Green retrofit of existing non-domestic buildings as a multi criteria decision making process

by

Jin Si

Institute of Environmental Design and Engineering

University College London

Primary Supervisor: Dr Ljiljana Marjanovic-Halburd, IEDE

Secondary Supervisor: Dr Sarah Bell, CEGE

A Thesis Submitted for the Degree of Doctor of Philosophy

University College London

2017

Student Declaration

The author of this thesis, Jin Si, confirms that the work presented in this thesis is her own. Where information has been derived from other sources, the author confirms that this has been indicated in the thesis.

Signature: Jin Si

....

Abstract

With increased awareness of natural resources depletion, environmental pollution and social issues, the importance of sustainable development has been emphasised. Sustainable development is accepted as a guiding principle to reconcile economic development with limited natural resources and the dangers of environmental degradation. The building industry is a vital element of any economy and can have a significant impact on the environment. By virtue of the large size of existing buildings, green retrofit of existing buildings is an effective approach to improve building sustainability and energy performance. Unlike domestic building retrofit, bound in the research, non-domestic building retrofit lacks a sufficient research and requires a further investigation.

Green retrofit of existing buildings is a complex decision making process. With the rise of sustainability agenda in the building sector, it is essential for decision makers to consider sustainability criteria, which address environmental, economic and social performance. Due to the intrinsic characteristic of existing buildings, technical challenges can emerge when integrating green technologies or measures. The qualitative and quantitative nature of these multiple criteria can increase the complexity of the decision making process. In addition, the decision making process may involve stakeholders from varying backgrounds. The conflicting perspectives can be the main barrier in the decision making of green retrofits.

This thesis proposes a framework for green retrofit of existing non-domestic buildings as a multi-criteria decision making process. The framework includes multiple phases: Site and Building Survey, Technology Listing and Screening, and Technology Evaluation with Multi Criteria Decision Making (MCDM) methods. By checking hierarchical information in the Site and Building Survey, basic information can be collected and implications for green technology can be gathered. The Technology Listing and Screening is used to propose potential technologies and further identify the qualified technologies. On top of these phases, technology evaluation with MCDM methods is suggested to conduct in four steps: 1) Criteria development by proposing a multiple criteria tree; 2) Criteria weighting by suggesting the default weights; 3) Technology scoring by presenting a simplified technology scoring approach; 4) Results synthesis. To propose the default weights, a professional survey has been designed to collect the views of experts from different backgrounds in the UK and China. Default weights have been suggested for all the expert group, the architect group, the engineer group, and other expert groups in both countries.

The framework has been applied to one UK university building for the retrofit. The main findings are: by using the proposed framework, the possibility of selecting green technologies can be increased; by using the MCDM methods for technology evaluation, the technology ranking can be identified. Scenario analysis and sensitivity analysis have been conducted for technology ranking by applying different sets of default weights. Results show that the changes of criteria weighting for Cost and Payback period can lead to technology ranking changes in all the UK expert scenario. The changes of criteria weighting for all the criteria can lead to a change in technology ranking in the UK architect scenario.

Acknowledgements

I would like to express the utmost gratitude to my supervisor Dr. Ljiljana Marjanovic-Halburd for all her invaluable help and endless encouragement throughout this dissertation.

My sincere thanks also go to Dr. Sarah Bell, Dr. Fuzhan Nasiri (Concordia University) and Dr. Zaid Chalabi for their helpful assistance and advice throughout the years. My many thanks also go to Sustainability team at UCL for their provision of valuable data for my pilot study.

The important part of this research, industry survey, has been facilitated with great assistance from Dr. Ben J F Croxford who has provided help with survey circulation. The survey has been also assisted by Gary Grant, Sofie Pelsmakers, So Young Hyun and Su Young Lee.

This work was made possible through funding provided by the European Commission and UCL Engineering Faculty, whose generous support I would like to acknowledge.

My gratitude and wishes go to all my PhD room colleagues, whose dedication to their work I greatly admire and friendship throughout the years I sincerely appreciate.

Finally, I would like to thank my mother for her tremendous amount of love, support and patience throughout my PhD life.

Table of Contents

Table of Tables

Table of Figures

Publications arising from this thesis

1. Jin Si, Ljiljana Marjanovic-Halburd, Fuzhan Nasiri, Sarah Bell (2016). Assessment of Building-Integrated Green Technologies: A Review and Case Study on Applications of Multi-Criteria Decision Making (MCDM) Methods. *Sustainable Cities and Society*. 27: 106-115.
2. Jin Si, Ljiljana Marjanovic-Halburd. Criteria weighting for green technology selection as part of retrofit decision making process for existing non-domestic. *Building and Environment.* (under review).

Chapter 1 Introduction

1.1 Research Background

The latest Fifth Assessment Report (AR5) prepared by the International Panel on Climate Change (IPCC) has stated that, due to a rapid growth in economics and population, anthropogenic greenhouse gas emissions (GHGs) have increased since the pre-industrial era. This is likely to be the dominant cause of the observed global warming since the mid-20th century (IPCC, 2014).

The main contributor to global warming is the excessive emission of GHGs, which primarily generate from energy consumption, especially through the combustion of fossil fuels. Global energy consumption is estimated to be growing significantly from 13.6 billion tons of oil equivalent in 2010 to 44.6 billion tons of oil equivalent by 2050 (Bilgen, 2014). The built environment, consisting of buildings, transportation networks, and utilities, plays a crucial role in energy consumption and the environmental impacts generation. The building sector alone has been estimated with energy consumption up to 40% of all primary energy, and its GHGs emissions have been found reaching up to 30% of global annual emissions (UNEP-SBCI, 2009).

The building sector has been identified as an urgent field to transform. Existing buildings, with a slow replacement rate of around 1.0-3.0% per annum, represent the largest stock in the building sector (Ma *et al.*, 2012). They are normally identified with poor energy performance and with a large potential to improve. For existing non-domestic buildings, different types of buildings can have varying energy consumption patterns. For instance, office buildings have shown higher energy consumption than the sector average for heating and double the average for cooling and ventilation. Hospitals consume 2.8 times the gross energy use intensity of office buildings. (U.S.EIA, 2016).

Energy performance for existing buildings can be improved through the application of green technologies and/or measures, which can be regarded as a practical approach to applying the concept of sustainable development into the building sector.

In this research, we consider all the technologies (and/or measures) which can improve building performance in terms of aspects of sustainability (energy, water, health and human wellbeing) as green technologies. Energy retrofit technologies can include energy conservation measures, such as building fabric insulation, enhanced glazing, window shading (Ardente *et al*., 2011; Chidiac *et al*., 2011; Xing *et al*., 2011; European commission, 2012), as well as energy efficiency strategies, such as control systems installation, lighting upgrades, thermal storage and heat recovery (Ma *et al.*, 2012). We also consider energy generation technologies using renewable energy sources as green technologies, which include PV system, Solar thermal, Wind turbine, Biomass boiler, Ground Source Heat Pump (GSHP) and Air Source Heat Pump (ASHP). Combined Heat Pump (CHP) is also included, which is not a renewable technology but is a highly cost-effective generation technology. In addition, technologies that can improve building sustainability in other aspects are also included, such as green roof, water efficiency systems and daylight optimisation.

Carbon Trust (2009) has estimated that adopting cost-effective technologies could achieve a net cost saving of more than £4.5 billion to the UK economy and this could also reduce carbon emissions from the UK's non-domestic buildings by 35% by 2020.

However, despite economic and environmental benefits provided by green technologies for building retrofits, there has been a slow uptake of these technologies in real-life practice (Carbon Trust, 2009; IEA, 2012). Researchers (Pan *et al*., 2012, Ma *et al*., 2012; Dangana *et al.*, 2012) have found that decision makers face significant challenges in the decision making process of green technology selection. These challenges can include:

1) Due to the rapid development of technologies, there is a lack of comprehensive knowledge about these technologies. This could be an obstacle to decision makers from delivering an informed decision.

2) Existing buildings have their own intrinsic characteristics. Existing non-domestic buildings, which are available in multiple types, can vary in their operational characters which could serve as opportunities or limitations in the process of green technology selection.

3) With multiple technological alternatives available, a comparison may be required. The comparison can be conducted against multiple criteria in environmental, economic, social and technical aspects. These criteria can be quantitative and qualitative, different in their attributes, which can pose a challenge for decision makers.

4) The decision making process of technology selection may involve multiple stakeholders, including but not limited to, the owner, tenants, the design team consisting of designers and consultants from multiple disciplines. They have diverse expertise and perspectives, making it difficult to reach an agreement for green technology selection. Researchers found that conflicting and opposing stakeholder requirements could be one of the main barriers in building retrofits (Rey, 2004; Lapinski *et al.*, 2006; Klotz and Horman, 2010).

In this sense, an effective framework is needed to be proposed addressing the challenges mentioned above. Relevant research can be found for this topic: Nelms *et al.* (2005) who developed a comprehensive framework for green technology assessment, proposed a multi-dimensional conceptual model and a six-phase screening approach for green technology selection. The effectiveness of this framework was demonstrated through a comparison between two case buildings applied with a green roof. Odhiambo and Wekesa (2010) proposed a systematic approach for building technology assessment for marginalized communities, where the poor urban population resides in informal shelters. A conceptual model was established to demonstrate interrelations between environmental, engineering and socio-economic objectives. Huang *et al.* (2012) performed a sustainability assessment of low carbon technologies for building sector in China. They reviewed existing assessment methods at multiple levels (industry, project and technology) and developed an assessment framework at building level. Ma *et al.* (2012) conducted a comprehensive review of crucial activities and elements influencing existing building retrofits. A systematic approach of identifying, determining and implementing the optimal retrofit measures was proposed for existing buildings. Methods of Cost-Benefit Analysis and Risk Assessment were suggested to evaluate potential retrofit technologies. Dangana *et al.* (2013) developed a decision-making framework of sustainable technology selection for retail buildings, which consists of phases of problem identification and structuring, model building and delivery, and results synthesis.

However, research gaps exist in current research. Most research merely emphasised technology assessment (Nelms *et al.*, 2005; Odhiambo and Wekesa, 2010). Limited research has been found in the discussion of technology listing and screening, which are important tasks before technology assessment. This is because a logical technology listing and cautious technology screening can save unnecessary assessment work for unqualified technologies. It could potentially open opportunities for a wider green technology utilisation. Thus, it is suggested that the research of green technology selection should be conducted from a more comprehensive view.

For technology assessment, single-criteria analysis, such as Cost Benefit Analysis is still dominant (Nelms *et al.*, 2005). To deliver a comprehensive assessment, multiple criteria can be included. For multiple criteria analysis, Multi Criteria Decision Making (MCDM) methods have proved effective (Dangana *et al.*, 2013), since they can deconstruct a complex decision making problem into steps. They are criteria development, criteria weighting, technology evaluation and results synthesis (Linkov and Moberg, 2012). It has been found that MCDM application in the technology selection, especially for existing building retrofits is still limited. Topics of criteria development and criteria weighting are worthy of further investigation (Rongxi *et al.*, 2009; Ali *et al.*, 2012; Pan *et al.*, 2012).

Finally, technology selection research has been conducted for scale of building sector, community or national level (Odhiambo and Wekesa, 2010; Huang *et al.*, 2012). Limited research can be found in the context of existing buildings retrofits, especially for non-domestic building retrofits.

