the characters "nd" (no dominance) will be attached to the two competing options, differentiating them from other options, whilst leaving the decision maker to make a final selection.

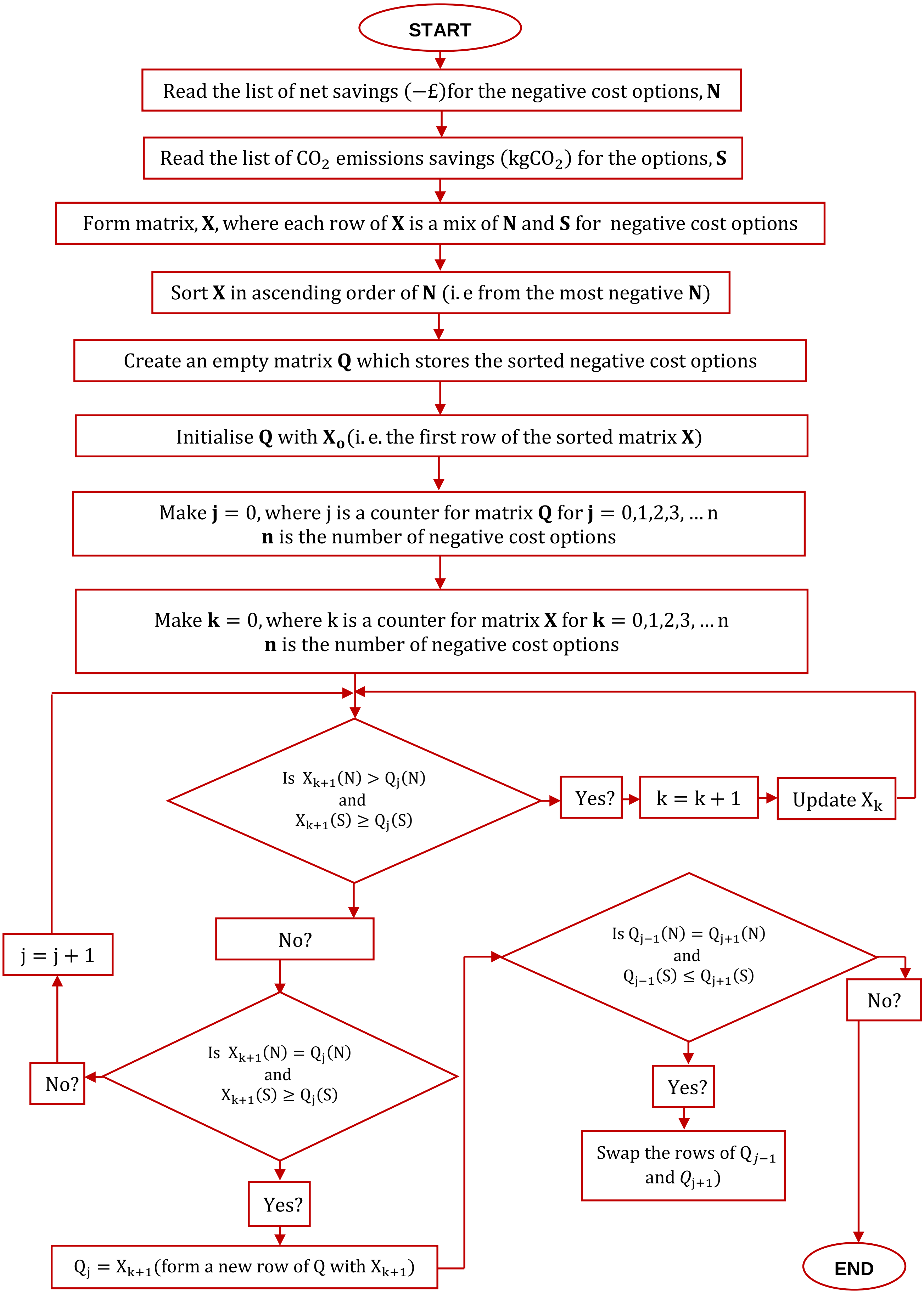



**Figure 4-24: Pareto optimisation scheme for ranking negative cost measures**

## 4.12. Approach taken to account for interaction within the DSS

As earlier mentioned, low carbon intervention options can be presented in MAC curves on a stand-alone basis if the desired outcome is to rank or prioritise measures in terms of their individual abatement potential and cost-effectiveness. However, low carbon intervention option often interact with each other and also interact with the energy supply systems when they are implemented in combination with one another. This interaction changes the emissions saving potential as well as the cost-effectiveness of the measures, in response to the measure with which they interact. Assuming the interaction of measures only affects 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 degree to which the effectiveness 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 (MacLeod *et al.,* 2010):

$$\mathrm{IF(XY)} = \frac{\text{Abatement potential of measure Y when applied after X}}{\text{Standalone abatement potential of measure Y}} \tag{4.17}$$

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 an interaction factor of 0.60 when implemented after measure X. To this end, whenever an abatement measure is implemented, the abatement potential of all the remaining abatement measures which interact with each other is calculated again by multiplying them by the appropriate interaction factor. 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 4-2 is established by carrying out an initial analysis of potential mitigation strategies that will interact with each other.

**Table 4-2: Initial assessment of interaction between measures based on interaction matrix**

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

As illustrated in a pairwise manner in Table 4-2, the interaction factors between any two options which interact with each other are computed using Equation 4.17. The estimation of interaction factor between any two options (i.e. the numerator of Equation 4.17) is complex and may be time consuming (MacLeod *et al.,* 2010). These interactions can be handled successfully by embarking on comprehensive systems-based modelling approach. This is important because of the existence of a non-linear relationship (which results from the timing of the service demand and the design of the building in question) in the manner with which the system interacts with the building (CCC, 2008). 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, due to multiple interactions which may occur in practice. In the context of the overall development of the current DSS model, multiple interactions are characterised as the product of aggregate two-way interaction factors. Further analysis regarding the estimation of interaction factor 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 published data and opinions from subject matter experts. For instance, Hazeldine *et al.* (2010) suggested that GHG emissions savings potential from space heating facilities are reduced by an interaction factor between 0.9 – 0.95, based on the relative energy performance of an average and well-insulated building.

### 4.12.1. Effect of interaction on the cost-effectiveness of abatement measures

Taking interaction into account comes with certain limitations which are very difficult to tackle. Interaction can lead to certain errors of judgement concerning the cost-effectiveness of both positive and negative cost measures. Two scenarios can be illustrated using numerical examples. First, consider two positive cost options A and B with abatement costs of £10/t$CO_2$e and £15/t$CO_2$e respectively. Based on the ranking criteria (cost per unit of $CO_2$ saved), option A is chosen in priority. However, if option A and B interact, the abatement option B may become cheaper, reaching a value of say, £5/t$CO_2$e, instead of £15/t$CO_2$e. As such, if options A and B are sorted based on the ranking criteria, option B could be prioritised over option A. In this example, the result conveyed is erroneous and misleading because option B is under estimated if option A is not implemented, thereby distorting the message of prioritisation within the MACC framework.

Second, in a stand-alone MACC where in measures do not interact, the measure can be ordered based on their cost-effectiveness, regardless of whether they have a positive cost or negative cost (note that the ranking anomaly discussed in Section 2.14.1 regarding negative cost measures still holds valid. The last statement is made for illustration purposes). However, when the cost-effectiveness of each measure is recalculated after interaction is taken into account, measures with negative costs exhibits a different behaviour as compared to those with positive costs. This behaviour can be explained using the following mathematical analysis:

Consider the effect of interaction on the width (i.e. the abatement potential of a measure) of the block. The amount of GHG mitigated by an option is reduced (in most cases), depending on the interaction factor. If the emissions corresponding to the effects of interaction is $\mathbf{e_{interaction}}$ then the effective emissions reduction, $\mathbf{E_{eff}}$, corresponding to the new width, is

$$E_{eff} = E_{no\ interaction} - e_{interaction} \tag{4.18}$$

Where $E_{no\ interaction}$ represent the emission saving from an option without considering interaction.

Now consider the height of the block, representing the cost effectiveness (£/$tCO_2$), $\mathbf{C_{eff}}$. Without the consideration of interaction, it is given by:

$$C_{eff} = \frac{N}{E_{no\ interaction}} \tag{4.19}$$

Where, **N** represents the net cost of an option. If interaction is taken into account, **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 interaction factor **f'** as the effective emissions saved divided by the total energy saved:

$$f' = \frac{E_{eff}}{E_{no\ interaction}} \tag{4.20}$$

The resulting cost-effectiveness is

$$C'_{eff} = \frac{N}{f'E_{no\ interaction}} = \frac{N}{E_{eff}} \tag{4.21}$$

Substituting (4.18) into (4.21) gives:

$$C'_{\text{eff}} = \frac{N}{E_{\text{no interaction}} - e_{\text{interaction}}} \qquad (4.22)$$

Equation 4.22 is numerically larger than $C_{\text{eff}}$, corresponding to a smaller emissions reduction for a given amount spent. The width of the block was found to be reduced by the effect of interaction. Also, Equation 4.22 shows that for a measure with a positive cost, the effect of interaction makes the measure more expensive (i.e. the cost-effectiveness worsens). The cost-effectiveness of the positive-cost measures increase as we traverse from left to right on the MACC and the effect of the interaction factors (IFs) is just to increase the rate at which the relative costs per height of the bars increase, which is the desired output.

However, if interaction $\mathbf{f}'$is taken into account for an option with a negative cost, **N**, this makes the measure seem more negative, i.e. less expensive and therefore suggest that for any given option, consideration of interaction has the effect of improving the cost-effectiveness. The effect of the interaction therefore makes it impossible to rank negative-cost measures according to the standard ranking criteria. This perverse result is a further confirmation of the findings of Taylor (2012) and supports the notion that the use of cost-effectiveness, measured in £/t$CO_2$e, for ranking negative-cost measures is not proper.

### 4.13. Modelling the effect of government incentives within the DSS

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 quicken 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).

#### 4.13.1. Feed-in-Tariff (FiT)

Feed-in-Tariffs is a grant scheme that was 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 unit of electricity (kWh) generated known as the "generation tariff". This price varies depending upon rated power and type of renewable energy system. Most up-to-date generation tariffs for each technology can be found on Ofgem website[2].

(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 related to the Retail Price Index and are manipulated to take the effect of inflation into account.

(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 4-25 indicates a possible scenario for a 20kW$_p$ PV installation which generates 17,000 kWh/year. Assuming 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:

(i) Generation Tariff = 17,000 x £0.135 = £2,295.00 ;

(ii) Export Tariff = 17,000 x 50% x £0.045 = £382.50;

(iii) Reduced bills = 17,000 x 50% x £0.115 = £977.50; so that the total annual returns is £3,655.00

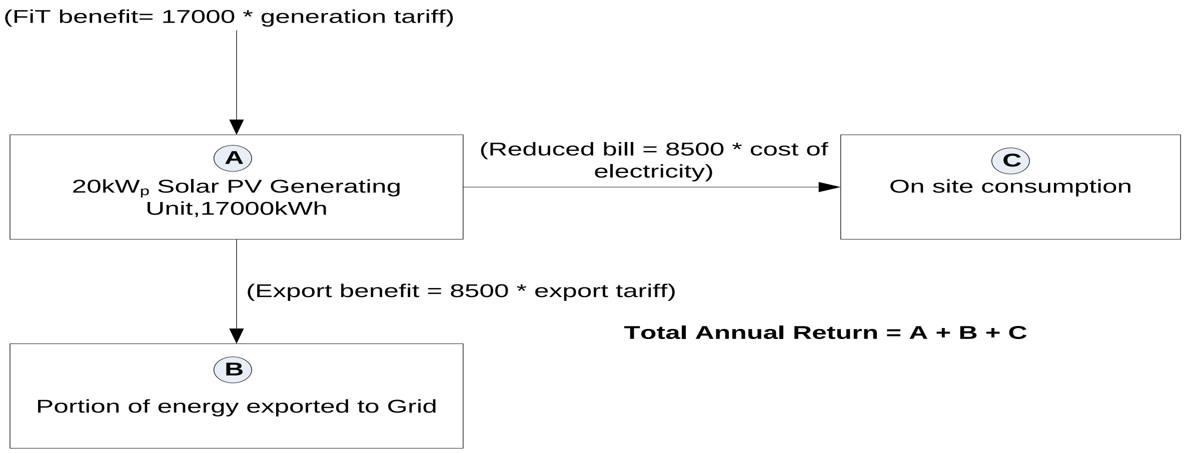



**Figure 4-25: Illustration of total annual return for a solar PV installation**

[2]See Ofgem website (http://www.ofgem.gov.uk/Sustainability/Environment/fits/Pages/fits.aspx) for the most up-to-date cost information regarding FiT and RHI.

### 4.13.2. Renewable Heat Incentive

The Renewable Heat Incentive (RHI) is a grant scheme set up by the UK Government in 2011 to encourage the implementation and use of renewable heating. It covers low carbon technologies such as ground source heat pumps, biomass heating and solar thermal systems. 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 28,000kWh/year will get a running cost savings of $14000 \times 4\text{p/kWh} = £560/\text{year}$, assuming cost of gas is 4p/kWh and a RHI of $14000 \times 8.9p/kWh = £1246/year$, yielding a simple total annual return £1806/year.

Based on the background introduction to FiT and RHI presented above, the effects of their consideration on the cost-effectiveness on a number of renewable technologies considered in this research are discussed and presented in Section 5.9.

## 4.14. Integrating both embodied and operational emissions with cost within a MACC framework

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 4-26, 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 4.8 and 4.9 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:

$$£/\text{tNetCO}_2 = \frac{\text{Total Investment Cost (£)} - \text{NPV of the cost of enery saved (£)}}{\text{E}_{\text{net}}(\text{tNetCO}_2)} \qquad (4.23)$$

The implication of Equation 4.23 regarding its effect on cost-effectiveness is discussed in Section 4.14.1.

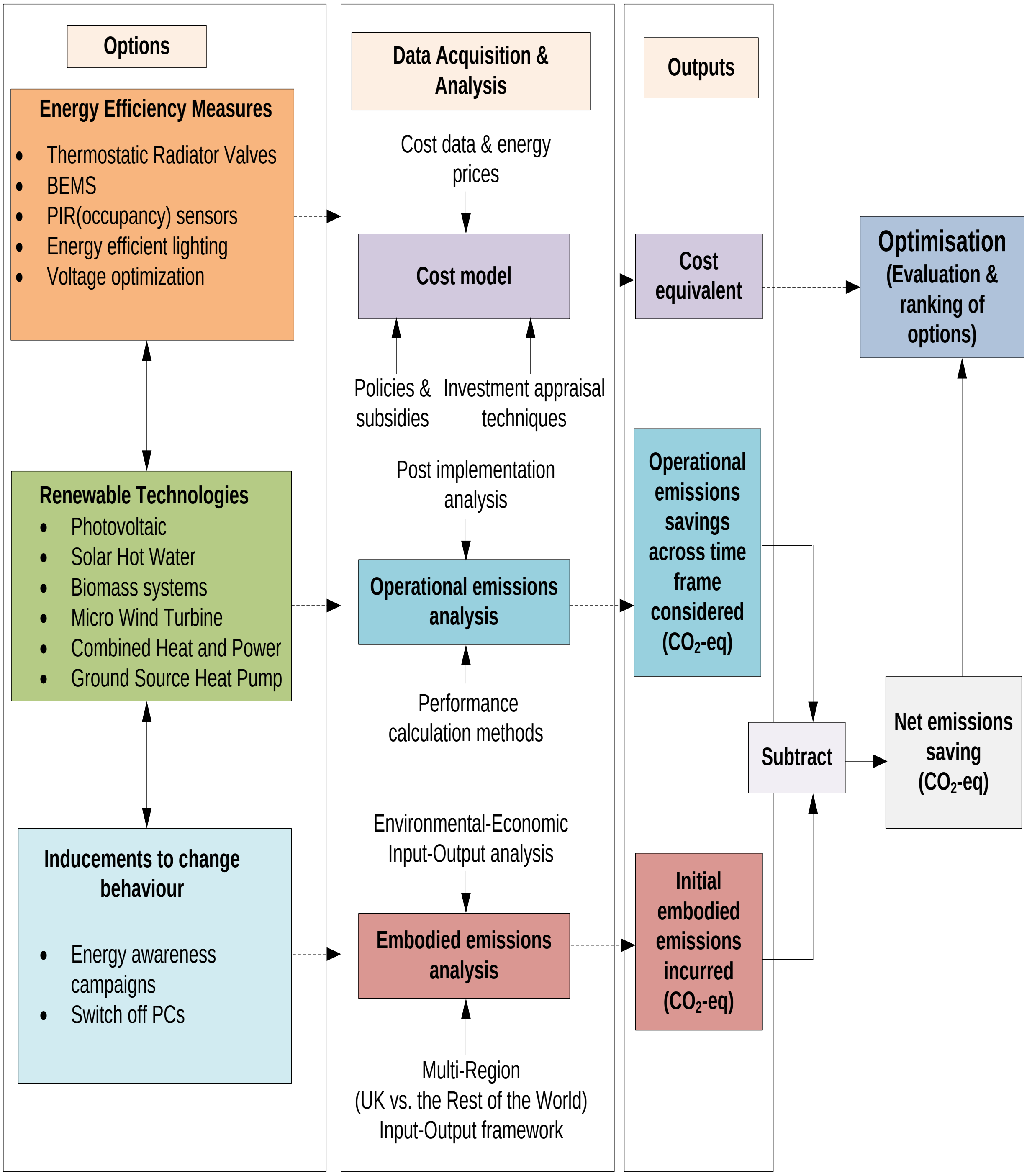



**Figure 4-26: Data flow diagram: Integrating embodied emissions into MACC**

### 4.14.1. Effects of embodied emissions on cost-effectiveness

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

$$E_{net} = gE - e_{emb} \quad (4.24)$$

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

$$C_{eff} = \frac{N}{S} \quad (4.25)$$

Where **N** represents the net cost 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 **g'** as the net emissions saved divided by the total energy saved:

$$g' = \frac{E_{net}}{E} \quad (4.26)$$

The resulting cost-effectiveness is

$$C'_{eff} = \frac{N}{g'E} = \frac{N}{E_{net}} \quad (4.27)$$

Substituting (4.24) into (4.27):

$$C'_{eff} = \frac{N}{gE - e_{emb}} \quad (4.28)$$

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 (4.24) and (4.28), giving:

$$C'_{eff} \times E_{net} = gE - e_{emb} \times \frac{N}{gE - e_{emb}} = N \quad (4.29)$$

This equals the area of the original block. It is worth noting that if a smaller effective emissions factor **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 4-27, is in line with the findings of

Taylor (2012) and supports the decision not to apply embodied emissions to negative-cost data within a MACC framework.

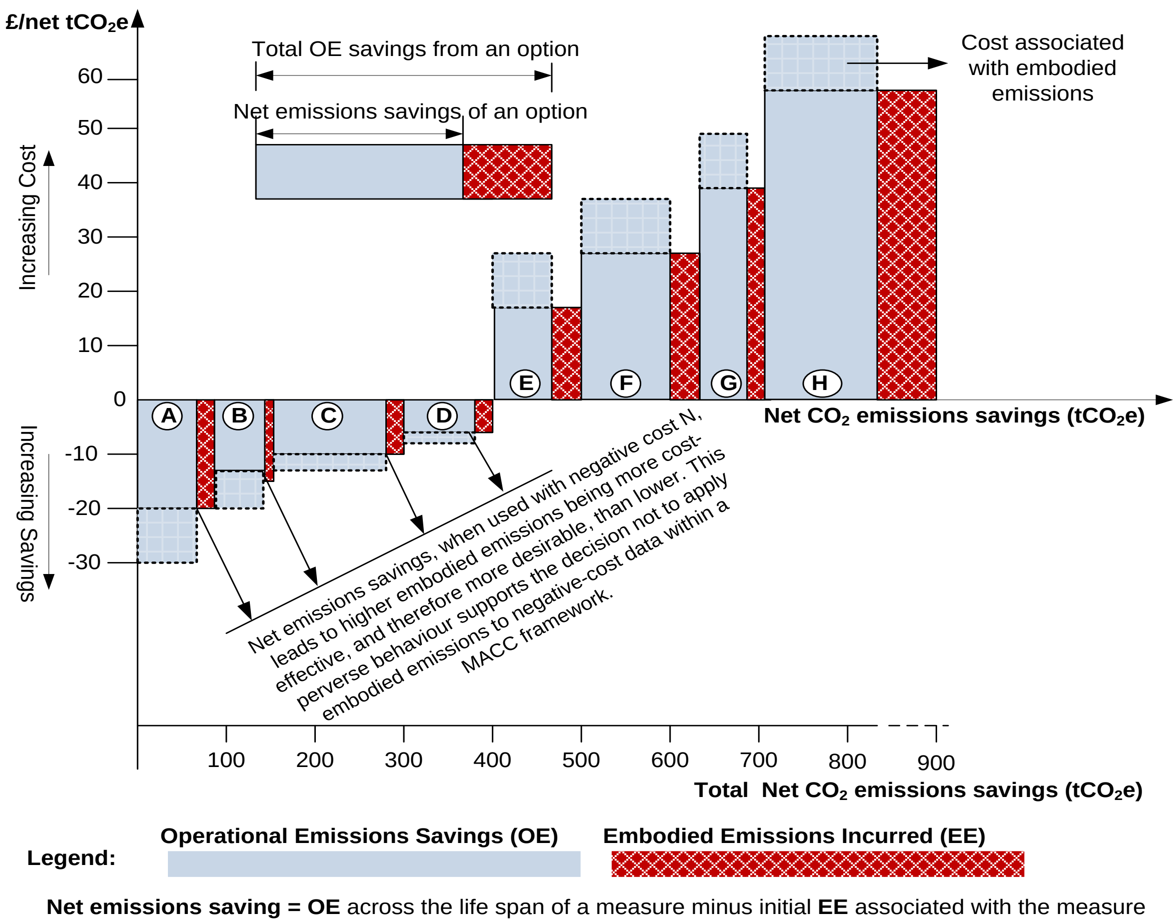



**Figure 4-27: MACC curve integrating economic considerations with operational and embodied emissions**

As shown in Figure 4-27, based on the positive regime, 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. Consequently, the height of each bar increases. The area of the difference between the initial height (before the consideration of embodied emissions) and the final height (after the consideration of embodied emissions) represents the costs associated with the embodied emissions of an option. For negative cost measures, the embodied emissions are evaluated so that the net emissions savings are established. The Pareto method described in Section 4.11.1 is used to rank the negative cost measures optimally. The result can be presented in graphical form as a bar chart stacked together where the ideal ordering and the net emissions saving potentials of each option are both indicated but without employing the concept cost-effectiveness, quoted in £/$tCO_2$ as a ranking criterion.

## 4.15. Sensitivity analysis- choice of discount rate and effect of energy prices

Results of the overall emissions reduction performance of abatement options can vary from study to study because it is influenced by several variables including the price of energy (gas and electricity) and the choice of discount rate. 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)* (Worrell *et al.,* 2004). The prescriptive approach is mainly employed when dealing with long-term issues such as climate change or large projects in the public sector and uses lower discount rates of between 4 and 10% (Worrell *et al.,* 2004).

The use of discount factors with lower numerical value present the benefits of considering future generations equally, but it may also lead to certain relatively short-term effects to be disregarded in support of more indeterminate effects that are long term (NEPO/DANCED, 1998). On the other hand, the descriptive approach employs the use of relatively high discount rates of 10-30% with the aim of reflecting the existence of energy efficiency investments barriers (Worrell *et al.,* 2004). The choice of discount factor can significantly affect results of the overall cost-effectiveness of an abatement project and hence the need for a sensitivity analysis. In this thesis, a discount rate of 5% is used throughout.

Regarding the effect of energy price changes, future fossil fuel prices are almost impossible to predict as they are driven by demand, global trends and events and financial markets situation. However, as the general trend of energy prices tends to be upwards, it is important to employ different price scenarios (e.g. reference, high, low) to assess the sensitivity of results (Figure 4-28) to changes in energy prices. Sensitivity analysis is therefore conducted to establish how the choice of discount rate and changes in energy prices can impact the results of the study. Numerical results showing these effects are presented in Chapter five (Section 5.10).

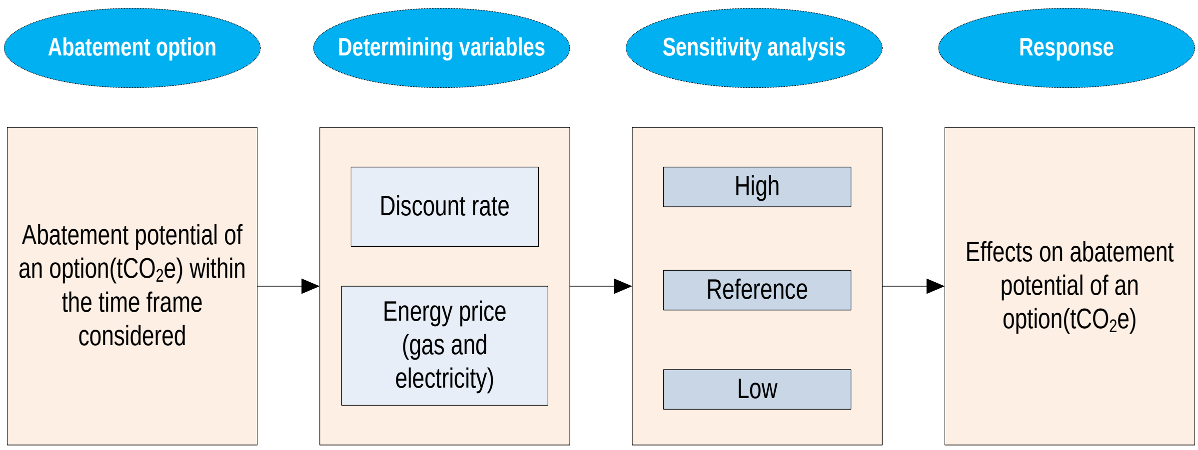



**Figure 4-28: Framework for sensitivity analysis**

## 4.16. Chapter summary

In this Chapter, a detailed analytical study devoted to the design concepts, engineering principles and computational frameworks taken to achieve the identified research problems highlighted in Chapter two was presented. The summary is depicted in Figure 4-29a and 4-29b.

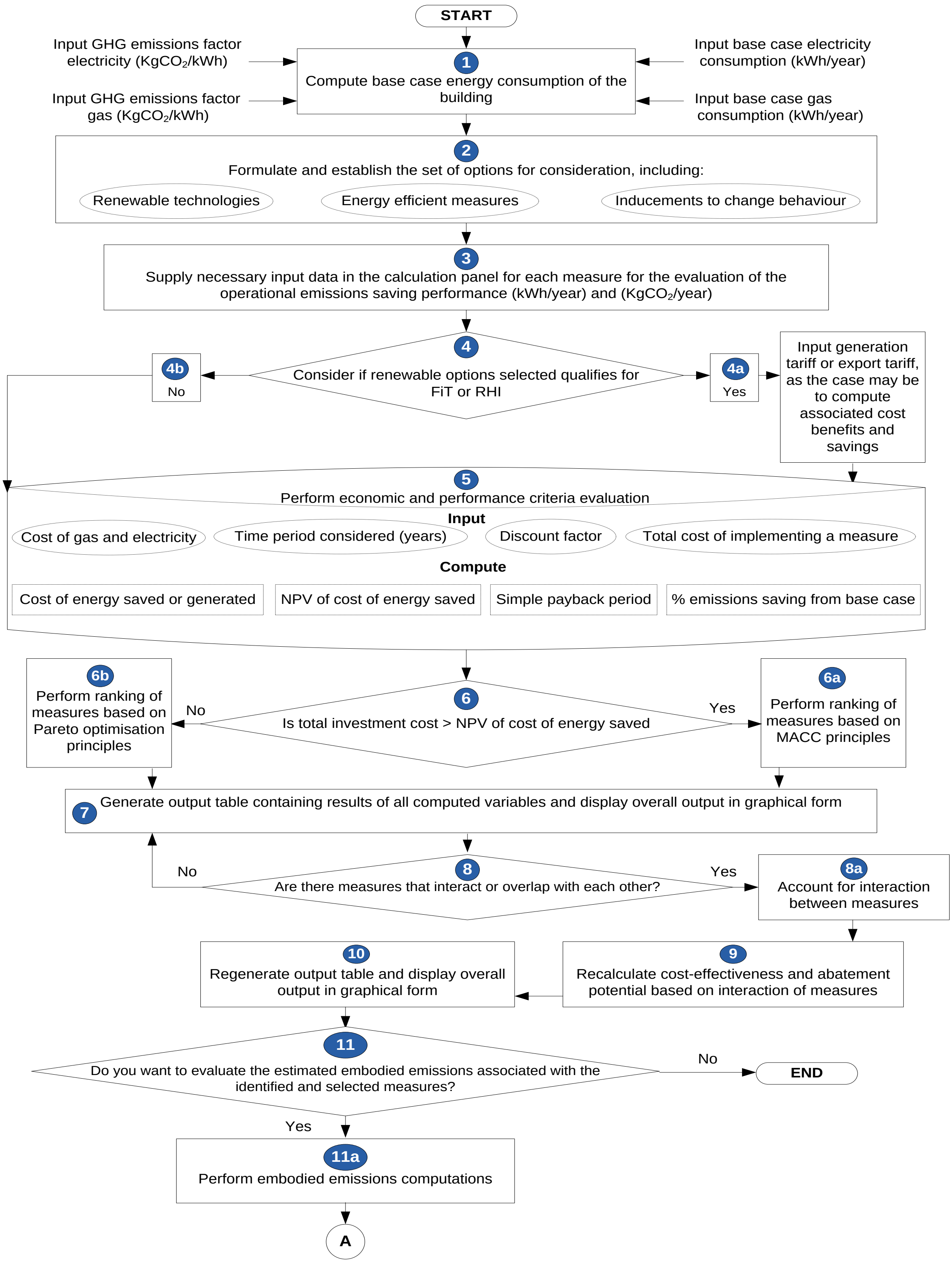



**Figure 4-29a: Overall structure illustrating the mode of operation of COBRA software**

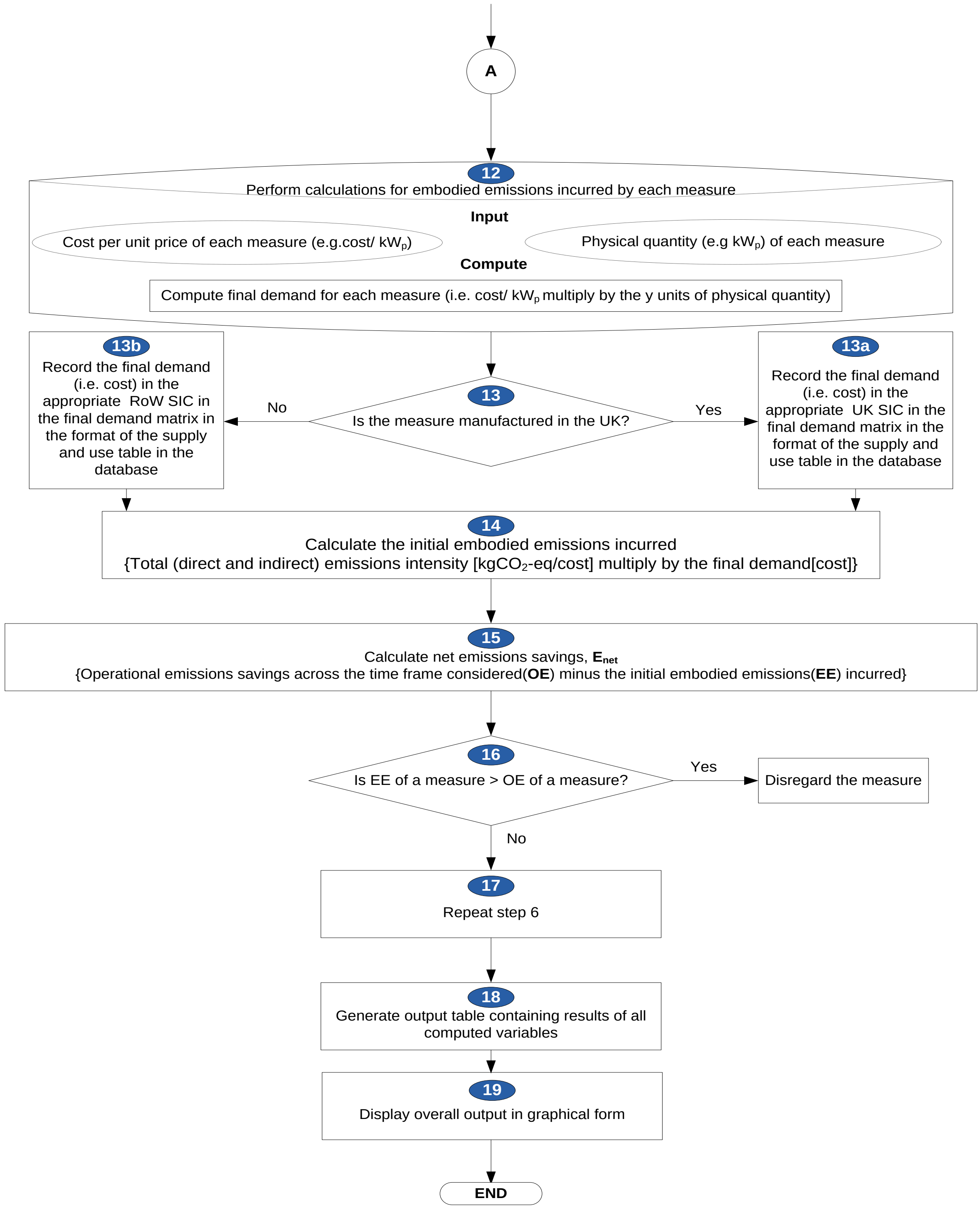



**Figure 4-29b: Overall structure illustrating the mode of operation of COBRA software**
**Figure 4-29: (a), (b) Overall structure illustrating the mode of operation of the COBRA software**

Figures 4-29a and 4-29b shows the overall structure of the COBRA software, illustrating how the overall DSS structure fits with each other and its step by step mode of operation. In Chapter five, results, analysis and discussion which stems from the extension of the decision support methodology to a case study building and other applications are presented.

# CHAPTER FIVE: RESULTS, ANALYSIS AND DISCUSSION

## 5.1. Introduction

This chapter presents the results, analysis and discussion that stems from the development of the decision support system described in Chapter four to its application to the case study building and other extended applications. Also included in this chapter is a brief summary regarding the broad-level findings of the current study.

## 5.2. 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 1993, it was the "Independent Newspaper Green Building of the Year in 1995" 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 10,000m$^2$. Occupancy level is about 2000 students and staff. The building is also characterised by high fabric insulation levels (e.g. U-values of the wall range between 0.29-0.36W/m$^{2o}$K). Further information on the case study building, including its envelope characteristics and related details are available in NPCS (1995). For the first year of operation, the energy consumption of the building, based on gross floor area, was 114 kWh/m$^2$ and 43 kWh/m$^2$ for gas and electricity respectively, with a corresponding $CO_2$ emission of 53 kg/m$^2$. Based on the DOE (1994) criterion, the reported energy consumption was equivalent to about half that of a typical university building (Figure 5-1 and 5-2).

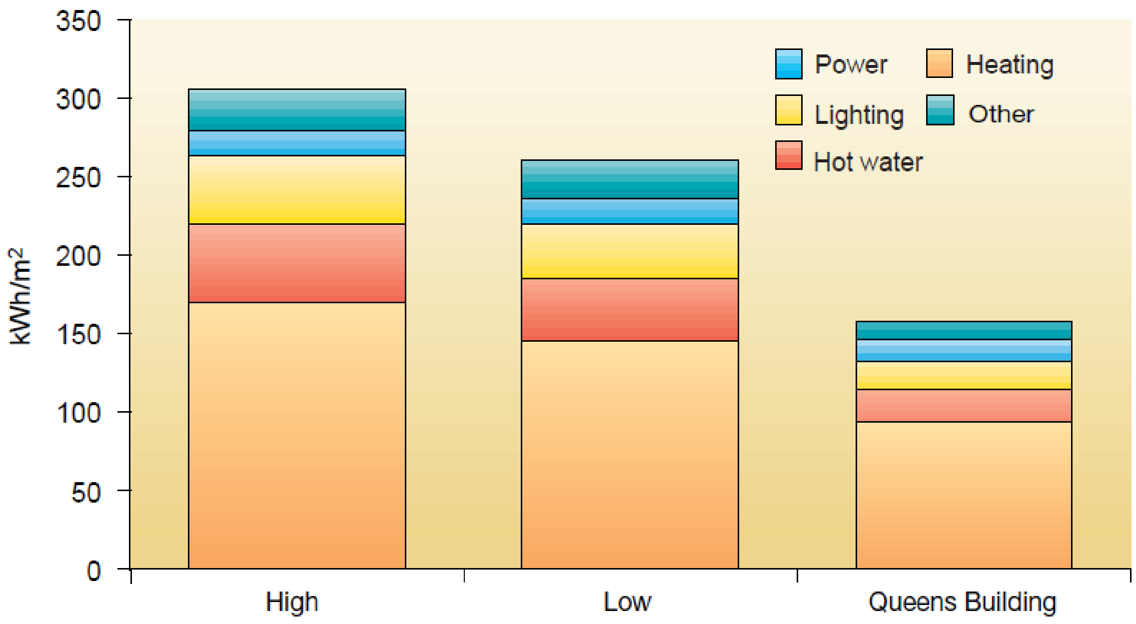



**Figure 5-1: Annual energy consumption of the Queens building in comparison to low and high criterion of DOE**

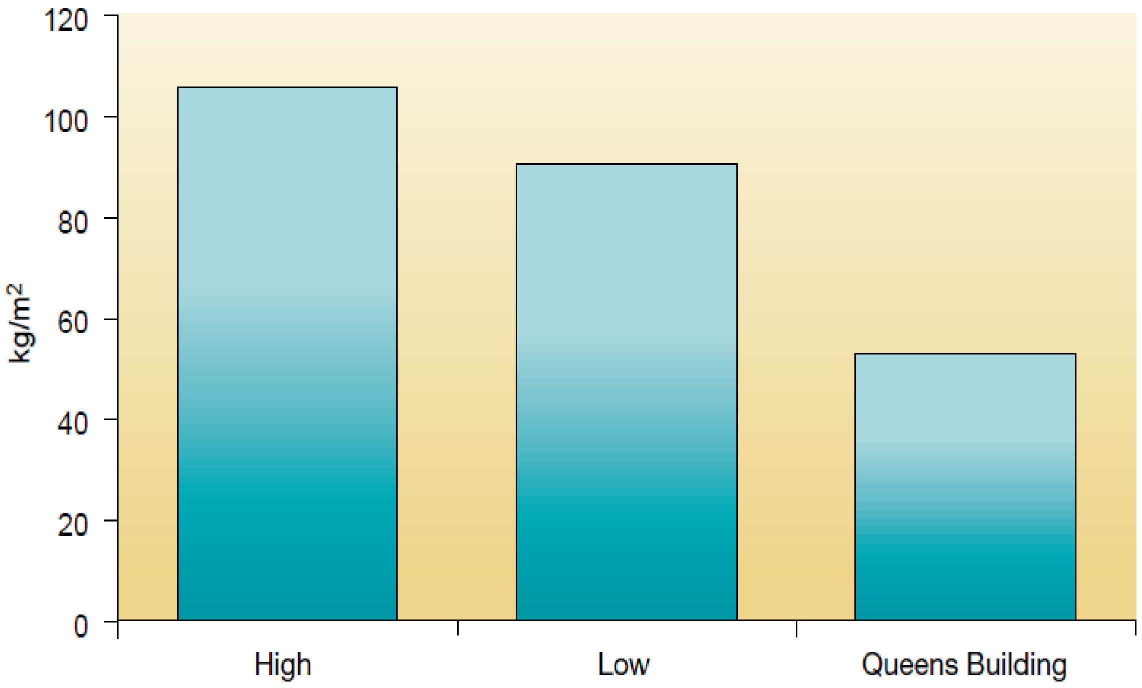



**Figure 5-2: Annual $CO_2$ emissions of the Queens building in comparison to low and high criterion of DOE**

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 of the UK's non-domestic 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.

### 5.3. Energy use in case building's $CO_2$ 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 (Carbon Trust, 2011) and 0.1836 $kgCO_2e$/kWh for grid-displaced gas (ibid), the baseline equivalent $CO_2$ emissions yielded 608.35$tCO_2e$ (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 5-3.

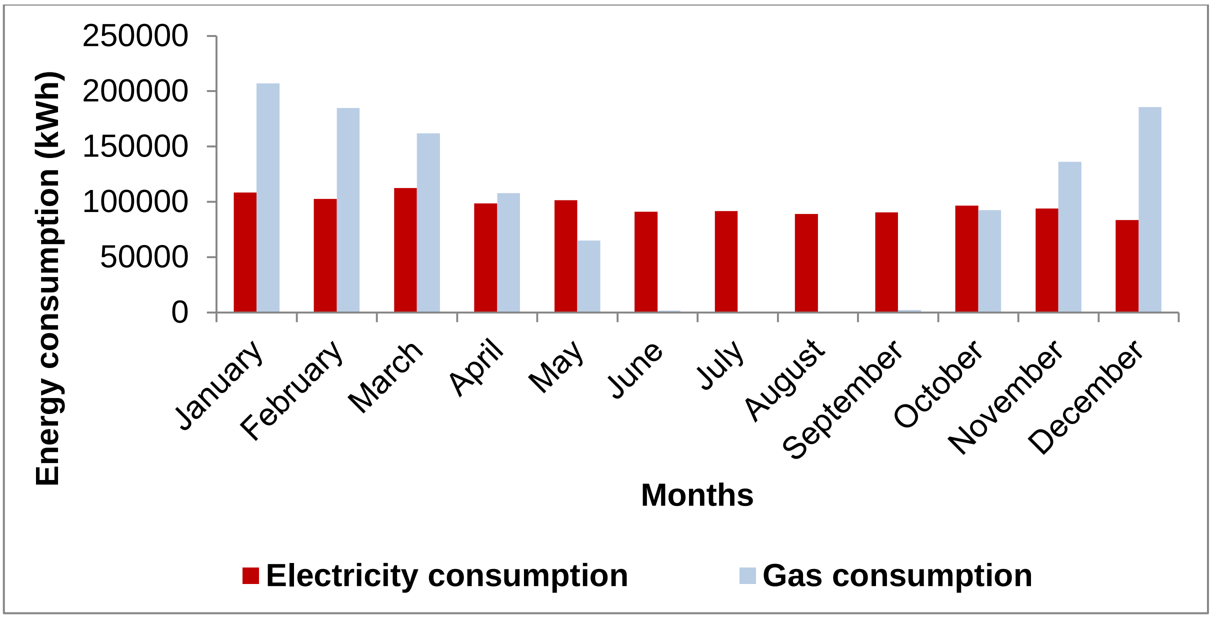



**Figure 5-3: 2010 baseline annual electricity and gas consumption for the Queens Building**

## 5.4. Indicative $CO_2$ savings – percentage reduction in $CO_2$ baseline

A range of building energy retrofit options (Table 5-1) were analyzed in terms of their operational emissions savings potential using the DSS model. The percentage savings of each of the selected intervention options were evaluated as a function of the baseline $CO_2$e emissions, on a standalone basis as shown in Figure 5-4. Assuming all options were implemented at the same time and that measures do not interact, emissions savings of 715.7t$CO_2$e 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 in Section 5.6.