This PhD research aims at developing an integrated framework of green technology selection for non-domestic buildings, by investigating the question of green technology selection from a comprehensive view. Non-domestic building characters will be discussed, with a logical approach of listing and screening potential technologies. Technology evaluation with MCDM methods will be another separate phase, with a further discussion on criteria development and criteria weighting. Thus, this framework is developed to address the following:

1) How to understand green technology characteristics from a comprehensive perspective with critical knowledge including benefits and limitations when they are applied in existing buildings.
2) How to fully understand non-domestic buildings, especially operational characteristics, from the perspective of its suitability of integrating green technologies.
3) How to further check the qualification of potential green technologies against screening criteria on different levels.
4) How to perform technology evaluation with MCDM methods practically by steps.

1.2 Research Aim and Objectives

This PhD research aims at investigating green retrofit of non-domestic buildings by developing an integrated assessment framework. To achieve this aim, research objectives include:

1) To cross reference green technologies specifications against operational characteristics of different non-domestic building types.
2) To develop an integrated framework of green technology selection phase by phase by including proposing technologies, screening technologies and evaluating technologies.
3) To propose a default multi-criteria tree covering sustainability criteria and technical criteria.
4) To suggest default weighting values for proposed multiple criteria and methods to

use these values.

5) To illustrate the use of each phase of the framework through real case study and make a scenario analysis by applying different sets of weighting values.

1.3 Research Structure and Chapter Layout

The research consists of eight chapters, which are organized following the sequential stages of the research methodology “review-analysis-synthesis”. Chapter 1-3 and Appendices A & B serve as a review of existing research with a discussion of background issues and main concepts, forming the basis of this research. Chapter 4-5 are mainly about the conceptualization and operationalization of the proposed framework, which includes framework development and framework application; Chapter 6 highlights the main conclusions of the research and summarises the original contributions to research. Practical limitations of this research are mentioned and future research suggestions are provided. The organization of chapters is shown in Figure 1.1.

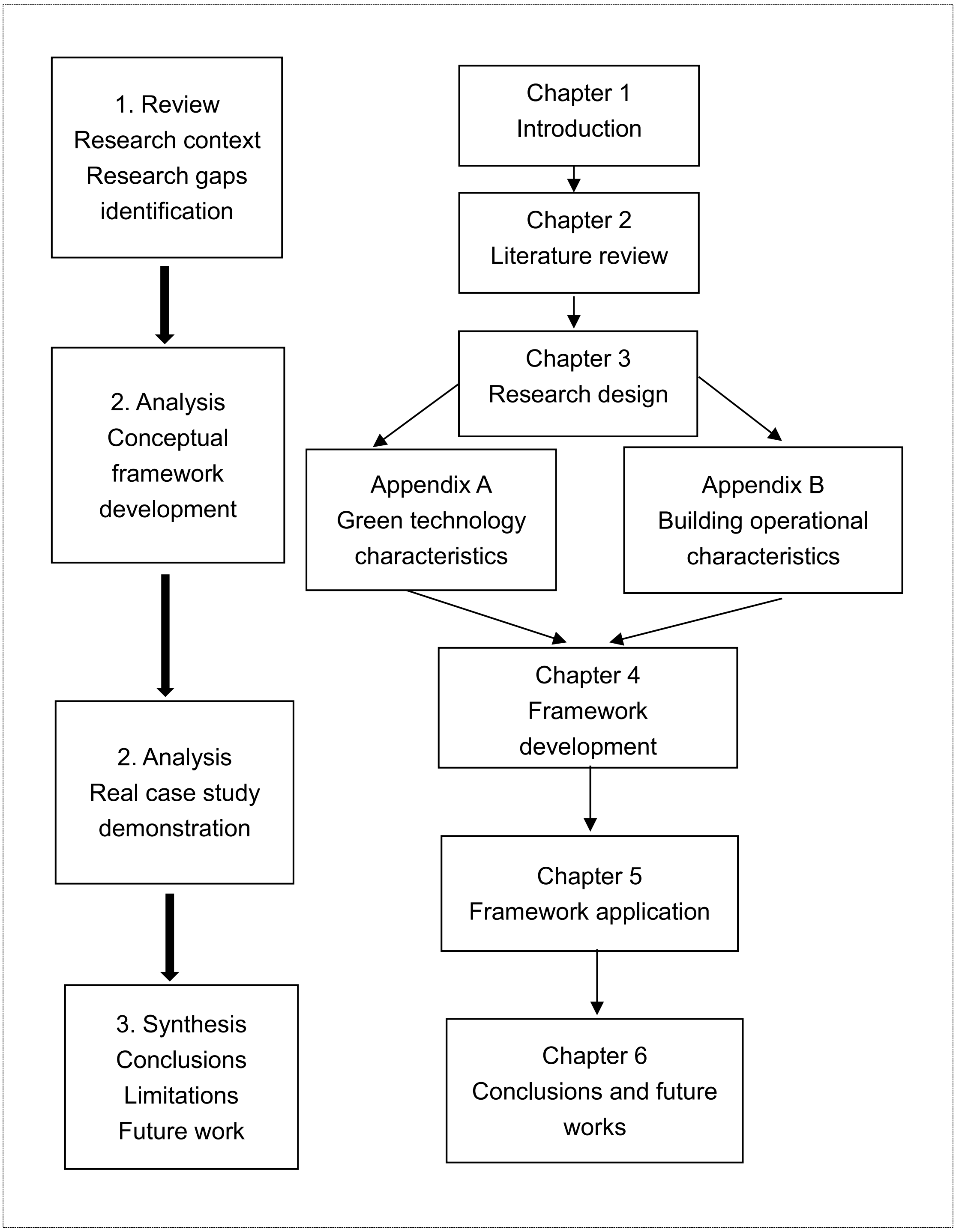


Figure 1.1 Thesis outline

Chapter 2 Literature review

2.1 Sustainable buildings

The building sector is one of the major consumers of energy and other natural resources, Buildings account for 40% of global energy use, 30% of energy-related GHG emissions, approximately 12% of water use and nearly 40% of waste (UNEP, 2015). Economic inefficiency in buildings represents increasingly high operation costs and difficulties of financial profit maximization. Social impacts caused by the building sector can include aesthetic degradation, disruption of communities and health risks for building occupants (Sev, 2009).

Sustainable building is a multi-dimensional concept, which is grounded on the three pillars of sustainable development: the environmental load reduction, economic profit maximization, and social benefits improvement (Anastaselos *et al.*, 2009). A sustainable building approach is considered as an effective approach for the building industry to achieve sustainability. Sustainable building starts at the planning stage of a building and continues throughout its life to its eventual deconstruction and recycling of resources to reduce the waste stream associated with demolition. The complexity of a building often suggested a multidisciplinary approach to sustainability assessment (Langston and Ding, 2001) and the sustainability assessment system for buildings can be grouped into three categories (Berardi, 2012):

1) Cumulative Energy Demand (CED) systems, focusing on energy consumption
2) Life Cycle Analysis (LCA) systems focusing on environmental aspects
3) Total Quality Assessment (TQA) systems, which evaluate ecological, economic and social aspects. These include sustainable building rating systems, such as LEED, BREEAM etc.

These three categories are further explained with examples as follows:

1) *Cumulative Energy Demand (CED) systems*

As highly efficient buildings are constructed, the energy needs during construction and demolition processes, together with the embodied energy in construction materials, become relatively more significant. Hernandez and Kenny (2010) have defined the life cycle zero energy building (LC-ZEB) concept for energy consumption equity in a whole life perspective. The CED systems use one single criterion in the assessment process.

2) *Life Cycle Analysis (LCA) systems*

LCA is a robust methodology refined based on manufacturing sector experiences. LCA assessments consist of four phases (ISO 14040, 2006): the goal and definition phase, the life cycle inventory, the life cycle impact assessment and the improvement assessment phase. LCA systems allow the comparison of products based on the same functional quality and assess the environmental paradigm of sustainability without considering social and economic impacts. Figure 2.1 shows the integrated LCA of the building life cycle. Life Cycle Cost analysis (LCC) is a method of analysing costs related to a production system or a product during its life cycle (Dahlén and Bolmsjö, 1996). When environmental cost is included in the LCC, it will be the Life Cycle Environmental Cost Analysis (Senthil Kumaran *et al*., 2001). These costs can be either direct (e.g. costs for waste disposal and raw material) or indirect (e.g. costs for environmental management systems).

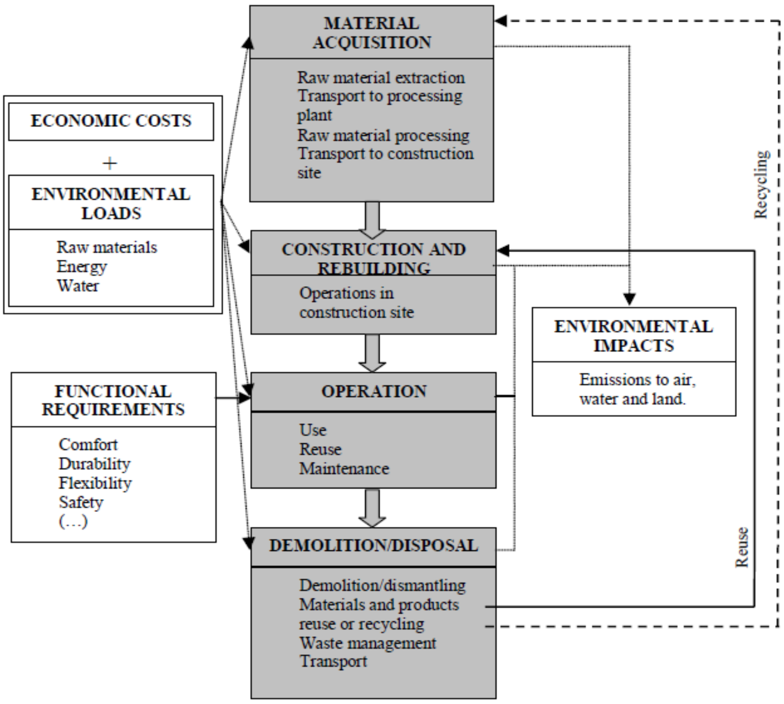


Figure 2.1 The integrated LCA of the building life cycle (Source: Bragança, Mateus and Koukkari, 2010, p. 2014)

3) Total Quality Assessment (TQA) systems

TQA systems aim at considering the three aspects of sustainability of buildings: environmental issues such as GHG emission and energy consumption, economic aspects such as investment and equity and social requirements such as accessibility and quality of spaces (Berardi, 2012). The most common TQA systems are the multi-criteria systems.

Several multi-criteria systems exist to assess building sustainability worldwide. As many are just adaptations of more famous ones to regional level or for specific scopes, only the most adopted systems are considered here. Most widely-used assessment tools can include BRE Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Green Mark Scheme and Building Environmental Assessment Method (BEAM).

Due to the aim of this research, building environmental assessment tools designed for existing building use will be discussed. These tools can include BREEAM In-use International, LEED for existing buildings: operation and maintenance, Green Mark for existing buildings and NABERS.

(1) Building environmental assessment tools for existing buildings

BREEAM was introduced in 1990 and was the first comprehensive method for building assessment. BREEAM In-use International Scheme updated until 2016 is a performance-based assessment method and certification scheme for existing non-domestic buildings (BRE, 2016). The scheme provides a holistic approach which enables buildings to be assessed and benchmarked across environmental issues (management, health and wellbeing, energy, transport, water, materials, waste, land use and ecology, and pollution) (BRE, 2016).