**Table 5-1: Estimated energy and $CO_2$ savings from options against the baseline energy consumption**

| Intervention Options | Energy saved or generated (MWh/year) | $CO_2$ saved (t$CO_2$e/year) | % $CO_2$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% |
| 38$kW_e$ Combined Heat and Power (Micro CHP) | 422.82 | 141.14 | 17% |
| 400$kW_{th}$ Biomass Boiler | 229.24 | 42.28 | 5% |
| 250$kW_t$ Ground Source Heat Pump (GSHP) | 380.77 | 21.45 | 3% |
| 15$kW_p$ Micro Wind Turbine | 16.24 | 8.52 | 1% |
| 44$kW_p$, 400$m^2$ Photovoltaic System | 34.79 | 18.25 | 2% |
| 7$m^2$ Solar Hot Water | 1.64 | 0.30 | 1% |

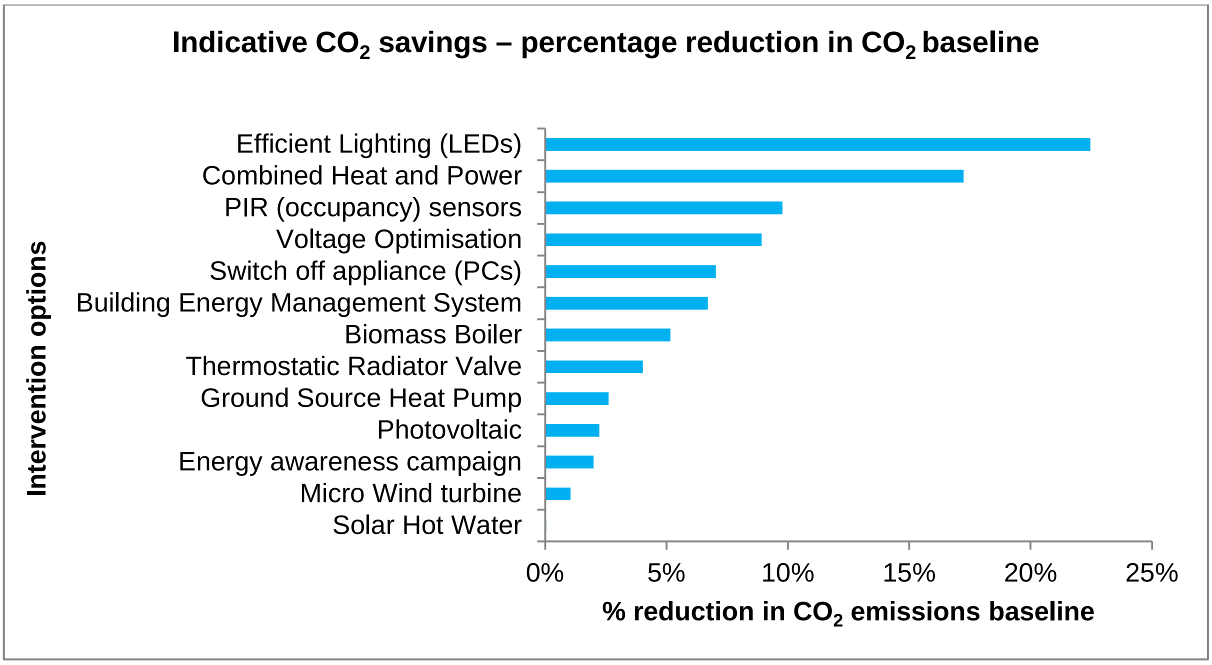



**Figure 5-4: Indicative $CO_2$ savings – percentage reduction in $CO_2$ baseline**

## 5.5. Estimating the cost-effectiveness and emissions savings for each option

The capital costs of each intervention option are estimated based on current market prices as well as a mix of literature and heuristic information. Net Present Value (NPV) concept at a discount rate of 5% for 15 years was used in the economic analysis to allow the flow of cash happening over an extended period of time to be considered at their equivalent value in comparison to energy prices of today.

### 5.5.1. Negative cost measures (illustration of ranking flaw)

Due to the problem related to the mathematical flaw with the standard ranking criteria ($C_{eff}$) discussed in Section 2.14.1 and 4.11, the results of cost-effectiveness for negative cost and positive cost measures are separated for illustration purposes. Table 5-2 shows the "cost-effectiveness" of negative cost measures based on the MACC approach and are plotted as depicted in Figure 5-5.

**Table 5-2: Estimated energy and $CO_2$ savings from options**

| 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] | MACC Ranking |
|---|---|---|---|---|---|---|---|---|
| TRVs | 8000 | 17998 | 186813 | -178813 | 495.17 | 495.17 | -361.12 | 1 |
| Switch off PCs | 0 | 10991 | 114082 | -114083 | 863.99 | 1359.16 | -132.04 | 2 |
| PIR sensors | 5000 | 15262 | 158414 | -153414 | 1199.79 | 2558.95 | -127.87 | 3 |
| EAC | 3500 | 3204 | 33258 | -29758 | 245.64 | 2804.59 | -121.15 | 4 |
| Voltage optimisation | 22500 | 13930 | 144588 | -122089 | 1095.03 | 3899.62 | -111.49 | 5 |
| LEDs | 70000 | 35089 | 364211 | -294212 | 2758.40 | 6658.02 | -106.66 | 6 |
| Micro CHP | 100000 | 28203 | 292741 | -192742 | 2117.11 | 8775.13 | -91.04 | 7 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| BEMS | 120000 | 17901 | 185808 | -65809 | 1379.13 | 10154.26 | -47.72 | 8 |

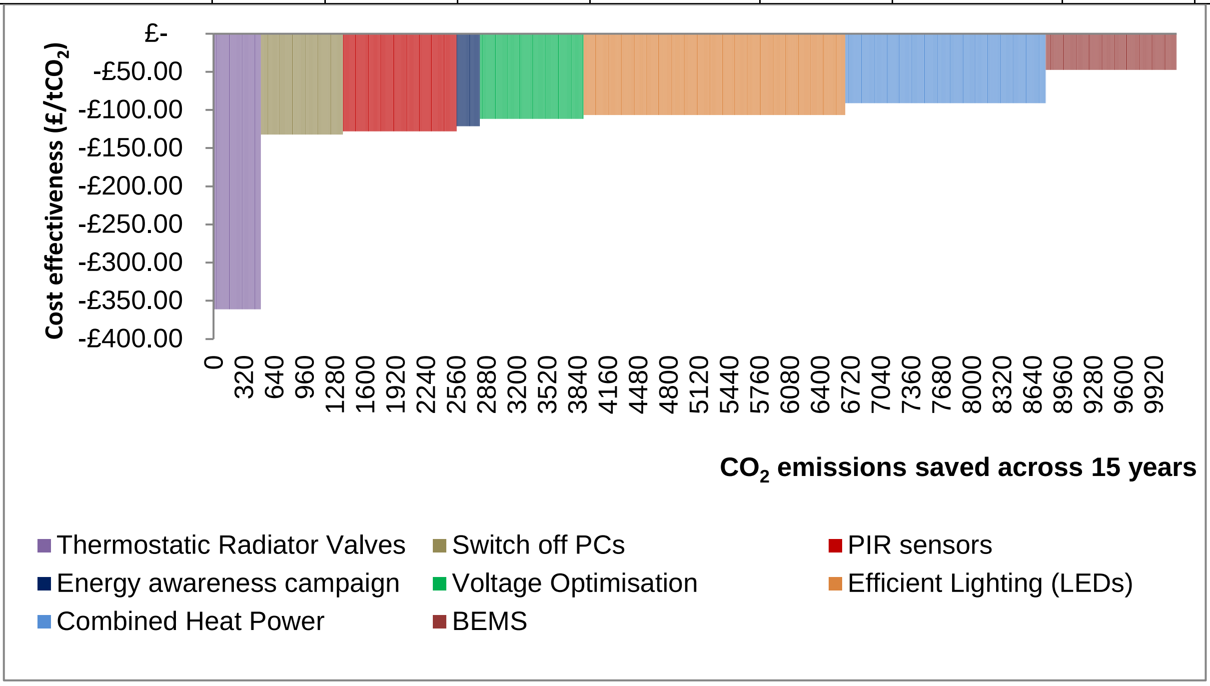



**Figure 5-5: Ranking of negative cost measures using the MACC approach**

As shown in Figure 5-5,the options are ranked in order of their "cost-effectiveness", with the installation of Thermostatic Radiator Valves (TRVs) being the most effective option, followed by switching off PCs and then installation of Passive Infrared (PIR) sensors and so on, in that order.

### 5.5.2. Correction of the ranking anomaly of negative cost measures using Pareto optimisation

Extensive discussions in Chapters two (Section 2.14) and four (Section 4.11) shows that a measure with the lowest $C_{eff}$ (e.g. TRVs as in the results above) is not necessarily the best option because, for abatement options with economic net benefits, the concept of cost-effectiveness leads to wrong priorities. Based on the data in Table 5-2, an inspection readily shows that the installation of LEDs should ordinarily be the first preferred abatement option in that the economic net benefit (-£294212) and the $CO_2$ emissions savings potential (2758.40t$CO_2$e) have the greatest magnitudes. This should then be followed by the installation of Micro CHP (net savings of -£192742 and emissions reduction potential of 2117.11 t$CO_2$e) and then voltage optimisation (net savings of -£122089 with emissions reduction of 1095.03 t$CO_2$e reduction).

However, the $CO_2$ reduction criterion ($C_{eff}$), leads to incorrect ranking and consequently a faulty decision, namely to the prioritisation of TRVs, Switch off PCs etc. before LEDs and Micro CHP etc., since TRVs, for example, has a smaller (i.e. more negative) $C_{eff}$ of -361.12/t$CO_2$e as compared to LEDs and Micro CHP with $C_{eff}$ of -£106.66/$tCO_2$e and -£91.04/$tCO_2$e respectively. It therefore follows that the concept of cost-effectiveness is invalid as already established in Chapters two (Section 2.14.1) and its use is termed not applicable (N/A) in this thesis.

If the technique of Pareto optimisation within a multi-criteria decision analysis (MCDA) framework, as described in Section 4.11.1 is adopted to prioritize the negative cost measures until all measures are accounted for, it will lead to a reasonably clear ranking order and identify measures that are wrongly ranked as shown in Table 5-3.

**Table 5-3: Estimated energy and indicative $CO_2$ savings from options**

| Intervention option | Capital cost (£) {C} | Cost of energy saved (£) | NPV of energy saved (£) {E} | Net savings or Net Cost (£) {N} [C-E] | $tCO_2$e saved over 15 years {S} | Cumulative savings ($tCO_2$e) | £/$tCO_2$ 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 | 634.15 | 44.77 | 9 |
| Wind Turbine | 60000 | 1625 | 16867 | 43133 | 127.75 | 761.90 | 337.63 | 10 |
| GSHP | 300000 | 14659 | 152162 | 147838 | 321.78 | 1083.68 | 459.43 | 11 |
| Photovoltaic | 200000 | 3482 | 36142 | 163858 | 274.17 | 1357.85 | 598.02 | 12 |
| Solar Hot Water | 10000 | 63 | 653.92 | 9346 | 4.56 | 1362.41 | 2049.58 | 13 |

*N/A: (Not Applicable)

The corresponding Pareto outputs plotted as a stacked bar chart is shown in Figure 5-6. The negative cost measures are ordered according to the total savings accruing from each measure and the bars are arranged so that ranking begins from 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 $tCO_2$e), which matches a larger (more positive) value of emissions saving potential (S), and a better financial gain (-£294,212), corresponding to a lesser (more negative) value of net cost (N). This is then followed by Micro CHP and so on. As such, the new ranking pattern based on Pareto optimization is now consistent with profit-maximizing behavior. For the positive cost regime where the MAC approach (i.e. the concept of cost-effectiveness) is still valid, MAC graph is plotted as a function of £/$tCO_2$ against cumulative $CO_2$ savings ($tCO_2$e) over 15 years is shown in Figure 5-7.

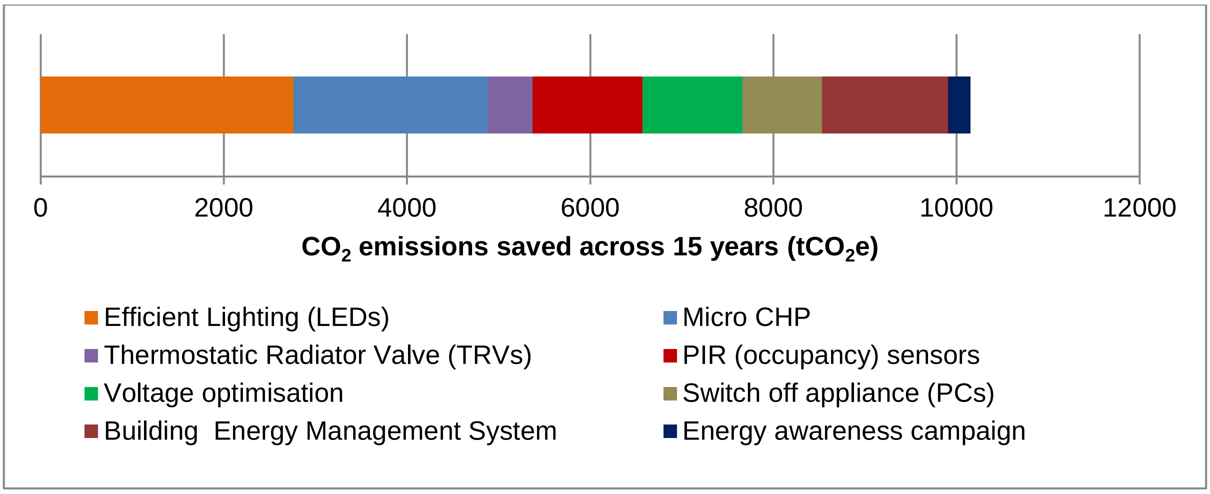



**Figure 5-6: Pareto ranking of negative cost measures (As a function of operational emissions only)**

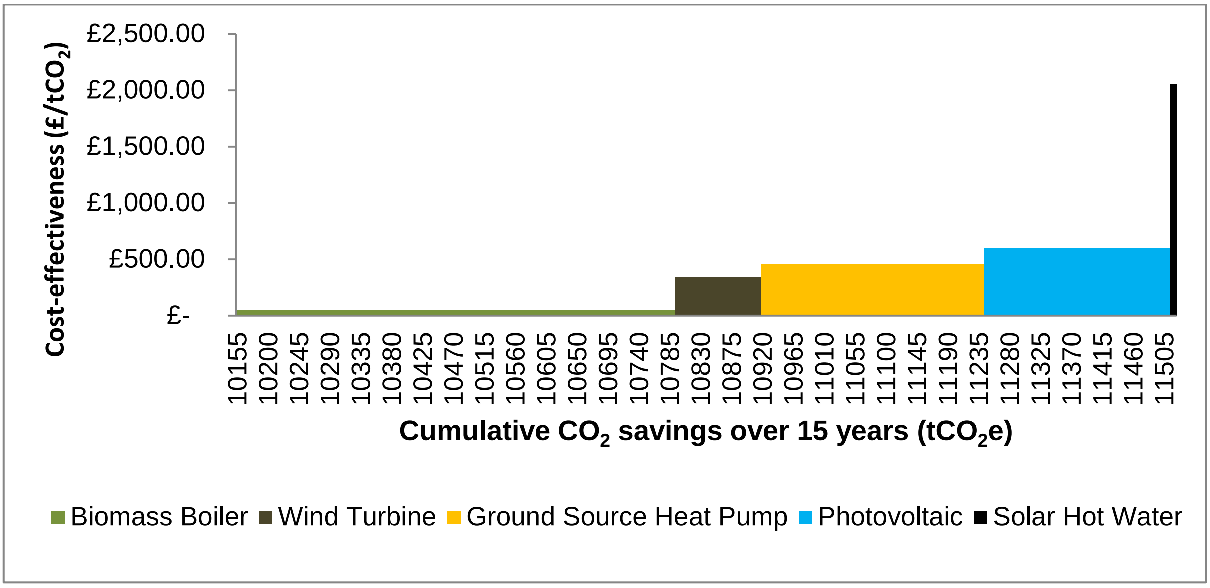



**Figure 5-7: MACC for positive cost low carbon intervention options (operational emissions only)**

The numerical example provided above regarding negative cost measures further shows that the standard ranking criteria ($C_{eff}$) does not represent a measure of cost-effectiveness and there is no alternative approach to avoid this ranking anomaly when prioritising options that yield a return on investment. As concluded by Taylor (2012), negative cost-effectiveness, quoted as a numerical value and expressed in cost/$CO_2$ abated, is not a valid concept.

Pareto ranking described in Section 4.11.1 can to a certain extent be interpreted to imply cost-effectiveness. A slight downside however with the use of the Pareto ranking approach is that its application to both positive and negative regimes within a classical MACC concept is not always consistent. More importantly, the separation of negative and positive-cost measures would be rendered invisible when all options are ranked based on Pareto optimisation, leading to the potential possibility of positive-cost measures being prioritised over negative-cost measures.

Several ways for the future representations of cost-effectiveness in a graphical manner, including their pros and cons are suggested by Taylor (2012). In the context of the current research, the profit-making and loss-making options are presented separately as shown respectively in Figures 5-6 and 5-7. As indicated, both figures are tied together such that the x-axis values in 5-7 (the positive MACC (i.e. loss-making options)) starts from the maximum value in 5-6. So in 5-7, the starting x-value is 10155 $tCO_2e$, emphasizing that the emissions savings begin in 5-6 and continue in 5-7.

Regarding negative cost measures, there is an argument that their ranking is less important for positive cost measures because one would always make a profit regardless of which option was implemented. In other words, provided an option yields a profit, ranking might not be absolutely necessary. However, it is beneficial to rank negative cost measures because few people will implement all of the options in a single operation, even though in theory, the more you implement the more profit you make. As a result, a choice needs to be made, and the ranking method provides a basis for the decision. The reason why few people will implement all the measures is partly due to the fact the concept of NPV doesn't tell the whole story about the economics of retrofit options. This is because neither limited availability of cash nor associated risks are taken into account, for example. Also, there are further complexities when more than one measure is implemented. For instance as described in Section 4.12.1, if two measures interact, there is a tendency that a negative cost measure get pushed into the positive cost regime and can no longer make profit. It follows that ranking of negative cost measures is still of paramount importance as demonstrated with the implementation of Pareto ranking.

## 5.6. Effects of interaction and overlaps on cost-effectiveness

In Section 4.12.1, the effect of interaction between measures was highlighted. It follows that an understanding is needed of the physical basis of each possible interaction. This has the potential of making implementation a complex task. To minimise this complexity, an approach based on an interaction factor (IF) which is calculated using Equation 4.17 is adopted.

Table 5-4 gives an indication of any two options which interact with each other. In reality, the interaction factors are computed using Equation 4.17, but as stated in Section 4.12, the evaluation of the numerator of this equation (i.e. the abatement potential of one measure when applied after another measure) is quite complex and time consuming and may require separate systems based modelling approach for individual interaction. Some assumptions and opinions from subject matter experts were therefore employed in some cases.

**Table 5-4: Initial assessment of interaction between measures based on interaction matrix**

| | INTERACTION MATRIX | First measures | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Photovoltaic | Solar Hot Water | Wind Turbine | Micro CHP | Voltage Optimisation | BEMS | Switch off appliance (PCs) | PIR sensors | Efficient Lighting (LEDs) | Biomass Boiler | GSHP | Energy awareness campaign | TRVs |
| Second measures | Photovoltaic | – | | | | | | | | | | | | |
| | Solar Hot Water | | – | | | | | | | | | | | |
| | Wind Turbine | | | – | | | | | | | | | | |
| | Micro CHP | | | | – | | | | | | | | | |
| | Voltage Optimisation | | | | | – | | | | EV | | | | |
| | BEMS | | | | | | – | | | | | | | |
| | Switch off appliance (PCs) | | | | | | | – | | | | | | |
| | PIR sensors | | | | | | | | – | EP | | | | |
| | Efficient Lighting (LEDs) | | | | | VE | | | PE | – | | | | |
| | Biomass Boiler | | | | | | | | | | – | | | |
| | Ground Source Heat Pump | | | | | | | | | | | – | | |
| | Energy awareness campaign | | | | | | | | | | | | – | |
| | TRVs | | | | | | | | | | | | | – |

As depicted in Table 5-4, boxes highlighted in red indicate measures that interact with each other and the orange indicates measures that could overlap with each other in a given abatement project scenario. As shown, lighting loads (i.e. LEDs) installations are influenced by the use of PIR. Similarly, the emission reduction potential of voltage optimisation is reduced when implemented after the installation of LEDs since LEDs are voltage independent (i.e. they are not linearly resistive and their power demands within the limit of their operating range are completely independent of supply voltage). Table 5-5 gives the estimated interaction factor when two options interact with each other and the corresponding abatement potential.

**Table 5-5: Effect of interaction on abatement potential of measures**

| Pareto ranking | Intervention option | Stand-alone abatement potential ($tCO_2e$) | Interaction factor | Abatement potential with interaction ($tCO_2e$) | Combined abatement potential ($tCO_2e$) |
|---|---|---|---|---|---|
| **Interaction** | | | | | |
| 1 | Efficient lighting | 2758.40 | 0.95 | 2620.48 | 2620.48 |
| 4 | PIR sensors | 1199.79 | 1 | 1199.79 | 1199.79 |
| 5 | Voltage optimisation | 1095.03 | 0.6 | 657.02 | 657.02 |
| **Overlap** | | | | | |
| **MACC & Pareto ranking** | **Intervention option** | **Stand-alone abatement potential ($tCO_2e$)** | **Interaction factor** | **Abatement potential with overlap ($tCO_2e$)** | **Combined abatement potential ($tCO_2e$)** |
| 2-Pareto | Micro CHP | 2117.11 | - | 2117.11 | 2117.11 |
| 9 | Biomass | 634.154.56 | - | - | - |
| 13 | Solar hot water | | - | - | - |

As indicated, when efficient lighting is installed in tandem with PIR sensors, using Equation 4.17, the interaction factor (i.e. IF [EP] = IF [PE]) is estimated to be 0.95 so that the abatement potential of efficient lighting becomes 2758.40 $tCO_2e$ multiplied by 0.95 giving 2620.40 $tCO_2e$. Because of the voltage independent nature of LEDs, the abatement potential of voltage optimisation is also reduced by an estimated interaction factor (i.e. IF [EV] = IF [VE]) of 0.6 resulting into an abatement potential of 657.02 $tCO_2e$. For the case of overlap among micro CHP, biomass and solar hot water, if it is assumed that the existing boilers within the building will be replaced by CHP, then it may no longer be necessary to include biomass or solar hot water in the basket of intervention options.

### 5.6.1. Limitation on the use of interaction factors

The approach taken to account for interaction between measures described in Section 4.12 and demonstrated in Section 5.6 above 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 measures, in an iterative process, are exchanged in and out of the base-line, allowing those measures with the lowest system cost to be identified (Kesicki, and Anandaraj, 2011; Morthorst, 1993). With reference to Figure 5-7 (i.e. the positive cost measures where the MACC approach is valid), let the technology options be represented as E, F, G, H and I for simplicity. It then follows that the results for option F will depend on the implementation of option E, while 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, H and I), 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 (Morthorst, 1993). This approach certainly provides a step forward compare to the approach described in this thesis, it still only represents part of the whole picture. As a result, 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 they are moved 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.

### 5.6.2. Effect of grid $CO_2$ emissions intensity on some low carbon technologies

Given the mode of operation of ground source heat pumps (GSHPs), based on the fact that free heat is harvested from the ground, producing, in principle, up to 4-5 times more energy compared to the energy put into it, it readily comes across as a technology with very good green credentials. Furthermore, since GSHP runs on electricity, which has a higher carbon intensity as compared to gas, giving it a favourable output-input ratio, known as coefficient of performance (CoP), it should in principle emit less $CO_2$ than a gas boiler, for example. Unfortunately, this supposed good green credentials are based on inappropriate assumption. This is traced to the fact that the $CO_2$ intensity of electricity from the grid in the UK used to be quoted as 0.422 or 0.43 kg$CO_2$/kWh, based on outdated power generation estimates (Jenkins *et al.,* 2009b), in the hopes that the steady decline in grid intensity would continue. Instead, it flattened out, at roughly 0.53 kg$CO_2$/kWh, as shown in Figure 5-8. The original data used for to generate the graph shown in Figure 5-8 is publicly available in Batey and Pout (2005).

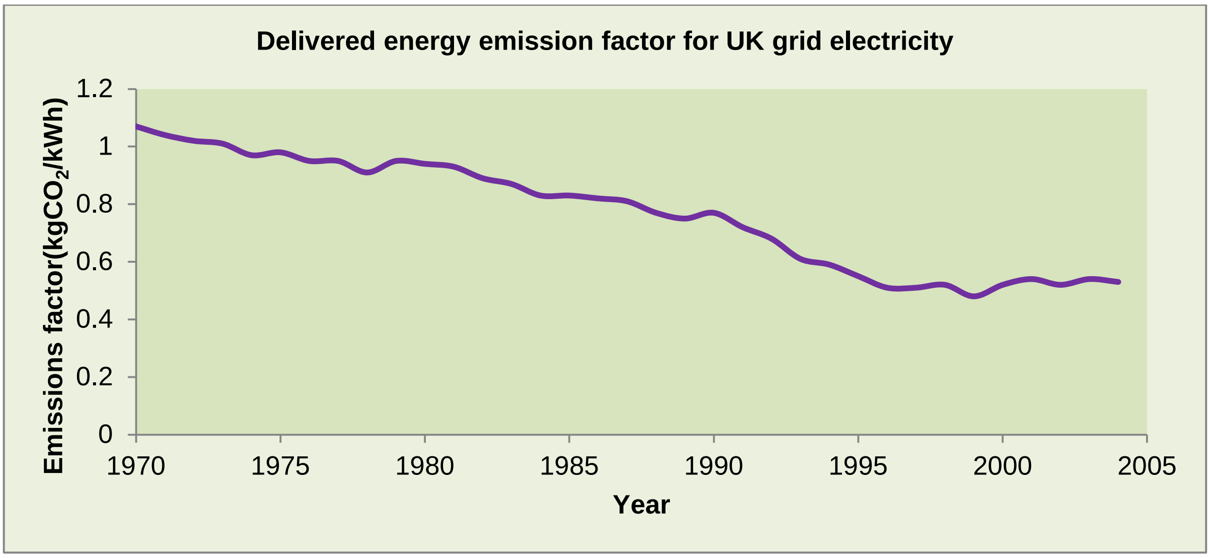



**Figure 5-8: Delivered energy emission factor for UK grid electricity**

The $CO_2$ emission conversion factor of 0.53 $kgCO_2/kWh$ is often a convenient value to use for generating indicative $CO_2$ emissions savings in building emissions analysis. However, the $CO_2$ intensity of the grid varies throughout the year and also over the course of a day (Jenkins *et al.,* 2009b). This variation can have implications for the use of several GHG emissions-saving technologies especially GSHP and micro-CHP. The $CO_2$ intensity of the electricity displaced by export from micro-CHP will have obvious effects on the carbon-saving potential of that technology (ibid). Ground and air-source heat pumps are more prone to variations in $CO_2$ intensity values (Jenkins *et al.,* 2008). If such systems are operating in a building during times of high grid $CO_2$ intensity, the carbon emissions of a building heated with a heat pump can be higher than expected.

Consider the case of replacing a low-carbon form of heating (e.g. gas condensing boiler) with GSHP. As shown in Table 5-6, the baseline emissions from the Queens Building is 787.23 $tCO_2e/yr.$, using gas condensing boiler and grid electricity.

**Table 5-6: Queens building baseline emissions (gas condensing boiler and grid electricity)**

| **Baseline Scenario** | | | | | |
|---|---|---|---|---|---|
| **Activities** | **Primary energy demand (kWh/year)** | **Assumed efficiency** | **Useful energy demand (KWh/yr.)** | **Emissions factor ($kgCO_2e/kWh$)** | **Emissions ($tCO_2e/yr.$)** |
| **Space heating** | 916968 | 85% | 779422.8 | 0.1836 | 143.10 |
| **Water heating** | 229242 | 85% | 194855.7 | 0.1836 | 35.78 |
| **Electricity consumption** | 1159642 | 100% | 1159642 | 0.5246 | 608.35 |
| | | | | **Total base line emission** | **787.23** |

Now consider the effects of using GSHP on the building, assuming it is designed to meet 50% domestic hot water demand. First, to get good performance (i.e. to maintain a high CoP) from GSHP, their output temperature needs to be kept at low temperature of around 40°C. This explains why they work fine for under floor heating applications. However, domestic hot water is normally stored at a temperature of about 50°C-60°C, so a backup system is needed to heat up the water for the rest of the day. The backup system is mostly an electric immersion coil which has a similar mode of operation like that of to an electric kettle but it is not endowed with the CoP advantage of GSHP.

Table 5-7 shows the emissions due to the GSHP (230 $tCO_2e/yr.$) and the backup system (609.03 $tCO_2e/yr.$), totalling 839.03 $tCO_2e/yr$. As shown, the savings is negative,-58.80 $tCO_2e/yr.$ (i.e. 787.23-839.03), representing -7%, relative to the baseline $CO_2$ emissions. This is economically unattractive, given that installed costs for a GSHP are around £1000/kW, 6-

10 times as much as a gas boiler. In addition, the emissions savings below assume a CoP of 2. In practice, the performance isn't always as good as this. Despite this "poor" performance, the emissions saving potential of GSHP are better when compared against a system based on a higher carbon fuel, such as heating oil with a carbon intensity of 0.265 $kgCO_2/kWh$, improving the performance of GSHP to about 3% compared to baseline $CO_2$ emissions. The value is higher with better CoP.

**Table 5-7: Queens building baseline emissions (GSHP and grid electricity)**

| **GSHP** | | | | | |
|---|---|---|---|---|---|
| **Activities** | **Useful energy demand (kWh/yr.)** | **Demand met by GSHP (kWh/yr.)** | **Primary energy demand (kWh/yr.)** | **Emissions factor ($kgCO_2e/kWh$)** | **Emissions ($tCO_2e/yr.$)** |
| Space heating | 779422.8 | 779422.8 | 389711.40 | 0.5246 | 204.44 |
| Water heating | 194855.7 | 97427.85 | 48713.93 | 0.5246 | 25.56 |
| Electricity consumption | 1159642 | 0 | 0 | 0.5246 | 0 |
| | | | | **Subtotal emission due to GSHP** | **230** |
| **Backup system(BS)** | | | | | |
| **Activities** | **Useful energy demand (kWh/yr.)** | **Demand met by BS (kWh/yr.)** | **Primary energy demand (kWh/yr.)** | **Emissions factor ($tCO_2e/kWh$)** | **Emissions ($tCO_2e/yr.$)** |
| Space heating | 779422.8 | 0 | 0 | 0.5246 | 0 |
| Water heating | 194855.7 | 1300 | 1300 | 0.5246 | 0.68 |
| Electricity consumption | 1159642 | 1159642 | 1159642 | 0.5246 | 608.35 |
| **Subtotal emission due to BS** | | | | | **609.03** |
| **Total emissions due to GSHP and BS** | | | | | **839.03** |
| **Savings due to GSHP and BS** | | | | | **-58.80** |
| **% Savings** | | | | | **-7** |

The above analysis readily brings to mind the dilemma that exists when using GSHPs where gas is available. As indicated, if gas is unavailable and a high carbon fuel such as heating oil is being replaced with GSHP, then they can make good environmental sense. It therefore follows that if the GSHP is being proposed as an alternative to a reasonably low-carbon form of heating (e.g., gas condensing boiler), alternative technologies must be thoroughly considered before recommending installation. It should not always be assumed that GSHPs will yield significant emissions savings, especially if they are not being used for under floor heating which can improve CoP significantly (Jenkins *et al.,* 2009b). Furthermore, GSHP are not cost effective compared to biomass boilers for typical heating functions. They can therefore be termed second-choice low carbon technology if biomass is not feasible.

## 5.7. Embodied emissions results

The results of using the methodology for the computation of embodied emissions described in Section 4.4.3 and applied in Section 4.9.2 are presented in this section. The physical quantities of each intervention option in terms of their design specification (as generated by the DSS), unit costs, final demand in monetary terms and assumed location of manufacture are presented in Table 5-8. The final demand is the product of the physical quantity (e.g.$kW_p$) of an option and its unit cost (e.g. £/$kW_p$).

**Table 5-8: Intervention options with their equivalent final demand in monetary terms**

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

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 and the corresponding emissions payback period across the fifteen years considered are shown in Table 5-9 and are depicted in graphical form as in Figure 5-9 and 5-10 respectively.

**Table 5-9: Embodied emissions and emissions payback period**

| Intervention options | Embodied emissions incurred ($tCO_2e$) | $CO_2$ saved ($tCO_2e$/year) | Emissions payback period (years) |
|---|---|---|---|
| 1.PV System | 104 | 18.25 | 5.7 |
| 2. Solar Hot Water | 6 | 0.3 | 20.0 |
| 3. Micro Wind turbine | 39 | 8.52 | 4.6 |
| 4. GSHP | 258 | 21.45 | 12.0 |
| 5. Biomass Boiler | 85 | 42.28 | 2.0 |
| 6. Micro CHP | 132 | 141.14 | 0.9 |
| 7. Voltage Optimisation | 15 | 73 | 0.2 |
| 8. BEMS | 101 | 91.94 | 1.1 |
| 9. Efficient Lighting (LEDs) | 17 | 183.89 | 0.1 |
| 10.TRVs | 4 | 33.01 | 0.1 |
| 11. PIR sensors | 2 | 79.99 | 0.0 |
| **Total** | **763** | **693.77** | **46.79** |

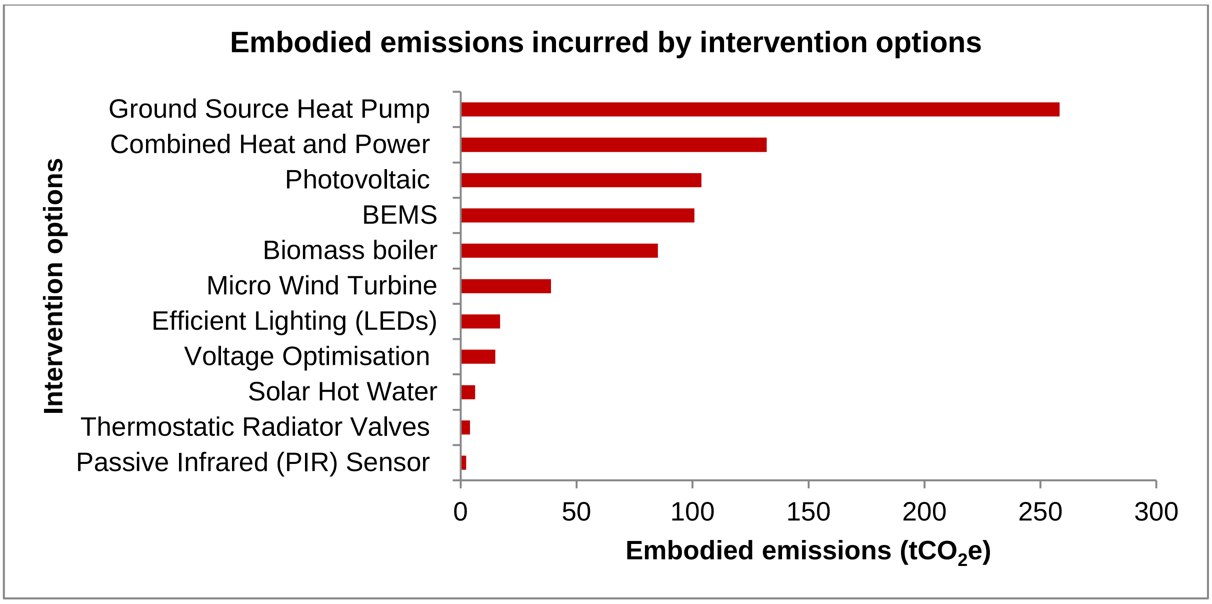



**Figure 5-9: Embodied emissions incurred by the intervention options**

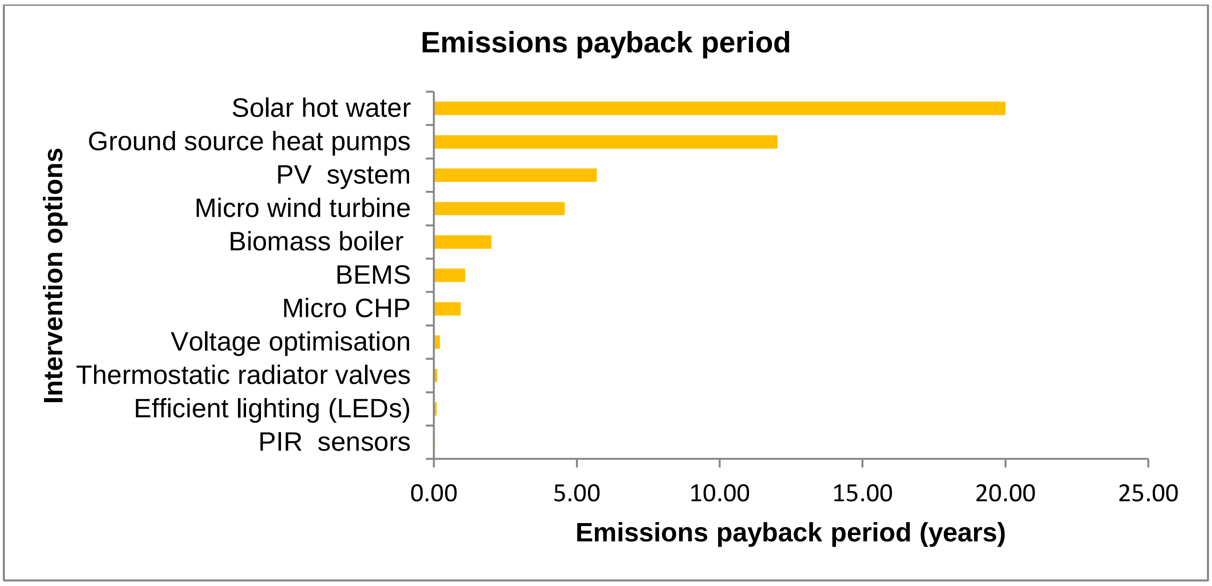



**Figure 5-10: Embodied emissions payback period**

As shown in Figure 5-9, the total embodied emissions incurred by the implementation of the options under consideration is evaluated to be 763 $tCO_2e$, a value which far exceeds the operational emissions savings in the first year of implementation, and requires about 47 years of operation to 'pay off' the embodied emissions incurred, assuming all options were implemented at the same time and there is no interaction between them. 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.

## 5.8. Integration of cost and both operational and embodied emissions into MACC

Extending the use of MACCs in a way which integrates financial considerations with embodied and operational emission into a robust and single ranking model can facilitate a more holistic view of the environmental impact of emissions abatement options. Embodied emissions related to a given set of low carbon intervention options can be estimated using the methodology described in Section 4.9. The results can then be used alongside the operational emissions savings to evaluate the net emissions saving (i.e. the difference between the operational emissions savings of a measure across the time frame considered and initial embodied emissions incurred in the production of the measure) of the abatement options. This will allow for the estimation of not just the costs associated with operational emissions savings, but also the sunk cost (i.e. cost that has already been incurred and cannot be recouped) of embodied emissions associated with the implementation of an option.

Based on the analysis presented in Section 4.14.1, the numerical effects of the inclusion of embodied emissions on how cost-effective an abatement option is, can be described based on two scenarios as follows. Consider the first scenario, where the effect of embodied emissions on the positive regime (i.e.the region containing measures that reduces emissions but incur a positive cost) of the generalized MAC curve based on the data in Table 5-3, is illustrated. As stated in Section 4.14.1, the effect of including embodied emissions is to decrease the emissions reduction potential of an option. Using the case of PV system as an example, where the net cost is £163,858 with operational emissions saving potential of 274.17t$CO_2$e across the time frame of 15-years, so that the cost-effectiveness is £598.02/t$CO_2$e.

As shown in Table 5-8, the initial embodied emissions associated with the PV is estimated to be 104 t$CO_2$e. Therefore, the net emissions savings ($E_{net}$) is 170.17 t$CO_2$e (i.e. 274.17 t$CO_2$e – 104 t$CO_2$e), shrinking the width from 274.17t$CO_2$e to 170.17t$CO_2$e. Using Equation 4.23, the cost-effectiveness now becomes £962.91/net t$CO_2$e (i.e. expansion in height of block from £598.02/t$CO_2$e to £962.91/net t$CO_2$e. Hence the change in cost-effectiveness due to embodied emissions is £364.89/t$CO_2$eso that the total sunk cost is £37,948.56 (i.e.£364.89/t$CO_2$e multiply by 104 t$CO_2$e). This numerical illustration shows that the consideration of embodied emissions of a positive cost abatement option **worsens** its cost-effectiveness which is in line with the analysis presented in Section 4.14.1.

Now consider the second scenario, where the effect of embodied emissions on the negative regime (i.e.the region containing measures that reduces emissions and also save money) of the generalized MAC curve based on the data set in Table 5-2, is illustrated. Taking the case of

Thermostatic Radiator Valve (TRV) with a net savings of -£178,813 and operational emissions savings of 495.17t$CO_2$e across the study period of 15 years, so that the "cost-effectiveness" is -£361.12/t$CO_2$e, as an example. With an estimated embodied emissions of 4 t$CO_2$e, the emissions saving is 491.17 t$CO_2$e. Applying Equation 4.23, the "cost-effectiveness" (used for illustration purpose since it is already established that it is potentially meaningless) becomes -£364.89/net t$CO_2$e. This change in "cost-effectiveness" from -£361.12/t$CO_2$e to -£364.89/net t$CO_2$e leads to higher embodied emissions being more cost effective, and therefore more desirable, than lower. The derivation of cost-effectiveness when embodied emissions are considered as provided in Section 4.14.1 shows that cost-effectiveness should **worsen** when embodied emissions are considered but this is not the case with negative cost measures. It follows that consideration of embodied emissions with respect to negative-cost measures within a MACC framework is invalid as earlier mentioned.

However, in the instance that it becomes pertinent to put a figure to the sunk cost in the form of embodied carbon cost associated with a negative cost measure, a positive change in cost-effectiveness can be calculated as shown below, from which the embodied carbon cost can be evaluated by multiplying the positive change in cost-effectiveness with embodied carbon incurred:

$$\Delta \text{ in cost} - \text{effectiveness } = \frac{|\text{Net Savings}|(£)}{E_{net}(tCO_2e)} - \frac{|\text{Net Savings}|(£)}{\text{Total } CO_2 \text{ saved } (tCO_2e)} \quad (5.1)$$

$$\Delta = \frac{|-£178{,}813\,|}{491.17} - \frac{|-£178{,}813|}{495.17} = £2.9/tCO_2e$$

So that the cost of embodied emissions associated with TRV is $£2.9/tCO_2e \times 4tCO_2e = £11.7$. The calculation is valid, since cost-effectiveness in this context is not used for ranking or investment appraisal purposes.

Table 5-10 shows the estimated $CO_2$ saved and net emissions savings due to the implementation of the intervention options under consideration. The negative cost options are ranked based on the Pareto optimisation technique described in Section 4.11.1, taking into account the effect of embodied emissions as shown in Figure 5-11. On the other hand, the cost-effectiveness (£/net t$CO_2$e) for each positive cost option is calculated for ranking purpose using Equation 4.23. The corresponding MAC curve is shown in 5-12. As shown in Figures 5-11 and 5-12, 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.

**Table 5-10: Estimated $CO_2$ saved and net emissions savings from options**

| 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 | 549.15 | 51.70 | 9 |
| Wind Turbine | 43133 | 127.75 | 39 | 88.75 | 637.90 | 486.01 | 10 |
| Photovoltaic | 163858 | 274.17 | 104 | 170.17 | 808.07 | 962.91 | 11 |
| GSHP | 147838 | 321.78 | 258 | 63.78 | 871.85 | 2317.94 | 12 |
| Solar Hot Water | 9346 | 4.56 | 6 | -1.44 | - | - | - |

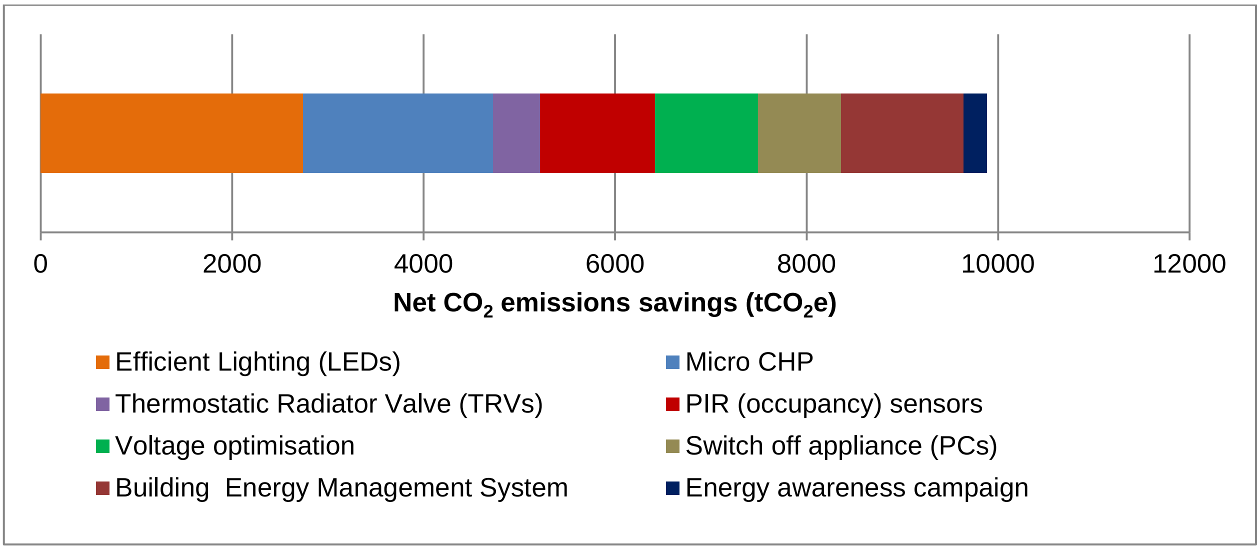



**Figure 5-11: Pareto ranking of negative cost measures (as a function of net emissions savings)**

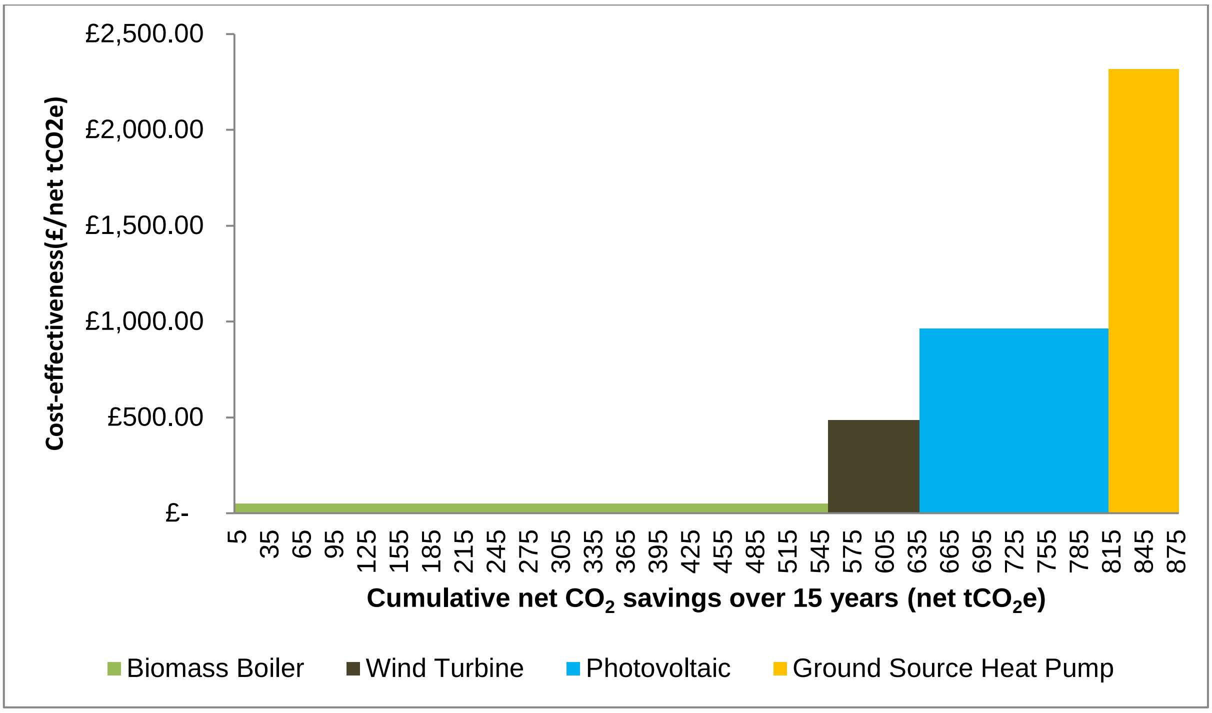



**Figure 5-12: MACC for positive cost measures (as a function of net emissions savings)**

The results presented above clearly demonstrates how the consideration of embodied emissions can affect the overall picture of a climate change abatement project and suggest that attention need to be paid to it. Based on the analysis above, 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. Also, under the time frame of 15 years considered, the implementation of solar hot water is found not to have a net emissions savings as its initial embodied emissions exceeds its total operational emissions savings. This explains its disappearance in the MACC curve shown in Figure 5-12. 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 5-11 and 5-12 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.

## 5.9. Effect of Government incentive and tariffs on cost-effectiveness

Based on the background introduction to FiT and RHI[3] presented in Sections 4.13.1 and 4.13.2 respectively, the effects of their consideration on the cost-effectiveness on renewable technologies are presented in this section. Simple total annual return as demonstrated in Sections

[3] In this thesis, 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.

4.13.1 and 4.13.2 are calculated. The NPV of the total annual return is then calculated by discounting all future financial savings to their present value equivalents using Equation 4.16. The following 6 scenarios (4 for FiT and 2 for RHI) are considered for both forms of incentives:

(i) Consideration of FiT, with part of the energy generated exported to the grid (operational emissions savings only)
(ii) Consideration of FiT, with 100% site usage (operational emissions savings only)
(iii) Consideration of RHI (operational emissions savings only)
(iv) Consideration of FiT, with part of the energy generated exported to the grid (net emissions savings, i.e. embodied emissions is taken into account)
(v) Consideration of FiT, with 100% site usage (net emissions savings, i.e. embodied emissions is taken into account)
(vi) Consideration of RHI (net emissions savings, i.e. embodied emissions is taken into account)

Table 5-11 shows the first three scenarios. As shown, the cost-effectiveness of each renewable technology improves making them more economically attractive when FiT and RHI are taken into consideration. For the case of FiT, 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 5-11. 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 5-11. The MACC representations are presented in Figure 5-13a and 5-13b. The options that 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.

**Table 5-11: 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- 50% exported to grid** | | | | | | |
| **Photovoltaic** | 34789 | *Generation*:4696.55<br>*Export*: 782.76<br>*Reduced bill*:1741.20<br>***Total*:7220.51** | 74946.42 | 125054 | 274.17 | 456.4 |
| **Micro CHP** | 193582 (Power)<br>229242 (Heat) | *Generation*:21294.05<br>*Export*: 4355.60<br>*Reduced bill*: 9688.79<br>Gas savings:8825.82<br>***Total*:44164.26** | 458409.89 | -358410 | 2117.11 | -169.29 |
| **Micro wind turbine** | 16235 | *Generation*: 4123.68<br>*Export*: 365.29<br>*Reduced bill*: 812.56<br>***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<br>*Reduced bill*: 3482<br>***Total*:8178.35** | 84890.55 | 115109 | 274.17 | 420.11 |
| **Micro CHP** | 193582 | *Generation*:21294.05<br>*Reduced bill*: 19377.58<br>Gas savings:8825.82<br>***Total*:49497.45** | 513766.60 | -413767 | 2117.11 | -195.44 |
| **Micro wind turbine** | 16235 | *Generation*: 4123.68<br>*Reduced bill*: 1625<br>***Total*:5748.68** | 59669.33 | 331 | 127.75 | 2.59 |
| **Renewable Heat Incentives (RHI) [SCENARIO III]** | | | | | | |
| **Biomass Boiler** | 229242 | *Generation*: 11691.34<br>*Reduced bill*: 8826<br>***Total*:20517.34** | 212962.97 | -92963 | 634.15 | -146.6 |
| **GSHP** | 380770 | *Generation*: 19485.57<br>*Reduced bill*: 14659<br>***Total*:34144.57** | 354419.34 | -54419 | 321.78 | -169.12 |
| **Solar Hot Water** | 1635 | *Generation*: 145.47<br>*Reduced bill*: 63<br>***Total*:208.47** | 2163.85 | 7836 | 4.56 | 1718.45 |

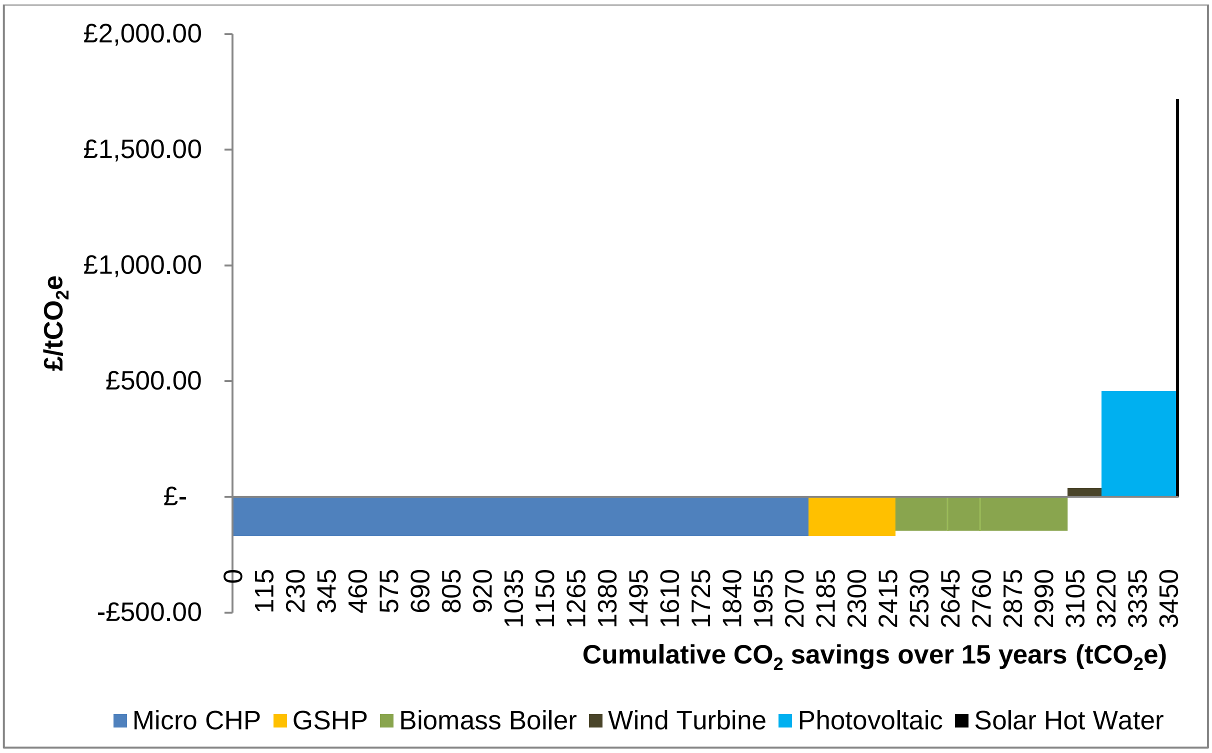



**Figure 5-13a: MACC for operational emissions savings from renewable technologies with consideration of FiT (when 50% of energy generated exported to the grid) and RHI**

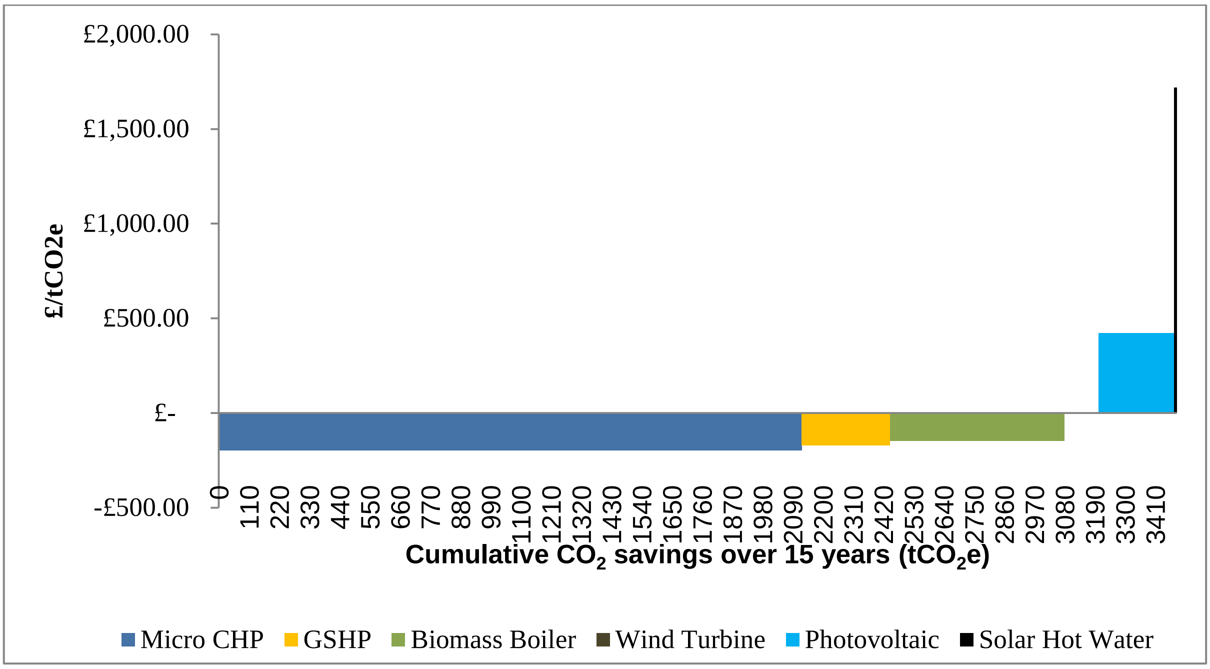



**Figure 5-13b: MACC for operational emissions savings from renewable technologies with consideration of FiT (100% site usage of energy generated) and RHI**
**Figure 5-13: Figures 5-13a and 5-13b**

The scenarios described above changes when embodied emissions are considered. The consideration of embodied emissions worsens the cost-effectiveness of an option. Table 5-12 indicates the results for second three scenarios. As shown, 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/$tCO_2$e. On the other hand, when embodied emissions are considered, the cost-effectiveness is £677.11/$tCO_2$e 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 (see Table 5-11) now becomes a positive cost measure when embodied emissions is considered as shown in Table 5-12. This analysis further demonstrates how the consideration of embodied emissions could shape future policy initiatives towards climate change adaptations. The MACC curves are shown in Figures 5-14a and 5-14b.

**Table 5-12: Effect of FiT and RHI on renewable technologies (net 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 IV-50%) exported to grid** | | | | | | |
| **Photovoltaic** | 34789 | *Generation*:4696.55<br>*Export*: 782.76<br>*Reduced bill*:1741.20<br>***Total*:7220.51** | 74946.42 | 125054 | 170 | 735.61 |
| **Micro CHP** | 193582 (Power)<br>229242 (H eat) | *Generation*:21294.05<br>*Export*: 4355.60<br>*Reduced bill*: 9688.79<br>Gas savings:8825.82<br>***Total*:44164.26** | 458409.89 | -358410 | 1985 | -158.02 |
| **Micro wind turbine** | 16235 | *Generation*: 4123.68<br>*Export*: 365.29<br>*Reduced bill*: 812.56<br>***Total*:5301.53** | 55028.07 | 4972 | 89 | 55.87 |
| **Feed-in-Tariff [SCENARIO V-All energy consumed on site]** | | | | | | |
| **Photovoltaic** | 34789 | *Generation*: 4696.95<br>*Reduced bill*: 3482<br>***Total*:8178.35** | 84890.55 | 115109 | 170 | 677.11 |
| **Micro CHP** | 193582 | *Generation*:21294.05<br>*Reduced bill*: 19377.58<br>Gas savings:8825.82<br>***Total*:49497.45** | 513766.60 | -413767 | 1985 | -182.43 |
| **Micro wind turbine** | 16235 | *Generation*: 4123.68<br>*Reduced bill*: 1625<br>***Total*:5748.68** | 59669.33 | 331 | 89 | 3.72 |
| **Renewable Heat Incentives (RHI)[SCENARIO VI]** | | | | | | |
| **Biomass Boiler** | 229242 | *Generation*: 11691.34<br>*Reduced bill*: 8826<br>***Total*:20517.34** | 212962.97 | -92963 | 549 | -123.87 |
| **GSHP** | 380770 | *Generation*: 19485.57<br>*Reduced bill*: 14659<br>***Total*:34144.57** | 354419.34 | -54419 | 63 | 525.55 |

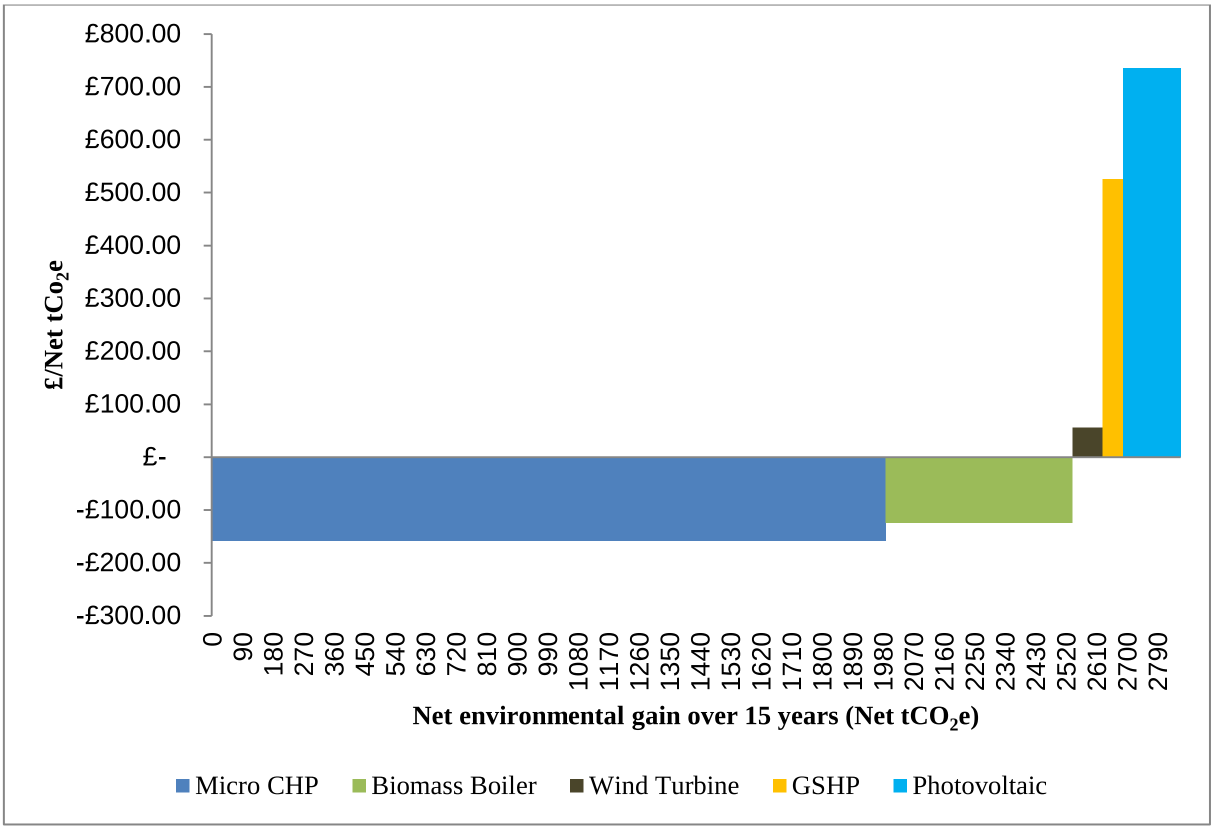



**Figure 5-14a: MACC for net emissions savings from renewable technologies with consideration of FiT (when 50% of energy generated exported to the grid) and RHI**

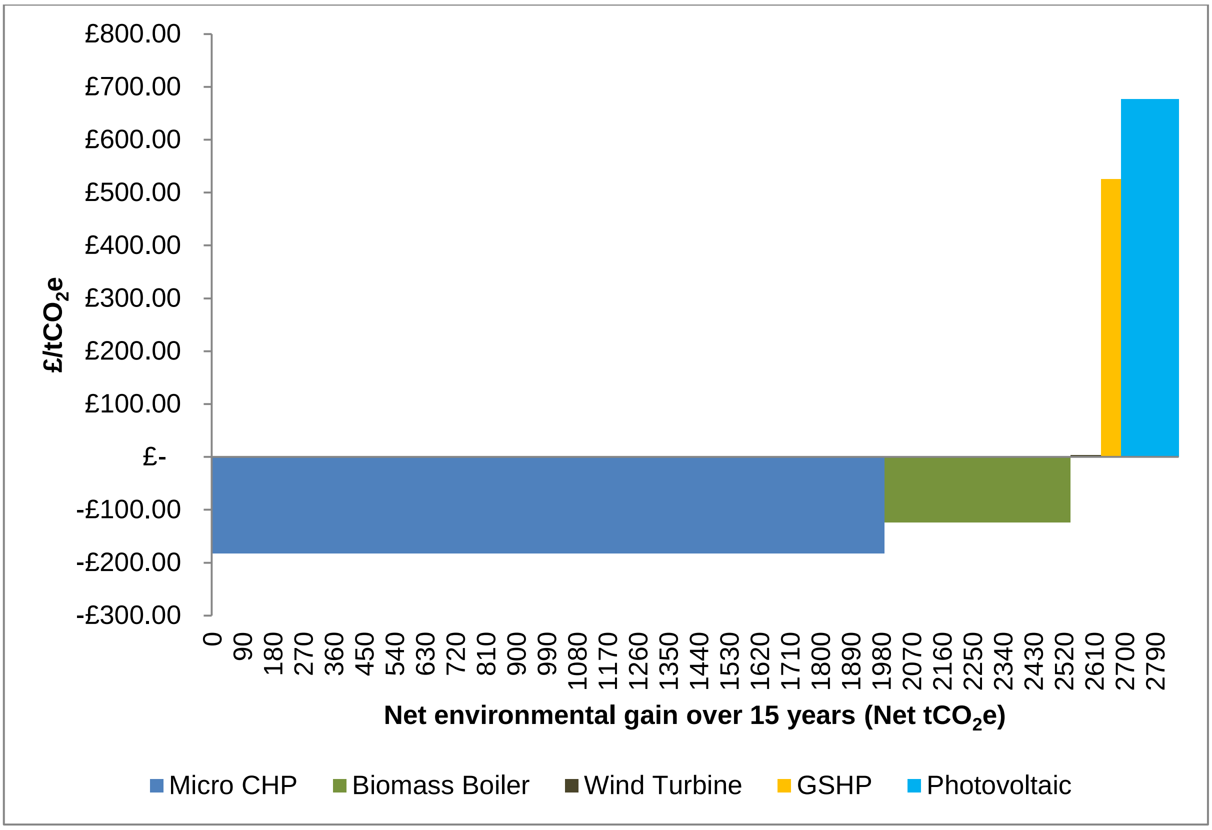



**Figure 5-14b: MACC for net emissions savings from renewable technologies with consideration of FiT (100% site usage of energy generated) and RHI**
**Figure 5-14: Figures 5-14a and 5-14b**

## 5.10. Sensitivity analysis

Analysis of how the choice of discount rate and effect of energy prices affects the outputs of the DSS is presented in this section.

### 5.10.1. Effect of discount rates

In this thesis, a discount rate of 5% is used throughout. Sensitivity analysis is therefore conducted to establish how the choice of discount rate can affect the results of the study. An increase in discount factor leads to reduced cumulative net present value of energy saved and net savings. Table 5-13 shows how different choice discount rate influences the outcome of the abatement options' potentials in terms of financial savings. As shown, a change in discount factor from say 5% to 10% reduces the cumulative net present value and net savings from £1777359 and -£758360 to £1302426 and -£283424 respectively.

**Table 5-13: 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 | 1,777,359 | -758,360 |
| 10 | 1,302,426 | -283,424 |
| 15 | 1,001,273 | 17,727 |
| 20 | 800,604 | 218,396 |

Figure 5-15 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.

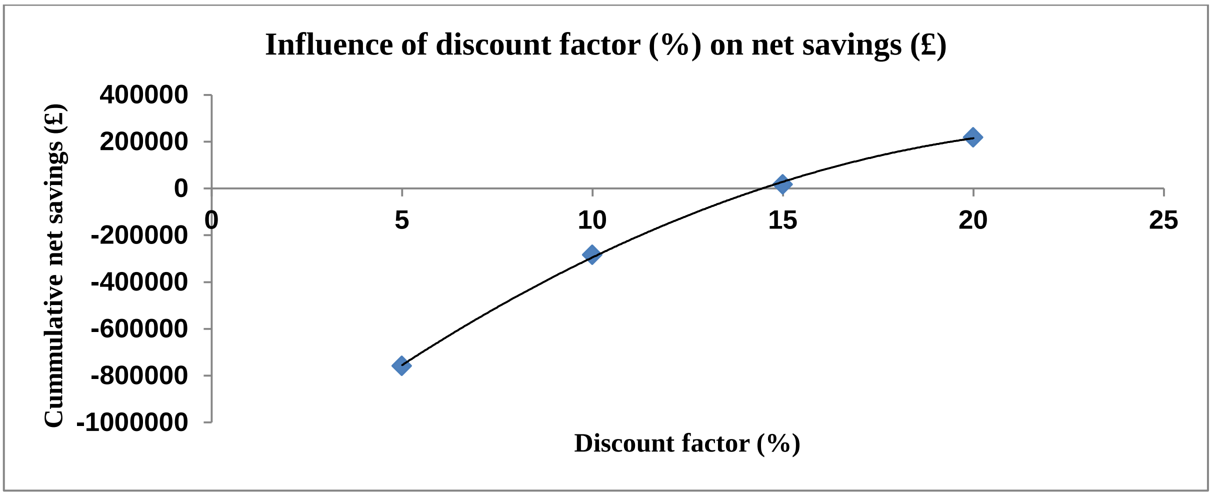



**Figure 5-15: Sensitivity analysis-influence of discount factor on net-savings**

### 5.10.2. Effect of energy prices

The effects of changes in energy (electricity and gas) prices on final decision outputs are presented in this section. The current energy price (i.e. reference price) for the present case is 3.85p/kWh and 10.01p/kWh for gas and electricity respectively. So assuming cost of energy increases and decreases by 40% as an example, then high and low price scenarios for electricity will be 14.01p/kWh and 6p/kWh respectively. For gas, it is high (5.39p/kWh) and low (2.31p/kWh). Table 5-14 shows how changes in the energy prices (assuming a constant discount factor) influences the outcome of the abatement options potentials of some selected options considered for sensitivity analysis.

**Table 5-14: Sensitivity analysis for $CO_2$ abatement potential with different energy prices**

| Example options | Capital cost (£) | Energy price range | Cost of energy saved (£) | NPV of energy saved (£) | Net costs(£) | Cost-effectiveness (£/$tCO_2e$) |
|---|---|---|---|---|---|---|
| **Example positive-cost measures** | | | | | | |
| **PV** | 200,000.00 | **Reference** | 3,482.00 | 36,141.97 | 163,858.00 | 598.02 |
| | | **High** | 4,874.00 | 50,590.45 | 149,410.00 | 545.29 |
| | | **Low** | 2,087.00 | 21,662.35 | 178,338.00 | 650.87 |
| | | | | | | |
| **Wind turbine** | 60,000.00 | **Reference** | 1,625.00 | 16,866.94 | 43,133.00 | 337.63 |
| | | **High** | 2,275.00 | 23,613.72 | 36,386.00 | 284.82 |
| | | **Low** | 974.00 | 10,109.79 | 49,890 | 390.52 |
| **Example negative-cost measures** | | | | | | |
| **Micro CHP** | 100,000.00 | **Reference** | 28,203.40 | 292,741.65 | -192,742.00 | N/A |
| | | **High** | 39,477.02 | 409,757.97 | -309,758.00 | N/A |
| | | **Low** | 16,910.43 | 175,524.48 | -75,524.00 | N/A |
| | | | | | | |
| **BEMS** | 120,000.00 | **Reference** | 17,901.24 | 185,808.75 | -65809.00 | N/A |
| | | **High** | 25,056.17 | 260,074.48 | -140074.00 | N/A |
| | | **Low** | 10,732.39 | 111,398.54 | 8601 | 6.24 |

As shown in Table 5-14, with an increase in cost of energy, more money is saved with every kWh of energy avoided from the source of energy. This improves the economics (i.e. NPV of energy saved) of any measure that saves energy or provides it in an alternative way. In other words, high cost of energy appears to make an option more valuable as demonstrated above. For the case of BEMS where both gas and electricity are involved, low energy prices, makes it appear less economically attractive because it changes from being a negative cost measure to become a positive cost measure. As the general trend regarding the price of energy is regarded to be upwards, this suggests that the worth of investing in renewable energy and energy efficient installations will increase, as the savings derived from running them will be greater.

## 5.11. Extended application of the current DSS

In this section, a number of applications which the current DSS can be put to are presented using case studies where applicable with availability of data.

### 5.11.1. Application to a scenario

**(i) Scenario description:**

A building that has achieved 40% reduction in baseline annual GHG emissions through improvements in the performance of the building fabric and building services system seeks a further 10% reduction in annual GHG emissions through the integration of appropriate renewable energy technology options.

**(ii) Required:**

It is required to use the DSS to aid decision about the best option to choose from a range of renewable energy technology options including Micro CHP, GSHP, Photovoltaic, Biomass, Solar hot water and Micro wind turbine to achieve the 10% target reduction , taking into account the implementation constraints that are peculiar to the building under consideration.

**(iii) Building energy data:**

The case building energy consumption data is given in Table 5-15. The building is heated with gas and the peak hot water demand is also provided by gas.

**Table 5-15: Baseline and energy demand and $CO_2$ emissions**

| Activities | Annual energy demand (kWh/yr.) | $CO_2$ emissions ($tCO_2e$/yr.) |
|---|---|---|
| Heating and hot water demand | 72,500 | 13.30 |
| Electricity consumption | 14,050 | 7.37 |
| **Total** | 86,550 | 20.67 |

As shown above, the total base line $CO_2$ emissions attributed to the building is 20.67$tCO_2e$/year. Therefore, 10% of this figure and hence the renewable energy reduction targets is 2.07 $tCO_2e$/year. The challenge therefore is to use the DSS to carry out the design aspects to aid the final selection of the most suitable option to settle for. To be clear, the task is which of the listed technology will achieve 2.07$tCO_2e$/year. It is important to clarify this because the current DSS looks at the performance of an option as a function of the energy (gas or electricity) requirement substituted by the energy generated by the technology option. As an example, the DSS calculates the electricity requirement replaced by the electricity produced by a PV system as a function of the baseline emissions.

Based on the data in Table 5-15, the DSS calculates 10% of 7.37$tCO_2e$/year. This is not what is required in this scenario. To handle this kind of problem within the DSS, the technologies options are split into gas-dependent and electricity-dependent and the calculations are carried out separately. So in this case, for electricity dependent options, total baseline emissions are seen as 20.67t$CO_2$e/year from electricity consumption and vice-versa. For the case of wind turbine and PV, 20.67t$CO_2$e is divided by the GHG emission factor electricity (0.5246 kg$CO_2$/kWh) to give an assumed value in kWh. Table 5-16 shows the outputs from the DSS. Cost of electricity and gas for the building are 8p/kWh and 2.31p/kWh respectively.

**Table 5-16: Emissions savings and related parameters from options**

| Technology Options | Capacity required | Energy saved or generated (kWh/year) | $CO_2$ saved (t$CO_2$e/year) | % $CO_2$ savings against baseline | Payback period (years) |
|---|---|---|---|---|---|
| Micro CHP | 6$kW_e$/10$kW_h$ | 43,500.00 | -0.98 | - | 45 |
| Biomass boiler | 100$kW_{th}$ | 14,500.00 | 2.67 | 13 | 63 |
| GSHP | 150$kW_t$ | 36,250.00 | 0.72 | 4 | 130 |
| Micro wind turbine | 12$kW_p$ | 3,940.14 | 2.07 | 10 | 63 |
| Photovoltaic system | 20$kW_p$, 185 $m^2$ | 3,940.14 | 2.07 | 10 | 330 |
| Solar hot water | 12 $m^2$ | 3,629.50 | 1.77 | 9 | 41 |

As shown in Table 5-16, 13% of $CO_2$ emissions savings can be potentially realised from installing a biomass boiler to meet the heating and domestic hot water demand of the building. However, the installation of the biomass boiler is constrained by certain design and implementation implications including: additional space for the boiler plant room, buffer tank and wood pellet storage; fire and safety concerns; absence of reliable biomass source within close radii to the building. As such, biomass boiler for space and water heating is not economically viable. For the case of wind turbine, 12kWp rating is needed to realise a 10% saving. However, implementation consideration requires a 20-25m high mast with 2.5 meter diameter 1.5kW rotor that to achieve the desired target savings for the building. Limited space, structural practicalities, and visual impact because the building is located in an urban area make it unsuitable for efficient wind generation.

For PV systems to work efficiently, the modules should face south and at an angle of inclination of 30° to the horizontal. Orientations of 45° of south have been found to be acceptable. For optimal outputs, it is vital that the system is prevented from shade as this may reduce output significantly. From an implementation perspective, the area of panel required for a 1$kW_p$ PV system is about 10$m^2$, but as shown in Table 5-16, to realise the 10% potential saving target, a total roof area of 185 $m^2$ PV panel is required. The case building has approximate area of 110$m^2$ of south facing pitch roof and a flat area of 66$m^2$. As such, the PV system is not technically viable from an implementation point-of-view. For the case of GSHP, a 4% emissions reduction is realisable, although it is not close to the desired 10% target. Additionally, there were no insufficient free land areas to consider horizontal ground loop pipes.

Design calculations for the Micro CHP clearly indicate that there are insufficient loads to make it technically or economically viable. Of all the renewable energy options considered, solar hot water is the only technically viable option because the case study building has a double pitched roof with adequate area where the solar water heating panels can generate a 10% $CO_2$ emissions reduction for the building. The analysis provided clearly demonstrates that the current DSS can be used for emissions savings potential calculations from a set of retrofit options and implementation challenges can then be investigated before making a final decision.

### 5.11.2. Comparison of embodied emissions of retrofit options -UK vs. ROW

In this section, the result of the extension of the application of the DSS, based on the mechanism (i.e. EIO within an integrated MRIO methodological framework) of its embodied emissions module, to estimate the environmental loads and emissions implications of consumption associated with the building energy retrofit options captured within the DSS is presented. The aim is to compare the embodied emissions associated with the options whether they are manufactured in the UK or from the ROW. The physical quantities of each retrofit option in terms of their design specification as generated by the DSS, their unit costs, final demand in monetary terms and equivalent embodied emissions results are recorded in Table 5-17. The numerical results for the embodied emissions estimates from both the ROW and the UK are illustrated in Figures 5-16 and 5-17 respectively. As shown, if all the retrofit options were manufactured in the UK, the total embodied emissions is 703 $tCO_2e$ and if they were imported from the ROW, the total environmental loads and emissions amounts to a total of 1242 $tCO_2e$. The embodied emissions associated with international flow trade therefore, far surpass the emissions from the UK by a value of 539 $tCO_2e$

**Table 5-17: Embodied emissions results-UK vs. ROW**

| Intervention options | Physical Quantity | Unit Cost [£/Unit] | Final Demand | Embodied emissions ($tCO_2e$) [Imports-RoW] | Embodied emissions ($tCO_2e$) [Domestic-UK] |
|---|---|---|---|---|---|
| PV system | 400 $m^2$ | £300.00 | £120,000.00 | 104 | 91 |
| Micro wind turbine | 15$kW_e$ | £2,500.00 | £3,7500.00 | 39 | 33 |
| Solar Hot Water | 7$m^2$ | £850.00 | £5,950.00 | 6 | 5 |
| Micro CHP | 38 $kW_e$ | £1,200.00 | £57,000.00 | 542 | 132 |
| Ground Source Heat Pumps | 250$kW_t$ | £1,000.00 | £250,000.00 | 258 | 221 |
| Voltage optimisation | 1 Unit | £18,000.00 | £18,000.00 | 18 | 15 |
| Efficient Lighting (LEDs) | 976 Units | £20.00 | £19,520.00 | 17 | 15 |
| BEMS | 1 Unit | £120,000.00 | £120,000.00 | 123 | 101 |
| Biomass boiler | 400 $kW_t$ | £200.00 | £80,000.00 | 128 | 85 |
| Thermostatic Radiator Valves | 200 Units | £15.00 | £3,000.00 | 3 | 3 |
| PIR (occupancy) sensors | 180 Units | £25.00 | £4,500.00 | 4 | 2 |
| | | | **Total emissions** | **1242** | **703** |

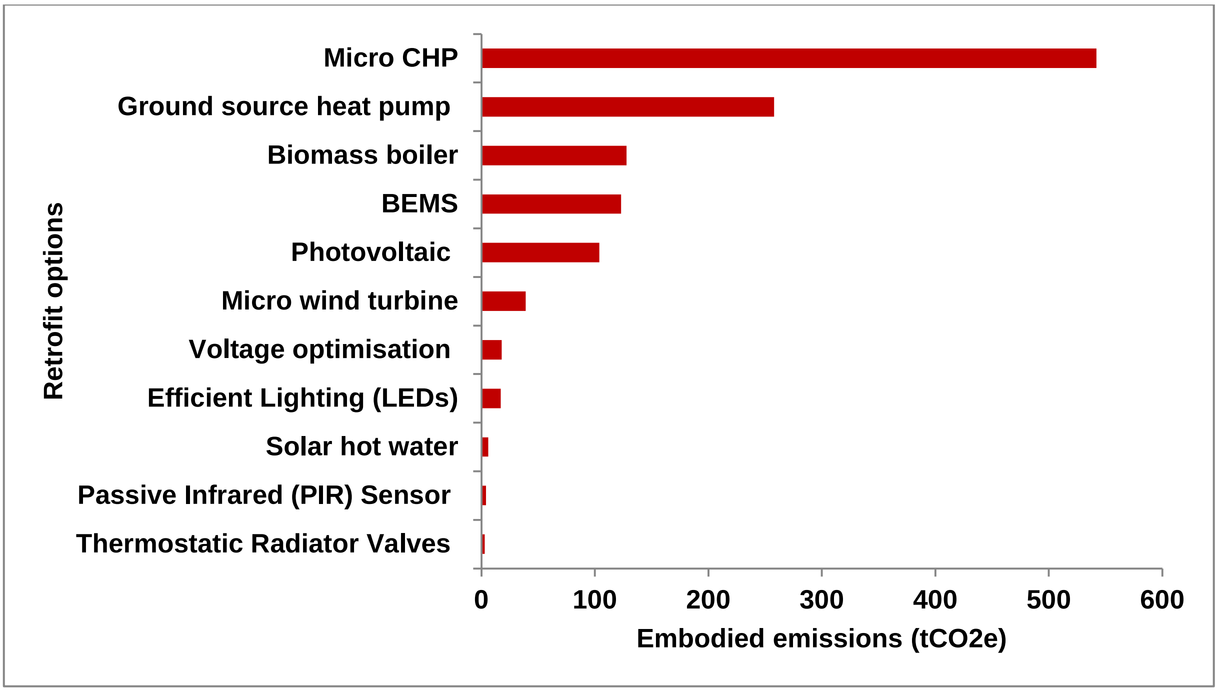



Figure 5-16: Embodied emissions of retrofit options, assuming all options are imported from the RoW

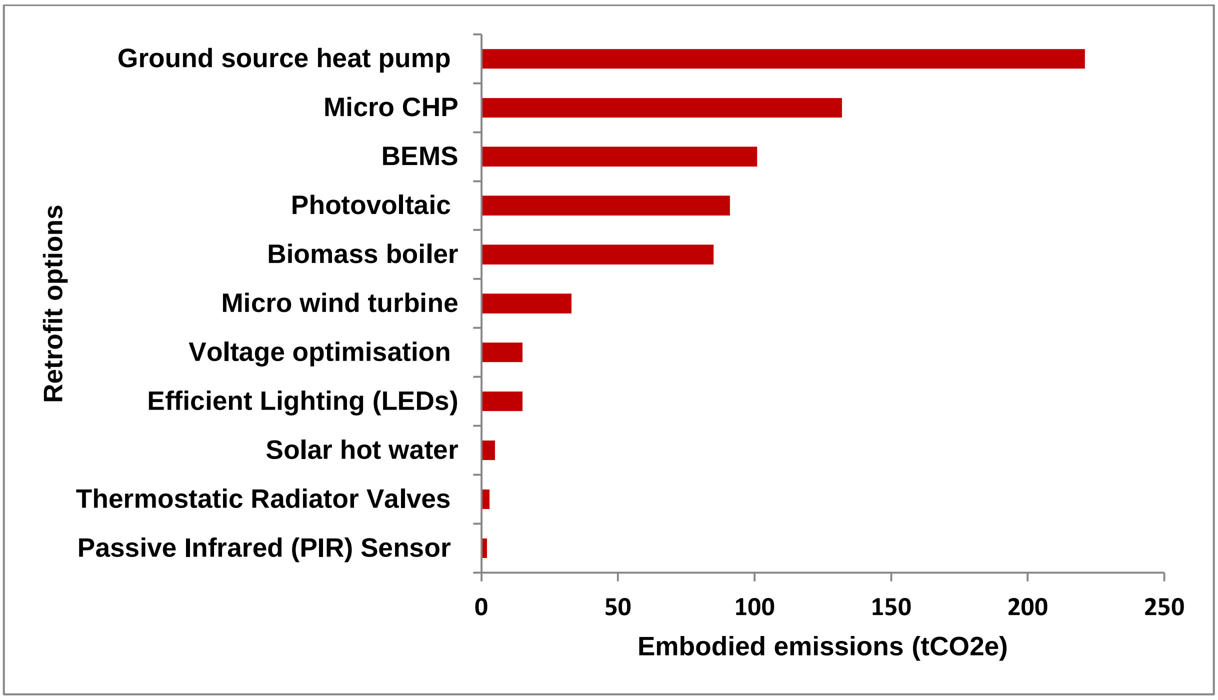
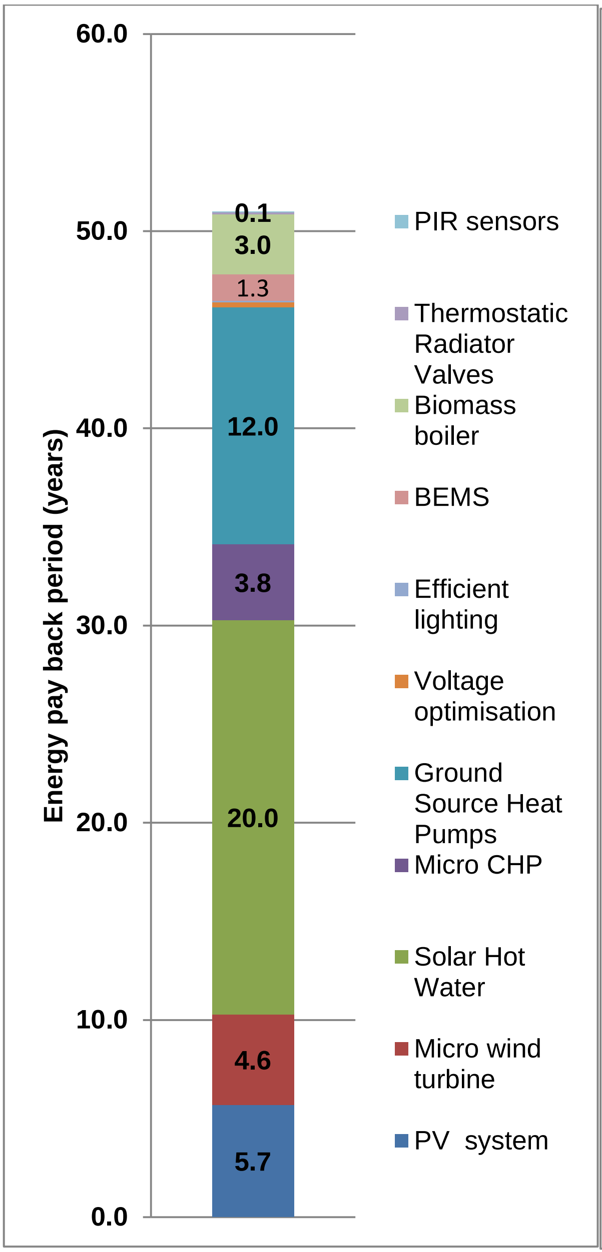



Figure 5-17: Embodied emissions of retrofit options, assuming all options are manufactured in the UK

In Table 5-18, the energy saved or energy generated and the corresponding energy payback period of each of the retrofit options as calculated by the DSS are presented. The individual estimated energy payback period for the ROW and UK are represented with stacked bar charts as depicted in Figures 5-18a and 5-18b respectively. If all the options considered are imported from the ROW, the estimated energy payback period is 51 years as compared to 40 years, if they were manufactured in the UK.