LEED was initially proposed by a panel of experts gathered by the U.S Green Building Council in August 1998. After extensive modifications, the LEED green Building Rating System (Version 2.0) was released in March 2000. Turner and Frankel (2008) found that LEED certified buildings can achieve more than 28% of energy savings compared to the national average level. Jo *et al.* (2009) claimed that a large amount of CO_2 emission could be reduced through energy efficiency improvement by the adoption of LEED rating tools. The LEED for existing buildings: O&M Rating System (USGBC, 2016) is a set of voluntary performance standards for the sustainable ongoing operation of buildings. It provides sustainability guidelines for building operations, periodic upgrades of building systems, minor space-use changes, and building processes.

The BCA Green Mark Scheme (Singapore BCA, 2005). was launched in January 2005 as an initiative to drive Singapore's construction industry towards more environmentally-friendly buildings. It provides a comprehensive framework for assessing the overall environmental performance of buildings (Singapore BCA, 2005). As for existing non-domestic buildings, the building owners and operators are encouraged to meet their sustainable operations goals and to reduce adverse impacts of their buildings on the environment and occupant health over the entire building life cycle (Singapore BCA, 2005).

The National Australian Building Environmental Rating System (NABERS) project, begun in 2001, aims to develop Australia's first comprehensive rating system for existing, operational buildings (NSW Government Office of Environment and Heritage, 2001). NABERS is being designed as a performance-based rating system measuring a building's actual environmental impact during operation, using real measurements rather than simulations, predictions or estimates (NSW Government Office of Environment and Heritage, 2001).

Table 2.1 is to provide a comparison of assessment categories for these building environmental assessment tools.

Table 2.1 Characteristics of Building Environmental Assessment tools for existing buildings (Source: Boonstra and Pettersen, 2003)

Building assessment tool	BREEAM In- Use International	LEED for Existing buildings: operations & maintenance	The BCA Green Mark Scheme for existing buildings	NABERS
Developer	Building research establishment (BRE), UK	Green Building Council (GBC), US	Building Construction Authority(BCA), Singapore	Office of Environment and Heritage on behalf of Federal, State and Territory governments, NSW Government, Australia
Year	2016	2009 version, Updated 2016	2005	2001
Categories	Management, health and comfort, energy, transport, water, materials, waste, land use & ecology, pollution	Sustainable sites, water efficiency, energy, and atmosphere, materials and resources, indoor environmental quality, innovation in operations, regional priority	Energy Efficiency, Water Efficiency, Environmental Protection, Indoor Environmental Quality, and Other Green Features and Innovation	Energy use, water use, stormwater volume and pollution, sewage outfall, site ecology/biodiversity, transport, waste, indoor air quality, comfort and toxic materials

(2) Examples of sustainable buildings

By using these above building environmental assessment tools, the environmental performance of buildings can be rated and sustainable buildings will be awarded. Sustainable buildings awarded with BREEAM award for 2015 in the scheme categories will be presented as examples.

For Office In-use category, Washington Plaza in Paris excelled in BREEAM categories such as Health and Wellbeing, Energy and Pollution and was awarded BREEAM OUTSTANDING certification (BRE, 2015). Retrofit measures adopted for this building include:

a) Green spaces were provided to create alternative areas for occupants' socializing (BRE, 2015).
b) A green wall 80 meters long and 7 meters' high was built to introduce biodiversity to the urban landscape (BRE, 2015).
c) A rainwater harvesting system with four 5,000 litre tanks was installed to water the green spaces (BRE, 2015).
d) A monitoring system has been installed to provide precise data of electricity consumption by use of appliances, lighting, heating and cooling systems. (BRE, 2015).

For BREEAM Offices Refurbishment and Fit-out category, the award was given to the Morelands Rooftop in London's Clerkenwell area (BRE,2015). Retrofit technologies and measures include:

a) Thermal performance of the building has been improved by enclosing the 4th floor facade with a skin of insulation, which has exceeded the requirements of Part L. The airtightness tests of 5.66m^3/hr/m^2 at 50 Pa has met "Good Practice" guidelines. (BRE, 2015).
b) Efficient lighting

   PIRs have been installed to reflect the office's occupancy and save energy. The new-built 5th floor has significant height (at 3.7m to ceiling), which can achieve daylight optimisation and less artificial lighting consumption. New lights on occupant-controlled triggers have been installed to further reduce the electrical load on the building (BRE, 2015).

c) Renewable technologies

PV panels have been installed to reduce electricity consumption and solar thermal panels have been installed to supply hot water (BRE, 2015).

d) Water saving fittings

Water saving fittings have been installed to toilets, taps and showers, which helps to save the equivalent of 78,049WC flushes per year (BRE, 2015).

e) Biodiversity

A large area of the brown roof has been included to provide a new opportunity for biodiversity on the complex, and the fabric of the building has been integrated with swift and swallow boxes (BRE, 2015).

f) Monitoring systems

The post-occupancy monitoring system enables occupants to check how the building spaces react to external weathers. A monitoring system has been deployed to provide precise and detailed measurements of the electrical consumption and to enable a breakdown of energy consumption by end-use (BRE, 2015).

Above BREEAM-awarded sustainable buildings have achieved a better building performance through an integration of multiple green technologies, which help them to improve the performance in energy efficiency, water efficiency and biodiversity. The selection of green technologies has followed a hierarchical process: from the reduction of energy demand through insulation, to the application of energy efficient measures, and to the installation of a whole building monitoring system, which can monitor the building energy performance and provide precise data of energy consumption by end-use.

2.2 Existing buildings retrofit

2.2.1 Retrofit potential of existing buildings

Due to relatively low replacement rate of new buildings, the maintenance, upgrading, rehabilitation and adaption of existing buildings should be focused. In the same time, the potential of carbon reduction through building retrofit is considerate. Existing buildings in the non-domestic sector have been commonly identified with poor building performance, representing as poor fabric, inefficient energy facilities, old control systems and overheating (Roberts, 2008). The large potential of CO_2 reduction is especially in heating through application of “renewable heat” technologies (Figure 2.2). These technologies will more likely benefit non-domestic buildings to achieve CO_2 emission reduction.

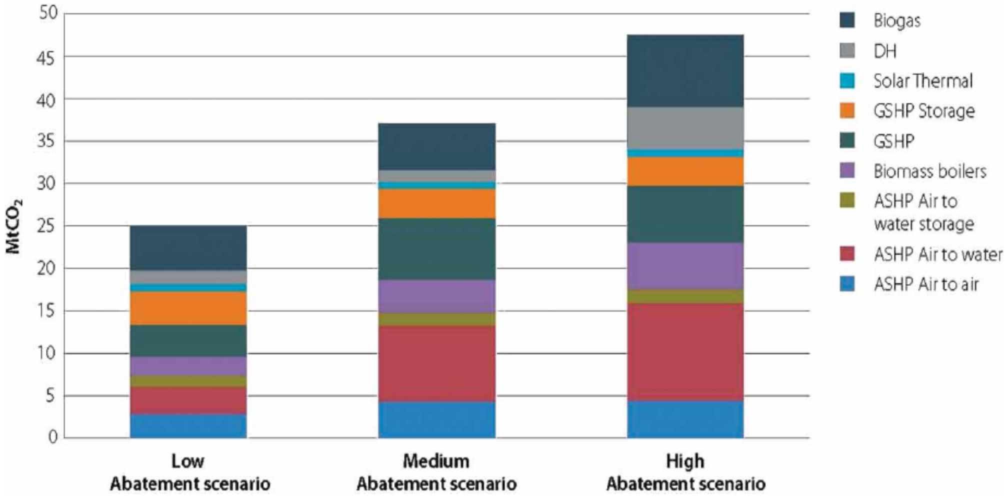


Figure 2.2 CO_2 reduction potential from renewable heat technologies for existing non-domestic buildings in the UK. (Source: Carbon Trust, 2009, p.7)

Carbon Trust (2009) has conducted a detailed survey about the carbon emission abatement potential in non-domestic buildings and identified the reduction potential is distributed in heating/cooling (70%), lights and appliances (19%), energy management (9%), insulation (4%) and process efficiency (1%). Carbon Trust (2009) has identified a range of cost-effective measures that can reduce carbon for existing non-domestic buildings in the report of “Building the future, today”. These technologies and their potential in carbon abatement are shown in Figure 2.3.

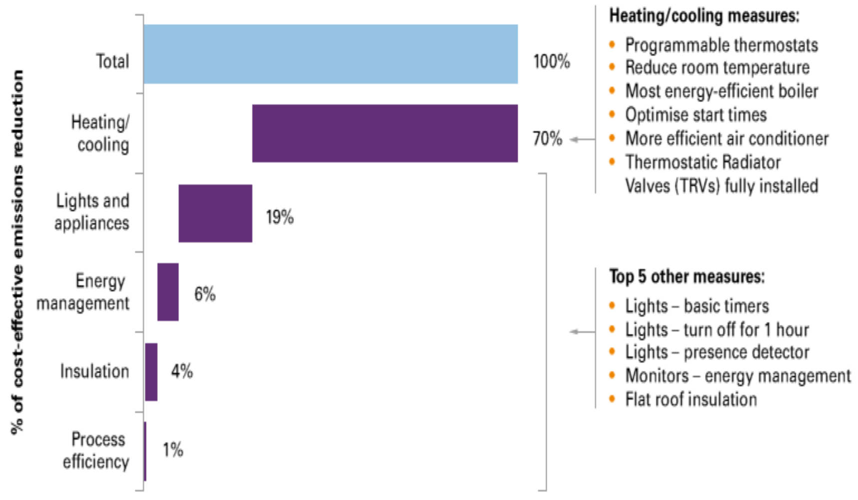


Figure 2.3 Cost-effective energy efficiency measures carbon abatement potential in existing non-domestic buildings in the UK (Source: Committee on Climate Change (CCC), 2010)

2.2.2 Methods of existing building retrofits

According to the USA Green building council, building retrofit refers to any kind of upgrades of an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, and improve the comfort and quality of the space in terms of natural light, air quality. Building retrofit is a complex process, which can be influenced by a range of factors (Ma *et al.*, 2012):

1) Policies and regulations, which mainly refers to energy efficiency standards, which set minimum energy efficiency requirements for existing building retrofits (Ma *et al.*,2012). Governments may also provide financial support for building owners and developers adopting retrofit measures to achieve retrofit targets (Ma *et al.*, 2012).

2) Client resources and expectations. Client resources and expectations decide the project targets and goals. Potential technologies are accordingly determined. It has been found payback period is the most widely used decision making rule (Harris *et al.*, 2000).

3) Retrofit technologies. Retrofit technologies help to improve building energy efficiency

and sustainability. Retrofit technologies can range from the basic retrofit measures of improving the insulation to the use of energy efficient equipment, advanced control technologies and renewable systems (Ma *et al.*, 2012). Selection of retrofit technologies can be dependent on multiple criteria, such as economic payback, complexity, and ease of implementation (Ma *et al.*, 2012).

4) Building specific information. Building retrofits are also influenced by building specific information, including geographic location, building type, size, age, occupancy pattern, operation, and maintenance, building fabric and services systems (Ma *et al.*, 2012). This information can influence building retrofits and the selection of retrofit measures.

5) Human factors. Human factors may include comfort requirements, occupancy types, management and maintenance, activity and access to control. The changes of occupant behaviour, occupant controls, and comfort range can help saving a significant amount of energy (Zeiler *et al.*, 2014).

Mickaityte *et al.* (2008) have proposed a conceptual model of sustainable building retrofit, which is to reconcile social, ecological, economic, cultural, architectural and technical requirements. In this model, principles are suggested to follow, including citizen's healthcare, effective energy use, rational resource use, environment conservation and affordability. The decision making process has been involved in this whole framework, but an actual step. The conceptual model is shown in Figure 2.4.

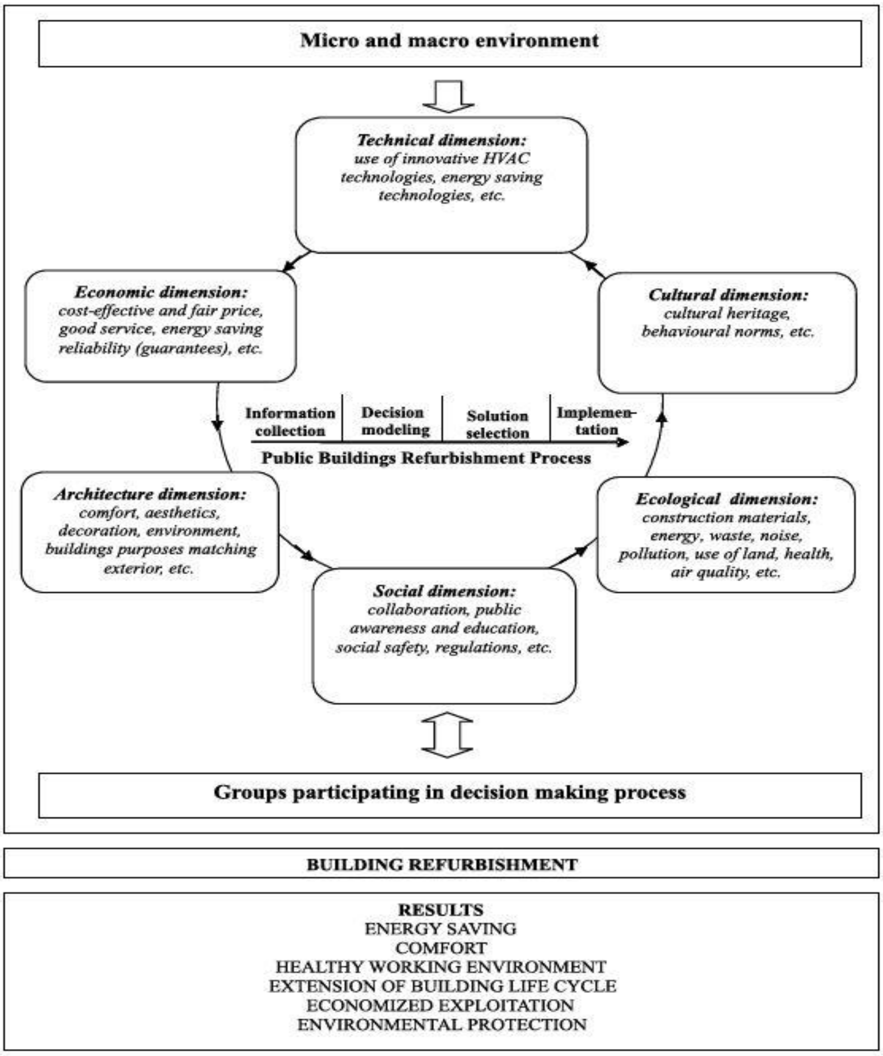


Figure 2.4 The conceptual model of sustainable buildings refurbishment (Mickaityte *et al.*, 2008, p. 58)

Kolokotsa *et al.* (2009) have proposed a framework for energy efficiency and energy management which can be used both for new construction and existing building retrofits (See Figure 2.5). In this framework, goals are suggested to propose from multiple perspectives of economic, environmental and social. Energy saving measures are identified based on pre-defined goals. Whether these suggested measures are accepted is decided after applying energy efficiency improvement methods and checking with sensitivity analysis. In this decision making process, building experts and building final users are encouraged to participate.

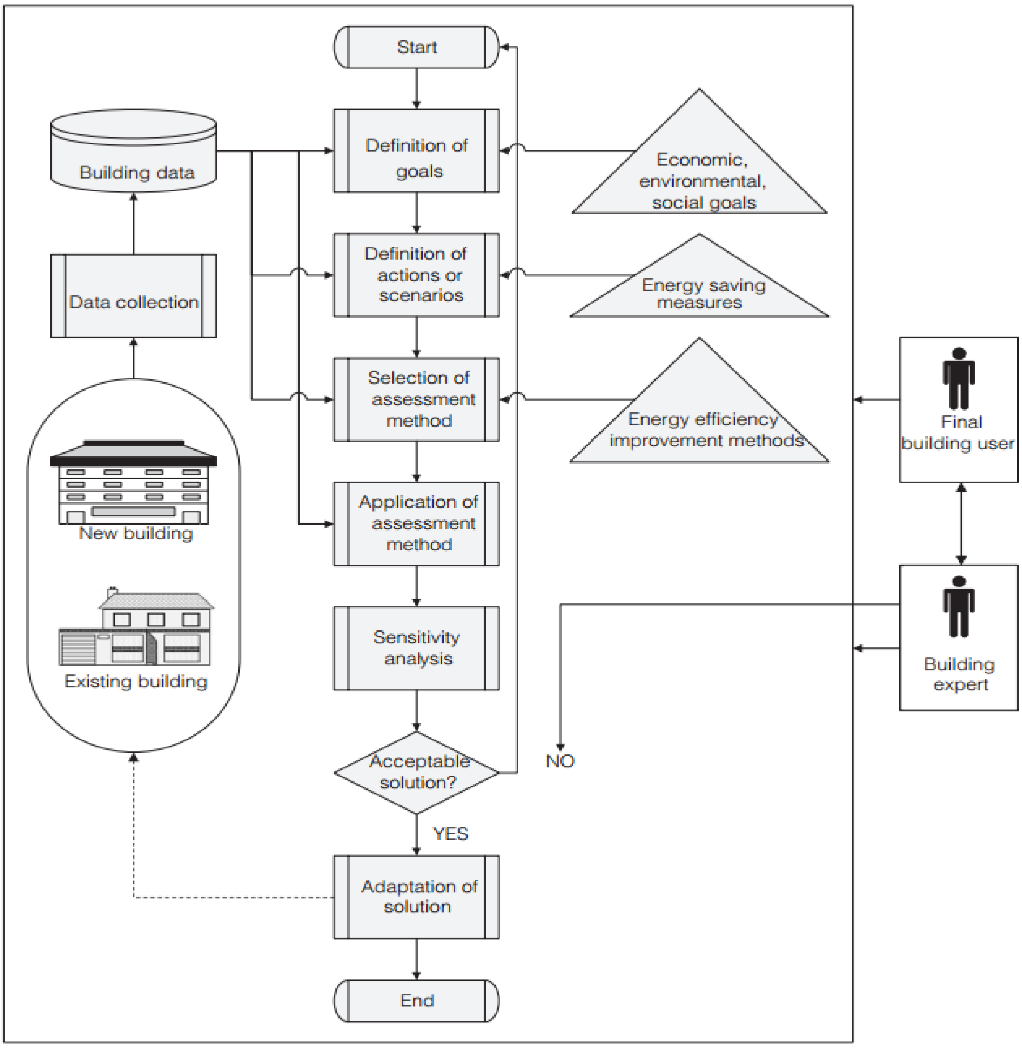


Figure 2.5 The methodology for building's design and operational improvement (Kolokotsa *et al.*, 2009, p.125)

Ma *et al*. (2012) have proposed a roadmap for building retrofits, shown in Figure 2.6. This roadmap is designed for any type of buildings retrofits. This roadmap consists of multiple phases including:

1) Project Setup and Pre-retrofit Survey

In this phase, decision makers, such as building owners or agents need to define the scope of the work and set project targets (Ma *et al.*, 2012). A pre-retrofit survey is essential to collect the basic information of buildings, current operational problems and main concerns from occupants (Ma *et al.*, 2012). The data and information collected from the pre-retrofit survey can help to understand the opportunities and limitations for the building retrofits.

2) Energy Auditing and Performance Assessment

In this phase, energy consumption data for the building are analysed and targeted energy wasting areas are identified (Ma *et al.*, 2012). Energy auditing is used to establish the energy use and cost. Based on this information, energy consumption control measures can be implemented and reviewed. Energy auditing includes walk-through assessment, energy survey and analysis and detailed energy analysis. Energy auditing provides essential data and information for Building Performance Assessment. Building performance assessment is to benchmark the case building with a typical building of the same type, which has reached the energy consumption standard. It has been seen there are several building rating tools to benchmark the building performance against multiple criteria, such as BREEAM and LEED.

3) Identification of Retrofit Options

After energy auditing and building performance assessment, a list of potential retrofit options can be proposed. To identify the optimal measure, a comparison can be performed based on specific mathematical models. These models can be an energy model, economic analysis model or risk assessment model. For a more general comparison of these measures with integration energy-relevant factors and non-energy-relevant factors, a multi-criteria analysis model is recommended.

4) Site Implementation and Commissioning

In this phase, selected retrofit measures are implemented on-site. Test and Commissioning (T&C) is then employed to tune retrofit measure operating in a good manner.

5) Validation and Verification

This phase includes two tasks: 1) Validation of retrofit measures, which is to identify energy savings from applied retrofit measures; 2) Post-occupancy survey, which is to understand whether occupants are satisfied with these retrofit measures.