Table 5-18: Energy saved/ energy payback periods-ROW and UK compared

| Intervention options | Energy saved or generated (MWh/year) | $CO_2$ saved/year ($tCO_2e$) | EPBP [RoW] (years) | EPBP [UK] (years) |
|---|---|---|---|---|
| PV system | 34.79 | 18.25 | 5.70 | 4.99 |
| Micro wind turbine | 16.24 | 8.52 | 4.58 | 3.87 |
| Solar Hot Water | 1.64 | 0.30 | 20.00 | 16.67 |
| Micro CHP | 422.82 | 141.14 | 3.84 | 0.94 |
| Ground Source Heat Pumps | 380.77 | 21.45 | 12.03 | 10.30 |
| Voltage optimisation | 139.16 | 73.00 | 0.25 | 0.21 |
| Efficient lighting | 350.54 | 183.89 | 0.09 | 0.08 |
| BEMS | 242.32 | 91.94 | 1.34 | 1.10 |
| Biomass boiler | 229.24 | 42.28 | 3.03 | 2.01 |
| Thermostatic Radiator Valves | 179.80 | 33.01 | 0.09 | 0.09 |
| PIR sensors | 152.47 | 79.99 | 0.05 | 0.03 |



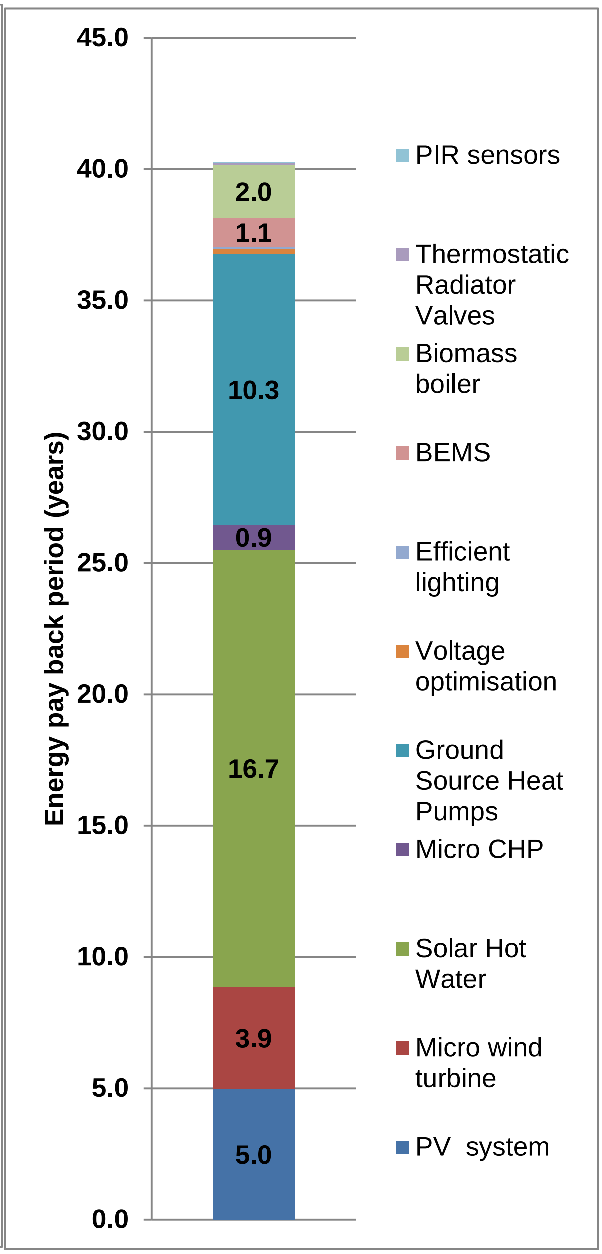




Figure 5-18a: EPBP (ROW) Figure 5-18b: EPBP (UK)

Figure 5-18: (a) EPBP (ROW) (b) EPBP (UK.

The knowledge of the comparison between products manufactured in the UK and the ROW can be used in policy analysis to ascertain the environmental impacts of international trade flows between different countries with the view to understand the consequences that the relocation of a given industrial sector within the UK to the ROW has on emissions. For instance, consider the case of biomass boiler as shown in Table 5-17, the embodied emissions associated with it when imported from the ROW (128 t$CO_2$e) is much higher than when manufactured in the UK (85 t$CO_2$e). From production-based perspective to GHG reporting (Barrett *et al.,* 2013), it will appear better if the biomass boiler are manufactured in the UK rather than importing them from the ROW.

Similarly, the results of the comparison of embodied emissions between the UK and ROW based on MRIO framework when integrated within Marginal Abatement Cost Curves (MACC), as a mechanism for evaluating intervention options as demonstrated in Section 5.8 (Figure 5-12, for example) can trigger innovations in product development processes and sustainable business models. This is possible as the approach readily puts both operational and embodied emissions into perspective based on performance and cost-effectiveness. This in turn can be useful in providing detailed information which can form the basis for the formulation of effective policies towards decarbonisation efforts. For example, consider the case of biomass boiler based on its cost-effectiveness. The net cost of biomass boiler is £28,389 as shown in Table 5-3 and 5-10. With the consideration of embodied emissions, its cost-effectiveness is £51.70/ t$CO_2$e, if manufactured in the UK (case 1) and £56.09 t$CO_2$e if it was imported from the ROW (case 2). As indicated, the cost-effectiveness of biomass boiler worsens due to GHG embodied in imported products. From a policy maker's point of view, there is more scope to regulate in case 2 as compared to case 1 since embodied emissions in international trade flows is taken into consideration. In doing so, a better understanding of consumption patterns can be facilitated and can assist in identifying robust policy framework (e.g. border leveling), business and consumer triggers that will lead to an overall emissions reduction.

## 5.12. Overall benefit of adopting an integrated approach

Making an environmentally sustainable choice requires information regarding the consequences of alternative designs (Lave *et al.,* 1995). For building stakeholders, consumers, businesses and regulators to make informed choices regarding retrofit options, knowledge of the environmental consequences of different choices in terms of impact and cost is crucial. Adopting an integrated approach of combining three key variables of emissions mitigation options: financial costs, operational and embodied emissions into a robust framework in the form of a

MACC as illustrated in Section 4.14.1 and implemented in Section 5.8 will allow trade-offs between various abatement options to be identified and communicated. This will ensure decisions that are informed both by environmental and financial considerations. Gaining knowledge of how embodied emissions compares with operational emissions will assist in putting climate change mitigation strategies into context and facilitate improvement initiatives with a positive emissions reduction profile.

The concept will also ensure environmentally sustainable choices regarding materials selection and design procedures are taken at an early stage where design changes can be made and preferential low embodied energy materials selection adopted when specifying climate change mitigation options. Similarly, the integrated approach helps with the understanding of how much of the emissions are embodied vs. how much are operational. This will help environmentally conscious organisations in disaggregating their emissions pattern based on operational emissions which feeds into their Scope 1 and 2 targets and embodied emissions which feeds into their Scope 3 emissions from purchasing and services. In doing so, organisation will gain an appreciable understanding of the split between embodied and operational emissions due to their activities and emissions saving targets from such organisations can be more holistic since financial cost and both operational and embodied emissions costs are taken into consideration.

Future legislation and policies which places a price on carbon and technologies are likely to mandate radical operational emissions reductions. As a result, the large existing building stock will require major refurbishment and/or rebuild effort and may further lead to an increase in embodied emissions. This suggests that embodied emissions are likely to become one of the key metrics to be addressed in whole-life building sustainability, and may in turn prompt future regulations to enforce the consideration of embodied emissions in building energy assessment in attempts to achieve the best-value retrofit plan. The development of the current DSS which takes a whole-life $CO_2$ emission accounting framework and an economic assessment viewpoint, clearly demonstrates how value is delivered across different parts of the techno-economic system, especially as it pertains to financial gains, embodied and operational emissions reduction potential.

If embodied emissions become a target for emissions reduction as is already being proposed by the European Union emissions trading scheme (EU ETS) using policy initiatives which puts emissions reduction targets based on carbon cap (London Renewable, 2004), it will force companies to rethink or restructure their emissions reduction strategies when it becomes mandatory for them to quantify and report the emissions associated with their products. In situations where companies find it difficult to meet their emissions reduction commitments through direct mitigation or through the purchase of emission allowances from other trading partners, they will suffer financial penalties. For instance, the EU ETS puts a financial penalty of 40 euro for every tonne of $CO_2$ emitted from 2005, increasing to 100 euro for every tonne of $CO_2$ emitted from 2008 (London Renewables, 2004). In the end, the associated costs will be passed on to consumers. The use of the current DSS which disaggregates emissions into its operational and embodied constituents can help decision makers to make environmentally sustainable retrofit choices.

### 5.12.1. Urgency for a holistic policy framework to include embodied emissions

Regulations on improving energy efficiencies and operational energy consumption are widespread in the construction sector across the world. However, despite extensive research on embodied energy of buildings, the extension of building policies to include embodied emissions has not become part of mainstream building sector policy developments. This is because of the long established challenges such as data, system boundary, uncertainties, methodological issues, lack of consistent framework, etc. in embodied emissions analysis. Recognising this, the International Standard Organisation through the ISO 14000 family of standards has traditionally provided the general guidelines for conducting embodied energy calculations. Subsequent efforts from the joint Life Cycle Initiative (LCI) between the United Nation's Environmental Program (UNEP) and Society for Environmental Toxicology (SETAC) as well as Public Available Standard 2050 (PAS 2050) from the British Standards Institution have led to further evolution and developments of these guidelines. In spite of these efforts, embodied emissions are not included in building sector policy developments targeting energy use and emissions.

A clear example of the lack of holistic policy framework is highlighted by the focus of the UK Government on addressing only operational emissions when announcing that new domestic and non-domestic buildings are to be rated as near zero carbon by 2016 and 2019 respectively. It is well established that potential emissions savings can be achieved from all the consumed operational energy in buildings through the contribution of energy from on-site renewable energy and low carbon technologies installations, as well as off-site renewable energy contributions that are supplied directly to the buildings. However, contemporary research has shown that these efforts can be negated by embodied emissions associated with buildings. Recognizing this, the first attempt for a holistic policy framework should start with amending the basic definition of zero carbon buildings.

Furthermore, the main challenges facing the calculations of embodied emissions need to be properly integrated into a consistent framework. This is so, as literature suggests that although significant research have been carried out in addressing these challenges, there is fragmentation and inconsistency in integrating advancements in embodied energy analysis together. As such, there is the need for a consistent framework on building sector embodied energy analysis. These can be developed along the lines of the Greenhouse Gas Protocol for Corporate Value Chain (Scope 3) Accounting and Reporting Standard which was developed under the auspices of the World Resource Institute and World Business Council for Sustainable Development.

Research, academia and businesses can work together to develop a consistent and comprehensive framework using state-of-the-art advancements in embodied energy research which addresses identified challenges such as system boundary completeness (*inter alia:* Dixit *et al.,* 2013), use of stochastic analysis to address data variability and uncertainty (*inter alia:* Acquaye *et al.,* 2011), communication of results (*inter alia*: Carlsson, 2005), use of hybridized approaches to solve methodological challenges (*inter alia:* Joshi, 1999), etc. Such a consistent framework would reduce ambiguity in embodied emissions calculations and so make it easier to include both operational and embodied emissions in a framework for building sector policy developments.

By omitting embodied emissions in the building sector, policy developments related to energy and emissions are in effect neglecting the bigger picture and truncating the wider benefits that can be derived from a more holistic policy framework.

In the chapter that follows, details are provided regarding the evaluation and validation of the decision support system.

# CHAPTER SIX: DSS EVALUATION AND VALIDATION

## 6.1. Introduction

This chapter provides a full description of the overall evaluation and validation of the decision support system whose developmental framework and output results are presented in chapters four and five respectively. The empirical methodological issues relevant to the quantitative and qualitative components of the sequential explanatory strategy (Section 3.3.1) employed in this study are presented in this chapter. Given that the current DSS was developed to help decision makers (e.g. energy managers) to analyse investments in energy efficiency, it is important to explore their views, perceptions, experiences, feelings and beliefs. Before delving into the details of the DSS evaluation, it is important to establish the extent to which the DSS can be generalised in terms of its application to a wide range of non-domestic buildings.

## 6.2. Generalisation

This research comprises an in-depth study of a single case-study building, and yet one of its desired objectives, stated in Section 1.4, is to come up with a methodological framework that will be applicable to a wide-range of non-domestic buildings. This raises concern regarding the degree to which generalisation from this research is valid. Maxwell (2005) draws a fine distinction between generic and particularistic research questions within the paradigm of generalisation. In the context of the current work, even though it focuses on the particular case of the Queens Building, which would suggest a particularistic research question, a generic research question which is concerned with the general challenge of reducing emissions from a wide-range of non-domestic buildings as a whole was asked as stated in Section 3.2.1.

This research is therefore primarily concerned with emissions reduction in non-domestic buildings despite using the Queens building as a case study. In terms of generalisation, certain results generated from the case study building may not be validly used to generalise up to a wider range of non-domestic buildings because of their complex nature and differences in functions. However, the current DSS can be applied to formulate economically and environmentally optimal retrofit strategies in similar cases where the same circumstances as the case study building prevail. Therefore, in order to enhance the extent to which the current DSS can be generalised to cover a wide variety of non-domestic buildings, the retrofit options considered are those based on the factors highlighted in Section 4.5.

A unique advantage derived from using the Queens Building as a case study is that it is an iconic building in terms of all aspects of design and construction, but the iconic status it once had, was lost due mainly to changes in use, and as such, it is representative of much UK building stock. For this reason, some emissions savings analysis derived from certain retrofit options can provide "generalisations to theory", implying that rigorous data analysis of certain events in the case study building can be extrapolated to some other buildings with similar characteristics, pattern and use. An example of such generalisation within the context of the current work pertains to the operational emissions saving potential derived from building energy management systems, for example, as described in Section 4.8.9, wherein the potential emissions savings were found to be 12% and 9% compared to the baseline electricity and gas consumption respectively. The reported figures correspond closely to the values quoted by most BEMS manufacturers. Another distinctive benefit and competitive edge which the use of the Queens building offers as a case study building is the uncommon and far-reaching access to the energy and sustainability managers; high quality data, documents and internal processes and mechanisms of the building over the 3.5 years period during which the research was conducted. This level of access provided a platform to develop a deeper understanding of formulated building energy retrofit intervention options.

## 6.3. Appraisal/verification of the calculation methods used within the DSS

This section details the evaluation, validation and verification of the technical aspects of the DSS.

### 6.3.1. Verification and validation of algorithms for operational emissions module

Within the DSS model, the appropriateness of the calculation methods used was thoroughly examined and their use was justified accordingly. The estimated operational emissions savings from renewable energy technologies captured within the model (details in Section 4.6 and Appendix A) were based on proven performance calculation methods using well-established and standard algorithms for low carbon energy sources as contained and validated in Building Regulation (2006); RETScreen (2005); London Renewables (2004) and existing peer-reviewed journal articles. These sources have validated the calculation methods by comparing their predictions to those of other methods. Estimates of potential operational emissions savings accruing from energy efficient measures such as BEMS and voltage optimisation were based on appropriate energy data analysis techniques (e.g. degree day analysis) as demonstrated and validated in Stuart (2011) and Carbon Trust (2010). Energy consumption half-hourly data used for the degree day analysis were analysed and checked for omissions and errors. Where omissions were detected, the data were interpolated to account for any loss of data.

Savings from other measures such as LEDs, PIR sensors are based on derived performance calculation methods checked by the energy manager, while other emissions saving estimates were based on reported figures by Government Agencies such as Energy Trust and OFGEM as well as opinions from subject matter experts. Model assumptions were verified and adjudged sound based on published articles and externally by the University's energy manager after undertaking an independent review of the model methodology. The validity of the overall model was also ascertained through journal articles which stems from the current research as peer-reviewed by the independent panel of journal reviewers.

Given that validation involves the formation of documented evidence which gives a high degree of satisfaction and assurance that a specific procedure or process will consistently yield results that meets its predetermined quality attributes and functional specifications (Huber, 2002), a validity check which is done by comparing outputs or results from a model to experimental data (i.e. real data) is pertinent. This requires an extensive data set from experiments to be related with the input data required for the model. Performing such task on individual retrofit technologies captured within the DSS is very challenging to achieve especially as it relates to research on energy use in UK buildings due to dearth of data on actual energy usage (Oreszczyn and Lowe, 2004). Due to lack of experimental data, the results from the model were sense checked by ensuring that model outputs were of an appropriate order of magnitude against benchmarked values for average energy yield pattern in the UK.

### 6.3.2. Verification and validation of the embodied emissions module

The method utilised for the estimation of embodied emissions associated with each intervention option captured within the DSS is the well-established EIO methodology in the form of 2-region (UK vs. ROW) MRIO Framework as detailed in Section 4.9. EIO method suffers from inherent limitations (Section 2.10.2) and the approaches taken to mitigate some of the limitations were described in Sections 4.4.3 and 4.9.2. An important step in the evaluation of embodied emissions is to ensure that the intervention options (i.e. products) under consideration are classified into the appropriate economic sector using the Standard Industry Classification (SIC) for the UK based on the Supply and Use Table, containing $224 \times 224$ disaggregated economic sectors within the MRIO framework.

Correct mappings of products to their appropriate sector (i.e. product-industry classifications) were ensured based on confirmation from the enquiry services department of the Office of the National Statistics, to avoid error and type-mismatch. The database of the embodied emissions module of the overall DSS was carefully structured to suit the format of the Supply and Use (S&U) table used for the embodied emissions analysis. Since the mathematical operation within the module to calculate embodied emissions involves the matrix multiplication of the total (direct and indirect) emissions intensities matrix (TIM) and final demand matrix (an 896 x 1 column matrix), a great deal of caution was taken to ensure that the final demand in pounds (i.e. the multiplication of the physical quantityin which a low carbon intervention option is quantified [e.g. $KW_p$] and its unit cost [e.g. £/ $KW_p$]) is recorded in the appropriate row of the appropriate segment (i.e.as domestic or imports) of the final demand matrix in the format of the S&U table.

The matrix calculations were initially carried out using Microsoft Excel functionalities to ascertain the correct values before the final implementation in the DSS. The data for original UK-MRIO-1 model put together by a team of Input-Output experts at the Stockholm Environment Institute, University of York was used for the I-O analysis. As a result, validity threats attributable to the embodied emissions calculations were minimised.

### 6.3.3. Verification and validation of economic module

For economic considerations, an established methodology of combining an energy use model with NPV analysis already used in previous research (Gorgolewski, 1995) was adopted in this modular component of the DSS. The broad approach and the specific method used for calculating NPV were in line with the PMT (i.e. payments for a loan based on constants payments and a constant discount rate) function in Microsoft Excel. It is an alternative to summing annual discount factors and has been used by Toke and Taylor (2007) for energy demand reduction analysis. Given that results of the overall emissions reduction performance of abatement options can vary from study to study because of their dependence on several parameters including price of energy and selection of discount rate, uncertainty about these factors was addressed by carrying out sensitivity analysis, through which the impact of changing the values of variables on the DSS outputs was explored.

### 6.3.4. Software verification, validation and testing

To mitigate the faults highlighted above, two approaches namely: (a) static testing, where the design and software requirements of the system are examined without running its underlying codes and; (b) dynamic testing which involves the running of the program codes using different set of data - are employed for validation and verification processes in the software engineering parlance. Software testing (i.e. validation and verification) involves five phases in its lifecycle including: (i) requirements analysis and specification; (ii) top-level design; (iii) detailed design; (iv) implementation and (v) acceptance testing. Standard tools such as static analysers and facilities for quality assurance exist for performing the tests in every stage of the software lifecycle development processes. Static testing is performed in the first four phases of the lifecycle processes while dynamic testing is performed in the last two phases.

In the context of the current work, such sophisticated approaches highlighted above were not used to check the extent to which the codified knowledge upon which the DSS operates based on accuracy and completeness. In part, this was due to lack of such facilities and time constraints and above all, such sophisticated approach to software testing were deemed out of scope for the current research. Rather, the potential programming errors which constitute a significant threat to validity for this research were tested for manually to minimise the threat. This involves line by line sense-checking of the codes to debug potential errors; ensuring that all outputs were of a reasonable order of magnitude; checking all the mathematical formulae and equations used for their correctness; Fagan inspection (e.g. review of design documents to find defects) pencil and paper reviews and additional checks using functionalities of Microsoft Excel to compare answers with model outputs; executing the code using different sets of data to check for errors and inconsistencies; matching codes with specifications; and independent walkthroughs of the system by a programming colleague. Furthermore, consistency problems caused by redundant rules, conflicting rules and unnecessary IF conditions were checked and finally, completeness problems ranging across missing rules because of unreferenced attributes values, control faults and gaps in the inference chains were scrutinised.

Notwithstanding these checks and validation procedures, there exists a significant risk that some unnoticeable human and programming errors may remain in the final DSS software. However, due to the rigorous approaches taken to error checking and the fact that those errors discovered as part of the overall validation and verification process did not have a substantial effect on the final model findings, it seems that the key outcomes and outputs emerging from the DSS development can be said to be reliable with a reasonable and satisfactory degree of accuracy and assurance.

### 6.3.5. Evaluation of the knowledge base

Knowledge base validation involves the checking of the accuracy of a system and it is achieved by extensive testing of the quality of the system. The value of a DSS depends on the validity of its knowledge base (Raggad and Gargano, 1999), so for a DSS to be useful, it must have knowledge depth (i.e. the ability to extend existing knowledge and draw inference on new knowledge) (De Kock, 2003). The current DSS contains components with such coded knowledge which are able to solve specific problems the system was designed for. Several checks were performed and experts were consulted to check the accuracy, consistency and completeness of the codified knowledge base of the DSS. This helps in verifying the richness of the reasoning of the system. This was done by demonstrating the DSS to experts so that its technical aspects can be examined with the view to establish how well it was built.

### 6.3.6. Documentation

As part of the process of building up trust with the usage of the DSS, a comprehensive documentation which details the computational frameworks, calculation processes as well as detailed description of its user interface and functionalities have been produced. This will allow users to have an appreciable understanding of the mechanics of the DSS and how the decision analyses are performed.

## 6.4. Subjective appraisal

This is usually achieved by interviewing the potential users. In this sense, the expert interviews carried out with staff in higher education institutions and energy-related organisations aims to provide valuable insight related to the perceived utility, relevance, ease of use, performance and completeness among other evaluation criteria of the DSS framework. The interviews aimed not only to provide the qualitative primary data required to evaluate the framework, but also to disseminate the final findings of the overall research outputs. In the sections that follow, the approach taken to conduct the interview for data generation for further analysis is presented.

### 6.4.1. Criteria for selecting subjects (interviewees)

DSSs are difficult to evaluate because of their diversity. DSSs are a set of resources, data and models that are placed at the hands of the decision-maker (De Kock, 2003). The individual decision-making actions determine the usage of the system. Care should therefore be taken in selecting potential subjects for the evaluation purposes. All the subjects identified were energy and allied professionals in Universities (e.g. DMU, Kent, and York) and energy-related organisations (e.g. E.ON, Carbon Trust, and European Commission among others). A priori, the identification and final selection of subjects for the interviews was based on certain crucial criteria.

Subjects include energy professionals and experts that: are currently and demonstrably active in building energy-related roles; are familiar with building retrofit, energy efficiency and on-site micro generation technology options; can influence retrofit purchasing decisions; are familiar with and understand the key characteristics of retrofit decision support systems and the delivery mechanisms for retrofit advice; are familiar with the use of MACC for prioritising $CO_2$ abatement options; understand the complexity surrounding the consideration of embodied emissions in lifecycle emissions analysis of buildings; and possess current knowledge of UK and EU policies pertaining to energy demand reduction in buildings and working knowledge of energy systems applicable to buildings. Above all, the subjects' availability was paramount.

### 6.4.2. Subjects (interviewees)

In total, 10 subjects were interviewed. They included energy managers, sustainability officers/managers, environmentalists, energy policy makers, investors, and sustainability consultants. Table 6-1 provides information about the function of each subject, their role and place of work (i.e. business sector).

**Table 6-1: Characteristics of the subjects interviewed**

| S/N | Business sector | Primary place of work | Role | Code number |
|---|---|---|---|---|
| 1. | Higher education institution | De Montfort University | Energy manager (outgoing) | **E1** |
| 2. | Higher education institution | De Montfort University | Energy manager (incoming) | **E2** |
| 3. | Higher education institution | De Montfort University | Sustainability manager | **S1** |
| 4. | Energy company | Eon (Nottingham) | Energy design manager | **E3** |
| 5. | Energy company | Eon (Nottingham) | Energy manager | **E4** |
| 6. | Public institution | European Commission | Policy maker | **P1** |
| 7. | Public institution | Carbon Trust | Sustainability consultant | **C1** |
| 8. | Higher education institution | Kent University | Policy analyst | **P2** |
| 9. | Higher education institution | York University | Policy maker | **P3** |
| 10. | Higher education institution | De Montfort University | Independent assessor | **I1** |

Prior to each interview, a high-level 15-20 minutes MS PowerPoint presentation was delivered by the researcher to give an illustrative description and understanding of the DSS in terms of its underlying mechanism, principles, logical assumptions, input-output relationships and systems components, including system structure, system requirements and system outputs. This was done with the view to make the subjects appreciate the principle upon which the DSS operates. Thereafter, the DSS tool was demonstrated to each subject during the appointed interview session. The interview sessions, based on semi-structured approach (Kumar, 2011) were carried out for direct assessment to allow for the exploration of any form of issues raised by the Subjects. The overall aim was to give the subjects the opportunity to describe their attitude towards the DSS based on their personal view and perspective. The responses were recorded with the consent of each subject using a smart phone. This was to ensure no information was lost. Overall, each interview/ demonstration session lasted between 60-90 minutes.

The goals of the demonstrations/presentation and appraisal were to: (i) ascertain any oversights or mistakes in the codified intelligence of the DSS; (ii) scrutinise the logic and reasoning of the DSS; (iii) discuss the overall performance of the DSS; (iv) identify the needs of the decision makers and ascertain if they have been met.

### 6.4.3. Set of interview questions

The questions posed to the subjects covers critical domains including the structural aspects of the DSS, the perception of the subjects and experience regarding the use of decision support tools to aid decision making. The interview was conducted by asking a range of open-ended questions to obtain data from the identified Subjects regarding the strengths and weaknesses of the DSS. Example questions include:

(i) How do you currently evaluate costs and benefits regarding the implementation of building energy retrofit intervention options for emissions reduction?

(ii) How well do you think the DSS will assist decision makers in the formulation and prioritisation of building energy retrofit intervention options?

The full list of questions is presented in Appendix B. The set of questions prepared were based on the methodological precepts described in Section 3.7 based on Figure 3-6. Although the overall purpose was to check the usefulness and relevance of the DSS, other criteria which could enhance its overall usefulness were also acknowledged.

## 6.5. Qualitative analytical procedures adopted for the research

Given that perception of the subjects regarding the relevance, perceived utility and experience as related to the use of the decision support system to aid their decision making is vital to the evaluation process, it is important to adopt an analytical procedure which allows for:

(i) The use of a standard framework, structure or theoretical precepts (e.g. Figure 3-6 in Chapter three) to recognize themes from the qualitative data;

(ii) The emergence of themes naturally, which further enhances rich findings from the data set.

This will provide further insight and enhance the identification of other salient issues which were not initially envisaged as part of the overall evaluation process. In doing so, the outcomes would enhance those from the quantitative energy model in an attempt to provide answer(s) to the overall research question which guides the current research.

In the light of the above, several qualitative analytical methods including thematic analysis, content analysis etc., were identified from past research work (McGrath, 2007; Braun and Clarke, 2006; Cassell *et al.,* 2006). In the context of the current work, a qualitative analytical method known as ***thematic-content analysis***, which combines the benefits of both thematic and content analysis, was adopted. A carefully selected, but not exhaustive, list of work that has adopted the thematic-content analysis include studies by McGrath, (2007); Fereday and Muir-Cochrane, (2006); Lathlean, (2006); Burnard *et al.* (2008); and McMillan, (2009). The concept of thematic-content analysis is further classified into two major categories namely; *deductive approach* and *inductive approach*, and each can be handled in a variety of ways as reported by Burnard *et al.* (2008).

### 6.5.1. Qualitative (interview) data analysis in this research

Verbatim transcripts of the tape-recorded interviews were analysed based on principles and techniques derived from a qualitative analytical method described above. The analysis followed generic approaches to qualitative data analysis. The first phase involved a detailed checking and re-checking followed by reading and re-reading of each interview transcript to minimise errors and to facilitate a deep understanding of the views expressed by the Subjects. Tentative 'tags' were then developed to capture the meaning and importance of each idea or theme.

The next stage included the categorisation and compartmentalisation of ideas or codes that are similar into unified themes; this was performed for each transcript and then common themes were established from all the transcripts. The theme tags were then screened and each transcript was coded to further categorise the themes. Based on standard methodological procedure of good practice in qualitative data analysis (McGrath, 2007), "credibility checks" were performed by two other persons who are pure social science researchers to validate the codes generated. This ensures rigour, credibility and conformability of the analysis, and eliminates or reduces bias (Cruzes and Dyba, 2011; Burnard *et al.,* 2008).

The next stage involved the integration of themes to establish relationships between the identified themes. Themes that are related were clustered together to produce a small set of themes that focuses on capturing the very essence of the Subjects' explanations. Following on from these an understanding of the meaning of the themes that emerged from the codes was achieved. The themes drawn from codes were then screened along the conceptual framework used in the research. Accordingly, key findings under each theme were presented using descriptive and interpretive reporting methods as adopted by Burnard *et al.* (2008). Thereafter, findings from the qualitative analysis were integrated with that of quantitative energy model, where applicable. The integrated findings were then discussed based on previous studies (e.g. Burnard *et al.,* 2008). This allows for the confirmation or repudiation of assertions made with respect to the DSS, and its underlying methodological assumptions as well as other problems examined in the research. Finally, profound insights were derived from the qualitative component of the research, allowing the identification of some issues which were hitherto not envisaged in the research.

## 6.6. Results of interview

This section presents analysis of the responses to the interview questions. It draws on the views and perception of the potential users in the hopes of gaining better understanding of what the system represent in relation to analysing investments in energy efficiency based on an optimal retrofit strategy as modelled within the DSS. The identified Subjects expressed a wide range of views (positives and negatives) about the DSS. Thematic-content analysis yielded six core themes or dimensions and twenty-five categories, which describes the key features of the DSS as observed by the subjects. The identified themes as indicated in Table 6-2 are basically conceptually independent, but there exists some degree of overlap.

**Table 6-2: Themes from the subject evaluation of the DSS**

| Themes/ dimensions/categories | Subjects that shared similar views and opinions | Frequency |
|---|---|---|
| **1. CONTEXT** | | |
| (i) Design context | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| (ii) Target users | E1, E2, S1, E3, E4, P1,C1, I1 | 9 |
| | | |
| **2. PRODUCTIVITY MEASURES** | | |
| (i) Timeliness (time to reach a decision) | S1, P1,C1, E2 | 4 |
| (ii) Result of the decision | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| (iii) Flexibility | E2, S1, E3, E4, P1,C1 | 6 |
| (iv) Understanding of the decision content | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| | | |
| **3. PROCESS MEASURES** | | |
| (i) Number of retrofit options captured | E3, E4, P1,C1, P2 | 5 |
| (ii) Performance/technical capability | E1, E2, S1, E3, E4, P1,C1, P2 | 8 |
| (iii) Format of output | E2, S1, E3, E4, C1, I1 | 6 |
| (iv) Volume of output | S1, E3, E4, P1,C1, P2 | 6 |
| (v) Amount of data used | E1, E2, S1, E3, E4, C1 | 6 |
| (vi) Level of analysis done | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| | | |
| **4. PERCEPTION MEASURES** | | |
| (i) Usefulness | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| (ii) Relevance | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| (iii) Ease of use | S1, E3, E4, P1,C1, P2 | 6 |
| (iv) Understanding | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| (v) Trust (conviction that the decision is correct) | S1, P1,C1 | 3 |
| (vi) Satisfaction | E1, E2, S1, E3, E4, P1,C1, P2, I1 | 9 |
| (vii) Completeness | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| (viii) Ease of learning | E1, E2, S1, E3, E4, P1,C1 | 7 |
| | | |
| **5. PRODUCT MEASURES** | | |
| (i) Quality of the DSS (e.g. documentation) | E1, E2, S1, E3, E4, P1,C1, I1 | 8 |
| (ii) Response time | E2, S1, E3, E4, P1,C1 | 6 |
| (iii) Overall rating | E1, E2, S1, E3, E4, P1,C1, P2, P3, I1 | 10 |
| | | |
| **6. EVOLUTIONARY ASPECTS** | | |
| (i) Policy initiatives and instruments | S1, E3, E4, P1,C1, P2, P3, I1 | 8 |
| (ii) Business opportunities | E3,E4,I1 | 3 |

In the sections that follow, a discussion of the emergence of themes and the categories with respect to current evaluation tasks are presented. Each theme is illustrated by quotations from the subjects using the Code Number defined in Table 6-1.

### 6.6.1. Context and potential users

This relates to the views of the subjects, either explicitly or implicitly, on the design of the DSS as it relates to the domain of energy and sustainability in the building sector. The aim is to quickly confirm if the overall usefulness of the DSS readily come across based on first impression and physical inspection by the subjects. Accordingly, all the Subjects acknowledged the domain-context of the DSS describing it as a comprehensive "*decision-aid tool based on techno-commercial evaluation framework for emissions reduction in buildings*" [P3], useful for energy managers, advisors and allied professionals [E2, P1] and also for policy makers to understand "*where is the best return for investment to reduce carbon*" [C1] and "*make choices about building energy efficiency strategies*" [S1]. As to the incorporation of embodied emissions in the DSS, two subjects envisaged the future application of the tool for public procurement [E4] and supply chain management [C1]. Detailed responses from the subjects can be found in Appendix C.

The views expressed above clearly suggest that decision makers need a tool which can assist in their decision making process by ensuring that environmental and economic determinants related to energy management and emissions reduction in buildings are improved. The development of the current DSS which takes a whole-life environmental and economic assessment perspective can demonstrate to the decision makers about how value is delivered across different parts of the techno-economic system. In doing so, the range of potential strategies that balance financial gains, return-on-investment, and GHG emissions reduction (including both embodied and operational emissions) can be established.

### 6.6.2. Productivity measures

In the context of the present DSS evaluation task, productivity measures relate to the categories of the theme that evaluates the impacts of the DSS on decisions. The categories include: timeliness (i.e. time to reach a decision); result of the decision; flexibility; and understanding of the decision content. As shown in the Table 6-2, a number of subjects expressed views regarding the productivity measures of the DSS. For instance, a Subject expressed his satisfaction concerning the **flexibility** which the DSS offers through the following statement:

"Does the model take into account local incentives and initiatives like FiT and RHI as that will be quite valuable [*Researcher answered yes and demonstrated it*]…. I think the fact that you take the incentives factor into consideration and you allow users the capacity to fill out options before calculations is quite good." [E2]

Possessing a deeper **understanding of the decision content** of the DSS will facilitate the exploration of alternatives and aid understanding of the decision phenomenon by the potential users. One of the Subjects gave a conditional remark to buttress this point:

"Well I assumed that of course the formulae you put are correct. There are no programming errors or mistakes. Once that is clear and sorted, of course this is an important improvement for a correct evaluation of the measures and it is important for decision making but its overall acceptance on whether politicians understands these concepts." [P1]

The same view was expressed by most of the Subjects interviewed. For instance, a Subject corroborated this by saying:

"…Of course you must know how to interpret the MACC drawing to appreciate the layout and final outputs from the tool. This is coherent. Nothing abstract. So once you understand the MACC, this is perfectly clear within the tool."[P3]

This is further supported by one subject who puts it succinctly:

"The logic of the methodologies and its implementation is coherently articulated in the flow of the DSS structure. It is also consistent with the way the practical DSS has been implemented in the tool."[P2]

**Timeliness** (i.e. time to reach a decision) is a key factor to put into consideration when evaluating a DSS as expressed by some of the Subjects. As an example, a Subject made the following comment about how long it takes to arrive at the final set of solutions:

"I find a bit long, the process of entering the data but I assume that most other classical tools require this long data entering procedures as well. So it is not much of a problem." [P1]

Another Subject also expresses a similar view:

"There seems to be quite a few steps involved. And it seems to be quite text-heavy. I think this issue pertains to flexibility and ease of use. It is relatively straightforward and easy to use if you have the requisite expertise." [S1]

The expressions above represent relatively positive views of the overall function of the DSS with respect to measures that relates to its productivity aspects. In the next section, the views of the Subjects regarding the measures relating to the process aspects of the DSS are explored.

### 6.6.3. Process measures

Process measures are the effects which the DSS has on decision-making including categories such as: number of retrofit options considered; performance/technical capability; DSS output format; volume of output; amount of data used; level of analysis done. With reference to Table 6-2, quite a number of the subjects expressed their views regarding features pertaining to the process measures of the DSS. Accordingly, two subjects conveyed the following views regarding **the number of options** which were examined within the DSS:

"Yeah…. I mean…I like the fact that the tool considers the most popular renewable technology options, at least within the context of the UK. I also appreciate the fact that it allows benefits derived from incentives such as FiT and RHI to be calculated. Very nice." [P3]

"It captures some of the measures we recommend for our clients except for passive measures like insulation that is not modelled within your DSS."[C1]

However, one of the Subjects raised concern as to why the retrofit options are limited to those captured within the DSS and asked about how difficult it will be to add more options to the DSS framework in the future. He stated:

"Good to see that the tool consider a number of retrofit options. How easy is it to add more options… because one of the retrofit options we deal with a lot is Air Handling Unit and is not captured within your model?" [E3]

The point raised by the Subject is a valid one. However, as stated in Section 4.5, the aim of the DSS is not to model every possible retrofit technology but to devise a DSS for comparison and selection from technologies that might be relevant to a case building.

As part of the DSS development, other parameters/categories under the process measures were taken into consideration as part of the overall quality of the system. These parameters are expected to enhance the functionalities and usability of the DSS. In the hopes of ascertaining whether such objectives are met as envisaged during the design and development phase of the DSS, some of the expressions from the Subjects were appraised accordingly. Thematic-content analysis of the statements from the Subjects appears to confirm their satisfaction as indicated by affirmative statements made by some of them. This is manifested in some of the statements below. Regarding the **format of the DSS output**, one of the Subjects said:

"I like the way the tool automatically generates the MACC outputs. One of the beauties of the MACC [used within the DSS], even though its negative portion is flawed, is that it presents the information for the customer or the analyst to make decisions…The information is all there so they can decide based on the MACC, whether they want to go for the cost first, from which they start implementing from the LHS or they go the carbon way where they start implementing the RHS ones first." [E4]

Detailed responses and views from subjects regarding other aspects of the process measures of the DSS are provided in Appendix C. The comments from subjects above as well as the ones in Appendix C are particularly important as they highlight the technical and performance capability of the DSS to address the need of the potential users such as energy managers. In DSS evaluation, certain criteria that are employed to ascertain the overall quality and completeness of a decision and the corresponding decision- making effectiveness include the number of options considered (Sharda *et al.,* 1998), the amount of information used (Silverman, 1992) and the trust (i.e. the degree of assurance or contentment of the users about the results derived from the DSS) (Parikh *et al.,* 2001).