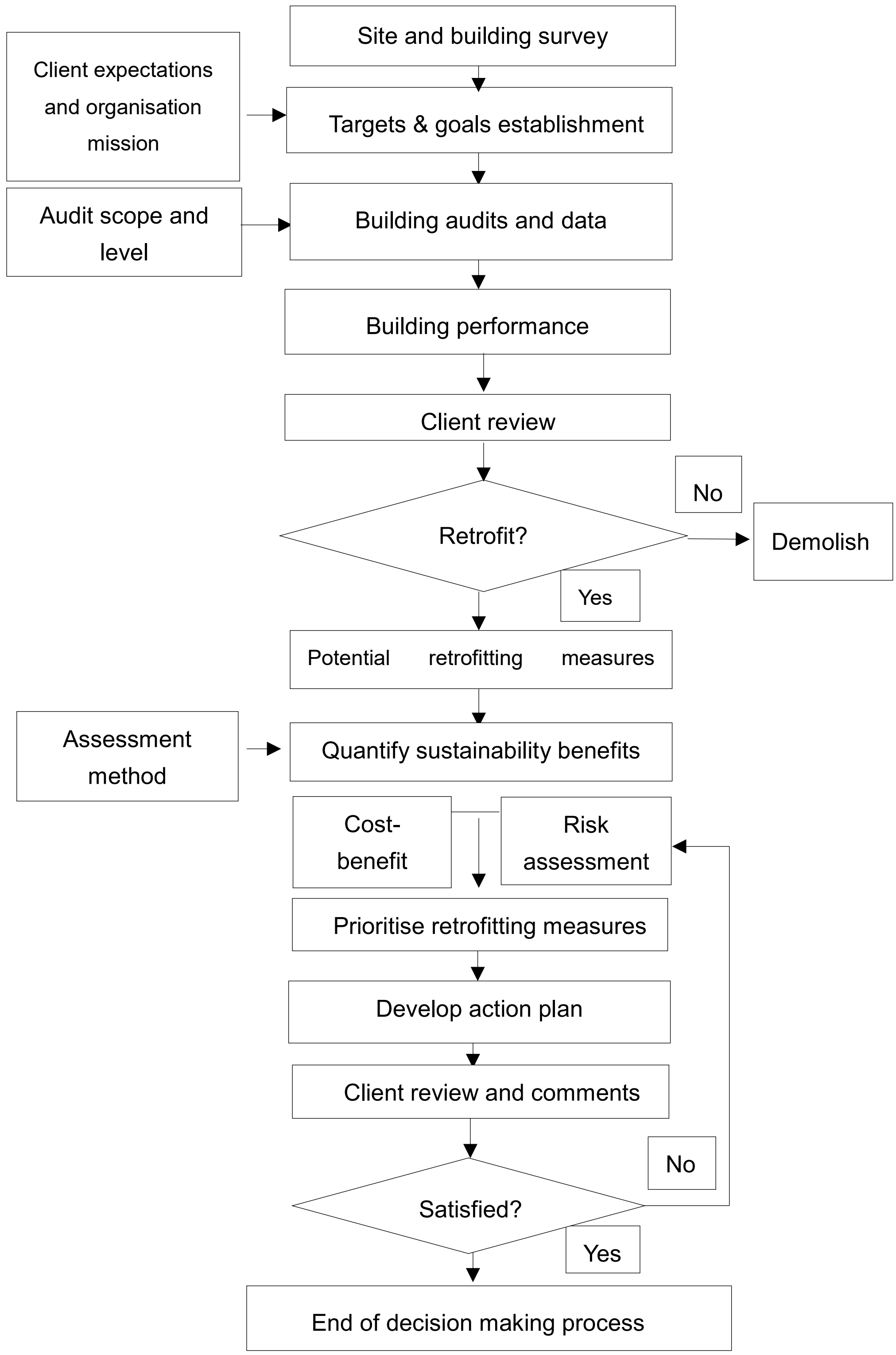


Figure 2.6 A systematic approach to a sustainable retrofit decision making process (Ma *et al*., 2012, p.893)

2.3 The practice of green technology selection

The selection of retrofit measures for existing buildings is a complex task. The success of retrofitting is subject to many uncertainties, including occupant behaviour, government policy changes, and climate volatilities, all of which directly affect the selection and performance of technologies. Other challenges may include financial limitations, long payback periods, and interruptions to operations. At the technical level, different retrofit measures may have different impacts on associated building sub-systems (Ma *et al*., 2012). With the rise of the sustainability agenda in the building sector, it is essential for the decision makers to consider sustainability criteria, which address environmental, economic and social performance (Si *et al*., 2016). The interdependencies and conflicting nature of these criteria are well recognised. The qualitative and quantitative nature of different criteria also increase the complexity of analysis. Dealing with these uncertainties and system interactions is a considerable technical challenge in any sustainable building retrofit project (Si *et al*., 2016).

Stakeholders typically concentrate first on potential alternatives and only afterward address the objectives and criteria that are required to evaluate the alternatives. This approach has been referred to as alternative-focused thinking (Keeney, 1992). The limitations of this approach are that stakeholders emphasise a specific alternative and only focus on a few of objectives, but not based on a comprehensive analysis. On the other hand, the value-focused thinking approach focuses first on values and then on the alternatives. This process helps to identify values and opinions of stakeholders and pinpoints sources of disagreement (Edwards and Von Winterfeldt, 1986; Belton and Pictet, 1997). In this way, decision makers are more likely to deliver an informed decision. The MCDM process is a typical and formal framework for the value-focused approach.

Current research about the decision-making process for building retrofits is commonly based on a single economic criterion, such as a cost-benefit ratio obtained through a financial performance analysis (Nelms *et al.*, 2005). Faced with the lack of established practices in the use of decision making tools, designers, and building managers are more likely to turn to intuition (Pan *et al.*, 2012). MCDM methods have been proposed to assist with the selection of green technologies for buildings (Dangana *et al.*, 2013). MCDM methods can deconstruct the problem of decision making into discrete steps, compare the relative importance of criteria and select the optimal alternative using rigorous mathematical models. These methods can clarify the interrelations between criteria and minimise the subjectivity of the selection (Linkov and Moberg, 2012). MCDM methods have been used to support design decisions for low carbon buildings (Dawood *et al*., 2013) and in the evaluation of climate change mitigation policy instruments (Konidari and Mavrakis, 2007).

2.3.1 Green technology selection and evaluation

Mohsen and Akash (1997) applied the AHP method to perform a cost-benefit analysis of multiple domestic heating systems for Jordan. They compared domestic solar water heating systems with other four types of heating systems: an electric heating system, central heating system, kerosene heater and LPG heater. With AHP, hierarchies were developed separately for the benefit and cost evaluation. The combined cost-to-benefit ratio was adopted to decide which solar water heating system is the most desirable one. The criteria weights used in this paper were proposed at a city-scale scenario and how these weights have been identified were not disclosed. When adopting the weights in this paper for an individual building, the proposed weights should be adjusted.

Wang *et al.* (2009) applied Grey Relational Analysis (GRA) method to compare different CHP systems, including industry systems and household systems. GRA is one of the MCDM methods to deal with the issues with complex interrelationships between criteria. Wang *et al.* (2009) have highlighted the importance of the accuracy of the criteria weights, for which, they have suggested to use the combination weighting method to confirm the criteria weights accuracy by balancing the subjectivity of stakeholders' preferences and the objectivity of the numeric data.

Sheikh and Kocaoglu (2011) conducted a comprehensive literature review of solar photovoltaic technology assessment and they found the existing research is lacking in the consideration of social, technological, economic, environmental and political criteria. Thus, Sheikh and Kocaoglu (2011) have proposed a list of the criteria in the aspects of social, technological, economic, environmental and political (STEEP) for renewable technologies, especially for solar PV selection at a regional scale. The criteria list has been proposed through the approach of literature review and consultation with experts. The criteria weights have been decided through the questionnaires. These criteria weights have been proposed for a community scale and should be adjusted when applied to other scales.

Collier *et al.* (2013) employed the Multi-Attribute Value Theory (MAVT) method to select the best roofing technologies among reflective, vegetated, and solar roofs. They have found the existing technology selection criteria are incomprehensive through investigating the literature. Thus, they proposed a list of comprehensive criteria in terms of economic, social and environmental aspects, with an emphasis on social criteria such as research, education, recreation, aesthetics and innovation values (Collier *et al.*, 2013). Collier *et al.* (2013) have suggested to assign numeric values to qualitative responses to social criteria. The responses of "strongly agree", "somewhat agree", "neutral", "somewhat disagree" and "strongly disagree" have been assigned with numerical values within a predefined numerical interval (eg. -1 to 1). A sensitivity analysis was conducted to assess the impact of weights on the results.

Nelms *et al.* (2005) developed a comprehensive framework for green technology assessment. The framework consists of a multi-dimensional conceptual model and a six-phase screening approach for green technology selection. The conceptual model is constructed in three dimensions: building systems and components as one dimension (x-axis), project life cycle as another dimension (y-axis), and performance measures as the third dimension (z-axis) (Nelms *et al.*, 2005). This conceptual model reflects the interaction of technology performance and its impacts on other building systems over the project life cycle. The procedural technology screening process includes six phases as below (Nelms *et al.*, 2005):

1) Preliminary review of performance measures;

2) Impact assessment on building components;

3) Technical performance assessment;

4) Economic assessment;

5) Allocation of weight values;

6) Synthesizing the alternative ranks and decision.

The applicability of the proposed framework was demonstrated through the real case study of integrating green roofs into two case study buildings.

Odhiambo and Wekesa (2010) suggested an approach for building technology assessment in marginalised communities, where the poor urban population resides in informal shelters. They developed a conceptual model to illustrate the interrelationship between the criteria of environmental, engineering and socio-economic. These criteria were identified through an extensive literature review and conducting several rounds of interviews with stakeholders. They recommend using the Simple Additive Weighting (SAW) to score the alternative performance.

Huang *et al.* (2012) performed a sustainability assessment of low carbon technologies for the building sector in China. The Multi-Attributive Assessment of the Clean Development Mechanism method (MATA-CDM method) at the project level was selected to consider both sustainability and low carbon requirements. The MATA-CDM method is a method to integrate the multi-attribute utility analysis into Clean Development Mechanism projects. Using the multi-attribute utility method (MAUT method), the assessments associated with an individual criterion are converted into a single utility value between -1 and 1. The results emphasised that geothermal and solar PV technologies outperform electrical heating systems.

Ma *et al.* (2012) conducted a comprehensive review of crucial activities and elements influencing existing building retrofits. Based on this, a systematic approach to identifying, determining and implementing the optimal retrofit measures was proposed for existing buildings. The cost-benefit analysis and risk assessment were suggested to assess the potential retrofit technologies. It has been pointed out many uncertainties are involved in building retrofits, such as climate change, service strategy, government policies, etc. (Ma *et al.*, 2012). To deal with these multiple issues, Multi-criteria decision analysis or multi-objective optimisation methods are recommended to conduct a trade-off analysis in the decision process. The importance of criteria selection and criteria weighting are also emphasised.

Dangana *et al.* (2013) proposed a decision-making framework of sustainable technology selection for retail buildings, which consists of problem identification and structuring, model building and delivery, and the synthesis of the final decision. The interviews have been organised to discuss the barriers, drivers, and opportunities for sustainable technology selection with all participants. This discussed information has been interpreted into the key criteria, including cost, risk, proven success, and transferability, which were weighted through the AHP method by Zaninab *et al.* (2013). The weighting results have shown that technology risks and costs as the most influencing decision criteria in green technology selection for retail buildings.

Through the literature review above, it has been found that the green technology selection can involve multiple criteria (Nelms *et al.*, 2005; Dangana *et al.,* 2013). Many studies stress the importance of criteria development in the decision making process (Sheikh and Kocaoglu,2011; Huang *et al.,* 2012). They suggest to comprehensively consider the criteria regarding economic, environmental, social and technical performance. *Economic criteria* mostly contain capital cost and operation and maintenance (O&M) cost (Zainab *et al.*, 2013; Collier *et al.*, 2013), installation time (Zainab *et al.*, 2013; Collier *et al.*, 2013), payback period (Huang *et al.,* 2005), maintenance complexity (Nelms *et al.*, 2007; Collier *et al.*, 2013) and available incentives (Nelms *et al.*, 2007). *Environmental criteria* can be the consumption of resources and environmental impacts (Collier *et al.*, 2013). *Social criteria* may include the organisation mission and welfare (Collier *et al.*, 2013), human health and safety, and employment creation

(Odhiambo and Wekesa, 2010). Researchers have found that green technology selection can be also influenced by organisational strategy and environmental certification opportunities (Richardson and Lynes, 2007; James and Card, 2012). Apart from economic, environmental and social criteria, *technical criteria* may include technology efficiency (Wang *et al.,* 2009), the complexity of implementation (Nelms *et al.*, 2007), the service life (Odhiambo and Wekesa, 2010), safety (Huang *et al.*, 2012) and proven success in practice (Wang *et al.*, 2009; Collier *et al.*, 2013).