### 6.6.4. Perception measures

Quite a number of the subjects shared views that are in line with the perception measures of the DSS as demonstrated in their statements from the interview transcripts that were subjected to thematic-content analysis. For instance, Subjects E1, S1, P2, P1 commented on this aspects of the DSS. Some excerpts are given below:

"Good tool. It will be useful for initial retrofit analysis in upcoming DMU retrofit projects."[E1]

"Well we don't use MACC at the moment but that is not to say we won't consider using them in the future. Especially because we are quite interested in scope 3 emissions and embodied emissions at DMU for our comprehensive approach to measuring our emissions…if we could see any benefits from using the DSS, not just to highlight energy and carbon emissions savings but also to identify embodied carbon as well…that is something we are definitely going to look at in the future…" [S1]

"The DSS provides users with an informed decision of not just the net environmental gain of intervention options available to them, but also the net environmental gain per economic cost. Hence, based on these constraints, users can be able to make a more holistic and accurate judgement based on emissions saving per pounds."[P2]

The statements above clearly indicate the acknowledgement of certain critical features of the DSS. Comment from Subject E1 confirms attributes such as **relevance and usefulness** of the tool. Similarly, concepts including **usefulness, relevance** and **completeness** are conveyed in the excerpts from Subject S1. In the statement that follows, issues pertaining to **ease of use**, **ease of learning, understanding, satisfaction** and **trust** were explored by the Subject:

"…So I think if somebody is going to use something like that (i.e. the DSS), it needs to be relatively straightforward and easy to use as it appears. But having said that, it will be relatively easy to use for people but they do want to go into it and analyse how the calculations are being done. So I think they should be able to do that as well. So, if you put in some figures and it brings out some results at the end, but there is no where you can actually access the mechanics of how it's being calculated, and then you may not be entirely comfortable or satisfied. Allowing that is part of building up trust with the tool kit so you actually understand what it is producing and you are comfortable with the results. So in essence, a good documentation will be quite useful."[S1]

The above quote clearly indicates that the DSS is quite **easy to use** and **learning how to use** it is pretty straightforward. However, the Subject emphasise the importance of **trust** (i.e. the extent to which the user believes or have confidence in the DSS results) and **satisfaction** regarding the use of the DSS. This is an integral aspect of subjective evaluation of DSS and suggests that a detailed documentation is vital to the overall implementation of the DSS. An important aspect of the DSS which interests some of the subjects relates to **completeness** of the DSS in that it includes embodied emissions in its framework. They regarded it as one of the unique selling point of the DSS. For instance, a subject commented:

"Well… I think it's the fact that it includes embodied emissions. As I said, it is something that we are looking at at DMU [embodied emissions]. We report on our operational emissions and ultimately we want to move from a stage where you just report it to where you are actually reducing as well. So if there is an assessment method that includes that within retrofitting, new build and things like that, then such a tool will be really good for us in terms of scope 3 reporting. And it's probably going to be the same for other organisations as well." [S1]

The expression above is further reinforced by two other Subjects who concurred that:

"Currently, existing tools to measure the embodied emissions of intervention options are very limited given that a lot of emphasis has been placed on the operational emissions. The DSS would therefore be very valuable given that it considers the whole life emissions of any intervention option. Such an analysis makes it a robust tool with very unique selling points."[P2]

"I think embodied emissions are coming in in form of scope 3 emissions and people have to work it out somehow. The use of this type of tool can help energy managers to give rough estimates of their scope 3 emissions."[I1]

In the same vein, a Subject confirms that the DSS has an unambiguous and understandable structure which will aid the **understanding** of the potential users regarding the outputs from the DSS. He stated:

"The logic of the methodologies and its implementation is coherently articulated in the flow of the DSS structure. It is also consistent with the way the practical DSS has been implemented in the tool."[P2]

Quite a number of constructive comments were given on the user interface of the DSS. Figures D-11 through to D-16 in Appendix D shows the user interface of the individual modules of the DSS. Surprisingly, most of the subjects were not concerned about how attractive in terms of colour and graphics, the user interface of the DSS was. They were mostly interested in the usefulness of the DSS. Nevertheless, when their views were sought, most of the subjects agreed that the user interface of the DSS was quite user-friendly and that the response time of the DSS was quite fast. A Subject however suggested that "the front end of the DSS can be made further improved in order to improve the satisfaction of user experience."

### 6.6.5. Product measures

Product measures pertain to the evaluation of the technical merit of the DSS and entails categories like quality of the DSS (e.g. documentation); response time and overall rating. These are essential aspects of DSS evaluation. Some of the subjects voiced their views on these measures. For instance, a Subject commented on the **response time**:

"The tool responds fairly fast to input data which is really quite a nice thing and suggest that much iteration of calculations can be carried out without much trouble. [P3]"

Almost all the Subjects gave very good and complementary comments regarding the **overall rating** of the DSS in terms of its purpose and overall functioning. Some of the comments are already embedded in the overall statements of the Subjects, but some specific statements are worth stating separately for the sake of emphasis. For instance a Subject [C1] said: "Overall, the entire concept is very sophisticated! Well done." Another Subject [P2] stated: "such a tool can be considered to be state-of-the-art in this field. It a robust tool with unique selling points. "Similarly, a Subject also mentioned: "putting all the ideas together into a single model is quite a considerable achievement." Additionally, Subject [P1] commented: "Overall, the DSS is extremely interesting and promising! Good work." Finally a Subject [S1] puts his words this way: *"So it's [the DSS] quite interesting and beneficial"*.

All the comments that emerged from the Subjects during the evaluation process of the DSS are of high significance as they contribute to the overall success of the system in terms of understanding and implementation. The approach taken to the evaluation of the DSS follows a well-established pattern adopted by researchers in the past and all the aforementioned themes and categories that arise were also in agreement with past works. For instance, Bailey and Pearson (1983) reported that the ability of a DSS to offer a wide range of functionalities and detailed output in an understandable format and well-structured manner is a crucial aspect of a DSS. Furthermore, a number of DSS researchers and developers including Parikh *et al.* (2001); Kanungo *et al.* (2001) and Finlay and Forghani (1998) have all suggested that very good documentation of a DSS, in terms of support and learning facilities, which allows the potential users of the DSS to learn about the domain of the decision is an integral aspect of improving the effectiveness of decisions.

Also, the degree to which a DSS is flexible and its ability to allow its users to explore a multiple number of alternatives are essential features (Nissen, 1999; Sharda *et al.,* 1988). Of all the attributes of a successful DSS, technical capability represents a critical success factor (Finlay and Forghani, 1998; Ram and Ram, 1996). The level of trust and transparency of a DSS regarding its underlying decision process and calculation procedure can improve the understanding of its users and can trigger wider applicability and acceptance (Papamichail and French, 2003). Finally, Bailey and Pearson (1983) and Finlay and Forghani (1998) submitted that the successful adoption of a DSS lies in the abilities of the potential users to understand its underlying facilities and functionalities.

Overall, none of the Subjects expressed contrary view to all the themes that emerged from the evaluation of the DSS, rather, each Subject reinforced its capabilities and functionalities in different ways. The only foreseeable differences of opinion relate to the consideration of embodied emissions which is of current interest but quite complex due to the fact that it is plagued with certain critical challenges as highlighted in Sections 2.7 to 2.8. However, as indicated in Chapter two, several Government schemes and plans have consistently indicated that embodied emissions are likely to become one of the key metrics to be addressed in whole-life carbon accounting. Their inclusion in the decision-making process regarding overall emissions reductions in buildings is therefore of paramount importance. In the section that follows, the views of the Subjects are sought to establish where the value of the DSS lies, given the fact that it integrates the three key variables of financial cost and both embodied and operational emissions for a balanced and effective decision making regarding emissions reduction in buildings.

### 6.6.6. Evolutionary aspects

Evolutionary aspects in the context of the current work relates to qualitative judgement about the possible extension of the functionalities of the DSS to trigger future regulations and policy concerning emissions reduction in the building sector. Also included are the possibilities of deriving potential business opportunities that could emerge by commercialising the DSS. It is important to state here however that most of the Subjects expressed disparaging views about certain issues concerning the evolutionary aspects of the DSS. This relates to concerns about the extent to which embodied emissions will be taken into consideration in lifecycle emissions assessment of buildings. While some of the subjects are of the opinion that the consideration of embodied emissions is important and should be accounted for in decision making, some of them are rather sceptical, mainly due to the fact that the topic of embodied emissions is not an exact science. For instance, some of the subjects are of the opinion that most decisions (from a purely end-user point of view) about emissions reduction are potentially driven by financial consideration and that the consideration of embodied emissions is of little significance. As an example, a subject expressed his views as follows:

"Most of our customers are interested in operational emissions savings but not embodied emissions. Embodied emissions are embodied emissions and they don't have control over it. They are concerned about cost rather than embodied $CO_2$. Such information might have value in the retail sector for example in Tesco as part of their supply chain management."[E4]

Another Subject corroborated the above view by saying:

"The problem lies in what perspective the advisor is taking. Because if it is a bank, most likely the evaluation will be more economic with no concern for embodied carbon. A lot of bankers look at the investment and the time it will take to recoup the money spent etc…but then of course it could become, for example, an obligation or requirement for efficiency evaluations. For example when emissions related to a given refurbishment project are capped at a certain level. [P1]

A Subject gave a detailed explanation of the frame of mind of customers about how they prioritise cost savings above emissions savings. He stated:

"…So the reality is that the company we have been dealing with would only be looking at measures that will give positive [financial] return back. So at the moment, I haven't come across a client that wants to invest purely for the carbon savings. At the moment, they are basically concerned about cost-savings."[C1]

The import from the above expressions further confirms the fact that building retrofit decision-making processes are generally targeted at reducing operational energy consumption and most importantly, maintenance bills. This explains why retrofit decisions by building stakeholders are typically driven by financial considerations. However, recent trends towards resource efficient design have shifted focus to the environmental merits of retrofit options, stressing the need to take a lifecycle view-point to emissions reduction. Significant effort towards consideration of embodied emissions is on-going but not without some difficulties as further captured by the subjects. When a Subject was asked about how the output from the DSS can assist in shaping and formulating improved policies targeting manufacturers of building energy retrofit options, he replied:

"Well. Very difficult question (smiles) because there are so many barriers already to tackle and this is where the sophistication in the decision-making process lies…. The tool is a very useful one as I say, but how decision-making will really change is difficult to see". [P1]

The above expression clearly suggests that there exist many barriers when it comes to the consideration of embodied emissions in policy development. The same subject further expanded on some of the problems associated with policy development when it comes to taking a holistic view to climate change mitigation strategies. He suggested that lack of interest in the impacts of embodied emissions by the public and industry stakeholders is a major hindrance towards holistic policy development to cover embodied emissions. He commented:

"Well, from a policy-making perspective, you have to take into account a lot of different variables and… what frequently happens is the difficulty associated with effective policy decision making, which involves consultations, experts and stakeholder engagement. Most times, you do your own thinking by developing a proposal for discussion with representatives of member states (I am talking from an European perspective now) after due consultations…but what happens is that discussion about this kind of concept (i.e. embodied emissions) sometimes don't get any attention…"[P1]

He further traced some of the policy development bottle-necks to very serious political and country-specific issues and difficulties in coming up with appropriate legislation which allows for the consideration of embodied emissions. He said:

"… Because, you see, for example, during discussion about energy efficiency directives or about carbon emissions etc., a member state can argue that ahhh…yeah…. but in our country, the tiles industry is so important. It provides employment opportunities and all that…so if you put a quota or a cap on carbon emissions, our industry will be ruined etc. So to summarise, you start from a well-conceived and coherent policy and then during the negotiations, you lose the battle and sometimes what comes out is open to challenges." [P1]

He concluded by suggesting that with the availability of consistent frameworks that are endowed with the capabilities to reduce ambiguity in embodied emissions calculations, there exists a chance that building sector policy developments which embraces the inclusion of embodied emissions will eventually come into limelight. He stated:

"But that said, such tools like this one, which has a scientific basis can reduce the level of subjectivity of such debates and make some policy makers and politicians to change their mind."[P1]

Another Subject also agreed with the fact that embodied emissions are becoming increasingly important but referred to the time-consuming nature of embodied emissions calculation as a potential hindrance. His view is stated below:

"It's something [i.e. embodied emissions] that certainly should be looked at and part of the problem for lifecycle assessment for individual projects is that it's quite a difficult thing to do. So to do that for one particular product, it's quite time-consuming to do. If you look at the renewable market and think about the entire different product available and all of the different suppliers…if you have to do LCA for every single product, every single supplier, that will be a really difficult thing to do."[S1]

He however submitted that if the challenge of calculating the embodied emissions is reduced to the barest minimum, decision-making which takes a holistic environmental view-point will be enhanced and policy instruments can therefore be developed:

"…But if you manage to do that, it will make it a lot easier to choose from different products because you will know the embodied emissions of each product and then make your choice based on that information. But as it stands at the moment, there isn't that level of detail, so you have to make some generalisations. So within those generalisations, there may be errors or inaccuracies and what have you. So in terms of developing policy and moving forward we need a deeper understanding of the entire concepts of embodied emissions. Data collection in terms of embodied emissions is happening at a slow rate and in time, I am sure it will get to a point where there will be plenty of LCA data available….but at the moment, our only approach is to use more generic approach, which provide some rough estimates."[S1]

A subject also commented on a number of challenges including unresolved methodological differences, data limitations, uncertainties, etc. that characterise the calculations of embodied emissions and suggested that for effective policy development to become active, the aforementioned fundamental limitations must be addressed:

"Currently, the inclusion of embodied emissions has not become part of main stream building sector policy developments. This may be attributed to a number of challenges such as unresolved methodological differences, data limitations, uncertainties, etc. As an example, the 2016 Zero Carbon Target set for new homes in the UK has set minimum carbon compliance emission levels. These are operational emissions targets. It is obvious that embodied emissions considerations have been neglected. Going forward in policy development in the building sector, this fundamental limitation must be addressed."[P2]

An interesting point made by one of the Subjects relates to the fact that most decision makers only understand languages that pertain to financial cost and do not have a deeper understanding of some of the standard metrics such as embodied emissions:

"I think the reality is that we deal with a lot of business people and they need to speak to head of a government. Interestingly, the project I am doing at the moment, I am dealing with the environmental directors (Head of Environment) but to secure the investments, they are speaking to finance directors. So I think it's important that one is using a metric that is understandable to a finance director who is not necessarily going to be familiar with some of this detailed approaches. But again, I think from a policy point of view, from an expert point of view, there is a lot of merit in this because it's more accurate way of looking at this."[C1]

Despite some of the challenges and administrative bottle-necks highlighted above, some of the Subjects are confident that in the nearest future, embodied emissions will become a standard metric for assessing sustainability projects and it may become mandatory for companies to measure and report the overall emissions (both embodied and operational) associated with their projects. They therefore believe that use of this type of DSS may provide the basis to address these problems and can trigger policy initiatives towards holistic emissions reduction in buildings. One of the Subjects stated:

"A key question for them [i.e. decision makers] is what is the financial return….so some of the overall metrics about cost per tonne of $CO_2$ abated are kind of a macro questions of not thinking about who is going to do this paying, it's just looking at what the most-effective way as an overall organisation or as a country is to reduce their carbon. I also think that the concept of including embodied emissions is very interesting and I think it is going to become more relevant as the in-use emissions falls as we basically deal with the efficiency of the existing building stock."[C1]

The same Subject shed more light on the overall importance of the consideration of embodied emissions in decision making. He further stated:

"I think at the moment, it is not a very important factor [i.e. embodied emissions]. As an energy manager, you will focus on energy and there wouldn't be anywhere in an energy manger's objective about embodied emissions in what is being bought. But I think considerations of embodied emissions are starting to creep in for procurement managers and some of the more forward thinking organisations are starting to include this. Again, though, the focus of them about embodied emissions is still focused on cost. So the area where that need is going to grow is in the procurement side and then probably in the future would see working together between procurement and energy managers to work on an organisation's overall carbon-emissions. I think it's the way forward. I think it's the future." [C1]

Two other Subjects also held a similar view which was stated as follows:

"I think embodied emissions are coming in in form of Scope 3 emissions and people have to work it out somehow. The use of this type of tool can help energy managers to give rough estimates of their Scope 3 emissions." [I1]

"At the moment not great [i.e. the idea of considering embodied emissions] but I think in the future, it will be. If you spend any time looking at blogs and common posts and some of the newspapers and websites, for example, especially on the production of wind turbines requires a lot of energy to produce them and people are starting to ask questions about that. So I think it's really good that a system that measured that is developed." [S1]

## 6.7. Suggestions for improvement

While it can be safely argued that the current DSS, based on the views expressed by the Subjects, met their expectations to a very large extent, some of the Subjects expressed concern about certain aspects of the DSS and provided some suggestions for improvements. For instance, one subject felt that the fact that the DSS is designed to operate on a web-based platform as against desktop-based is quite disadvantageous, given that the DSS may require upgrades and improvements from time to time. He lamented:

"I think the fact that it can be hosted online on the cloud rather than a desktop version is a bit worrisome. This is because if the project is taken forward in order for users to have up-to-date versions at all times in real time when the functionalities are improved, it might be difficult for users." [P2]

The same subject also suggested that the user interface could be improved and made more attractive when he said: "The front end can be further improved in order to improve the satisfaction of user experience." A subject [S1] also suggested that the DSS "seems to be quite text-heavy" and suggested that unnecessary text be eliminated. Another Subject suggested that the modus operandi of the DSS should be made more flexible by allowing users to go back and forth in the middle of an operation to allow comparative analysis of different calculation scenarios. This is inferred from the view expressed by the Subject:

"Are you able to save and go back and forth during the use phase of the model? Because the user might want to try various scenarios and then make specific choice afterwards." [E2]

An important point raised by one of the Subjects is that various performance calculation methods to calculate the potential operational emissions savings from the identified abatement options exist and the results might be slightly different. To this end, the Subject is concerned about how the DSS can allow the bypass of its calculation methods for operational emissions savings and allow the user to benefit from the optimisation module of the DSS which ranks the negative cost measures. The Subject said:

"It looks like the tool itself calculates the engineering solution; so…. And it operates in form of a model as against going to site looking at what will fit. Is there flexibility to by-pass one of the steps so the engineers who have been to site can come up with an engineering solution and tailored cost for the particular technology…?…So the main use for us is the optimisation module where we can put in our data which we engineered and it optimises the solution for us using your technique" [E4]

A similar view was expressed by another Subject:

"Could you bypass the calculation methods in your model and allow for users to input data directly. This will be useful even if there are no equations or mathematical formulae to characterise it but they do know how much it saves and are only interested in proper ranking?" [I1]

An interesting and valid point raised by a Subject pertains to format of output especially as it relates to visibility. He appreciated the novel approach taken to the integration of the key variables of financial costs and both operational and embodied emissions, but suggested that it will be nice if both embodied and operational emissions can be separated on the graphical output. His expression is well captured as follows:

"I think…well….. On one of the graphs you showed [talking about a graph that was illustrated during the PowerPoint presentation]…you showed the embodied emissions as a red area next to the main graph. I think finding a way of showing it on the Pareto for negative cost measures and MACC for positive cost measures will be quite good. I think having that visibility of how much of the emissions are embodied vs. how much are operational really helps, because actually from an organisational point of view, the operational carbon will feed into their Scopes 1 and 2 targets; whereas at the moment, the embodied emissions would feed into Scope 3 emissions from purchasing and services. It will give them visibility and it helps." [C1]

All the Subjects interviewed acknowledged the fact that the ranking criteria for negative-cost measures within a MACC framework is fundamentally flawed and appreciated the way and manner with which the Pareto technique was used to adopted to correct the ranking flaw. A Subject [E4] commented that "*One of the beauties of the MACC even though its negative portion is flawed, is that it presents the information for the customer or the analyst to make decisions*". However, the way the result from Pareto optimisation technique was displayed were confusing and poses some level of difficulty to a number of Subjects. Some Subjects expressed concern regarding certain issues about the Pareto's graphical output including, continuity (i.e. break in flow between positive-cost measures and negative-cost measures), physical appearance, misconception about interpretations of the separation of the positive and negative regime of the classical MACC approach. A Subject gave an elaborate view on this aspect as stated below:

"On the Pareto plot, that choice of representing information is missing in that respect. It is just one line based on a computer model having optimised it for you. What I think will be much more useful as an analyst- and this is purely my view- or looking at it from the customer's point of view is shown in that diagram where you actually drew on the board [Pareto optimal points] where it plots the measures out for you and then the customer can say OK… LED is obviously the best one by a long shot and the customer can make an informed decision about the ones that is slightly more difficult or slightly more…yeah…marginal traces as it were…and I think that analysis is very useful for the customer but if I show the customer the Pareto plot, they yeah…. It will be a little more like telling them what to do and in what in order…and most customers usually don't like being told exactly what to do. They like to be able to see the reasoning themselves." [E4]

Two Subjects also echoed the above views:

"…What we are saying is that for us and from a commercial perspective to make it easy to understand is to have a similar chart to a MACC where you can have your abatement on the x-axis and net savings on the y-axis. The current Pareto plot you have will be lost but it will give you a better understanding of the plots. This is particularly important because some organisations are only interested in cost-savings while some others are interested in $CO_2$ savings." [E3]

"I suppose the question then is how…..so the merit of the existing ways is that…even though it's flawed, you can see the positive and negative measures in a whole suite as you can see them crossing over. Because a lot of mind set of people I'm dealing with is that where is the cut-off point? Where does it stop making sense to do it? So I think that's one thing that's quite good with the existing method."[C1]

The import from the above expressions suggest that it is of paramount importance to establish a unique way to represent the Pareto chart which is currently plotted as bar charts stacked together, in a way that will be readily understandable to the potential users. Quite a number of possible representation styles, including the merits and demerits of each style were put forward by Taylor (2012). It therefore follows that both regimes (positive and negative) of MACC should be presented together to facilitate effective decision making and minimise confusion relating to representation and interpretations. Two Subjects made some recommendations about the possible way to present the data to reduce the confusion to the barest minimum:

"Another approach will be to ignore the graphical display for the Pareto ranking and stick with the traditional MACC display because it does contain all the information you need. It does contain the area of the rectangle, which is the cost. May be what you need is a little bit of text describing what the correct ranking is underneath. So it displays the information you need in terms of costs and carbon. [I1]

"Talking about the final graphical output in terms of MACC and Pareto, the MACC gives you that choice between costs of the $CO_2$. It gives you that two-dimensional choice. If the Pareto output can be presented in a two-dimensional output in form of a chart, from a visual perspective, it will be lot easy to understand." [E3]

## 6.8. Discussion and summary on the evaluation of the DSS

Evaluation is an integral part of the lifecycle of the development of a DSS and should therefore be factored into the overall development process (Papamichail and French, 2005; De Kock, 2003). Generally, the process of evaluation should commence before the technical phase (i.e. analysis, design, development, testing and implementation) of the DSS and should be a routine beyond the lifespan of the DSS (ibid). This is particularly important due to the fact that the DSS will be used by human beings. As such, seeking their views as part of the evaluation process is crucial.

Quite a number of approaches, including technical and subjective approaches exist for the evaluation of DSS as highlighted in the preceding sections. In the context of the current work, the methods employed are those that are pretty straightforward and readily available. Detailed analytical techniques exist for high-level software validation and verification, but getting into such details was beyond the scope of this research. As part of an evaluation process, coming up with a strategic framework during the development phase of a DSS requires the selection of appropriate approaches for developing the structure and components of the DSS and most times the procedure can be very difficult (De Kock, 2003). In this study, a great deal of effort was put into the design phase of the DSS, where its structure and the interrelated components were mapped out in an efficient manner. Several prototype designs were developed before the final adoption of the best option suitable for implementation.

The assessments of the technical aspects of the DSS were based on the procedures described in Section 6.3 which include technical verification and performance validation, and were quite straightforward. To ascertain the views of the potential users of the DSS, subjective assessment based on thematic-content analysis framework was adopted. The subjective assessment was carried out to have an idea of how quality and effective are the resulting decisions that stems from the use of the DSS. A detailed explanation facility describing the structural dynamics of the DSS and its modus operandi was developed.

In the course of the evaluation process, it was discovered that every subject wants the DSS to be tailored to their own specific need by including additional functionalities and flexibility. However, experience has shown that it is not always valuable to develop a tool that provides a wide range of functionalities in the hopes of satisfying the requests of many potential users as much as possible. This notion is supported by Parikh *et al.* (2001) who submitted that a system which provides too much functionality is less limited but that if the system is not easy to use, the potential users might find it unacceptable. A key success factor in the implementation of a DSS is ease of use (Finlay and Forghani, 1998) and has been proven to aid confidence levels and increased usage (Papamichail and French, 2005). It follows that care must be taken regarding the trade-off between simplicity and comprehensiveness of the functionalities the DSS offers.

Getting access to subjects was quite challenging but help from supervisors led to 10 subjects being interviewed. Most of the Subjects are familiar with the use of DSS, but some of them still embrace the use of manual calculation approaches to make decisions about emissions reduction strategies in buildings. To improve the wider acceptability of the DSS and increase the confidence level of the users, care was taken to demonstrate in detail the mode of operation of the DSS. Based on the interviews conducted, it was inferred from the responses of the subjects that they are of the opinion that the DSS is very useful and offers a well-structured and highly organised method towards the evaluation of economically and environmentally optimal retrofit of buildings.

Overall, the DSS evaluation received positive feedback and quite a considerable number of encouraging and constructive comments as well as suggestion for improvements.

# CHAPTER SEVEN: CONCLUSION AND FUTURE WORK

## Chapter overview

Based upon the findings from the review of literature in presented in Chapter two; the formulation of a problem statement (stated in Chapter 1, Section 1.2); the answers to the emerged research questions based on the detailed methodology described in Chapter three; the final design and implementation of a decision support system for investment appraisal of building retrofit options presented in Chapters four and five respectively; as well as the overall evaluation and validation of the DSS described in Chapter six, the summary of conclusions and key findings from the numerous analysis carried out during the course of the activities which stems from this research are presented in this chapter. Also presented are the main contributions to knowledge that this work makes to research and scholarship, the limitation of the research and an outline of possible future extension of the current research.

## 7.1. Introduction

The goal of this section is to describe how the research aims and objectives enumerated in Section 1.4 are met. To recapitulate, the central aim of this research is to develop a robust decision-making methodology that will rank and sequence a range of intervention options for reducing greenhouse gas emissions. The intended output is the best-value approach to emissions saving in a non-domestic building, taking into accounts both operational and embodied emissions and the cost of each option. Essentially, the focus of the work is to extend and deepen the knowledge of the field of decision support systems for building retrofit advice by integrating the three variables of cost and both embodied and operational emissions. Based on this premise, the achievement of the research aim could be said to have been met as a result of the following research activities and numerous analysis that have been conducted as highlighted in the succeeding sections.

## 7.2. Initial review of the relationship between embodied and operational emissions

In this study (Sections 2.5-2.9) as with previous studies, it was demonstrated that the building sector constitutes a critical part of the climate change problem as it represents the single largest contributor to global greenhouse gas arising from primary energy demand. Energy is a key issue since it constitutes one of the most important resources used in buildings across their lifecycle. The goal, therefore, is for the built and natural environment to design and construct buildings with minimum environmental impact. Total lifecycle emissions resulting from buildings consists of two components, namely, operational and embodied emissions. Whereas, considerable efforts have gone into reducing operational emissions from buildings, little attention is paid to embodied emissions. This prompted a critical review of the relationship between embodied and operational emissions over the life cycle of buildings to verify and highlight the increasing proportion of embodied emissions that is one consequence of efforts to decrease operational emissions. It was established that it is increasingly important to acknowledge the significance of embodied emissions when considering GHG emissions reduction strategies.

The need to calibrate the performance of buildings in terms of both embodied and operational emissions in order to reduce total lifecycle emissions is also highlighted. This suggests that embodied emissions analysis results can serve as a standard indicator of $CO_2$ emissions and could be adopted to evaluate environmental impacts of buildings. However, achieving such a goal is plagued with difficulties. Some of the factors include: methodological challenges; lengthy and demanding data collection process needed for quantification; the focus of regulations on in-use energy and carbon and a lack of appropriate legislation. Behavioural influences and the complex interplay, in terms of different motivations of key stakeholders, involved in a building's delivery process also further compound the problem. Other factors include lack of accurate and consistent data set as well as a lack of interest in the impacts of embodied energy by the public and industry stakeholders and many more. Despite these setbacks, this study emphasises the value (described extensively in Section 2.9) that comes with the inclusion of embodied emissions when making decisions regarding emissions reduction strategies in buildings.

## 7.3. Design and development of the overall decision support system

A review of existing Decision Support Systems (Section 2.17.1) 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 the aforementioned factors above. Given the current emphasis on a lifecycle approach to emissions reduction, a gap therefore exists in the field of DSS for energy management in buildings. This research 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 design and development of the DSS described forms the bulk of the activities carried out during the course of this study. Further insights into the methodical development process are presented in the Sections (7.3.1 to 7.3.5) that follow.

### 7.3.1. Performance analysis of operational emissions saving and embodied emissions incurred by options within the DSS

Within the overall DSS, the energy saving predictions from each retrofit measure was based on a number of calculation and evaluation methods as discussed in Chapter four (Section 4.8). The chosen evaluation/calculation method for a measure is a function of the nature of the measure. The calculation method adopted within the DSS for the calculation of embodied emissions associated with each retrofit option is underpinned by the use of Environmental-Economic Input-Output (EIO) methodology based on the 2-region Multi-Regional (UK and the Rest-of-the-World [RoW]) Input-Output (MRIO) framework as described in Chapter four (Section 4.9). The DSS makes 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. This is carried out to compare emissions associated with products manufactured in the UK and the RoW with the view to facilitate better understanding of the UK consumption pattern and identify policy, business and consumer triggers that will lead to an overall emissions reduction.

### 7.3.2. Establishment of ranking criteria and key performance indicators

A range of ranking criteria and key performance indicators for benchmarking energy efficiency of buildings were highlighted in Section 2.12 and it was established that some of the criteria are incompatible and it is practically impossible to find a global solution to satisfy all of them at the same time. In this study, what is required is a criterion that has a unique attribute which relates cost to $CO_2$ emissions savings potential (i.e. a criterion which shows the relationship between the marginal quantities of $CO_2$ reduced and the associated marginal costs per unit of $CO_2$), focusing on building energy retrofit options. The quest to establish this criterion prompted the adoption of the ranking principles derived from the use of marginal abatement cost (MAC) concepts where such a criterion is employed.

To this end, the adoption of MACC as a useful tool to identify abatement options which deliver the most economically efficient reductions in GHG emissions and prioritize mitigation options within the building sector is demonstrated in this thesis. 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 (see Sections 4.11.1 and 5.5). In specifics, the following points are concluded about the use of MACCs within the DSS:

- The concept of MACC works correctly where an abatement option has a positive cost (i.e. an option in the positive regime of the MACC). This stems from the fact that if all the positive-cost options are compared with each other, the option with the least value of $C_{eff}$ (i.e. cost-effectiveness, £/t$CO_2$) yields the smallest financial expenditure per tonne of $CO_2$ abated, and therefore represents the optimal value. So, for a positive-cost measure, the calculated value of £/t$CO_2$ truly represents the cost of for every tonne of $CO_2$ abated
- If an option yields a negative net cost, representing a profit or net financial gain, the final ranking based on MACC principles occasionally favours abatement options that yield low $CO_2$ emissions savings. This suggests that for abatement options with economic net benefits, the concept leads to wrong priorities. This is because a smaller $C_{eff}$ (i.e. a more negative value of $C_{eff}$) is realised by a higher financial gain, which is the goal that is desired, or by a reduction in the potential emissions savings, which is the direct opposite of what is anticipated
- This implies that the measure with the lowest numerical value $C_{eff}$ does not necessarily represent the best option. The result is unreliable, since it supports the maximization of financial returns but minimization of the $CO_2$ emissions saving for negative cost options. It therefore follows that it is inappropriate to use the concept of cost-effectiveness, expressed as £/t$CO_2$ or equivalent, for prioritising negative cost measures
- The concept of $CO_2$ reduction cost is therefore restricted to the economically unattractive options, i.e. those that have positive net cost. It follows that there is no other criterion of interest when debating the economics of emissions reduction options. Against this backdrop, the conclusion is that negative cost-effectiveness, quoted as a numerical value, is an invalid concept. There is therefore the need for a different approach for ranking negative cost measures

In this study, Pareto optimization technique based on the theoretical formulations by Taylor (2012) was implemented within the DSS, based on the logic presented in Figure 4-24, to correct the ranking anomaly with negative cost measures. Pareto optimisation offers a better ranking approach, producing to a reasonably ranking order and recognizes measures that are incorrectly ranked, restoring the consistency with profit-maximizing behavior. A slight downside of the Pareto ranking approach is that its application to both positive and negative regimes within a classical MACC concept is not always consistent. More importantly, the separation of negative- and positive-cost measures would be rendered invisible when all options are ranked based on Pareto optimisation, leading to the potential possibility of positive-cost measures being prioritised over negative-cost measures. Therefore, negative cost measures are ranked based on Pareto optimisation and positive cost measures are ranked based on MACC.

### 7.3.3. Handling the effects of interaction and overlap between options

In Section 2.14.3 and 4.12.1, it was highlighted that abatement measures are implemented in combination with one another and that the individual emissions savings potential of each measure cannot be added up, since such an approach can significantly over-estimates the total emission savings due to interactions and overlaps between certain measures. It follows that an understanding is needed of the physical basis of each possible interaction.

In this thesis, the use of interaction factor, calculated as the quotient of the abatement potential of one measure (say Y) when applied after another measure (say X) divided by the standalone abatement potential of measure Y. This interaction changes the emissions saving potential as well as the cost-effectiveness of the measures, in response to the measure with which they interact, based on the interaction factor. The use of interaction factor gives the degree to which the cost-effectiveness of a measure is reduced when two or more measures interact with each other. Based on the consideration of interaction between measures within a MACC framework, the following points are deduced:

- The abatement potential (e.g. $tCO_2e$) of an option is reduced by the effect of interaction
- For a measure with a positive cost, the effect of interaction makes the measure more expensive (i.e. the cost-effectiveness worsens). The cost-effectiveness of the positive-cost measures increases as we traverse from left to right on the MACC and the effect of the interaction factors is simply to increase the rate at which the relative costs per height of the bars increase, which is the desired output
- For a measure with a negative cost, the effect of interaction makes the measure seem more negative, i.e. less expensive and therefore suggests that for any given option, consideration of interaction has the effect of improving the cost-effectiveness. The effect of the interaction therefore makes it impossible to rank negative-cost measures according to the standard ranking criteria. As demonstrated with the mathematical proof in Section 4.12.1, it tend to underestimate, numerically, the marginal costs of the most attractive options, and to overestimate the marginal cost for the least attractive options.
- This perverse result further buttresses the findings of both Taylor (2012) and further analysis presented in this thesis, and supports the notion that it is inappropriate to use the concept of cost-effectiveness, quoted in £/$tCO_2e$, for ranking negative-cost measures.

### 7.3.4. Sensitivity analysis

The overall emissions reduction performance of abatement options can vary from study to study because of their dependence several variables such as energy price and choice of discount rate. Uncertainty about these factors was addressed by carrying out sensitivity analysis, through which the impact of changing the values of the variables on the DSS outputs was explored. 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.

Regarding the effect of energy price changes, future fossil fuel prices are almost impossible to predict as they are driven by demand, global trends and events and financial markets situation. However, as the general trend of energy prices tends to be upwards, sensitivity analysis carried out under different price scenarios (e.g. reference, high, low), assuming a constant discount factor, to assess the sensitivity of results (i.e. the DSS's output) to changes in energy prices shows that an increase in cost of energy leads to more money being saved with every kWh of energy avoided from the source of energy. This improves the economics (i.e. NPV of energy saved) of any measure that saves energy or provides it in an alternative way. In other words, high cost of energy appears to make an option more valuable. This suggests that the worth of investing in renewable energy and energy efficient installations will increase, as the savings derived from running them will be greater. By extension, as building retrofit options become more efficient overtime, there will be a decline in the total mitigation potential, resulting in higher costs/t$CO_2$e.

Based on the effects observed above, one might ask why can't the Government just increase energy tariffs to encourage renewable energy and energy efficient installations in the building sector with the overall view of reducing fossil fuel consumption? The fact remains that it is not that easy and straightforward. In part, this is due to the fact that not everyone could afford higher energy prices. On the other hand, the issue is basically a political one. A good example of such political difficulties is the way energy prices became a major issue following the Labour Party leader's conference speech in September 2013 regarding an energy price freeze. This explains why the Government chooses not to manipulate energy prices because it is ideologically committed to free markets; however it realises that investors need incentives to install renewable energy systems, offering a set of subsidies that are designed to deliver a particular rate of return. Based on this development, Government's incentives such as FiT for PV (for example) have dropped due to fall in price of PV systems.

It follows that merely increasing energy prices will have adverse effects on those who live in flats, for example, or with homes whose roofs are otherwise unsuitable for the installation of say PV system. It is important to state however that in 2010, a small addition to energy bills was introduced by the Government to generate revenue to be used by energy companies to pay for insulation and new boilers for 'hard to heat' buildings, especially for the elderly and those affected by fuel poverty. The move was very effective, though not without some controversy as it has recently being removed to be replaced by general taxation. In essence, the logjam between politics (through policy initiatives) and energy efficiency drives requires a 'conflict' resolution mechanism that will strike a balance between them.

### 7.3.5. Integration of embodied emissions with operational emissions and cost

The key innovation of the current research is to integrate the three key variables of financial costs, and operational and embodied emissions into a robust method of ranking and sequencing building energy retrofit options according to the identified criterion. The difficulties encountered in the evaluation of embodied emissions are acknowledged. However, as new government schemes and plans indicate that embodied emissions are likely to become one of the key metrics to be addressed in whole-life building sustainability, it is important to have a consistent and comprehensive framework towards the computation of embodied emissions. Research, academia and businesses can work together to develop a consistent and comprehensive framework using state-of-the-art advancements in embodied energy research which addresses identified challenges such as system boundary completeness; use of stochastic analysis to address data variability and uncertainty; communication of results; use of hybridized approaches to solve methodological challenges etc.

If such a consistent framework is achieved, it would reduce ambiguity in embodied emissions calculations and so make it easier to include both operational and embodied emissions in a framework for building sector policy developments. In this thesis, amidst the uncertainty of embodied emissions results, an attempt was made to integrate cost and both operational and embodied emissions into a single model. The following points are deduced from this integration:

- When net emissions (achieved by integrating embodied emissions with operational emissions) and financial cost are considered within the MACC framework, a decrease is seen in the total emissions reduction available from an option and a consequent overall reduction in the total emissions savings of an abatement project
- For positive cost options, 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. For negative cost options, it would suggest that for any given option, increasing the embodied emissions has the effect of improving the cost-effectiveness

- This perverse result is again in line with the findings of Taylor (2012) and the numerous extensive analyses presented in this thesis and support 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 are established. Pareto optimisation technique is then used to rank the negative cost measures
- 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. Subsequently, the ranking of options is altered.
- For the particular 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.

## 7.4. Development of the DSS and identification of the optimal retrofit pathway

As highlighted in the preceding sections, economic considerations are integrated with operational emissions savings and embodied emissions incurred into a single DSS model. The overall methodological approach takes into account the use of selected carbon abatement technologies that will satisfy a range of criteria (environmental, demand, cost and resource constraints); treatment of uncertainty; hierarchical course of action; and the evaluation of 'best' case scenario. The development of the current DSS which takes a whole-life $CO_2$ emission accounting framework and an economic assessment viewpoint, has successfully demonstrated how value is delivered across different parts of the techno-economic system, especially as it pertains to financial gains, embodied and operational emissions reduction potential. Overall, the following benefits and extended applications can be derived from the DSS model:

- The output of the DSS provides an indication of financial benefits (i.e. energy savings) and the environmental merit of the measures across any time period considered
- The final DSS output indicate the scenarios where measures that lead to net emissions reduction also save money, and also puts into perspective measures where the investment cost cannot be recovered
- The integration of the three key variables within the DSS will facilitate a more holistic view of the environmental impact of emissions abatement options
- The use of the DSS can assist in gaining knowledge of how embodied emissions compares with operational emissions by putting climate change mitigation strategies into context and facilitate improvement initiatives with a positive emissions reduction profile.
- The concepts illustrated within the DSS will also ensure environmentally sustainable choices regarding materials selection and design procedures are taken at an early stage where design changes can be made and preferential low embodied energy materials selection adopted when specifying climate change mitigation options
- The integrated approach employed within the DSS will provide an understanding of how much of the emissions are embodied vs. how much are operational. This will help environmentally conscious organisations in disaggregating their emissions pattern based on operational emissions which feeds into their Scope 1 and 2 targets and embodied emissions which feeds into their Scope 3 emissions from purchasing and services. Possessing this type of disaggregated information, the selection of abatement options is not restricted only to the direct energy or resource consumption, but it also provides the opportunity to reduce lifecycle emissions effectively by taking the supply chain into considerations
- Based on the above point, the DSS could aid organisation to gain an understanding of the split between embodied and operational emissions due to their activities, and emissions saving targets from such organisations can be more holistic since financial cost and both operational and embodied emissions costs are taken into consideration
- The DSS outputs allows trade-offs between various design options to be identified and communicated and ensure decisions are better informed than before due to the inclusion of embodied emissions
- Extended application of the DSS allows the identification of environmentally and economically optimal retrofit pathways towards decarbonisation of the non-domestic building stocks and provides valuable guidance when planning future retrofit projects

- The DSS developed addresses the needs of university energy managers and allied professionals regarding efficient and reliable investment decisions that are informed by both environmental and financial considerations
- The DSS has been created in the form of a Microsoft Visual studio and Excel application and is named Computed Optimised Building Retrofit Advice (COBRA). An extended application of the model can be used to frame policy decisions towards holistic GHG emissions reduction strategies

## 7.5. Validation of the overall decision-making methodology

The overall DSS presented in this thesis is designed for use by energy managers, sustainability managers and even policy makers. Its evaluation and validation is therefore crucial. The technical aspects of the DSS as well as the views of its potential users were rigorously assessed based on three approaches namely: (i) the verification of the technical components of the DSS; (ii) validation of the performance characteristics of the DSS and (iii) subjective appraisal of the DSS by gaining the views of its potential users.

Technical verification entails checking the "*black box*" to get rid of programming errors and checking the extent to which the system has been built well; checking the accuracy of its outputs; and ascertaining whether the advice produced is sound or not. Although standard approaches in software engineering to software validation were not employed, the overall system was checked by an independent assessor to check for bugs where necessary.

Performance validation involves the assessment of the performance aspects of the system with the view to ascertain how effective its mode of operation is; how well it performs its functions and to what extent is the knowledge base of the system accurate and complete. The system was tested a number of times and demonstrated to the potential users.

Subjective appraisal was embarked upon in the hopes of gathering thoughts and opinions from potential users to measure the usefulness and usability of the system. It also includes establishing the extent to which the system addresses the requirements of its potential users and assessment of its ease of use.

Several evaluation criteria grouped into 6 themes or dimensions and 25 categories emerged from the DSS evaluation process. Some of the criteria explored include, usefulness, overall relevance, understanding, trust and lots more. Overall, the DSS evaluation receives quite a considerable number of encouraging and constructive comments as well as suggestion for improvements.

## 7.6. Major contributions

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 involves the use of systems and methodological frameworks that aid the strategic decision making process of choosing options that are both economically viable and environmental friendly (Doukas *et al.,* 2009). 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.