These multiple criteria can be interrelated in the green technology selection process, for which, researchers (Ma *et al.,* 2012; Zainab *et al.,* 2013; Collier *et al.,* 2013) recommended to use multi-criteria analysis or multi-objective optimisation methods facilitating trade-off analysis between these criteria. AHP and MAUT were two most commonly-used MCDM methods in the green technology selection. Wang *et al.* (2009) and Ma *et al*. (2012) showed that appropriate criteria selection and criteria weighting are crucial when using these methods. Researchers (Collier *et al.*, 2013; Ma *et al.* ,2012) also claim that the criteria tree organisation is the key to the formulation of the MCDM problem. Collier *et al*. (2013) proposed the criteria consistent with sustainability, while Ma *et al.* (2012) organised the criteria into three categories: cost, benefit and risks. It has been found that it is still limited in the research of technology selection at the building scale (Dangana *et al.,* 2013).

2.3.2 Stakeholder perspectives in green technology selection

Several studies indicate that conflicting stakeholder perspectives are the main barriers in the decision making of sustainable retrofits (Yudelson, 2010). Rey (2004) proposed a multi-criteria assessment methodology for existing building retrofits, which simultaneously takes environmental, social, and economic criteria into account to support the decision-making process. The author emphasized that varying stakeholder opinions have a great importance in the selection of the most suitable retrofit strategy, and collaboration between stakeholders is required. Banville *et al.* (1998) describes stakeholders as everyone with a vested interest in a problem that can either affect, be affected by or is both being affected by and affecting the problem. In the context of green technology selection, stakeholders can come from backgrounds of architecture, design, engineering or planning. Architects may emphasise green technology performance on improved comfort, health, and productivity. Engineers may focus on technology performance during installation and operation, for example, technology safety and durability. Planners may be motivated to select green technology that can increase social performance, like community engagement. Experts with a background in ecology may emphasise recycling opportunities for technology disposal.

Apart from stakeholder perspectives, criteria weighting can also be varying under country contexts. Relevant research can be found for criteria development for different countries but they have not focused sufficiently on rank-order weighting. In China, researcher (Huang *et al.*, 2012) focus on microeconomic efficiency and the contribution to industrial development under economy criteria; GHG emission reduction, contribution to the industrial development and land resources under environment and energy criteria; employment generation and technology safety under society criteria. Equal weighting was used in this research when integrating technology performance scores. Luong *et al.* (2012) have found that in the UK for the sustainability assessment of renewable technologies for non-domestic buildings, life cycle cost, government schemes, expenditure on energy and income from energy are included under economic criteria; resource usage by building, technology capacity and environmental impact are included under environment; direct impacts of technology for social criteria; and performance of the system, durability, flexibility and adaptability under are included under technical criteria.

Criteria weighting to investigate stakeholder perspectives can be found in existing research. Chen *et al.* (2010) have proposed a total of 33 sustainable performance criteria for construction method selection in concrete buildings. An industry survey has been designed to collect perceptions of experienced practitioners on the importance of the criteria (Chen *et al.*, 2010). A scale of 1-5 (where 1 is ‘least important’, 2 ‘fairly important’, 3 ‘important’, 4 ‘very important’, and 5 ‘extremely important’) was used for criteria weighting. The rating scale (1-5) indicated the rank order of criteria importance and the weights ("severity index" used in the paper) of all the criteria were further calculated. The importance of all the criteria was categorised into levels based on the weights. The survey results show that social awareness and environmental concerns are important in construction method selections. Five criteria are weighted and categorised at the "High" importance level: "construction time", "initial construction costs", "constructability", "material costs" and "lead-times" (Chen *et al*., 2010).

Pan *et al*. (2012) have proposed decision criteria for building system selection in housing and quantified the relative importance for them. The research has employed a multi-methodological strategy within a case-study-based design. Decision criteria are initially compiled through a literature review and identified with main stakeholders through semi-structured interviews. Criteria weighting was conducted in a one-day workshop. Several weighting techniques including direct rating, the point allocation, and AHP were provided for flexible use. Criteria weights were verified in another five case studies. Results show that cost, time and quality are the most important criteria in technology selection. By using interviews and workshops, this research enables an in-depth exploration of organisational and project specifics for decision.

Zainab *et al*. (2013) have investigated decision criteria and their weights from the perspective of retailers in the selection of sustainable technologies for retail buildings. A two-stage approach was adopted: the initial stage was to identify decision criteria with stakeholders using semi-structured interviews; the second stage was to invite stakeholders to complete AHP questionnaires which were filled by main stakeholders in a one-day workshop, where the method can be explained and the importance of consistent judgement can be mentioned. Results have shown that risk is weighted as the most important criterion and sustainability was weighted as the least important criterion.

Menassa and Baer (2014) have developed a House of Quality (HOQ) model to synthesize stakeholder opinions and determine the technical importance of retrofit measures against stakeholder requirements. They compiled 30 potential stakeholder requirements through a literature review and their importance is suggested to be measured on a scale of 1 to 5 (from "not important" to "extremely important"). They have categorised retrofit measures for mechanical system components, electrical system components, plumbing system components and building envelopes. These retrofit measures are weighted for the importance of sustainability criteria. The overall technical importance is calculated by integrating the importance weights of stakeholder requirements and technical solutions to achieve sustainability. This model is tested in a case building and primary reasons for implementing sustainable retrofits are identified: "to save energy", "reduce costs", and "adhere to policy".

From the literature review, it has been found that researchers generally hold a view that criteria weighting is a crucial step in the decision making process of construction methods, building systems or sustainable technology selection. Decision criteria are normally compiled through a literature review and can be verified with stakeholders in interviews or workshops (Pan *et al.*, 2012; Menassa and Baer, 2014). Criteria weighting can be conducted by interviews, workshops or questionnaires. Direct weighting or pairwise comparison weighting with the AHP method can be applied (Pan *et al.*, 2012; Zaniab *et al.*, 2013). AHP method and consistency requirements can be explained to participants in interviews and workshops. Consistent judgments are more likely to achieve. However, such a group meeting is not always possible, when criteria weights are intended to be collected from experts in different organisations or even different countries.

2.4 Decision Making Process and Multi-Criteria Decision Making (MCDM) methods

From the literature review about the practice of green technology selection, Multi-Criteria Decision Making (MCDM) methods have been found popular in dealing with green technology selection and stakeholder perspective analysis. However, the research of green retrofit of non-domestic buildings as a multi-criteria process is not sufficient. Thus, we suggest conducting an overview of MCDM methods and provide a theoretical foundation for the framework development.

2.4.1 Decision Making Process

Turban and Aronson (2001) argued that the decision making process is a pure art acquired over a long period through experience and learning from trial and errors. Decision making today is even more complicated due to “more alternatives to choose from”, “large cost of making errors”, “more uncertainties” and “the need for quick decisions” (Turban and Aronson, 2001). Decision making processes range from highly structured to highly unstructured decisions. Structured processes are routine and typically repetitive problems for which standard solution method exists, while unstructured processes are fuzzy and complex problems which require more sophisticated methods to deal with (Simon, 1977; Turban and Aronson, 2001). An unstructured decision making process refers to decision processes that have not been encountered in quite the same form and for which no predetermined and explicit set of ordered responses exists (Mintzberg *et al.,* 1976).

Considering the research objective for this thesis, which is to develop a structured decision making process for green technology selection, it will focus on the review of structured approaches. In addressing structured decision making problems, Dodgson *et al*. (2009) suggested multi-criteria decision making for addressing “complex problems that are characterised by any mixture of monetary and non-monetary objectives” by “breaking the problem into more manageable pieces to allow data and judgements to be brought to bear on the pieces”, and then “reassembling the pieces to present a coherent overall picture to decision makers”. The following will introduce MCDM methods and typical methods.

2.4.2 Multi-Criteria Decision Making (MCDM) methods

Multi-Criteria Decision Making (MCDM) is one of most well-known branches of decision making. MCDM concentrates on problems with a small set of discrete and predetermined options or alternatives. A particular MCDM problem has the following elements (Norris and Marshall, 1995):

(1) Finite set of alternatives

The alternatives in MCDM are finite and always a small set of options are involved. It is distinguished from multi-objective decision making, which has infinite alternatives and trade-offs between these alternatives are typically described by continuous functions (Norris and Marshall, 1995).

(2) Multiple attributes

The attributes in MCDM are referred to as "goals" or "decision criteria". Attributes represent different dimensions, from which alternatives can be trade-off. Attributes can be arranged into a hierarchical manner, including a major criterion and an expanding sub-criterion. All of the criteria represent different perspectives of viewing alternatives (Norris and Marshall, 1995).

(3) Incommensurable units

Different criteria can have different units of measurement. Some specific attributes may be hard to measure, such as the public image of green buildings. MCDM can provide effective methods to measure this type of criteria (Norris and Marshall, 1995).

(4) Decision matrix

The decision matrix has a row corresponding to each alternative being considered and a column corresponding to each attribute being considered (Norris and Marshall, 1995). A problem with a total of m alternatives characterized by n attributes is described by an $m \times n$ matrix [X] shown below. The element X_{ij} in the matrix is termed as the j th attribute value for alternative i.

$$[X] = \begin{bmatrix} X_{11(\text{Information about alternative 1 with respect to attribute 1})} & & X_{1n(\text{Information about alternative 1 with respect to attribute n})} \\ & X_{ij(\text{Information about alternative i with respect to attribute j})} & \\ X_{m1(\text{Information about alternative m with respect to attribute 1})} & & X_{mn(\text{Information about alternative m with respect to attribute n})} \end{bmatrix} = [X_{ij}] \qquad (2\text{-}1)$$

There are four steps included in MCDM methods: Criteria Development; Criteria Weighting; Alternatives Scoring; Synthesis and Selection.

2.4.2.1 Criteria Development

Ye *et al* (2006) has claimed that a good criteria selection should be systematic, consistent, independent, measurable and comparable. The criteria are suggested to organise into different levels, from general ones to specific ones. On the same level, criteria should be mutually exclusive, and they should be inclusive against the upper level of criteria. This rule is not easy to comply when it comes to the organisation of sustainability criteria, due to the interrelationship between economic, environmental, social and technical criteria. A structured approach is suggested to organise these criteria to avoid information overlap (Si *et al.*, 2016). For instance, the criterion of boiler efficiency can be dealt with as technical criterion, but also can be considered for the criteria category of financial cost, environmental performance or social performance. This depends on how to interpret this criterion and to which depth this criterion has been explained. When the boiler efficiency has been improved, the costs can be reduced, and the GHG emissions can be minimised, and at the same time, human wellbeing, which is an important aspect of social performance, can be improved. Thus, a precise definition of the criteria should be given and structuring principles should be clarified in the early stage of MCDM process (Si *et al.*, 2016).

Multiple criteria can be compiled through literature review, surveys, interviews and workshops (Pan *et al.*, 2012). After the compilation, an extensive list of criteria could be generated from stakeholders who have not enough knowledge about the interrelationships between these criteria. Methods are available to slim down the long criteria list after an investigation of the criteria interrelationships (Ibáñez-Forés *et al.*, 2014). These methods include Delphi method, Least Mean Square (LMS), Minmax deviation and Correlation Coefficient Method.

The Delphi method is to narrow down the number of the criteria through several times of discussions or surveys with experts (Rowe and Wright, 2001). The LMS method is to remove the criteria with a similar performance represented by alternatives, which is to keep more significant criteria in the list (Guo, 2007). The Minmax deviation method has the similar principle with the LMS method, which is to remove the criteria with the same weights assigned by stakeholders (Ye *et al*., 2006). The Correlation Coefficient Method is to decide the criteria based on their correlation. If the correlation coefficient between two criteria is close to 1, one of them would be removed. (Papadatos and Xifara, 2013).

2.4.2.2 Criteria Weighting

Weighting methods are classified into equally weighting and rank-order weighting (Pöyhönen and Hämäläinen, 1998). In equally weighting, criteria have equal weights. In rank-order weighting, criteria weights are distributed and ranked. Rank-order weighting methods include objective weighting method, subjective weighting method and combination weighting method (Wang, Jing and Zhang, 2009). The objective weighting method is characterised by mathematical models, a complex calculation process and intensive data requirement (Løken, 2007), which have been found fallen into disuse (Ibáñez-Forés *et al.*, 2013). The subjective weighting method is to collect criteria weights directly from stakeholders by interviewing or questionnaire. The combination weighting method is used to balance the merits and limitations of the objective weighting method and the subjective weighting method, but the process is very complex and not widely-used (Wang, Jing and Zhang, 2009).

Current research has seen a wide use of subjective weighting methods. Typical subjective weighting methods include Simple Multi-Attribute Rating Technique (SMART), Swing method and Pair-wise comparison methods. In SMART, the least important criterion is initially assigned with 10 points and more important criterion is assigned with increased points but no exceeding 100 points (Zardari *et al.*, 2015). In Swing method, the criteria which are expected to be improved dramatically are assigned with the most points (100 points), and the other criteria will be given with fewer points depending on their expected improvements. The pair-wise comparison method is to compare the relative importance of the two criteria (Linkov and Moberg, 2012). The analytic hierarchy process (AHP) is one of most commonly used pair-wise comparison methods, with a 9-scale to indicate the relative importance of the criteria. Since individual judgements can never agree perfectly, the degree of consistency achieved in the pair-wise comparison is measured by the consistency ratio (Saaty, 1990). Saaty (1989) advocates the use of consensus by voting to reach a common pairwise comparison matrix or by aggregating individual judgments using the geometric mean of the individual pairwise comparison matrix. The former approach is applicable when the members can meet as a group. The latter can be used when a group meeting is not applicable (Dyer and Forman, 1992).

2.4.2.3 Alternatives Scoring

After the criteria development and criteria weighting, alternative scoring can be conducted to evaluate the overall performance of the alternatives. The alternative performance may be evaluated with quantitative data or in qualitative information (Collier *et al.*, 2013), which can be dealt with in different ways. The quantitative data should be normalised to compare criteria with different dimensions and distribution. The qualitative information can be converted into the numerical values through pre-defined utility functions. One of the most commonly used utility function is the linear utility function, in which, the interpolation method is used to assigned the numerical values to the qualitative performance by setting the maximum and minimum values (Collier *et al.*, 2013). When the utility function is not easy to develop, the AHP method can be used as an alternative way to assign the relative numerical values to the qualitive information.

2.4.2.4 Synthesis and Selection

Synthesis and selection is the final step of MCDM process, which is to select the suitable model to decide the overall performance of alternatives. Several methods including Multi-Attribute Utility Theory (MAUT), AHP and Outranking are used for synthesis (See Table 2.2).

MAUT methods are the elementary methods, which are classified into the Weighted Sum Model (WSM) and the Weighted Product Model (WPM). The WSM method uses an addition of values in the calculation while the WPM method deploys a multiplication. AHP is developed based on the WSM model, with an addition of weighted alternative performance. Outranking methods are used in the cases that some alternatives outperform the others. These methods are based on the principle that a disadvantage on a particular criterion can be compensated by advantage on the other criteria (Pirlot, 1997). When dealing with different ranking results derived from different synthesis methods, the aggregation methods can be deployed to assess which synthesis method is the best. The aggregation methods include voting methods and mathematical aggregation methods. The mathematical aggregation methods are further classified into hard and soft aggregation methods (Wang *et al*., 2009).

Table 2.2 Overview of MCDM methods (Source: Pohekar and Ramachandran, 2004; Linkov and Ramadan, 2004)

Method		Main characteristics
Multi-Attribute Utility Theory or Multi-Attribute Value Theory (MAUT)	Weighted sum model(WSM)	Good for single dimensional problems, but not always suitable for multi-dimensional MCDM problems
	Weighted product model(WPM)	Can be applied to single and multi- dimensional problems, but is not suitable qualitative criteria assessment.
Analytical Hierarchy Process(AHP)		Deconstructed an MCDM problem into a hierarchy of criteria and sub-criteria to be recomposed systematically to generate the rankings of decision alternatives. The identification of criteria weights is challenging and is mostly influenced by decision makers' judgments and preferences.
Outranking	PROMETHEE	Applicable to decision problems that involve few criteria with a large number of alternatives.
	ELECTRE	
	TOPSIS	

2.4.3 Review of typical MCDM methods

Multi-Attribute Utility Theory (MAUT)

MAUT method is the most commonly utilized MCDM method identified in this study (Fishburn, 1967; Keeney, 1974). MAUT is essentially an extension of Multi-Attribute Value Theory (MAVT) and is "a more rigorous method for how to incorporate risk preferences and uncertainty into multi criteria decision support methods". Under MAUT, there are two different models, the Weighted Sum Model (WSM) and the Weighted Product Model (WPM) methods (Fishburn, 1967; Keeney, 1974).

1) The WSM method

The WSM method is commonly used in single dimensional problems. The assumption based is the additive utility assumption, which means the total value of each alternative is equal to the sum of the products (Fishburn, 1967). The difficulty will emerge when the WSM method is applied to multi-dimensional MCDM methods. This problem can be solved in WPM method.

2) The WPM method

The WPM method is similar to WSM, and the difference lies in the equation where the addition is replaced by multiplication (Miller and Starr, 1969). Each alternative is compared with the others by multiplying a number of ratios, one for each evaluation criterion. If the term R (A_k/A_L) is greater than or equal to one, then it indicates that alternative A_k is more desirable than A_L. The WPM is sometimes called a dimensionless analysis because it uses the quotient to reduce the dimension of the units.

Analytic Hierarchy Process (AHP)

AHP is one of most widely-used MCDM methods to enable a consideration of quantitative data and qualitative information. The process using AHP include four steps (Saaty, 1980):

1. Structuring different levels of hierarchy between criteria and alternatives;
2. Composing the matrices of pair-wise comparison (MPC);

3. Weighting the criteria and scoring the alternative performance;
4. Synthesising the criteria weights and alternative scores.

For the first step, hierarchy structuring follows the rule that the overall objectives are placed on the top, and below them, are more specific criteria. For each of the criteria, there are a range of alternatives. To rank these alternatives, all the criteria will be firstly given weighting values, which can be conducted through the pair-wise comparison. Alternatives are also compared in pairs, and the results are organised into a scale of 1-9, indicating the relative importance from the equal importance (value of 1) to the extreme importance (value of 9). (Mafakheri *et al.*, 2007).

The pair-wise comparisons are conducted between criteria to identify their relative importance. In the matrices of pair-wise comparison, criteria weights are calculated following the following steps (Konidari and Mavrakis, 2007):

1) Each element within the column of MPC is divided by the sum of the column;
2) Elements of the same row are added up and the sum is divided by the number of criteria of sub-criteria, which is to normalise each element of these matrices and to produce criteria weights;
3) This procedure is followed for all levels.

A typical pairwise comparison matrix is shown as [A] in Equation (2-2):

$$[A]= \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} c_1/c_1 & c_1/c_2 & \cdots & c_1/c_n \\ c_2/c_1 & c_2/c_2 & \dots & c_2/c_n \\ \vdots & \vdots & \ddots & \vdots \\ c_n/c_1 & c_n/c_1 & \cdots & c_n/c_n \end{bmatrix} \tag{2-2}$$

In the above matrix, a_{ij} is a pair-wise comparison between sub-criteria c_i and c_j in terms of the upper criteria. We can have a matrix of the pair-wise comparison for each layer of criteria to reflect the decision makers' preferences.

If matrix [A] satisfies the cardinal consistency property of $a_{ij}a_{jk} = a_{ik}$, it is referred to as reciprocal. For a reciprocal matrix [A], we have the equation (2-3):

$$[\mathrm{A}][w] = \lambda_{\max}[w], \tag{2-3}$$

where $\lambda_{\max}$ refers to the largest eigenvalue of [A], and $[w]$ is the weight vector that corresponds to the alternatives. Given the value of $\lambda_{\max}$, the consistency of decision makers' judgments can be checked. The consistency index (C.I.) is computed using the equation (2-4), where *n* is the size dimension of the matrix.

$$\text{C.I.} = \frac{\lambda_{\max} - n}{n-1}, \quad (2\text{-}4)$$

In order to interpret the C.I. value of a particular matrix, a ratio called C.R. is calculated using the equation (2-5):

$$\text{C.R.} = \frac{\text{C.I.}}{\text{R.I.}} \quad (2\text{-}5)$$

where the random Index (R.I.) is the average C.I. value of a large sample of randomly generated reciprocal matrices (Saaty, 2000). R.I. have different values for different dimensions of matrices, which are 0 for a 2×2 matrix, 0.58 for 3×3, 0.90 for 4×4, 1.12 for 5×5, 1.24 for 6×6, 1.32 for 7×7, 1.41 for 8×8 and 1.45 for 9×9. The ratio of C.I. value and R.I. If C.R.$<$0.1, the consistency is accepted; if C.R.≥0.1, the matrix is not consistent and the judgments should be adjusted (Saaty, 1980).

Outranking method

1) The ELECTRE method

The ELECTRE method, short for Elimination and Choice Translating Reality method, was first introduced by Benayoun *et al.* (1966). It is used to deal with outranking problems. The outranking relationship of two alternatives A and B, is that although the score of A is higher than B obtained through pair comparison, the decision maker still takes risk to choose B, just because the decision maker is more certain about the performance of B.

2) The TOPSIS method

The TOPSIS method, short for Technique for Order Preference by Similarity to Ideal Solution was developed by Hwang *et al.* (1980) as an alternative to the ELECTRE method. The basic concept of this method is that the selected alternative should have the shortest distance from the ideal solution and the farthest distance from the negative ideal solution in a geometrical sense.

2.5 Research gap

Through a review of existing building retrofit practices, it has been found that conceptual frameworks of building retrofits from multiple criteria abound in the research. However, it is rare to see practical suggestions on how to conduct this multi-criteria analysis to select green technologies and/or measures. Additionally, research on technology listing and screening need more discussion and investigation, since they are important phases prior to technology selection and evaluation. All these phases should be considered for an integral framework of building retrofits.

Through a review of green technology selection and evaluation, we found that single-criteria analysis, such as Cost Benefit Analysis is still dominant. Multi Criteria Decision Making (MCDM) methods can be found in technology selection and evaluation, but still limited.

Through a review of stakeholder perspectives for green technology selection, it has been identified that criteria weighting is an important phase to involve different stakeholder perspectives and the weighting values play crucial roles in changing the selection results. This phase should be further investigated for building a retrofit decision making process.