Tools to support decision making can be grouped either as bottom-up (technical) or top-down (macroeconomic) (Phdungsilp, 2010). DSSs used for policy support that takes the top-down approach incorporate observation and assumptions from the whole economy and across sectors. This does not involve any detail on energy consumption and technology change to be incorporated in the analysis as compared to bottom-up approaches. DSSs are therefore best used as bottom-up technical models to support project specific analysis by building up the aggregate characteristics of a building from specific technological, environmental and economic information (current and forecast). DSS however also have a role to play in improving policy discussions in the building sector and providing better insights (for instance through the creation of an efficient and standardised decision making process) when integrated with other top-down policy approaches.

Inherent challenges existing in such model developments such as data gaps, data uncertainties, methodological choices, etc. may impact on the outcomes of any analysis; hence discussions of the use of tools such as DSSs should therefore be made with these challenges in mind. As stated by Ryghaug and Sorensen (2009), the slow uptake of energy efficiency measures in the building sector can be traced to: limitations of public policy to encourage energy efficiency, limited efforts on the part of the government to regulate the building sector and a conformist building industry. However, innovation driven by development tools such as a DSS as demonstrated extensively in this research can stimulate new policies (Phillips-Wren *et al.,* 2009) to address energy efficiency measures in the building sector (Juan *et al.,* 2010) and support energy efficiency planning (Phdungsilp, 2010).

The development of the DSS presented in this thesis 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).

Adopting a techno-economic evaluation methodology for energy retrofit of buildings, the DSS developed in this thesis integrates economic (cost) and net emissions (embodied and operational emissions) cost or benefit parameters. 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 optimization scheme that consists of integrated modules for data input, sensitivity analysis and ranking based on MACC principles and Pareto optimization. The integration of the three variables, supported with novel mathematical proof, led to the establishment of the relationship between both operational and embodied emissions and cost for a given retrofit option. To this end, the development of the current DSS provides a significant contribution to the understanding of optimal decision making in the field of energy and sustainability with a focus on non-domestic buildings. The research contributes to knowledge, practice and policy in the field of sustainable energy systems engineering and policy formulations by extending and deepening knowledge of the field of decision aid analysis for building retrofit advice through the development of a novel and robust decision support system.  A summary of key contributions to knowledge from this research is depicted in Figure 7-1.

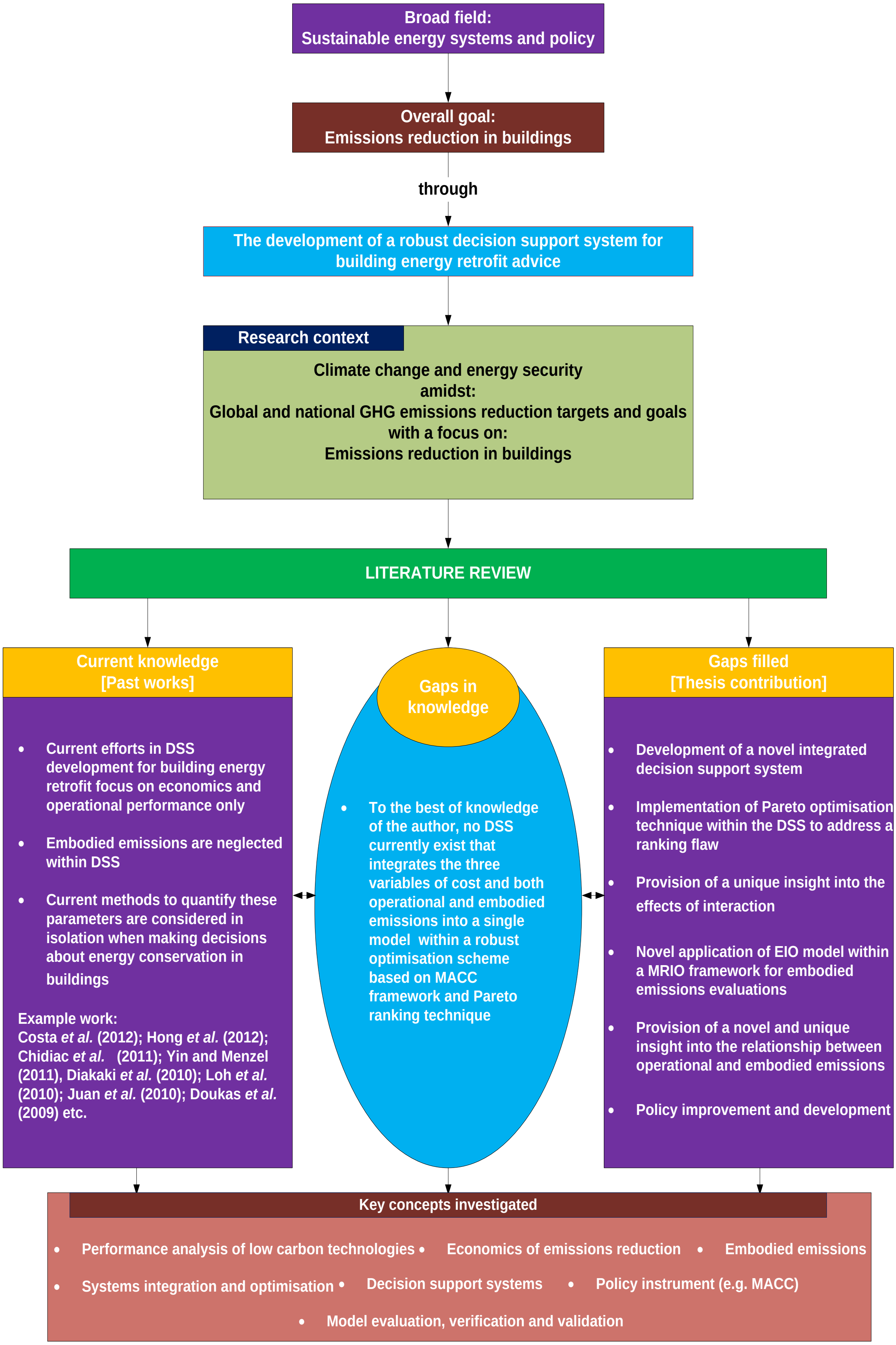



Figure 7-1: Major contribution of the current research

Based on Figure 7-1 and the overall presentation in this chapter, the contribution of the work undertaken by the researcher can be summarized as follows:

- Development of a novel unified decision support system for evaluation of environmentally and economically optimal retrofit of buildings to enhance efficient and reliable investment decisions that are informed by both environmental and financial considerations
- Implementation of Pareto optimisation technique within the decision support system to address a mathematical error in the standard ranking criterion for measures that yields a negative cost within a marginal abatement cost framework
- Insight into the effects of interaction between building energy retrofit options, supported with mathematical formulations and analysis, through the use of interaction factor
- Novel application of economic input-output (EIO) model within a multi-region input-output (MRIO) structure to estimate the embodied emissions of a number of building energy retrofit options, providing insight into the UK consumption pattern and identifying policy, business and consumer triggers that will lead to an overall emissions reduction strategies
- Novel mathematical proof and analysis of the relationship between operational and embodied emissions for a given retrofit option through the integration of both types of emissions and financial costs into a single model
- Novel extension of the marginal abatement cost curve to cover embodied emissions to frame policy initiatives and identify business and consumer triggers with the view to shaping future decisions towards holistic climate change mitigation strategies

## 7.7. Limitations of the work

Despite the novel approach taken to the integration of the three variables of cost, operational and embodied emissions within the DSS, there are certain limitations which are associated with its design, creation and applications. Some of the limitations include focus on finite set of retrofit options especially as it relates to non-inclusion of passive measures like wall insulation and window glazing within the operational emissions module of the DSS as stated in Section 4.5.1. Another limitation is one described in Section 5.6.1 regarding the use of interaction factors to account for interaction between measures. As discussed, the use of interaction factor deals with pairwise interaction only, so it does not capture everything there is to interaction between measures. Also, the use of pure EIO within a MRIO framework was adopted within the DSS to evaluate the embodied emissions of a number of retrofit options. This approach possesses some limitations as discussed in Section 4.9.6. Eliminating these limitations could be achieved as part of future work as detailed in the next section.

## 7.8. Future work

Despite the findings and innovations presented in this thesis, further work is needed to reinforce the accuracy of predictions from the DSS. In the subsections that follow, the research tasks that form the basis of future work are presented.

### 7.8.1. Consideration of time dimension within MACC for long-term policy planning

Given the pace at which innovative low carbon technologies for emissions reduction evolve, it is expected that in the long-term, the cost of such technologies would decrease due to factors including: research and development; changes in price of technologies; changes in price of energy (gas and electricity); learning effects and investments; economies of scale and indirect effects of policies that are not GHG-related; the effects of grant schemes and their present lifespan predictions; issues relating to value added tax (VAT) and the impact of legislations. Against this backdrop, it is important to take processes that are dynamic into consideration by developing dynamic MACCs where all the aforementioned factors will be accounted for.

The development of dynamic MACCs is important because as technologies become more efficient over an extended period of time, total abatement potential of options will decrease, leading to increased cost per tonne of $CO_2$ saved. It therefore follows that while maintaining the use of MACCs for appraising the present "cost-effectiveness" of different climate change mitigation strategies, the formulation of policies should embrace the analysis of the cost dynamics (i.e. the rate of change of the cost-effectiveness over a given period of time) of the strategies. This is important as positive-cost measures within the MACC framework could become remarkable in long-term policy due to change in cost of implementation and benefits accruing from improvements in technology. A time-based curve could therefore be drawn for each measure with the view to estimate the time when the cost-effectiveness will be attained.

### 7.8.2. The use of hybrid lifecycle approach within an improved MRIO framework

The embodied emissions module of the current DSS is based on the pure input-output model within a MRIO framework, benefiting from its economy and system-wide approach allowing for the estimation of embodied emissions along the production and supply chain to the sector responsible for consumption or final products grouped together. This offers completeness and avoids systems boundary issues commonly encountered with process-based analysis.

However, data used for I-O model are aggregated at the level of economic sectors as against individual products, making it difficult to account for precise and specific emissions associated with one particular product within a sector. A processed-based approach to embodied emissions estimations offers this specificity. To improve the results of embodied emissions within the DSS, the specificity of process analysis could be combined with the completeness of input-output analysis to produce what is collectively known as hybrid lifecycle assessment, where specific (primary) data on individual technologies are integrated with data from input-output model. By combining the benefits of both process and input–output analysis, fundamental errors and limitations associated with each method can be eliminated, improving both accuracy and precision whilst enhancing the overall embodied emissions predictions within the DSS.

The MRIO framework used within the current DSS presents the ROW as a breakdown of 113 countries. Currently, a World MRIO Framework has been developed and released which can present the ROW as a breakdown of 186 individual countries each with 25 harmonised sectors. This World MRIO designed and developed by Lenzen *et al.* (2013) is accessible at http://www.worldmrio.com.This large integrated collection of input-output data from many countries will increase wider coverage and accuracy when calculating emissions accruing from imports. The embodied emissions database of the current DSS can therefore be augmented for future development with this new and rich MRIO data and framework as part of further research activities to take the current work forward.

### 7.8.3. Application of Structural Path Analysis to identify supply chain hotspots

The use of Structural Path Analysis (SPA) as a systematic technique and analytic procedure which can be used to unbundle major contributors of embodied emissions associated with the supply chain of a bundle of products and services purchased by an organisation has been extensively demonstrated by researchers including Acquaye *et al.* (2011); Wiedmann (2010); Lenzen *et al.* (2009). This is achieved by using SPA to identify supply chain hotspots. Results generated through the adoption of SPA can be used to identify and address suppliers that contribute the most to embodied emissions. This can assist in the identification and prioritisation of scope 3 emissions. Possessing this type of disaggregated information, the selection of abatement options is not restricted only to the direct energy or resource consumption, but it also provides the opportunity to reduce lifecycle emissions effectively by taking the supply chain into considerations. The SPA technique can also be applied to international supply chains. To this end, as part of further research, it is proposed that the DSS be modelled such that the SPA of the supply chain of building energy retrofit options can be investigated. The use of SPA within a hybrid framework can allow the embodied emissions associated with the specific procurement of a retrofit option to be evaluated. The result can be used as a benchmark for similar products; assist in the identification, quantification and ranking of paths with high $CO_2$ emissions; and helps in identifying wide-ranging opportunities for restructuring and enhancing the green credentials of companies or sectors in industry.

### 7.8.4. Incorporation of uncertainty analysis into the evaluation of retrofit options

Walker *et al.* (2003) defines uncertainty of a system as any deviation from the achievable ideal of completely deterministic knowledge of the relevant system. In energy assessment, dealing with uncertainty is key to making a well-informed decision, as any decision made without taking uncertainty into consideration is not worth making at all (Acquaye, 2010). Generally speaking, all scientific investigations benefit from an understanding of the uncertainties of results caused by uncertainties in the input data. The complexity and uncertainty in emissions assessment strategy is augmented by data issues, variations in technologies and the number, diversity and interactions of processing steps (Acquaye, 2010; Dixit *et al.,* 2010). Regarding embodied energy assessment of each of the intervention options, data uncertainty can arise because of the errors and variability existing in input data as a result of sampling errors, old data, incomplete data, missing data and aggregation. Similarly, economic information sources like energy tariffs, interest rates, changes in policies and product cost, usually diverge and they can affect decision -making (ibid).

To this end, decisions that take into account the uncertainty in results will be much more informed as quality and credibility of results are improved. Therefore, as part of future work, sampling methods in the form of Monte Carlo analysis within a stochastic modelling framework could be employed as it offers the best approach for handling uncertainty in input data. Real Options (RO) Theory can then be used to establish more about the adoption of different options under uncertainty. This will facilitate how a set of recommendations responds to uncertainties. The end result will provide a mechanism that classifies recommendations into those that are robust with typical uncertainties, followed by a range of less robust options.

### 7.8.5. Further research into building sector emissions policy

It is suggested that further research be carried out to determine how embodied emissions associated with building energy retrofit products can be used to complement product energy rating schemes for operational energy use. Further investigation is also required to bridge the gap between policy development and formulations and quantitative results of embodied $CO_2$-eq appraisals. The development of such building sector-specific emissions policy will enhance a holistic approach to the reduction in the increasing energy use of buildings and the built environment at large and facilitate improvement initiatives with a positive emissions reduction profile.

### 7.8.6. Improvements on the overall software development of the DSS

Finally, the overall development of the DSS into software should be further optimised to address some of the weaknesses highlighted by the potential users including, greater visibility of outputs, desktop operability and improved integration. This entails a range of activities and software design approaches including testing the DSS with a wider range of building types; creation of avenue to allow for the inclusion of maintenance costs associated with the identified retrofit options; addition of other fuels other than gas and electricity which the DSS currently focus on; and development of visualization of the Pareto ranking data into a two-dimensional (i.e. emissions savings and cost) graphical output to aid understanding of the users of the DSS.

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# APPENDIX

## Appendix A: Flowcharts describing the performance calculation methods for selected retrofit options

### A1 Photovoltaic system

The overall output from a PV system largely depends on the annual irradiation (i.e. annual average insolation) for a particular location. The rate at which sunlight hits the PV module is dependent orientation and angle of inclination. It is therefore important to the factors into account using appropriate charts which shows various percentage yearly outputs available for various orientation tilts. For most PV systems (e.g. crystalline silicon solar cell), the PV module conversion efficiency is 14% (Tiwari, 2002). Due to due to rise in cell temperature, intermittent reduction in solar intensity and deposition of dust particle, the efficiency of conversion of the PV system is reduced to 11% (Nawaz and Tiwari, 2006; Tiwari and Ghosal, 2005). The next parameter of interest is the packing density factor or packing factor and it is the area occupied by PV cells in a module divided by the actual area of the same PV module. The area of cells in a module is given by the product of the area of a single cell and the total number of cells.

Further, there are electrical losses, usually put at 15% that the PV system suffers. These losses are attributed to the inverter, transformer and connecting electrical resistance (Nawaz and Tiwari, 2006; Tiwari and Ghosal, 2005). Additionally, there are electrical losses (about 6%) that are considered for electrical efficiency (ibid). The overall annual average energy output of the PV system is considerably reduced due to these losses. With known values of all essential parameters listed, the output per functional unit of PV panel installed can be calculated. The target saving in terms of $CO_2$ emissions can be ascertained first and the PV system is designed to meet the set target based on the aforementioned parameters. A range of carbon reduction levels (%) can be adopted in the calculations procedure until a satisfactory result for roof area, the capacity of generation (i.e. total output) of the PV system is met. The overall PV system rated output is given by the module rated output ($kW_{peak}/m^2$) × Area of the PV system required ($m^2$). The flowchart illustrating the calculation procedure adopted within the DSS is shown in Figures A-1a and A-1b.

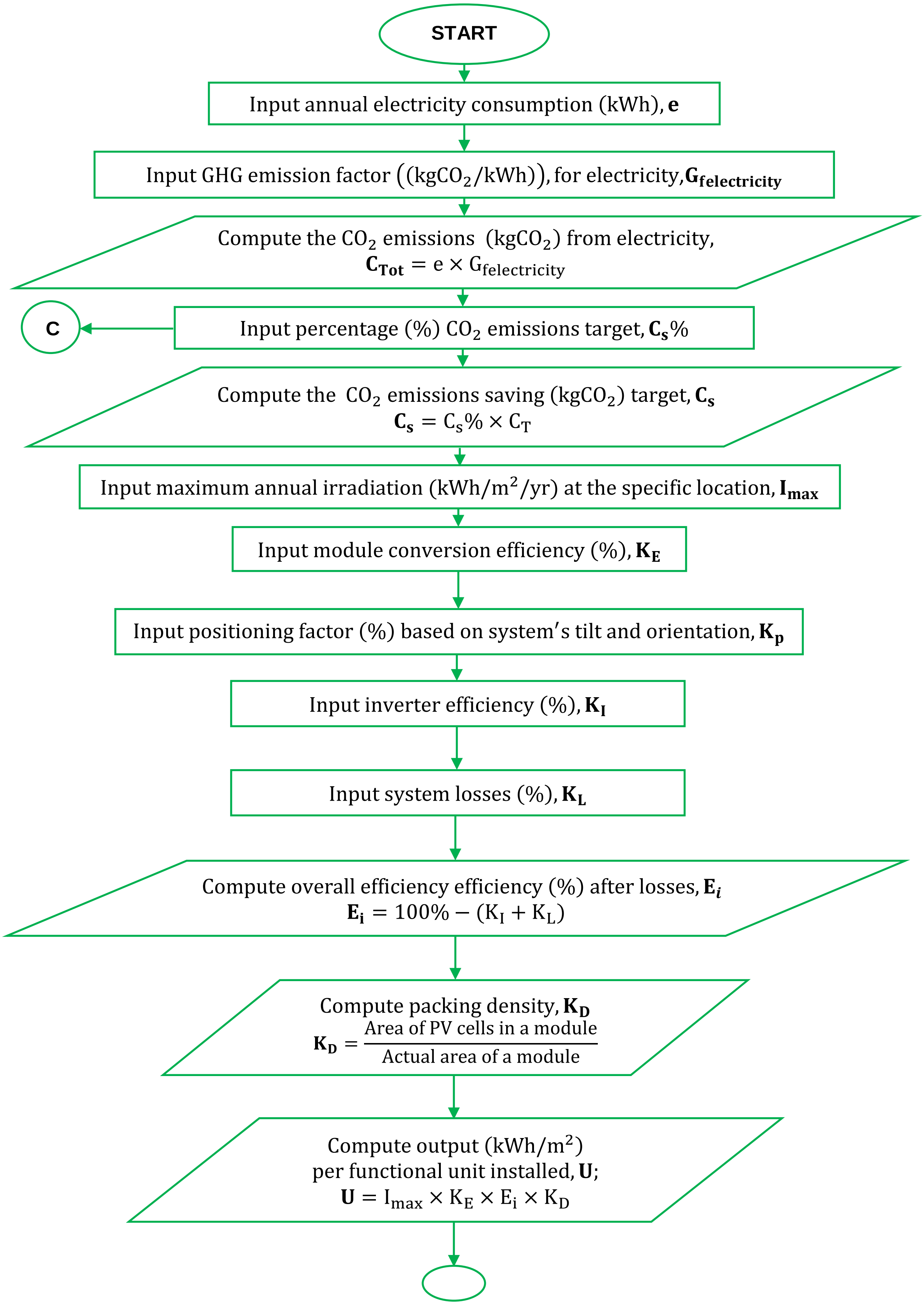



**Figure A-1a: Performance calculation method for PV system**

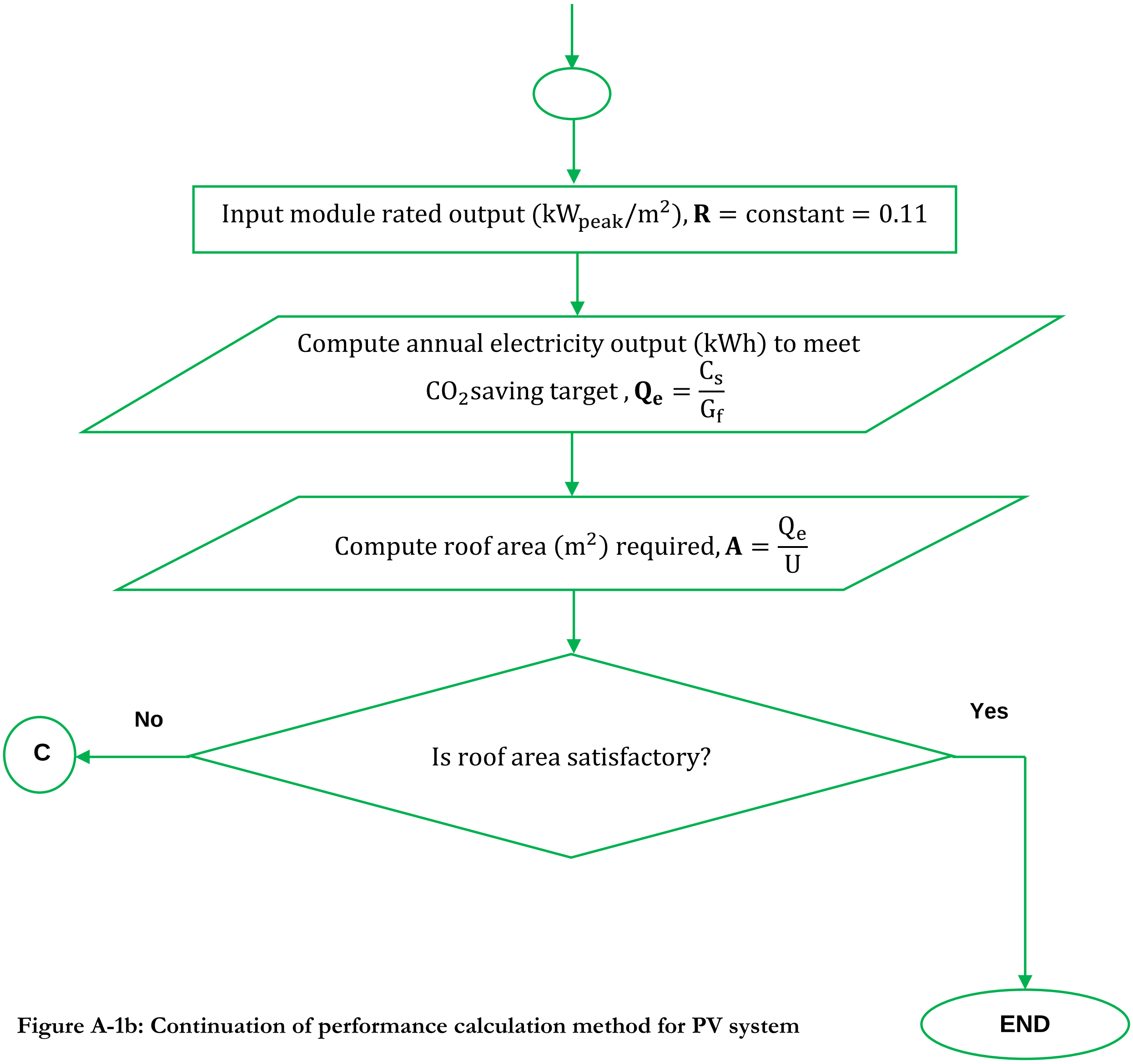



**Figure A-1b: Continuation of performance calculation method for PV system**

**Figure A-1: (a) Performance calculation method for PV system (b) Continuation of performance calculation method for PV system**

## A2 Wind turbine

The availability of wind resources in terms of speed and rate of occurrence affects the performance of a wind turbine. Due to the exponential character exhibited by electricity generation as the wind speed decrease or increase, there is a significant variation in the corresponding emissions saving output (Kubik *et al.*, 2011).

Average site speeds are usually taken at weather stations but wind speeds increase with height due to the "wind shear" and therefore it is important to determine the wind speed at the wind turbine hub. This is achieved by relating the local velocity (V) at a height (Z) to the velocity at the point of measurement ($V_m$). There are two approaches, namely, *power-law approach* and *log-law approach* for estimating wind speed at hub height from measurements at a reference level (Bañuelos-Ruedas *et al.,* 2011). Before adopting any of the two approaches, speed of wind at a reference height must be known. Also, for the power law approach, another coefficient known as wind shear coefficient $(\alpha)$must be established and for the log law approach, a roughness length $(Z_o)$ must be known (Kubik *et al.*, 2011). The calculation of both coefficients can be carried out based on site measurements. To ensure similarity in results of both approaches, it has become a practice in the wind industry to have them checked where possible (Wheatley *et al.,* 2010 as cited by Kubik *et al.*, 2011).

**(i) Power-law approach**

Power-law functions as employed in wind power calculations and also ventilation calculations, take the form:

$$V_z = V_m K Z^{\alpha} \qquad (A1)$$

Where $V_z$ is the velocity at a hub height, $Z$; $V_m$ is the wind speed measured at some reference point (i.e. at the weather station).$V_m$is usually measured at about a height of 10m, since at a research level, the resources to conduct field investigations is limited (Kubik *et al.*, 2011). $K$ is a constant and α represents the wind shear exponent or power law exponent and depends on the nature of the terrain (i.e. surface roughness). See Table A-1 for the values of $K$ and α.

**Table A-1: Values for constants K and α in different terrain (Panofsky and Dutton, 1984).**

| Terrain | K | α |
|---|---|---|
| **City** | 0.21 | 0.33 |
| **Urban** | 0.35 | 0.25 |
| **Open country** | 0.68 | 0.17 |

The empirically derived power law is common engineering practice adopted by the wind industry experts (Wheatley *et al.,* 2010 as cited by Kubik *et al.*, 2011). This stems from the fact that as the coefficient of wind shear ($\alpha$) has varying values because of a number of factors such as the topography of a region, time of day, season variations and atmospheric stability (Gipe, 2004).

**(ii) Log-law calculation approach**

The log-law approach is theoretically more accurate (PLA, 2005; Manwell *et al.,* 2010). Its validity is considered under definite assumptions about the stability of the atmosphere, and actual profiles may differ from the log law (Kubik *et al.*, 2011). In using the log-law approach, it is important to take into account the effects of turbulence near the ground and the corresponding modification of the wind boundary layer in urban environment where building, road and vegetation variations constitute a very rough surface (Manwell *et al.,* 2010; DWEA, 2002). This is particularly so in the centre of large cities where tower blocks or skyscrapers make for very large variations in surface level. The values of surface roughness for different terrain types, and corresponding 'roughness class', commonly used in the wind power industry are detailed in (DWEA, 2002).

At the point where surface roughness is noticed, the effective base of the boundary layer is not at ground level, but at some point nearer the top of the obstructions like trees and buildings. This effect can be considered in the calculations by identifying a "displacement" height (d) which is the height where the logarithmic velocity profile is taken to be zero. Panofsky and Dutton (1984); Mertens, (2003) suggested the displacement height can be taken as 75% of the average building height, $h_b$:

$$\text{Displacement height, d} = 0.75\text{h}_\text{b} \qquad (A2)$$

After taking the displacement height into account, the logarithmic relationship between height and reference velocity becomes:

$$\text{V}_\text{z} = \frac{\ln\left[\frac{\text{Z}-\text{d}}{\text{Z}_\text{o}}\right]}{\ln\left[\frac{\text{Z}_\text{ref}}{\text{Z}_\text{o}}\right]} \times \text{V}_\text{m} \qquad (A3)$$

Where $\text{Z}_\text{o}$ is the roughness length and its estimation can be greatly influenced by seasonal variations in local terrain characteristics due to changes in foliation, snow cover, and vegetation (Kubik *et al.*, 2011); $V_m$ is the velocity measured at a reference height, $\text{Z}_\text{ref}$; Z is the wind turbine hub height. The denominator term in Equation A3 is to account for the fact that the reference velocity was measured at one particular height above ground (often 10m). The formulae is not valid at heights below the displacement height, in particular, Mertens (2003), suggested it is not accurate below a height, $Z \geq 20Z_o + d$.

After calculating local wind speeds at hub height using any of the two methods described above, the next step in estimating wind resources is to calculate the wind turbine power output. The power output can be estimated by using wind turbine manufacturers supply 'Power Curve' data that correlates wind speed to power output directly. Using the unitary power output as shown in the flowchart in Figure A-2, the $CO_2$ emissions saving target can be determined first using a range of carbon reduction levels (%) and the turbine capacity worked around it until a satisfactory result in terms of total output (i.e. generation capacity) is achieved.

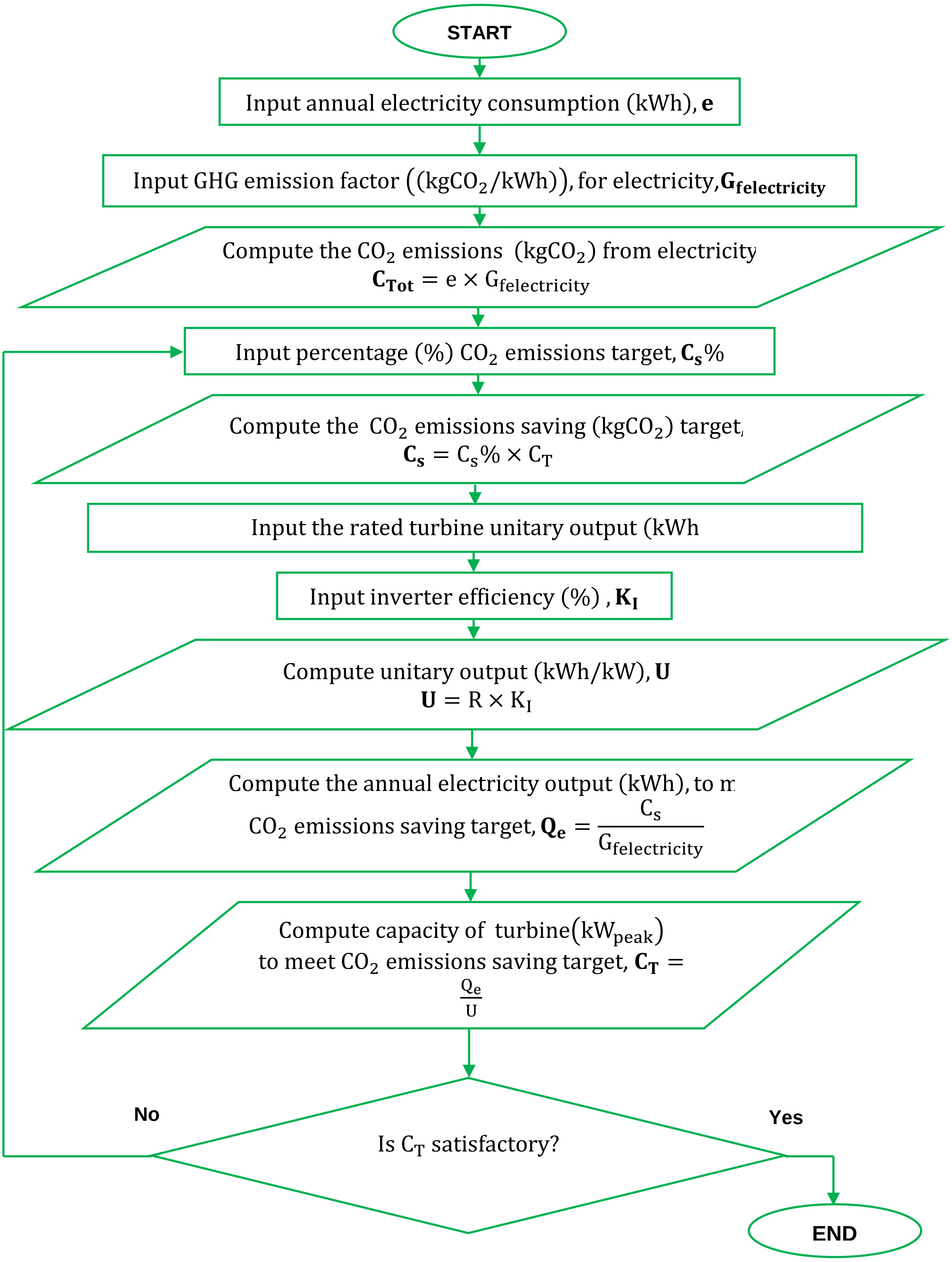



**Figure A-2: Performance calculation method for micro wind turbine**

## A3 Solar hot water

The principle of operation is such that a solar collector (i.e. an absorbing surface that is dark in colour) captures radiation from the sun, converting it into heat energy whilst minimising heat losses due to convection. The heat generated is then transported into a storage vessel through circulating fluid, or in some cases, the solar collector could be directly linked with the heating circuit (DECC, 2013).

There are various types of solar collector and the selection depends on the temperature of the application under consideration and the time of the year it will be used. The design parameters for each type are different which lead to performance suitable for different applications. The performance of solar thermal systems are affected due to variations in design characteristics such as antifreeze or drain back systems, twin coil or preheat cylinders and control systems (Building Regulation, 2006). The performance calculation method used within the overall DSS to estimate potential emissions savings from solar hot water systems is shown in the flow chart in Figures A-3a and A-3b.

As shown, the first requirement is to ascertain the annual hot water demand of the building under consideration. This estimates on certain assumptions about hot water consumption pattern. For more accurate values, hot water demand can be obtained from well-established tables detailed in the Applications Handbook from the staples of ASHRAE (1995). Hot water energy requirements per day can also be estimated based on total floor area ($m^2$) as detailed in SAP (2005, pp.57). Detailed calculation procedure for estimating hot water demand is provided in SAP (2012, pp.132). Therefore hot water demand/year can then be calculated.

Values of monthly factors for hot water use and temperature rise of hot water drawn off are detailed in SAP (2012, pp.132) for calculating the energy content of water used. For simplicity, if it is assumed that cold water enters the boiler from the mains at a temperature $\theta_i$°Cand needs to be heated to a temperature$\theta_f$°C, and given that 1litre of water weighs 1kg (i.e. density of water is 1kg/litre), then the energy content of water and the corresponding hot water demand in kWh ($Q_{hot\ water}$) can be calculated using:

$$\mathbf{Q_T}(\text{kWh}) = \frac{\text{V}_y \times \text{specific heat capacity of water} \times \Delta\theta}{3600} \qquad (A4)$$

Parameters such as *annual maximum irradiation in location*, *solar hot water systems conversion efficiency*, *utilisation factor* etc. are supplied as shown in Figures A-3a and A-3b. Solar collectors are described by their efficiency equations. Similar wind-independent efficiency equation exists for glazed and evacuated collectors, but the efficiency equation of unglazed collectors is wind-dependent (RETScreen, 2004). Most manufacturers specify this value as part of the product design but if not specified, the conversion efficiency for glazed or evacuated collectors can be calculated using (Duffie and Beckman, 1991):

$$K_E = F_R(\tau\alpha)G - F_R U_L \Delta T \qquad (A5)$$

Where:

$K_E$ is the conversion efficiency (i.e. the energy collected per unit collector area per unit time);

$F_R$ is the heat removal factor of the collector;

$\tau$ is the transmittance of the cover,

$\alpha$ is the shortwave absorptivity of the absorber;

$G$ is the global incident solar radiation on the collector;

$U_L$ is the overall heat loss coefficient of the collector,

$\Delta T$ is the temperature differential between the working fluid entering the collectors and outside.

Values of $F_R(\tau\alpha)$and $F_R U_L$are supplied by the user or chosen from RETScreen Online Product Database for solar collectors. For both glazed and evacuated collectors, the parameters$F_R(\tau\alpha)$ and $F_R U_L$ are independent of wind. "Standard" values are also available for both types of collectors. For glazed collectors, the value of the parameters are given as $F_R(\tau\alpha) = 0.68$ and $F_R U_L = 4.90(W/m^2)/°\text{C}$. These values have been found by Chandrashekar and Thevenard (1995) match test results for thermodynamics collectors. Generic evacuated collectors are also given as: $F_R(\tau\alpha) = 0.58$and $F_R U_L = 0.7(W/m^2)/°\text{C}$ and have been found to correspond to a Fournelle evacuated tube collector (Hosatte, 1998 as cited in RETScreen, 2004).

Utilisation factor is a function of the rate which the solar collector is producing compared to what the system could produce. In electrical engineering, **utilization factor** is the ratio of the maximum load on a system to the rated system capacity. The utilisation factor is then applied which the effect of reducing the system has output if it is large in relation to the heat load. Manufacturers supply this value for the solar hot water system. Given all the known parameters, the system output/functional unit $(kWh/m^2)$ installed is then calculated. Assuming the system is required to supply 50% (maximum recommended) of the hot water requirements, since it is practically impossible to meet the complete yearly hot water demand by increasing the capacity of the system. This is particularly so as insolation is maximum during summer when the demand for hot water is minimal. Solar water heating systems use solar collectors and a liquid handling unit to transfer heat to the load, generally via a storage tank with the aid of a circulating pump. The energy consumed by the circulating pump can be calculated by multiplying its power rating by its run time. The use of electricity for the pump should be kept as low as possible to avoid over dimensioning of the power of the pump. With known value of the energy loss without thermostatic control (given to be 75kWh/year based on DTI side-by-side testing), the $CO_2$

emissions associated with the operation of the SHW can be calculated. The next steps in the flowchart are followed to compute the overall emissions saving potential from SHW.

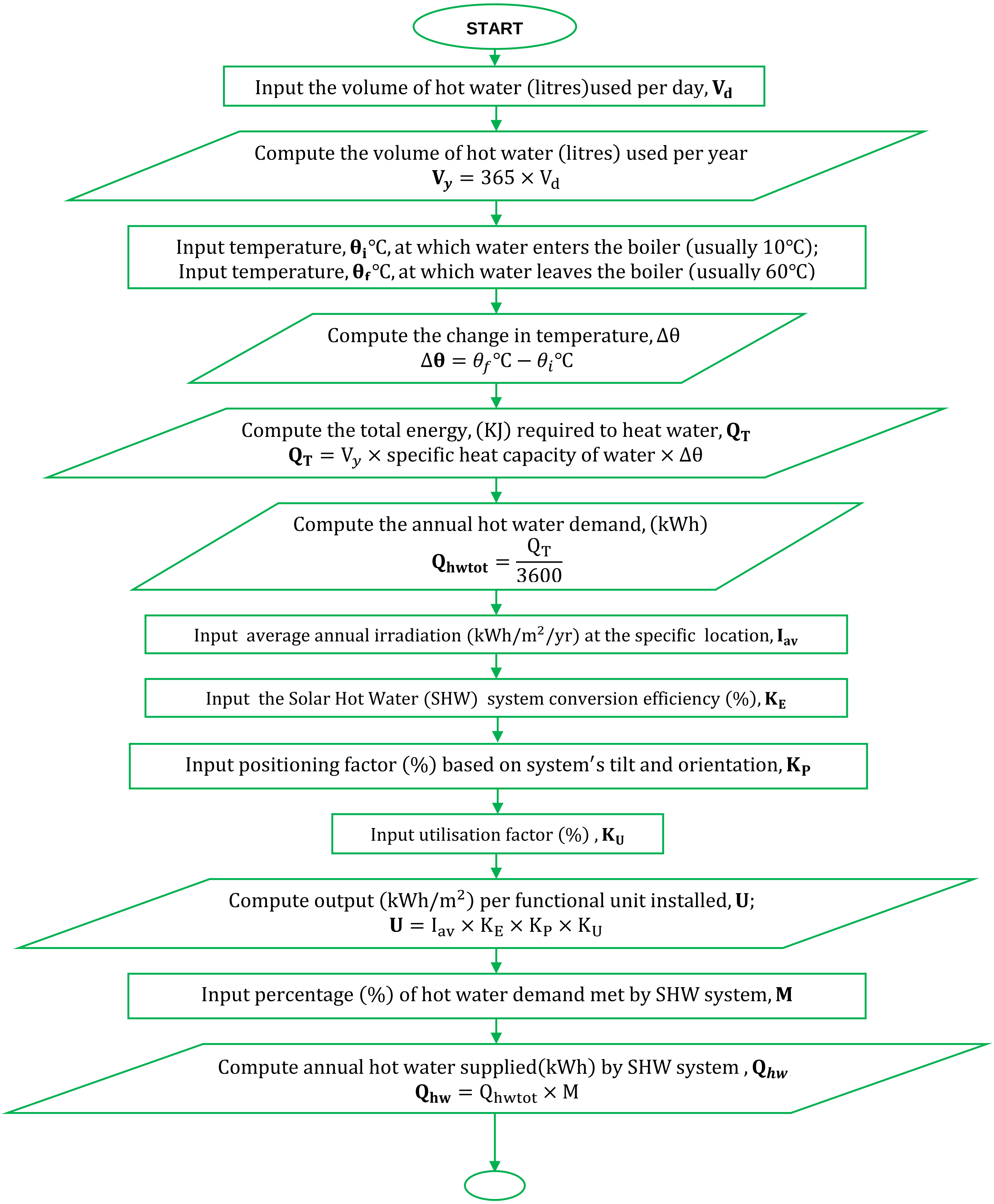



**Figure A-3a: Performance calculation method for Solar Hot Water**

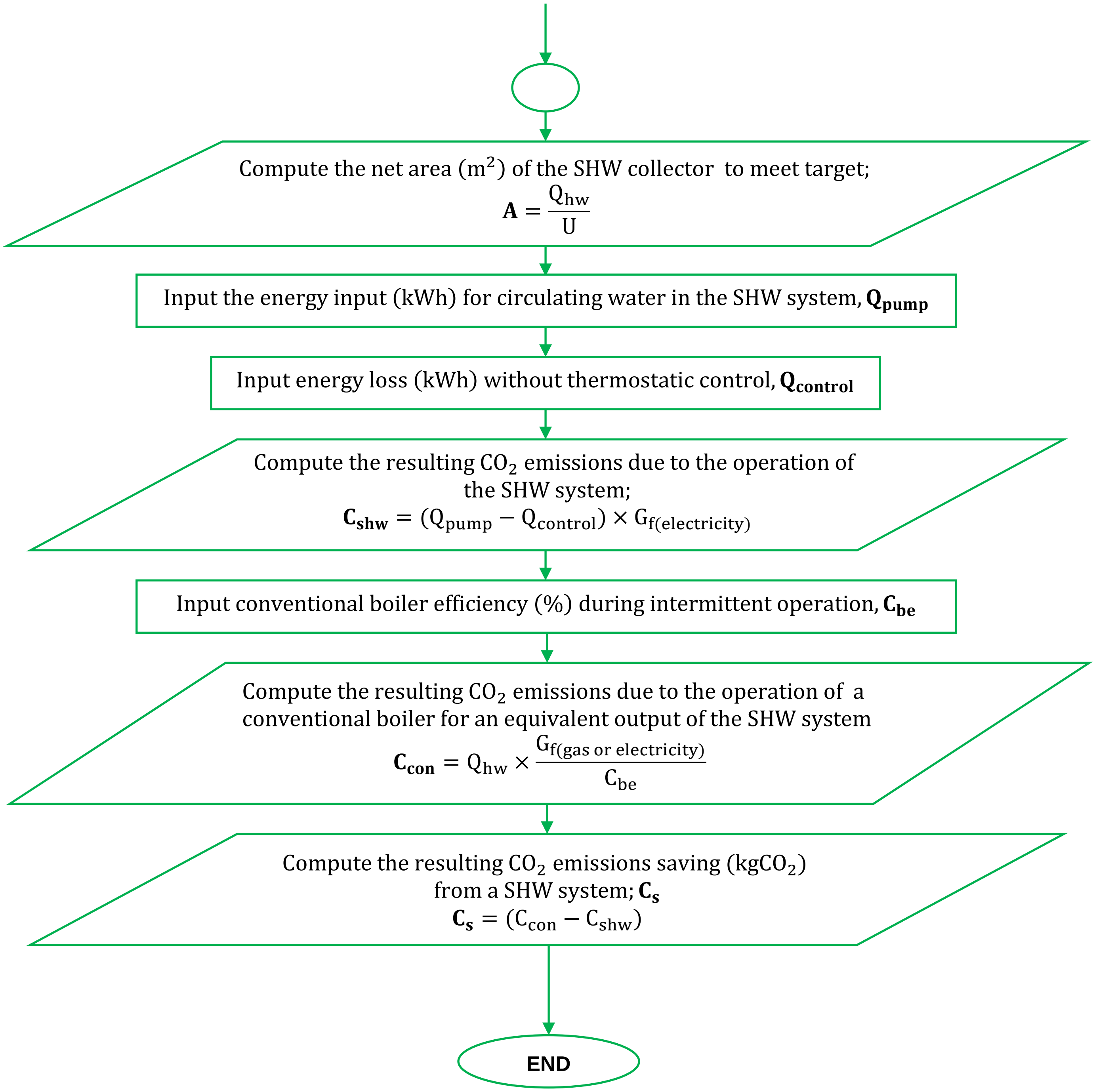



**Figure A-3b: Continuation of performance calculation method for solar hot water**

**Figure A-3: (a) Performance calculation method for Solar Hot Water (b) Continuation of performance calculation method for solar hot water**

## A4 Ground source heat pump

Heat is transported slowly in the ground where the heat storage capacity is high with slow changes in temperature. This is possible because the thermal conductivity of the soil and is the reason some heat generated from the cooling season can be transferred to the heating season and vice-versa (RETScreen, 2005). This constant cycle between the air and the temperature of the soil yields a potential thermal energy which can be used for heating or cooling a building (ibid). Further details of mode of operation of GSHP are detailed in literature (e.g. RETScreen, 2004)

In the context of the overall development of the current DSS, the performance calculation method used to estimate potential emissions savings from GSHP is shown in the flowchart in Figures A-4a and A-4b.As shown, basic information such as the annual energy demand (kWh) for the provision heating and hot water and the heating demand (%) which the GSHP is design to meet supplied by the user of the DSS, from which the annual heating supplied (kWh) by the pump is calculated. The effectiveness of heat pumps is measured by the CoP – coefficient of performance and is defined as the ratio of the heating capacity to the input power. The Mid-range CoP achievable is usually taken to be 2.5. Seasonal average CoP of 3.0 is widely reported in literature and completed projects, although several well designed system achieved 3 and above. As mentioned earlier that electricity used to operate a GSHP, the resulting electrical energy consumption of the heat pump is then calculated by dividing the annual heating supplied by the pump by the CoP. This then allows for the effective heat supplied to be calculated.

The electrical energy consumption of circulating pump for GSHP is then supplied based on manufacturers' information (this is about 130kWh/year for a typical single family house). The next steps in the flowchart are then followed, noting if the building marked for retrofit is currently being heated with gas or electricity, so that the overall emissions savings from GSHP can be estimated. GSHP benefits are high if they replace the heating system of a building that is currently being heated by electricity and can meet 100% heat energy demand residential applications.

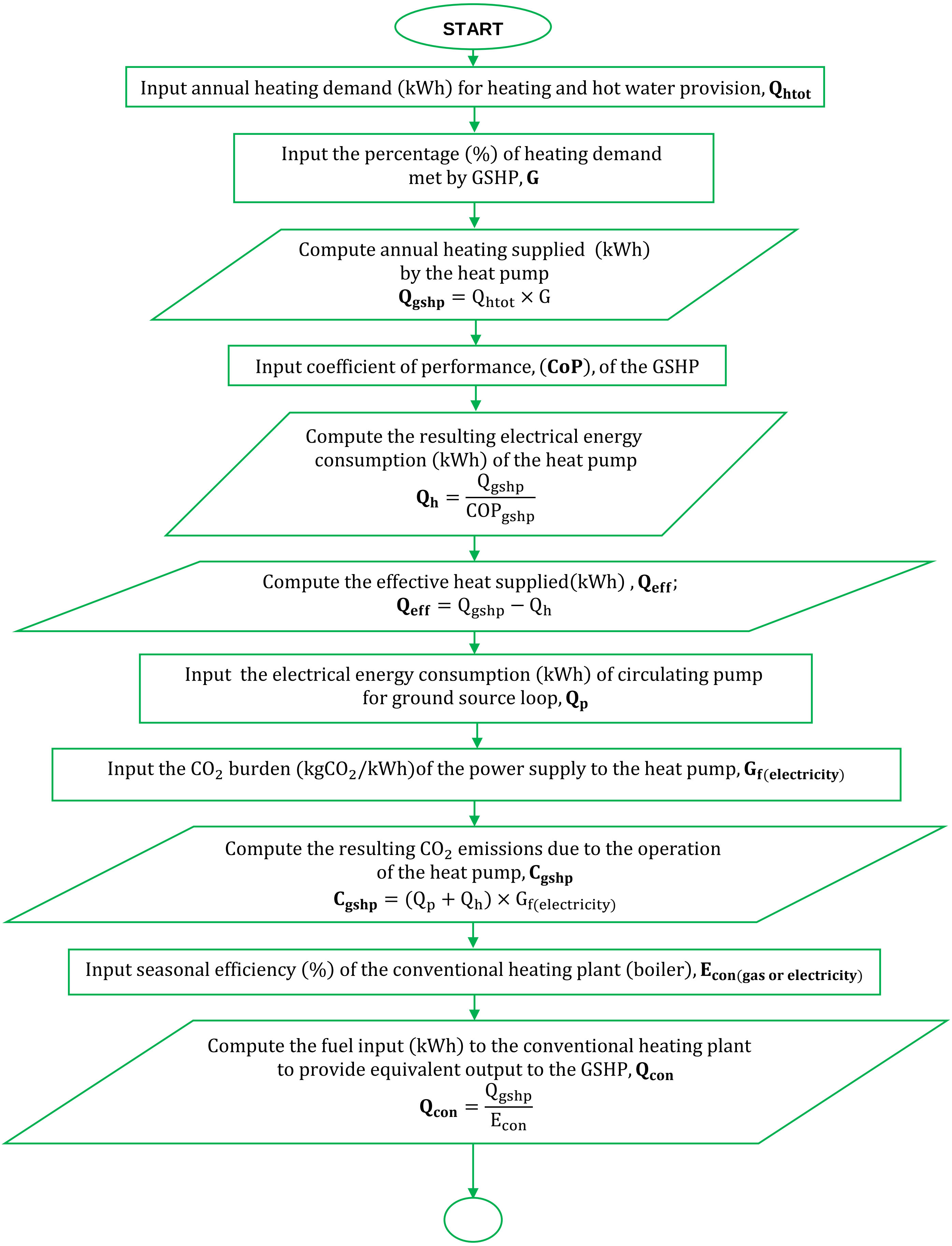



**Figure A-4a: Performance calculation method for ground source heat pump (GSHP)**

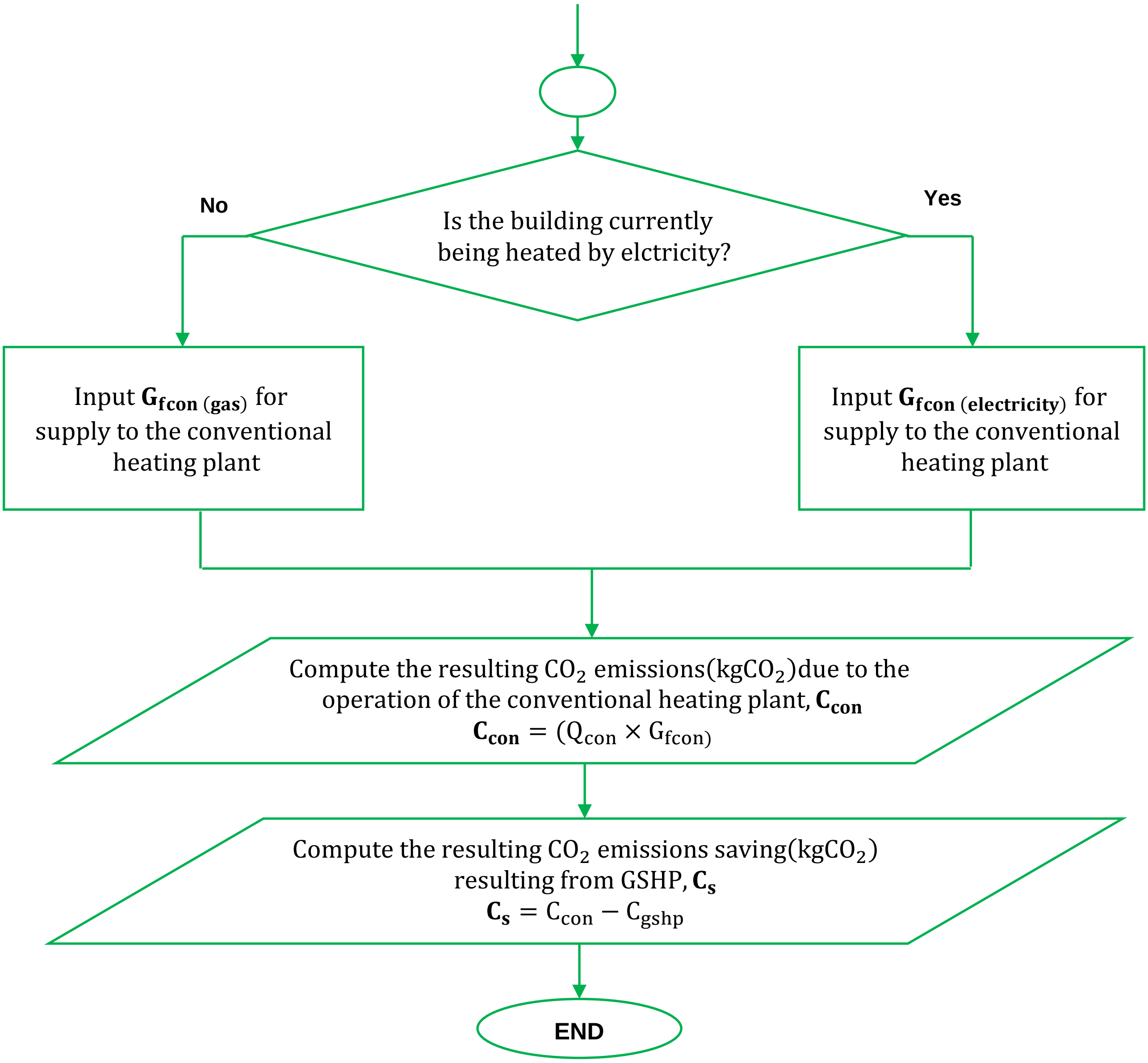



**Figure A-4b: Continuation of performance calculation method for GSHP**

**Figure A-4: (a) Performance calculation method for ground source heat pump (GSHP) (b) Continuation of performance calculation method for GSHP**

## A5 Micro combined heat and power (CHP)

Traditional power generation only make use of the electrical energy generated by the turbine-generator set. The turbine exhaust steam usually contains insufficient energy for further electrical energy generation. The heat in the exhaust steam is often rejected to large bodies of water or the environment, resulting in a waste of a large amount of the energy content of the fuel (Boles and Çengel, 2002). The principle behind CHP is the recovery of these wasted heat produced through fuel combustion in electricity generation system. This recovered thermal energy is used either to pre-heat the working fluid within the system (Boles and Çengel, 2002) or used as process heat to satisfy other heating loads, such as space or water heating (Brodrick *et al.,* 2005). The overall efficiency of the system is increased due to the cogeneration of electricity and heat. Efficiency increase in the range of 25–55% to 60–90% has been reported and depends on the type of equipment used and the application (RETScreen, 2005).

In the context of the overall development of the current DSS, the performance calculation method used to estimate potential emissions savings from Micro-CHP is shown in the flowchart in Figures A-5a and A-5b. As depicted, basic information such as the heating demand (kWh) for a year for heating and provision of hot water and the percentage of heating demand the Micro-CHP is to meet are supplied by the user of the DSS, from which the annual heating supplied (kWh) by the Micro-CHP is calculated. The rated heat output (kW) of the micro CHP as specified by the manufacturer is supplied by the user, from which the full hours run (equivalent) can be estimated. The net electricity generated by the Micro-CHP is then calculated by multiplying the rated electricity output (kW) of the micro CHP as specified by the manufacturer, with the full hours run. Similarly, the annual fuel consumption (kWh) by the Micro CHP is calculated by multiplying the rated fuel consumption (kW) of the micro CHP as specified by the manufacturer, with the full hours run. The corresponding $CO_2$ emissions associated with each step is calculated by multiplying with appropriate GHG emissions factors. The next steps in the flowchart are then followed, so that the overall emissions savings from Micro-CHP can be estimated.

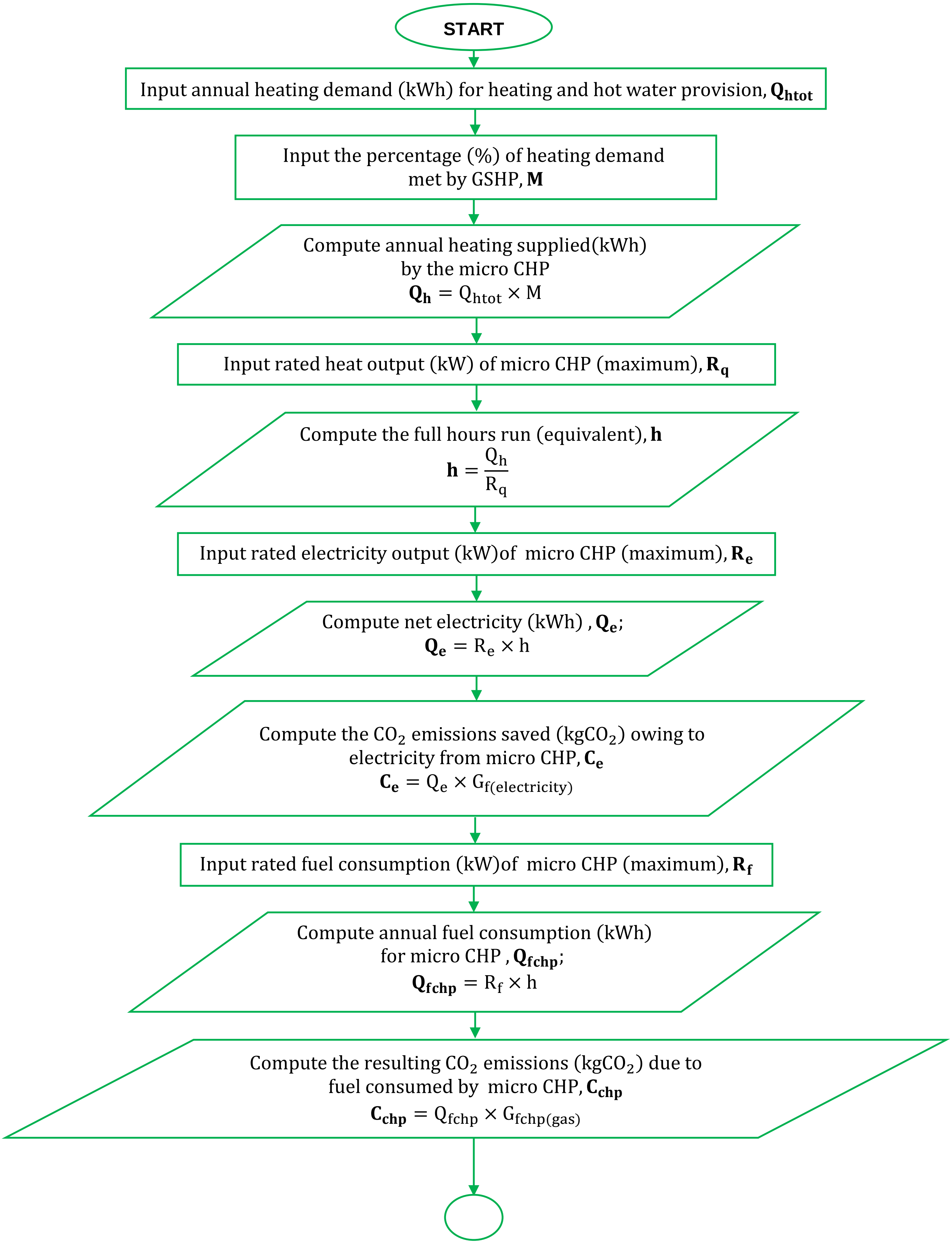



**Figure A-5a: Performance calculation method for Micro CHP**

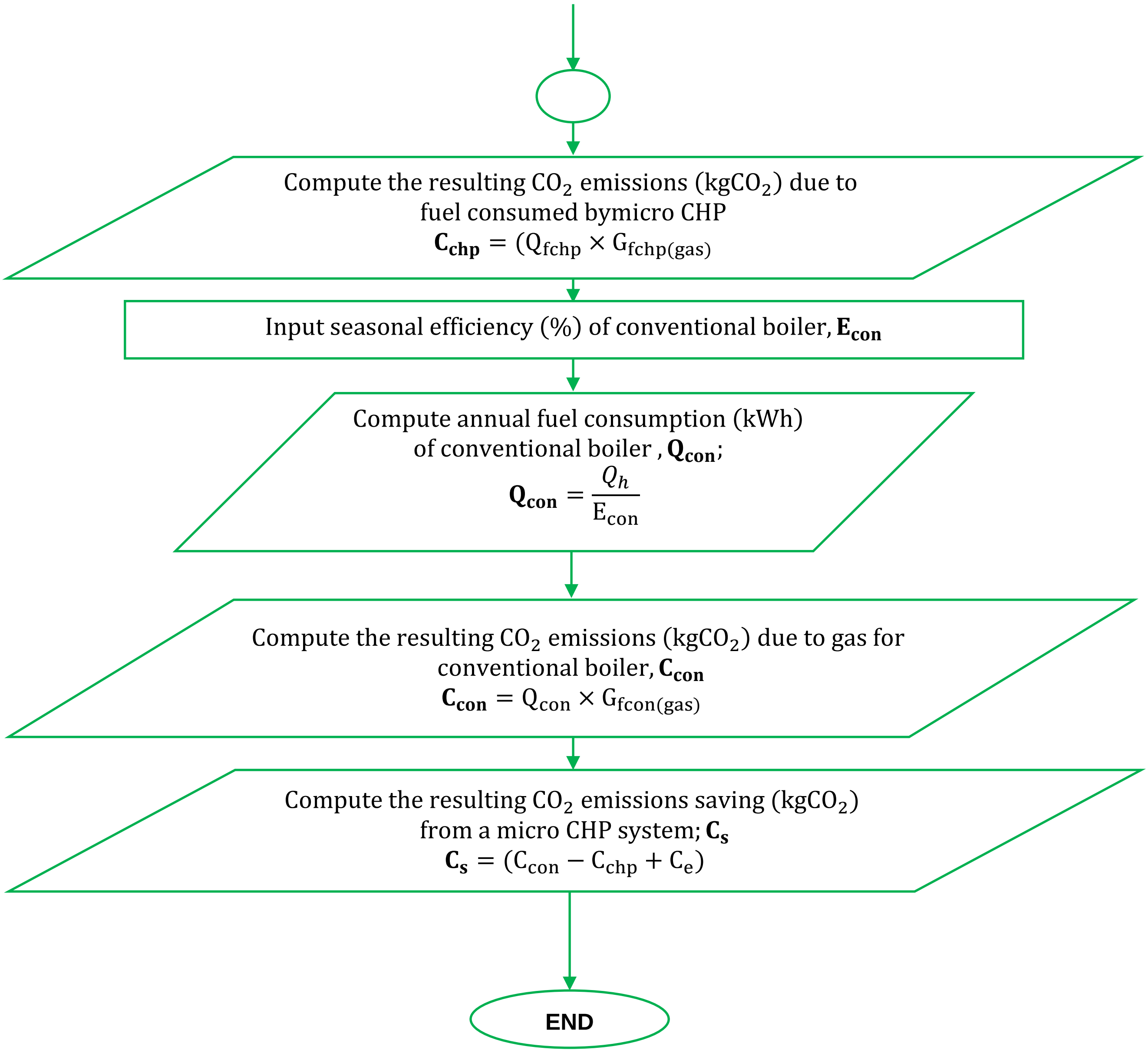



**Figure A-5b: Continuation of performance calculation method for Micro CHP**

**Figure A-5: (a) Performance calculation method for Micro CHP (b) Continuation of performance calculation method for Micro CHP**

## A6 Biomass Heating

Biomass is converted into a form that is manageable until it can be directly fed to the heat or power generation plant, thereby replacing fossil fuel and by extension reduction in $CO_2$ emissions (Building Regulation, 2005). The heat generated can be transported put to use for the ventilation and space heating requirements of buildings or an entire community (NRCan, 2002). As a result, applications can range from large-scale heating boilers to individual house room heaters to CHP generations. Principle of operation of Biomass heating system is well covered in RETScreen (2005).

Based on the current DSS, the performance calculation method used to estimate potential emissions savings from Biomass Heating System is shown in the flowchart in Figure A-6. As depicted, basic information such as the annual heating demand (kWh) for heating and hot water provision and the percentage of heating demand the Biomass heating system is to meet is supplied by the user of the DSS, from which the annual heating supplied (kWh) by the Biomass heating system is calculated. All the calculation parameters marked (′) in the flowchart indicates that the required values for the particular biomass fuel and the comparison case (e.g. gas, oil, waste heat etc.) should be obtained. The seasonal efficiency (%) of boiler plant as specified by the manufacturer is supplied by the user, from which the content of the calorie of the fuel input to the biomass heating plant can be estimated. Similarly, the seasonal efficiency (%) of the comparison heating plant as specified by the manufacturer is supplied by the user, from which the fuel input (kWh) to the comparison heating plant can also be estimated. The next steps in the flowchart are then followed, so that the overall emissions savings from Biomass heating systems can be estimated.

## A7 Efficient lighting (LEDs)

In commercial buildings, about 20-45% of energy consumption is from lighting (Carbon Trust, 2009). Significant amount of energy savings can be realized with a minimal capital investment on the energy saving lighting technology (e.g. high frequency lighting, LED lighting, low energy lighting).LED lighting can provide substantial energy savings. LEDs typically have a long lifetime and will need less frequent replacement than many other lighting types (Carbon Trust, 2012). The flow chart shown in Figures A-7a and A-7b give the performance calculation for energy and emissions savings when existing lighting systems are replaced with LEDs.

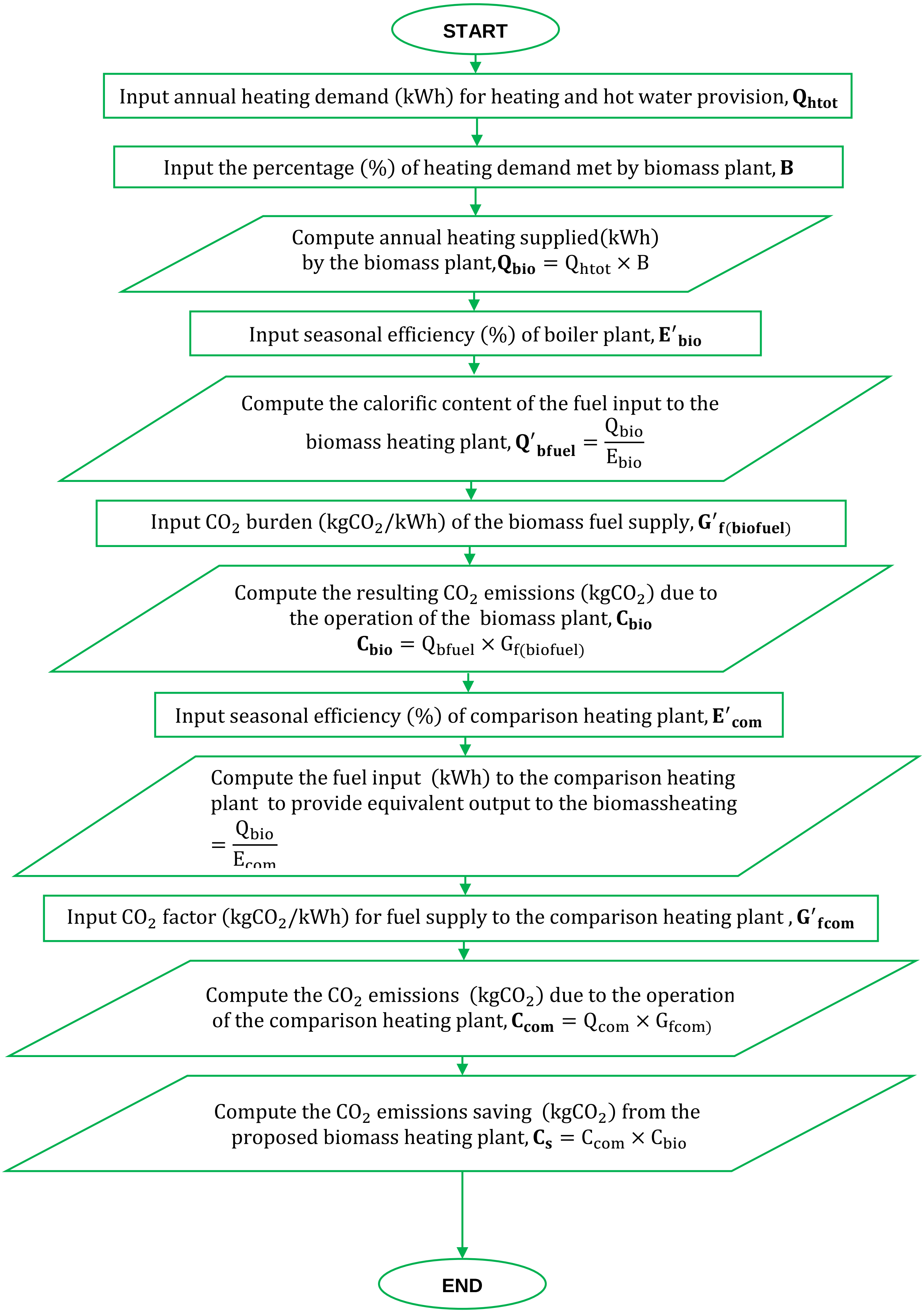



**Figure A-6: Performance calculation method for biomass heating plant**

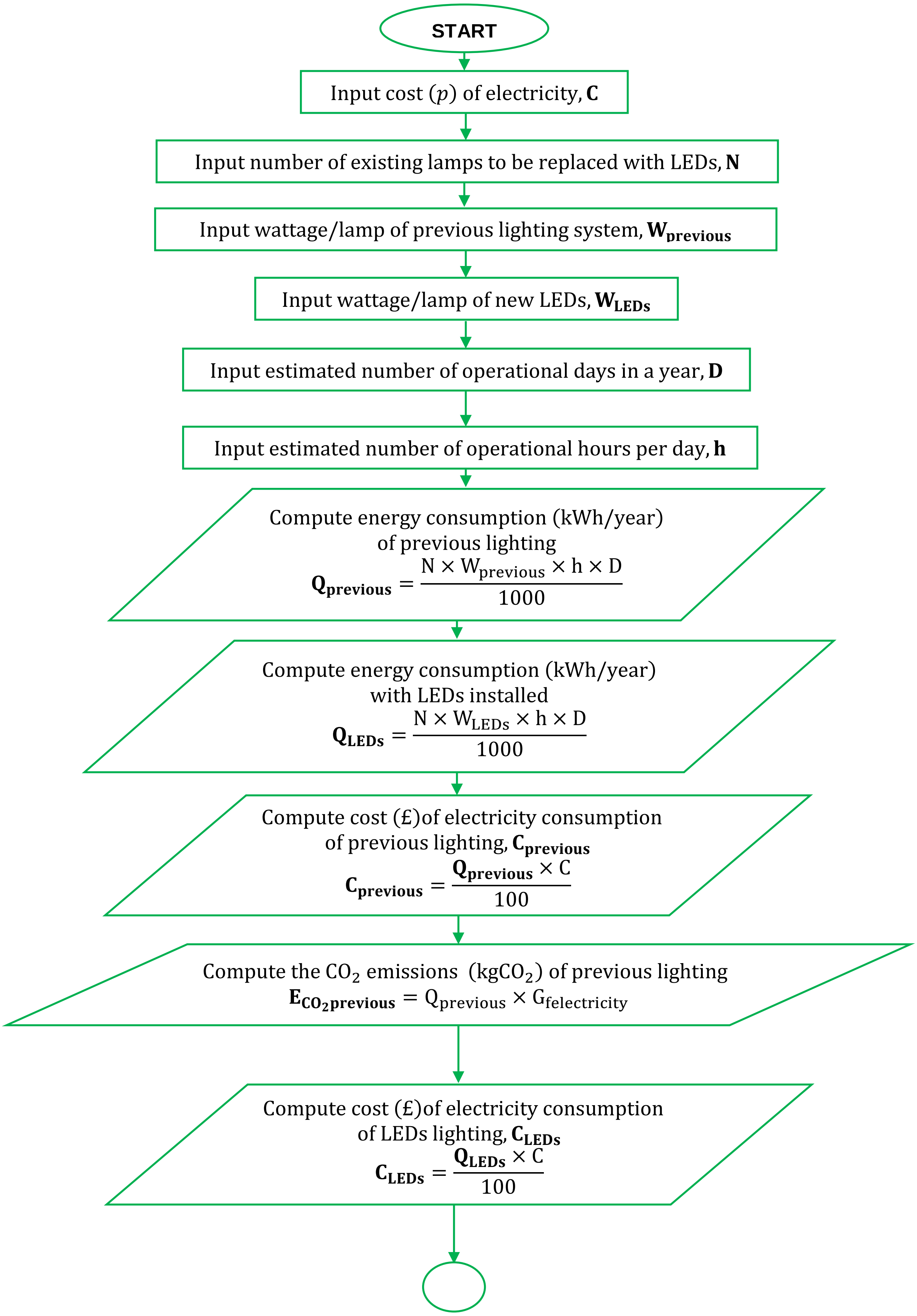



**Figure A-7a: Performance calculation method for LEDs**

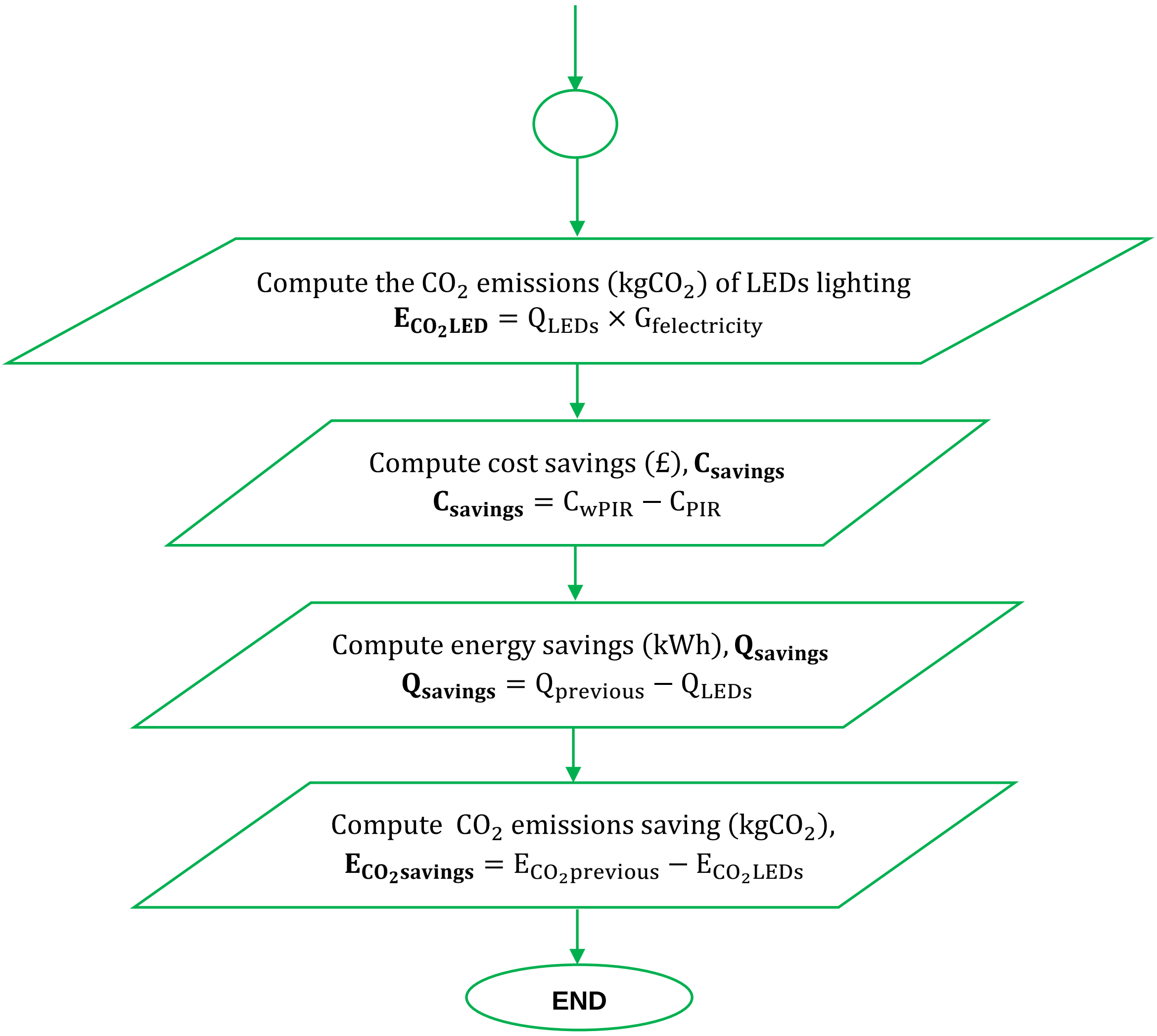



**Figure A-7b: Continuation of performance calculation method for LEDs**

**Figure A-7: (a) Performance calculation method for LEDs (b) Continuation of performance calculation method for LEDs**

## A8 Passive infrared (occupancy) sensor

Passive Infrared (PIR) sensors are microelectronic devices that measure infrared (IR) light radiating from objects within their spectrum. PIR sensor installations ensure that lighting only comes on when required, and most importantly that lighting is switched off when an area is vacated. High quality PIR sensors are a cost effective solution for commercial and domestic end users in reducing energy consumption and carbon footprints. Savings start as soon as the sensors are installed. The flow chart shown in Figures A-8a and A-8b shows the performance calculation for energy and emissions savings derived from the installations of PIR sensors.

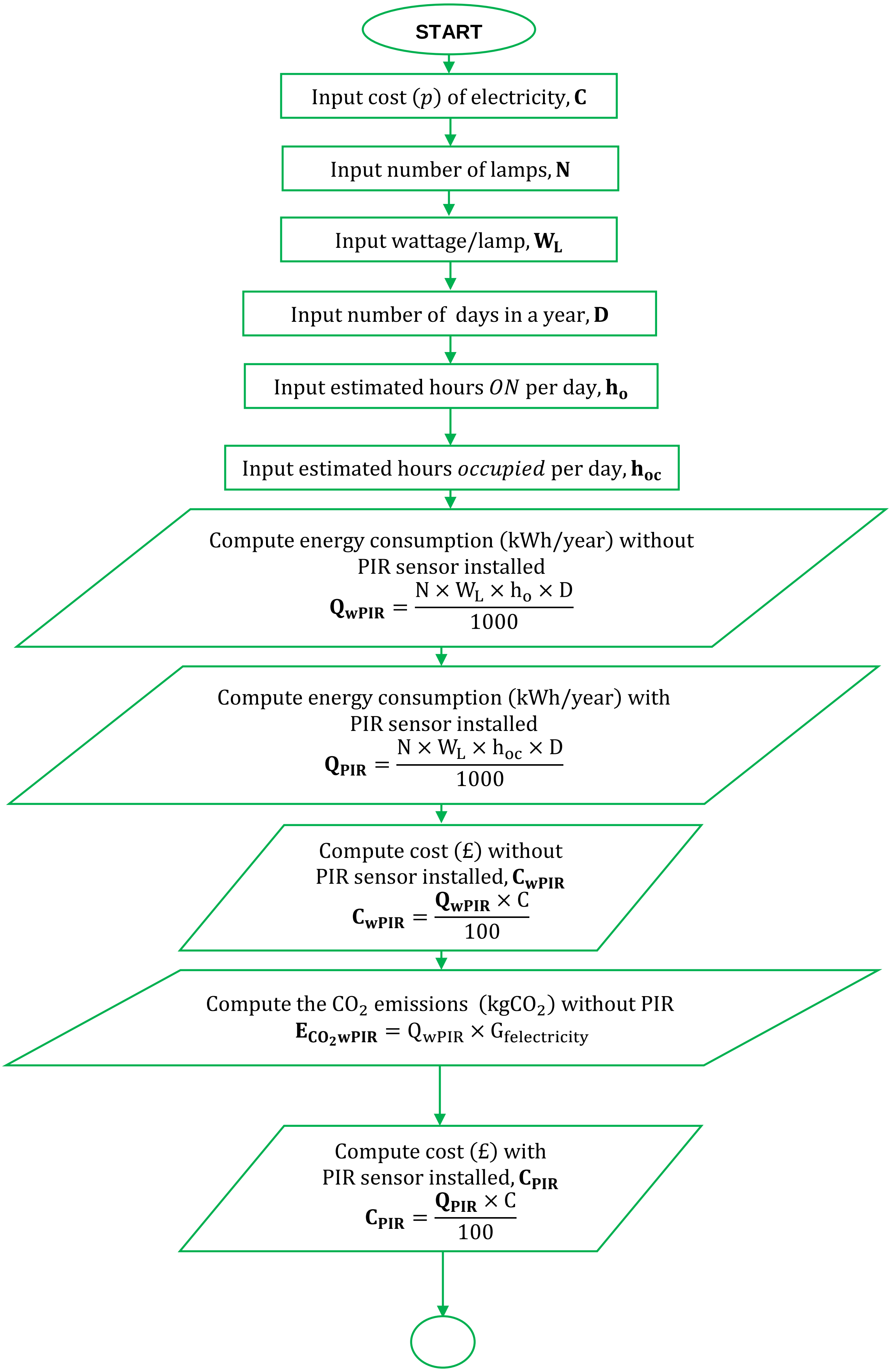



Figure A-8a: Performance calculation method for PIR

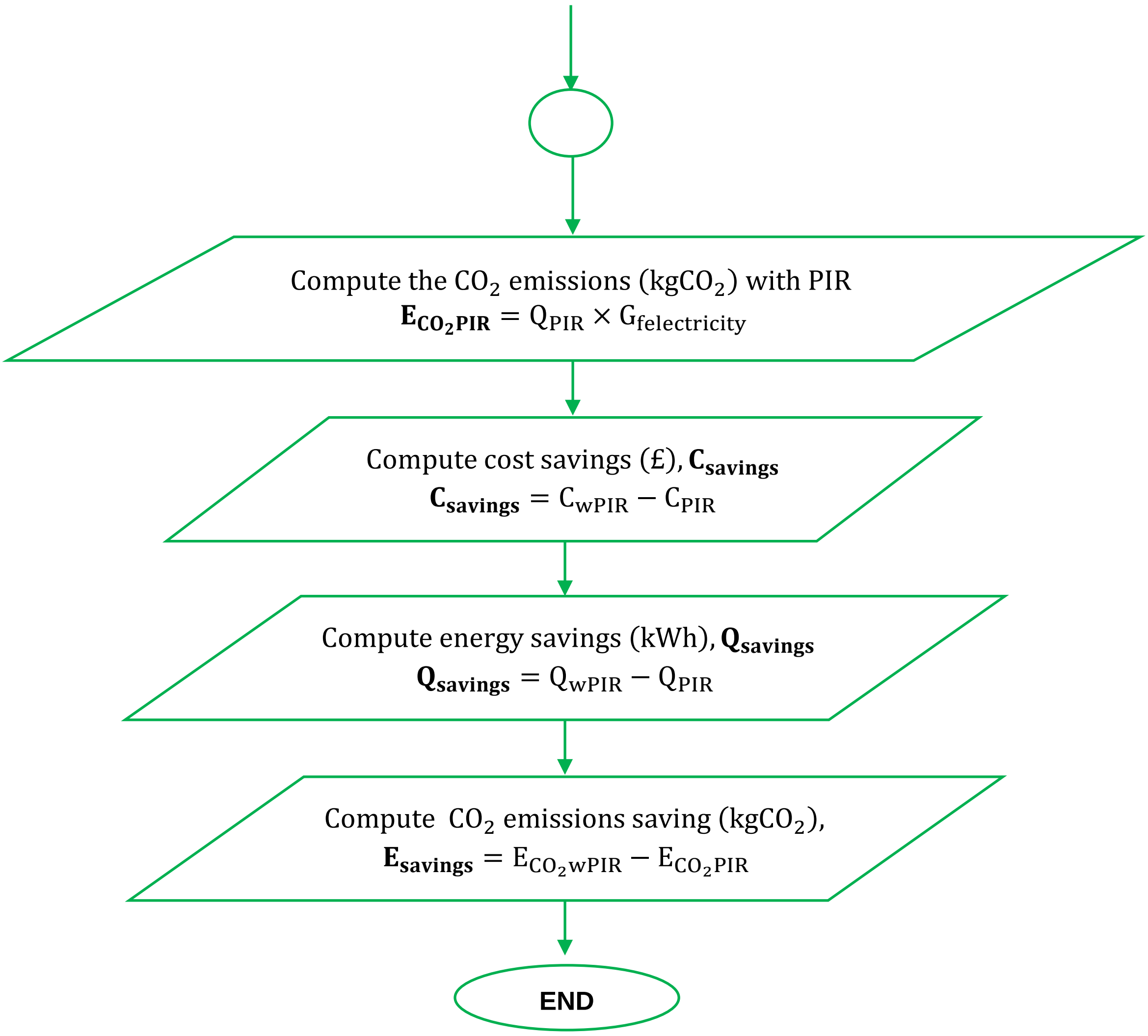



**Figure A-8b: Continuation of performance calculation method for PIR**

**Figure A-8: (a) Performance calculation method for PIR (b) Continuation of performance calculation method for PIR**

## A9 Potential energy savings from BEMS

BEMS allows the facilities to be centrally managed by controlling the energy-consuming equipment to reduce energy use while maintaining a comfortable environment. BEMS acts as the "brain of the building" and the vital elements of its installation are time and adequate temperature control of HVAC systems, hot water plant, alarm monitoring, compensation of room temperature against outside temperature and sometime lighting (Energy Institute, 2011). BEMS might be installed in a building that has no existing system, replace obsolete pneumatic controls or optimise an existing direct digital control system, but most importantly, the energy savings depend on how inefficiently the building was operating before installations (Kamm, 2007).

## A10 Theory of voltage optimisation

Voltage management can have a substantial impact on energy consumption because the overall power transmission mechanism by the National Grid is supplied at a voltage that is higher than is generally required. As illustrated in Figure A-9, the UK's nominal voltage is 230V but the average voltage delivered is 242V (Carbon Trust, 2011; Powerstar, 2010). This surge in voltage implies that energy usage is not only higher but it can also reduce the lifespan of equipment. It therefore follows that voltage optimisation can increase the life span of equipment by reducing the voltage of the electricity supplied to equipment. This will in turn minimise consumption while maintaining the operating conditions specified by the manufacturer of equipment (Carbon Trust, 2011).

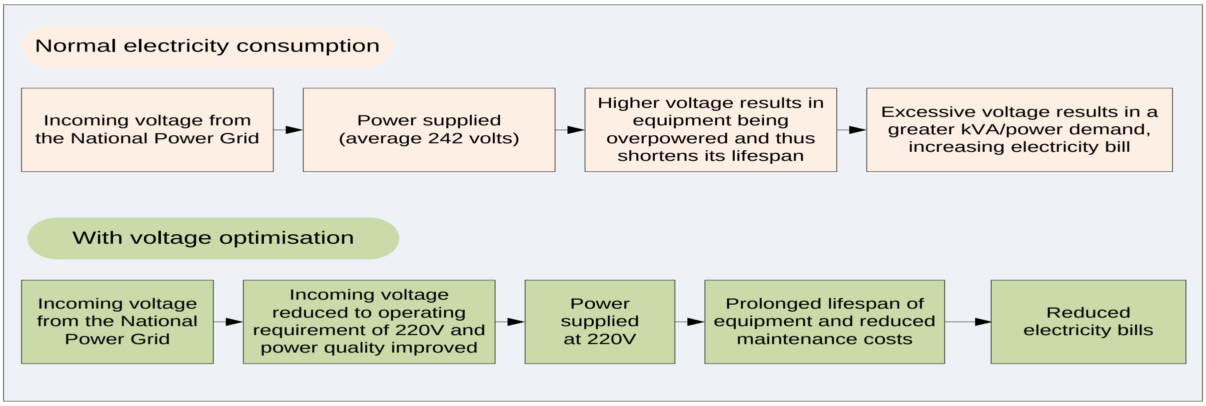



**Figure A-9: Voltage optimisation scheme**

The relationship between electrical power consumption $(W)$ and voltage $(V)$ for a constant resistance $(R)$, given by $P = \frac{V^2}{R}$ is the simple theory upon which the potential energy saving from the implementation of voltage optimisation is based. This implies that for a simple load with linear resistance, the power consumed is directly proportional to the square of voltage of the supplied electricity. It therefore follows that the higher the supply voltage, the higher the resulting energy consumption. Equipment that exhibits such electrical characteristic is termed ***"voltage dependent"***, so that, with a simple linear resistive load, a 1% increase in supply voltage will cause a 2% increase in power demand. However, there are electrical devices that are not simple linear resistive (i.e. their power demands, within their designed range of operation), are not dependent on the voltage supplied electricity. Such loads are termed ***"voltage independent"***. Therefore, to effectively understand how much energy and cost savings associated with voltage optimisation, it is important to identify what proportion of the electrical loads are depends on voltage, what proportion are not dependent on voltage and the number of hours of operation of each load type.

Energy savings from the implementation of voltage optimisation completely depends on the building's loads and therefore a full site survey is essential. Hence, the evaluation of the potential energy savings from voltage optimisation involves certain survey steps, including (Carbon Trust, 2011): voltage and power levels measurements at the incoming supply point(s); voltage drops measurements across the site; determination of the proportion of energy consumption that depends on voltage; identification of any loads that are critical; calculation of potential savings in energy; and decision on the power rating of voltage management equipment. Different energy consumption savings of between 12–15% are widely reported in literatures and voltage optimisation equipment manufacturers (Powerstar, 2010), and in some cases, energy savings of up to 26.1% have been recorded (Simmonds, 2011).

## A11 Energy awareness campaign

The estimation of potential emissions savings from activities such as driving energy awareness campaigns is difficult to predict or measured with impeccable precisions. As such, the values used in the flowchart in Figure A-10 within the overall DSS framework is representative savings derived from such efforts with other non-domestic buildings across the UK. For instance, the UK NHS sustainable development unit reported 3% emissions reduction each, from both gas and electricity against the baseline energy consumption of small/medium acute Trust (NHS, 2010).

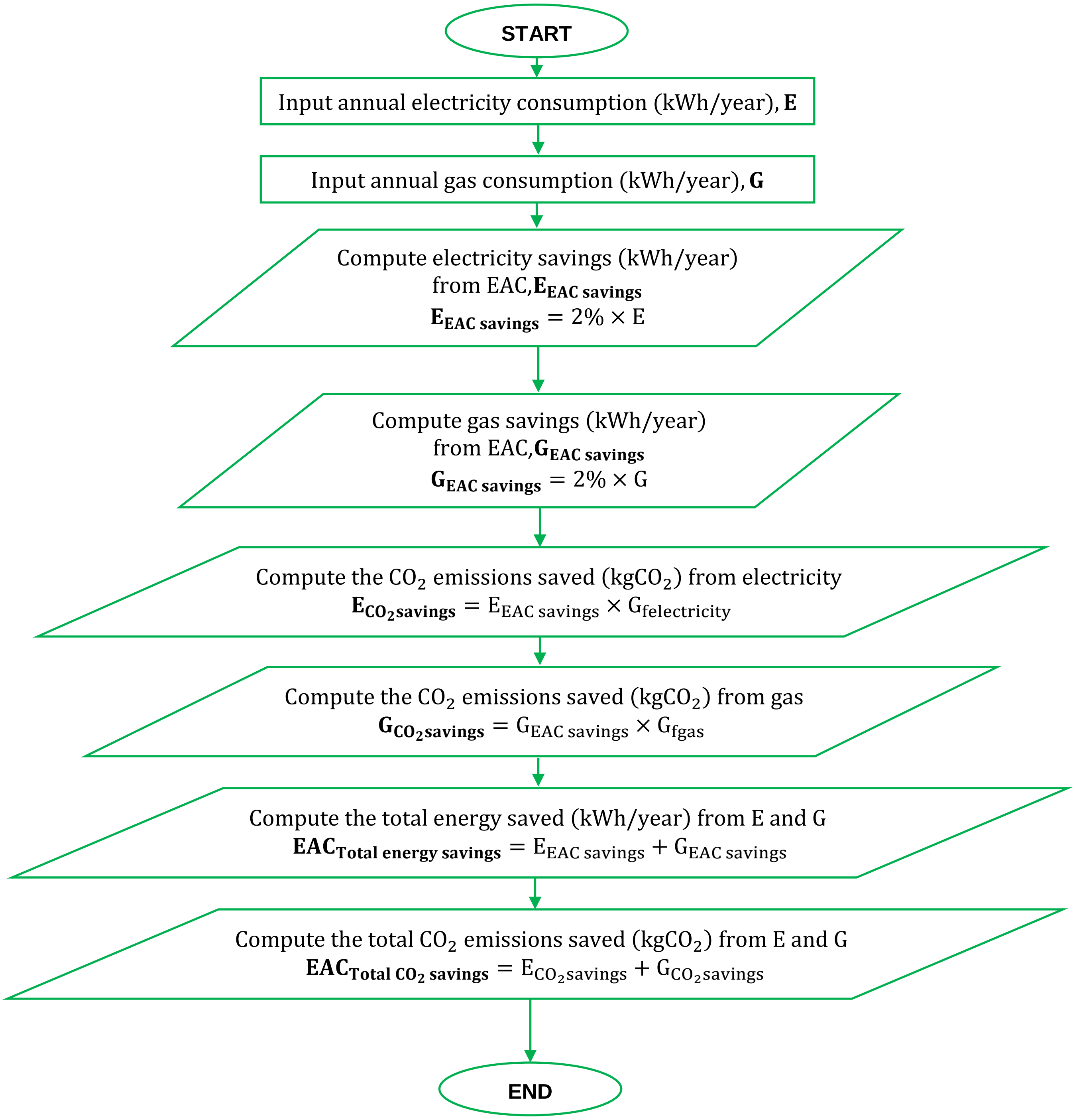



**Figure A-10: Performance calculation method for Energy Awareness Campaign (EAC)**

**Appendix B: Proposed Interview questions for the evaluation/validation of the DSS**

**Proposed name of the DSS: Computed Optimal Building Retrofit Advice (COBRA)**

The purpose is to collect opinion to measure the utility of the DSS in order to establish whether it addresses the need of the targeted users. The DSS in intended to support different types of user including: investors, property managers, energy managers, sustainability managers, environmentalists and energy policy makers, in making decisions about building energy retrofit intervention options.

The following general and more role-specific questions have been formulated:

## I. General questions

1. How do you currently evaluate costs and benefits regarding the implementation of building energy retrofit intervention options for emissions reduction?
2. How well do you think the DSS will assist decision makers in the formulation and ranking of building energy retrofit intervention options?
3. How well do you think the DSS represents the concepts being modelled and how suitable is it for the purpose it was designed for?
4. How well does the structure and layout of the DSS enable decision makers to evaluate and compare building energy retrofit intervention options in terms of their operational performance and environmental merits?
5. Were you aware that there is a problem with the standard way of ranking measures when they make a profit? In your opinion, how serious is the flaw in the existing method for ranking the cost-effectiveness of such negative cost measures?
6. To what extent does this flaw influence your view about prioritising negative cost measures and suitable do you find the alternative ranking method proposed?
7. How sound do you consider the results derived by the DSS and how well would it assist in aiding your decisions regarding investments in building energy retrofit options?
8. What do you find most beneficial and effective about the DSS and why?
9. What do you dislike and/or find most restrictive or ineffective about the DSS and why?
10. What specific changes and/or modifications would you suggest regarding the utilisation of the DSS?

## II. Specific questions

**A. Investors/property managers/Energy managers/Sustainability managers**

1. Embodied emissions are those related to the construction of a piece of equipment. Future regulations may require such emissions to be considered by the installer in attempts to achieve the best-value retrofit plan. How valuable do you find the DSS to include an option to include such calculations?
2. To what extent do you think the knowledge of embodied emissions estimates of a building energy retrofit option will affect your decisions about choice of manufacturers?

**B. Energy policy makers**

1. Repeat question 1 from II A above.
2. What ways do you think the DSS output will assist in shaping and formulating improved policies targeting manufacturers of building energy retrofit options?
3. To what extent do you think the overall output of the DSS can facilitate improvement initiatives with a view to realising emissions reduction?
4. What do you consider to be some of the fundamental limitation of building energy policies in terms of consideration of whole lifecycle emissions of the building?

**C. Environmentalists**

1. Repeat question 1 from II A above.
2. How do you think the use of MACCs to integrate embodied and operational emissions with cost will facilitate a holistic view of emissions abatement options?
3. In what way do you think the concepts modelled in the DSS will improve designers' choices of materials and environmental design procedures when specifying building energy retrofit options?

## Appendix C: Detailed transcripts of the DSS evaluation

### C1 Context and potential users

As one of the Subjects puts it:

"Yeah…it comes across fairly contextual. It is readily obvious that this is a decision-aid tool based on techno-commercial evaluation framework for emissions reduction in buildings. Based on the presentation and demonstration of the software, I find the tool comprehensive and it addresses a critical field of application in the era of climate change". [P3]

Another Subject described the DSS, from a first impression perspective, regarding its potential users:

"I think it's a great idea-bringing all those things together but I don't pretend to understand what you have lived and spent three years on, but I think it is a very useful way of making decisions for energy managers and related professionals."[E2]

The submissions above confirm the supposed domain and context upon which the DSS was developed. It is equally important to ascertain views of the Subjects as to whether the DSS targets the right audience that will be its potential users. A subject has this to say:

"Well…yeah…good idea. It could be a very relevant tool for advisors. Of course. This is a tool for energy and environment professionals and not ordinary users."[P1]

Three other Subjects said:

"Yes, I think this could be particularly interesting for policy makers, because they are not thinking about who pays less. They are looking at an overall level of thinking, actually where is the best return for investment that is going to reduce carbon."[C1]

"This is quite a useful tool for energy professionals such as energy managers. It will aid their decision making when it comes to making choices about building energy efficiency strategies. Very good idea."[S1]

"…It will also find application in public procurement where, for example, you organise a call for tender and it could part of the overall requirement to report embodied emissions." [E4]

"…But I think considerations of embodied emissions are starting to creep in for procurement managers and some of the more forward thinking organisations are starting to include this. It will be a quite useful tool for procurement and supply chain management."[C1]

An important aspect of the evaluation process was to measure the utility of the DSS in order to establish whether it addresses the need of the targeted users. The DSS is intended to support different types of users (Table 6-1) in making decisions about building energy retrofit intervention options. It is therefore important to gain an understanding of how they currently evaluate costs and associated benefits regarding building retrofit advice. This will establish whether the current DSS will be of value to them or not. Against this backdrop, some of the Subjects have this to say:

"Currently we don't enter into such detailed analysis of options because these evaluations are normally done by external experts whom we contract such functions to perform impact assessment for retrofit options…We don't use these types of tools directly but we trust the expertise of the company that works for us. However, having this kind of system as an in-house tool for prior analysis will be quite useful." [P1]

Another Subject mentioned:

"The main way we assess is mainly on financial payback period. Payback period in terms of return on investment. So, majority of our large projects are from DMU finance…so it comes in internally and they look for payback period of roughly…well its mainly 4 years for all investments for energy savings. That's shows the guide that they work with but they will look at business cases on a real basis…so if it looks good (i.e. the return on investment looks good), even though it is slightly greater than 4-5 years, they will still fund it. So it is done on a case by case basis using manual calculations." [S1]

Two other Subjects also shared their views. They stated:

"…so we would basically look at key measures of payback period, net present value, internal rate of return. And we look at carbon savings for each measure. So we have in the past used MACCs as a way of talking to our different customers about different options… at the moment what we have moved away from doing is actually talking about MACC because we are finding that it's quite hard for them to understand."[C1]

"Individual economic and environmental methodologies and analysis are used. This is done without the use of any tool or DSS which coherently brings the environmental and economic considerations together."[P2]

## C2 Process measures

Another Subject put it in the following way:

"I think the new lay out of the Pareto chart you adopted (I like the way it addresses that problem). I think the …A drawback with it is that it doesn't clearly show you when the cut-off point is between positive and negative measure are. The Pareto approach ranks them but it is not clear where they become cost rather than return."[C1]

Two other Subjects expressed their views:

"The results are presented in MACC which is very useful. It enables comparative measurements of a particular intervention option against others" [P2]

"I like the graphical illustration of the embodied emissions estimates of the retrofit options. Quite helpful."[E1]

The statements above clearly indicate that the subjects appreciate and understand the outputs generated by the DSS. This is important because the ability of a DSS to generate outputs in a clear and understandable manner for its targeted audience is an important feature suggesting the DSS has a clear and understandable format. This can, in turn, fast track an effective decision making by the decision maker. Overall, the Subjects found the **format of output** of the DSS understandable and quite satisfactory. Figure D-11 in Appendix D shows a sample decision output from the DSS.

It is important to state however that one subject is of the opinion that the MACC is conceptually difficult to understand, especially at household level and that he has decided not to use it as a decision-making tool. This suggests that the **format of the output** of the current DSS, which takes the form of MACC, might pose some difficulties to some clients. He lamented:

"…So for most recent projects for example, we decided not to mention it (i.e. MACC) and how we basically present the options is looking at the overall cost savings/year which was the contribution therefore to their targets. We look at the capital investment and the annual return and then the payback period. What we intend to do is to rank the measures purely on simple payback period."[C1]

However, the same subject stated that despite the conceptual difficulty of MACC, it still finds applications and wider use in the policy analysis domain. He stated:

"As mentioned earlier, the MACC is conceptually difficult to understand and I think the fact that there is a flaw makes it…Further emphasises it a complex concept and I think it definitely have value and that's where it comes back to policy-maker point-of-view where you are dealing with experts who are going to be looking at the detailed overall environmental effects."[C1]

Furthermore, the subject further highlighted the use of the MACC concept concerning how effective it is a policy instrument which combines the unique attributes of seeing the relationship between financial cost and emissions savings:

"I think the consideration of carbon savings would probably come and they will start moving towards those things especially as the cost of the options begins to reduce due to increase in demand and so they may well start becoming positive and also as energy prices go up. So in any way, at that line in the MACC where negative is going to positive, I think it is going to be moving effectively to the right. So the more this measures that are currently positive will start moving into the negative." [C1]

Other essential aspects of the process measures pertaining to the DSS are volume of output; amount of data used and level of analysis involved. To further ascertain that the DSS satisfy the aforementioned criteria, statements from the Subjects were scrutinised with the view to draw inference from them. Some of the Subjects had these to say:

"The tool demonstrates the use of quite a considerable amount of data especially the input-output data from a multi-region perspective, for the embodied emissions calculations. I mean…It is not entirely precise but it does give a rough estimate of the embodied emissions attributed to the option because the approach covers a wider systems boundary."[P3]

"I can see that a great deal of effort was put into the development of the tool. It made use of a great deal of data. Very sophisticated. The level of analysis is detailed and uses well established engineering concepts. Very good."[P1]

"It looks like the tool itself calculates the engineering solution which is quite useful; so…And it operates in form of a model as against going to site looking at what will fit…" [E4]

"The DSS output gives a clear indication of the need and benefits of considering embodied emissions in buildings and how the intervention options are sequenced and ranked according to the constraints. Such a tool can be considered to be state-of-the-art in this field." [P2]

The import of the expressions above clearly indicates that all the Subjects were quite satisfied with the functionalities of the DSS based on the aforementioned criteria. As shown, the statement by the Subject [P3] demonstrates the use of significantly high **amount of data** which in turn yield required **volume of output** to aid decisions. This confirms the robustness of the DSS. The declaration by Subject [P1] demonstrates the fact that a **thorough level of analysis** was involved in the overall development of the DSS. Subjects [E4] and [P2] also share this notion as indicated in their statements above.

Performance and technical capability are important attributes of a DSS in that it measures its ability to carry out detailed calculations based on correct algorithms to produce results that can aid logical decisions. It gives an indication of the response of the DSS when certain decision parameters are varied and shows the ability of the DSS to consistently provide similar pattern of output under given conditions. It is therefore important to ascertain the views of the Subjects on this essential attribute of the DSS. One of the Subjects said:

"It logically models the environmental and economic considerations based on state-of-the-art methodologies. The concepts have been well implemented thereby ensuring that the purpose of implementing such a DSS is achieved."[P2]

It can easily be deduced from the above statement that the Subject acknowledges the technical capability of the DSS in that it employed state-of-the-art methodologies to determine the financial costs and operational performance of retrofit options and provide an indication of their environmental merit based on the embodied emissions results. The same Subject also gave a positive comment on the unique approach taken to the integration of the measures of financial cost and both embodied and operational emissions into a single decision-making framework. He said:

"The integration of the underlying methodologies and the manner in which the ranking of the results are performed in order to mitigate the limitation with MACC are very useful. The implementation of the whole framework within a tool is also very beneficial."[P2]

He further added:

"The DSS is a very practical and provides an easy way to implement the ranking options for building energy retrofit. It also provides a holistic approach of measuring the important parameters which decision makers look out for."[P2]

The above statements clearly demonstrates the Subject acknowledges the technical capability of the DSS to rank building energy retrofit options based on a defined criteria regarding emissions reduction in buildings. Another Subject expressed satisfaction about the fact that the DSS takes embodied emissions into consideration and the methodology adopted to calculate it:

"…I also like the concept of including embodied emissions. It is very interesting and I think it is going to become more relevant as the in-use emissions falls as we basically deal with the efficiency of the existing building stock."[C1]

Subjects [S1] and [E2] shared similar views:

"Well… I think it's the fact that it includes embodied emissions. As I said, it is something that we are looking at in DMU (embodied emissions)."[S1]

"Yeah….The separate calculation platforms for embodied emissions to compare emissions from UK products with those imported is particularly interesting. It allows me to compare emissions from both sides. I find it particularly useful."[E2]

Another Subject commented on the ability of the DSS to reveal the effects of varying parameters such as cost of energy (electricity and gas):

"I like the fact that the DSS allows you to input different gas and electricity prices to carry out different calculations based on different scenarios when selecting retrofit options. The use of net present value concept is equally very good."[E1]

Of all the Subjects interviewed, none of them was aware of the fundamental flaw regarding the ranking of negative cost measures within a MACC framework and they all acknowledged that it is indeed a serious problem when it comes to decision making about energy efficiency in buildings. A Subject expressed his view on the ranking anomaly:

"No. Not at all. I was not aware of such detail problem. It will be more useful if the message is passed across to companies or research centres that are big users of the MACC, for example McKinsey to help them refine their existing research work based on MACC."[P1]

Four other Subjects expressed their unawareness of the ranking problem with negative cost measures:

"No. I wasn't aware of that. No. Yeah…It seems to me quite a considerable flaw… And it will be more of flaw if it was something we use in terms of, you know…Defining what we invest in and how much we invest. So in going forward, we will be aware there is that flaw. So identifying this and suggesting a way to rectify it is quite a considerable achievement as it will impact on my choices of options."[S1]

"So I think I hadn't explicitly thought about that- the angle which your research has highlighted. So that's new for me. I think it comes back to this questions of why I have chosen not to talk about it (MACC)… talking about the question of conveying the meaning because what we want and trying to do is to engage people, to drive changes and see how people are buying equipment and all that."[C1]

"Issues with negative cost abatement measures are limiting issues in the use of MACC. This problem has not been well addressed in extant literature." [P2]

"Given that the MACC is used as a policy instrument for climate change mitigation strategies, the ranking error is quite significant and must be addressed. It will be useful if this kind of findings is expressly communicated to the policy makers so they can be aware of this problem at a macro level."[P3]

An inference that could be drawn from the above statement is that all the Subjects recognise the negative impact of the misrepresentation of the ranking of negative cost measures in MACCs and all of them would like to see a solution to the problem. To this end, some subjects commented on the use of Pareto ranking to address the problem in the DSS. A Subject said:

"It is my opinion that the use of Pareto optimization as undertaken in this study helps to address this flaw in MACC.."[P2]

Two other Subjects added:

"I think the new lay out of the Pareto chart you adopted (I like the way it addresses that problem)."[C1]

"I think the use of the Pareto method to correct the flaw in MACC is excellent. However, on the Pareto plot, that choice of representing information is missing in that respect (i.e. showing cost/tonne of $CO_2$ and $CO_2$ saved as in the case of classical MACCs). It is just one line based on a computer model having optimised it for you."[E4]

## Appendix D: Screenshots of the DSS

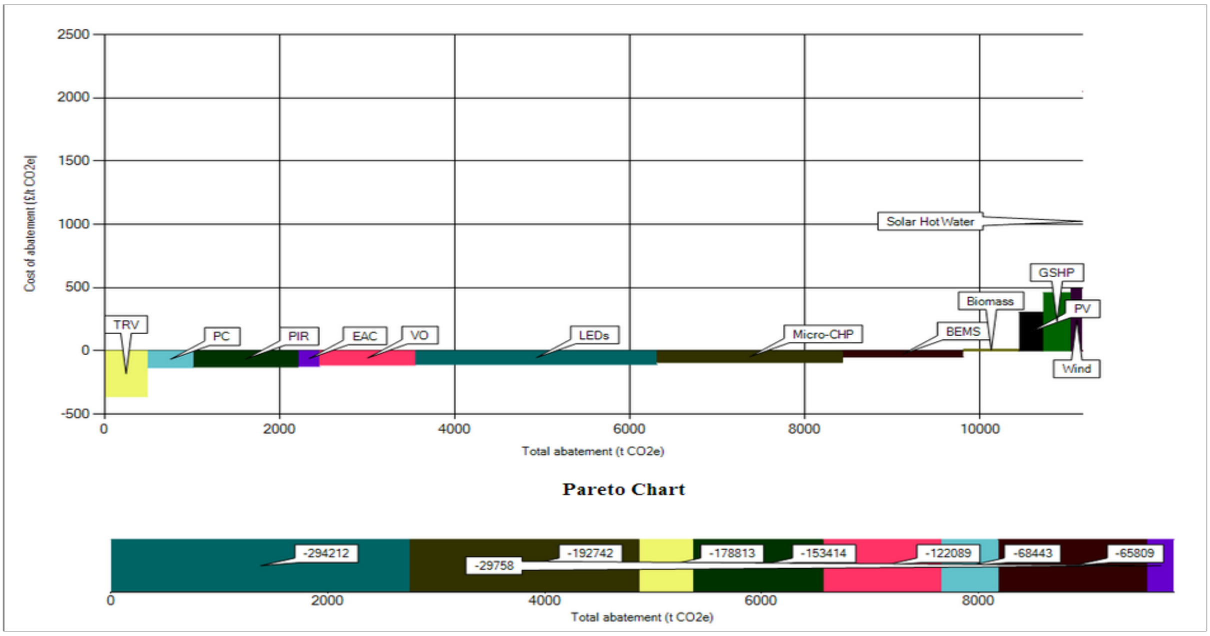



**Figure D-11: Sample output from the DSS**

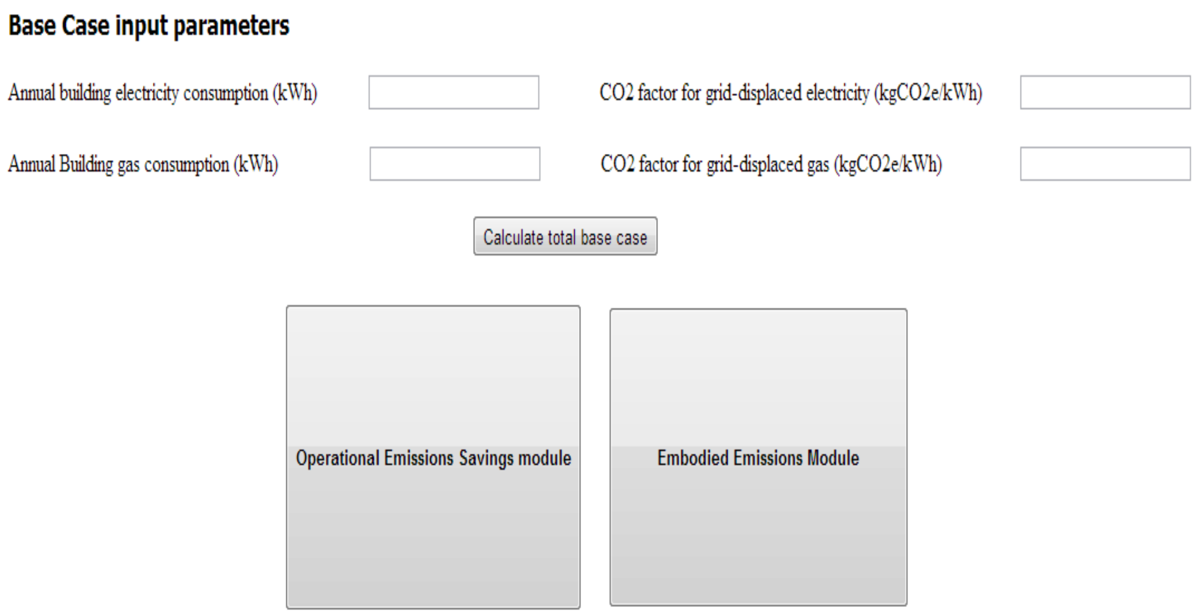
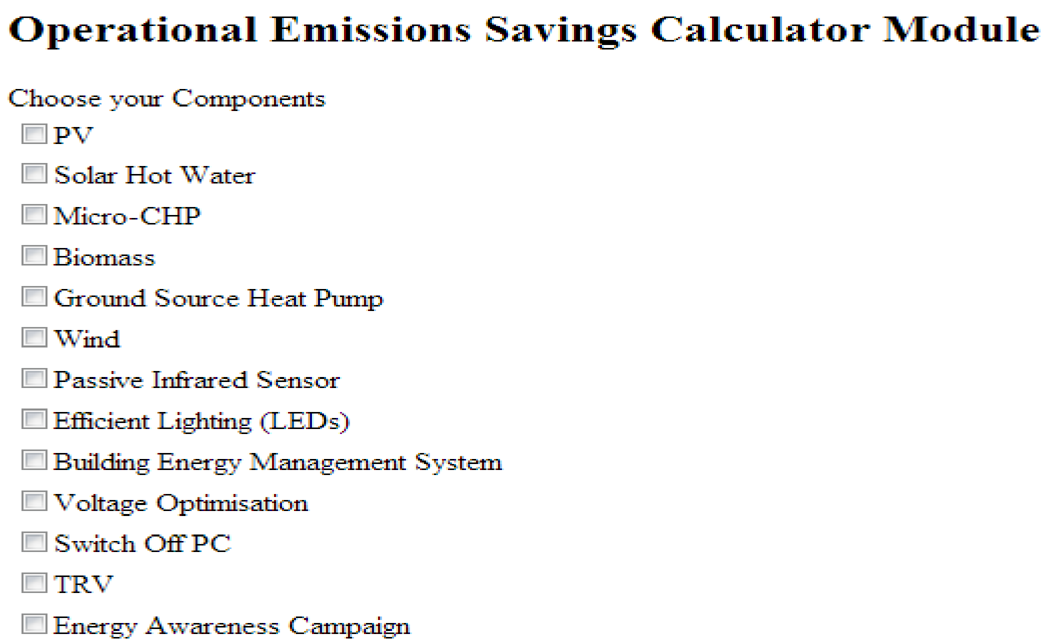



**Figure D-12: User interface one**

[This figure illustrates the first page the users will encounter. It is the interface that represents the module where the baseline energy (gas and electricity) consumption of the building is estimated after the user supply the necessary input parameters]



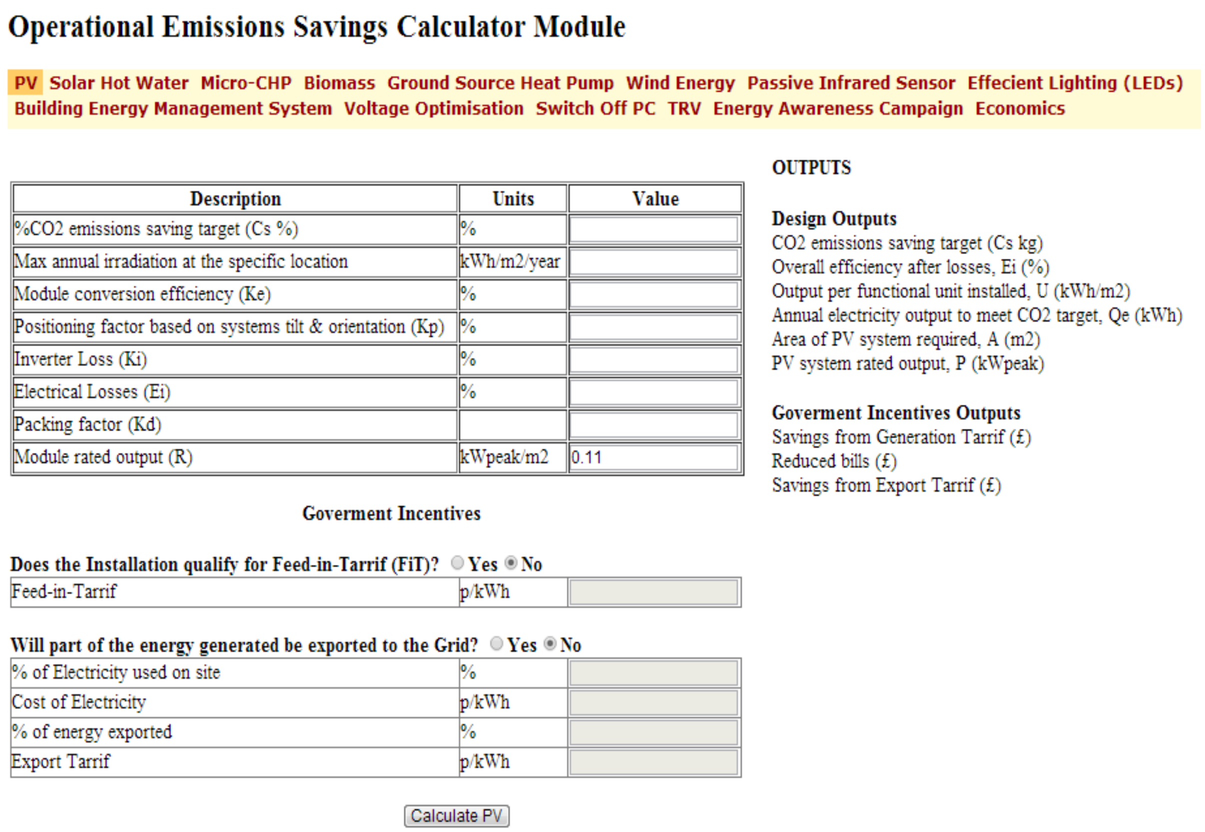
# Operational Emissions Savings Calculator Module

Choose your Components

- ☐ PV
- ☐ Solar Hot Water
- ☐ Micro-CHP
- ☐ Biomass
- ☐ Ground Source Heat Pump
- ☐ Wind
- ☐ Passive Infrared Sensor
- ☐ Efficient Lighting (LEDs)
- ☐ Building Energy Management System
- ☐ Voltage Optimisation
- ☐ Switch Off PC
- ☐ TRV
- ☐ Energy Awareness Campaign

**Figure D-13: User interface two**

[This figure illustrates the next page of the DSS which gives the users the privilege to select the relevant options relevant for their case building before proceeding to the performance calculation panel where necessary input parameters are supplied to produce the potential operational emissions saving and associated benefits from the selected option]



## Operational Emissions Savings Calculator Module

PV Solar Hot Water Micro-CHP Biomass Ground Source Heat Pump Wind Energy Passive Infrared Sensor Effecient Lighting (LEDs) Building Energy Management System Voltage Optimisation Switch Off PC TRV Energy Awareness Campaign Economics

| Description | Units | Value |
|---|---|---|
| %CO2 emissions saving target (Cs %) | % | |
| Max annual irradiation at the specific location | kWh/m2/year | |
| Module conversion efficiency (Ke) | % | |
| Positioning factor based on systems tilt & orientation (Kp) | % | |
| Inverter Loss (Ki) | % | |
| Electrical Losses (Ei) | % | |
| Packing factor (Kd) | | |
| Module rated output (R) | kWpeak/m2 | 0.11 |

**Goverment Incentives**

**Does the Installation qualify for Feed-in-Tarrif (FiT)?** ○ Yes ◉ No

| | | |
|---|---|---|
| Feed-in-Tarrif | p/kWh | |

**Will part of the energy generated be exported to the Grid?** ○ Yes ◉ No

| | | |
|---|---|---|
| % of Electricity used on site | % | |
| Cost of Electricity | p/kWh | |
| % of energy exported | % | |
| Export Tarrif | p/kWh | |

Calculate PV

**OUTPUTS**

**Design Outputs**

CO2 emissions saving target (Cs kg)
Overall efficiency after losses, Ei (%)
Output per functional unit installed, U (kWh/m2)
Annual electricity output to meet CO2 target, Qe (kWh)
Area of PV system required, A (m2)
PV system rated output, P (kWpeak)

**Goverment Incentives Outputs**

Savings from Generation Tarrif (£)
Reduced bills (£)
Savings from Export Tarrif (£)

**Figure D-14: User interface three**

[This figure illustrates the interface of the DSS regarding the panel where individual performance calculations are carried out based on inputs from the user. As indicated, the user selects the appropriate technology and the DSS generates the results after necessary data are input into the system. The case illustrated here is that of the performance calculation method for a PV system and the associated panel for evaluating the benefits that may accrue from feed-in-tariff.]

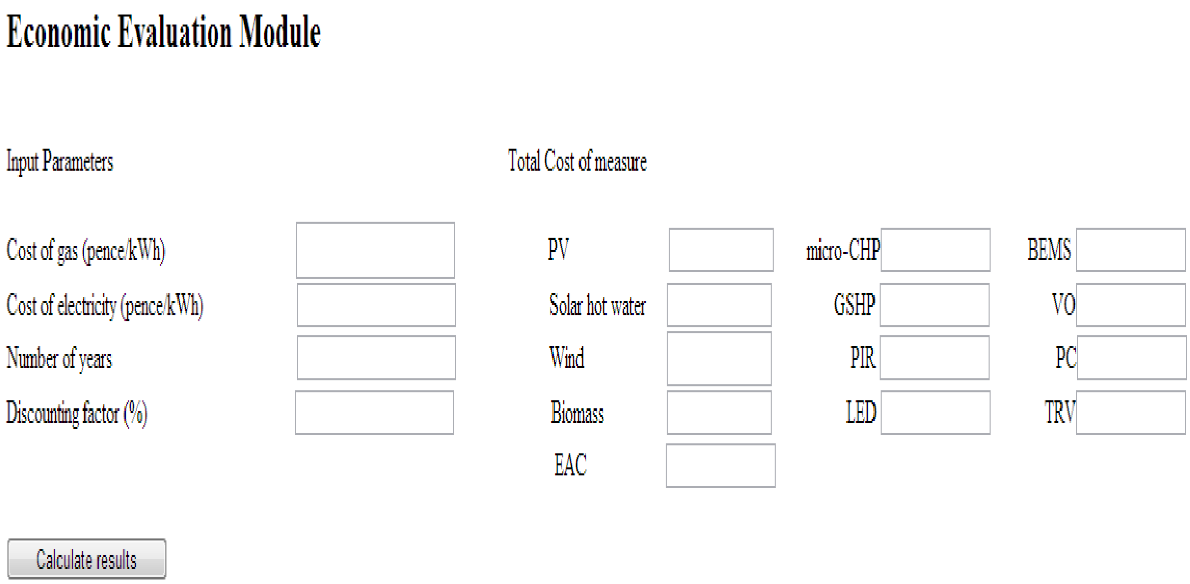
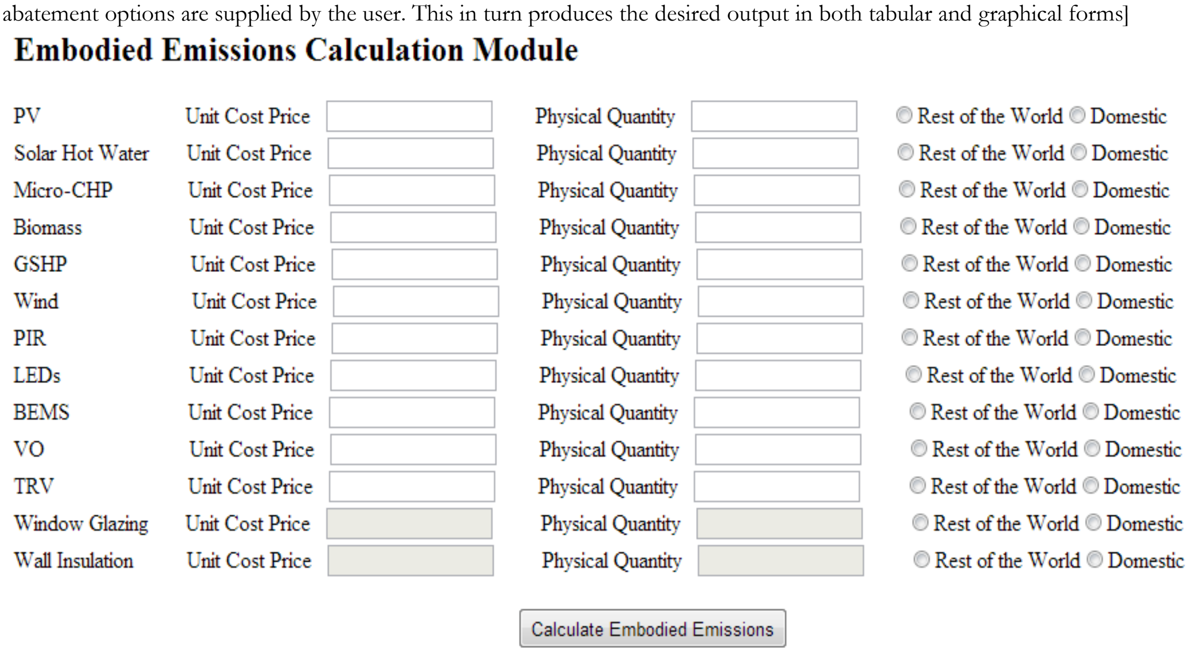



**Figure D-15: User interface four**

[This is the interface that represents the economic module of the DSS where parameters such as cost of energy (gas and electricity, number of years considered, discount factor and the individual capital and implementation costs of the selected abatement options are supplied by the user. This in turn produces the desired output in both tabular and graphical forms]




**FigureD-16: User interface five**

[This is the interface that represents the embodied emissions calculation module of the DSS where parameters such as unit cost price of the particular physical quantity (e.g. £/m² for the case of a PV system) and the actual numerical value of the physical quantity (e.g. 400m² of roof top area) are supplied by the user. This in turn produces the final demand in cost equivalent from where the user can select location of manufacture (i.e. whether the product is produced domestically or imported from the rest-of-the-world. From which the final outputs are presented in both tabular and graphical formats]

**Appendix E: Awards, recognition and scholarly activities that stems from this research**

- Reviewer- Industrial Engineering and Management (February, 2014)
- Invited to contribute a chapter to a book entitled: Future City Architecture for Optimal Living. Published by Springer and jointly edited with Professor Panos M. Pardalos, University of Florida, USA. (November, 2013)
- Nominee – Under 35 best paper award, Building and Environment (October, 2013)
- Recipient, DMU fund for Cumberland Lodge residential postgraduate research conference on 'Life beyond the PhD' (August, 2013)
- Peer reviewer- Energy and Buildings (August, 2013)
- Member, International Programme Committee and Reviewer- International Conference on Sustainable Design and Manufacturing Cardiff, Wales, UK. 28-30 April 2014
- Reviewer-West Africa Built Environment Research (WABER) Conference (WABER, 2013)
- Recipient, Peer-Reviewed Prize, Research Degree Students' Poster Competition, DMU, Leicester (April, 2013)
- Recipient, National Science Foundation (NSF) USA, Conference Award, Engineering Sustainability'13 (February, 2013)
- Peer reviewer- Sustainable Cities and Society (November, 2012)
- Nominee - Experts' discussion forum for the International Energy Agency (IEA) Task XXIV on Demand Side Management (DSM) – reporting on "*Closing the loop - behaviour change* in DSM. Energy Change Institute, Oxford University (October., 2012)
- Nominee, United Kingdom Energy Research Centre (UKERC) Annual Assembly and Summer School. Warwick University (June, 2012)
- Nominee, GREENBRIDGE Summer School: *Local Practices for a Global Society: Applying Sustainability in Universities.* Cambridge University (July, 2011)
- Recipient, 2nd Prize, Research Degree Students' Poster Competition, DMU, Leicester (May, 2011)