By identifying these research gaps, we intend to further explore green retrofit of existing buildings as a multi-criteria decision making process. In this decision making process, green technology selection is our focus and an integrated assessment of framework will be developed for green technology selection. We clarify our research boundary by emphasising the technology part and by excluding occupant behaviour.

Chapter 3 Research Design

3.1 Purpose of the research and the proposal of a mixed-methods approach

The purpose of this research is to develop an integrated assessment framework of green retrofit for non-domestic buildings. To achieve this purpose, five research objectives have been developed. To achieve these multiple research objectives, a mixed-methods approach has been proposed. The selected methods include *Literature review*, *Survey approach*, *Data analysis* and *Case study*. In Case study, scenario analysis and sensitivity analysis have been also applied. The following is to provide an explanation on how individual research method can help to achieve the research objectives.

The first objective is "to cross reference green technologies specifications against operational characteristics of different non-domestic building types". This objective should base on an extensive literature review on characteristics about green technologies and non-domestic buildings. The review of green technology specification will investigate into the aspects of design, financial, and environmental considerations as well as planning permissions about selected green technologies. The review of building operational characteristics will investigate the building function, occupancy hours, energy end use, and health and safety requirements. Based on the literature review, the interrelationship of green technologies and building characteristics can be identified. The interrelationship will be explained in two aspects: 1) Based on existing building characteristics, what are the potential technologies; 2) what green technologies may be applicable to different types of non-domestic buildings.

The second objective is "to develop an integrated framework of green technology selection phase by phase by including proposing technologies, screening technologies and evaluating technologies". The organisation of the framework development should base on the review of existing frameworks of green technology selection and other relevant frameworks of building retrofits. The review of existing frameworks and knowledge of building retrofits is crucial for the framework development. The review of multiple criteria decision making (MCDM) methods into green technology selection is essential to identify the key steps in the MCDM process.

The third objective is “to propose a default multi-criteria tree covering sustainability criteria and technical criteria”. Two topics are included in this objective: criteria proposal and criteria organisation. The proposal of sustainability criteria and technical criteria will be conducted based on an extensive literature review of sustainability assessment for green technologies and technical performance assessment for green technologies. After referring to the existing research, a comprehensive criteria list will be proposed. The criteria selection and organisation will be further carried out based on their information and interrelationship.

The fourth objective is “to suggest default weighting values for proposed multiple criteria and methods to use these values”. The default weighting values will be proposed through the *survey approach*. A survey questionnaire will be designed for this research to gain knowledge about green technology selection in the building industry. Expert opinions will be collected for the criteria tree and criteria weighting. *Data analysis* include quantitative analysis and qualitative analysis. In quantitative analysis, descriptive analysis is used to describe the sample characteristics. AHP method is used to calculate the default weighting values. Qualitative analysis is used to analyse the collected information for the open question in the questionnaire.

The fifth objective is “to illustrate the use of each phase of the framework through real case study and make a scenario analysis by applying different sets of weighting values”. *Case study* is used to demonstrate the effectiveness of the proposed framework. In the real case study, each phase of framework will be carried out, from green technology proposal, to green technology screening and finally to the green technology evaluation. In the green technology evaluation, scenario analysis will be performed by applying different sets of criteria weights. To identify the key criteria that can influence the technology ranking results, the sensitivity analysis is conducted and the influence of criteria weights change on technology ranking results will be discussed.

The way how selected research methods can serve the research objectives and tasks is shown in Table 3.1.

Table 3.1 Research methods for research objectives and tasks

Research objectives	Research tasks	Research Methods
Literature Review	1) Sustainable buildings	Literature review
	2) Existing buildings retrofit	
	3) The practice of green technology selection	
	4) Decision Making Process and Multi-Criteria Decision Making (MCDM) methods	
Framework Development	1) Green technology characteristics (Appendix A)	Literature review
	2) Building operational characteristics (Appendix B)	
	3) Development of an integrated assessment framework of green technology selection	
	4) Proposal of default weighting values for multiple criteria	The Survey approach Data analysis
Framework application	To show how to apply the conceptual framework into real-life cases	Case study Scenario analysis & sensitivity analysis

3.2 The conceptualisation of the proposed framework

The conceptualisation of the green technology selection framework is the crucial part in this research. It has shown that there is no such an integrated selection framework of green technology for non-domestic buildings in the existing research. Literature review will be conducted to investigate the following questions:

1) What are the general knowledge and common phases in the frameworks of existing building retrofits?

2) Are these phases organised to make the frameworks comprehensive and logical?
3) How to integrate MCDM methods into the framework? And which steps in the MCDM methods should be emphasised and carefully addressed?

The general phases in the existing frameworks of existing building retrofits include information collection, decision modelling, solution selection and implementation. To develop a framework of green technology selection, it is suggested to provide more details on information collection through site and building survey. This information will be collected from existing research, especially the technical documents from ASHREA, CIBSE and BRE. After the site and building survey, a list of potential green technologies can be listed. Before the formal technology evaluation, technology screening is suggested making the decision process much more logical. The screening results could be one single suitable technology left, multiple technologies left and no suitable technologies left. For the decision making of multiple technologies, MCDM method is suggested to be integrated by steps. Criteria development and criteria weighting are the most important steps in the MCDM process, which are required more research. For the case of no suitable technology left, rechecking the potential technology list for more possibilities is suggested.

3.3. The survey approach

The *Survey approach* is mainly used to collect attitudes and preferences from populations. Surveys can be conducted through observation, in-depth interviews, structured interviews and survey questionnaires. The survey design, in general, includes the steps of survey sampling, question design, pilot survey and formal web-based survey.

3.3.1 Survey sampling

Sampling methods basically have two types: probability sampling and non-probability sampling (Pascal and Yves, 2005). Probability sampling decides samples randomly and the latter category decides samples with a certain purpose. Probability sampling methods include methods of simple random sampling, systematic random sampling, stratified random sampling and stratified sampling method (Ardilly and Tillé, 2006). Non-probability sampling methods include specific methods of quota sampling, purposive sampling, snowball sampling, self-selection sampling and convenience sampling methods (Ardilly and Tillé, 2006).

This survey aims at collecting expert opinions on decision criteria of green technology selection. These experts are expected to have working experience in building retrofits and be familiar with sustainability criteria. Given this special requirement of survey participants, one stage sampling method is not likely to identify the suitable survey sample. Thus, a multi-stage sampling strategy with multiple sampling methods is adopted: 1) to identify professional groups in built environment; 2) to determine expert groups who have working experience in building retrofit; 3) to select an individual expert to be the final sample. Figure 3.1 illustrates the multi-stage sampling strategy.

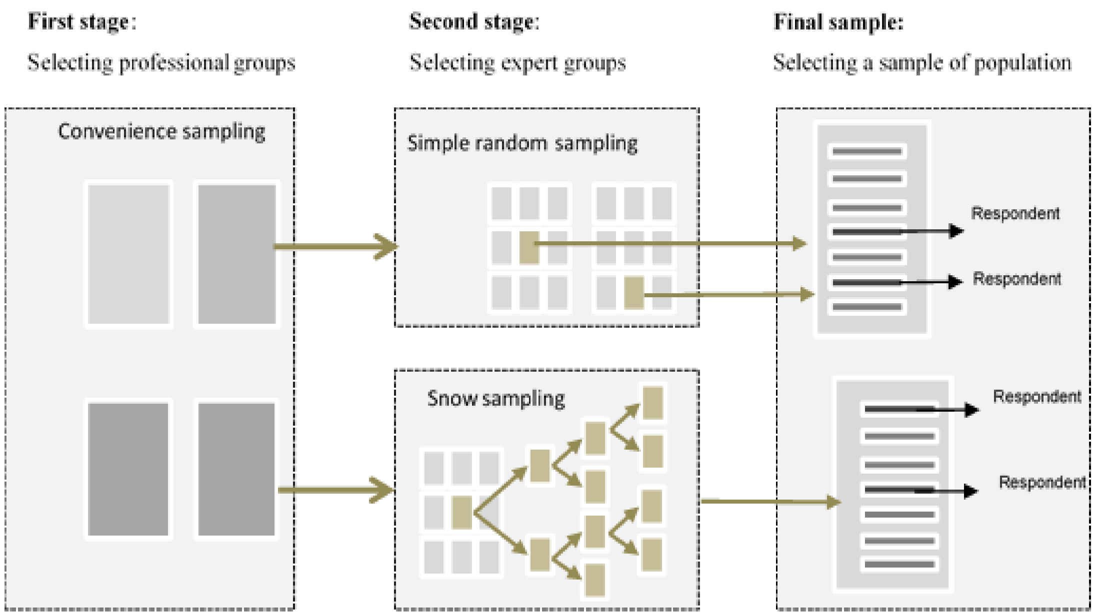


Figure 3.1 Multi-stage sampling method

Different sampling methods are applied to each stage. On the first stage, convenience sampling is used to identify professional groups due to their possible interest in participating in the survey (Bryman, Becker and Sempik, 2008). Targeted professional groups in the UK and China are listed in Table 3.2 with size estimation.

Table 3.2 Targeted professional groups and their size estimates

Country	Professional groups	Approximate Number
UK	Alumni community in Environmental design and Engineering	668
	Industry corporation intranet	50
	LinkedIn Connection	50
	Total	768
China	Institutes of Architectural Design	100
	Industry corporation intranet	50
	Higher Education Connection	50
	Total	200

In the second stage, two sampling methods are applied: Simple random sampling method and Snowball sampling method (Pascal and Yves, 2005). The latter one is mostly used in qualitative research to focus on a small number of participants but the selection of participants is crucial to the overall usefulness of the research findings (Fowler, 2013). Given the particular requirements for survey participants in this study, the combination of both sampling methods was used in order to maximise the reach. The response rate is not easy to calculate because the size of expert groups cannot be calculated.

3.3.2 Question design

The survey questions have been divided into three groups:

a) Respondent's relevant professional experience;

b) Further criteria development;

c) Criteria weighting for the proposed criteria.

The first group of questions consist of multiple-choice questions designed to collect basic information about respondents' professional experience relevant to retrofit projects. The second group of question is the open-format question, which is used to collect the suggestion for further criteria development which are not listed in the proposed criteria tree, see Figure 3.2.

The third group of questions which aim to inform criteria weighting is based on a 1-9 scale developed by Saaty (1980). The scale design is important for survey respondents who are not familiar with the AHP method to comprehend the principle. The scale has been designed by adapting a common scale with numbers, which is commonly used in research with the AHP method. The scale used in the survey is to show the relative importance of two criteria immediately, which enables respondents to provide their opinions directly instead of spending time on figuring out the meanings of scale values. Figure 3.3 illustrates the design of criteria weighting question.

Is there any criterion you want to add? If so, please also indicate its parent criterion on the hierarchy above. [For example: Community engagement (Social)]

Figure 3.2 Open-format question

For criteria weighting, apart from the pairwise comparison method, direct rating method can be also used. The direct rating method is to use direct numerical values to judge the importance of the criteria (Von Winterfeldt and Edwards, 1986). Although the direct rating method is straightforward and easy to implement, it just can provide a fairly structured not highly structured decision process for criteria weighting, which is limited to offering a logic and rational weighting for evaluation criteria. In this sense, AHP method is selected to collect the valuable weighting values from experts through pairwise comparison, which can clearly present the preference of decision makers against each set of two criteria.

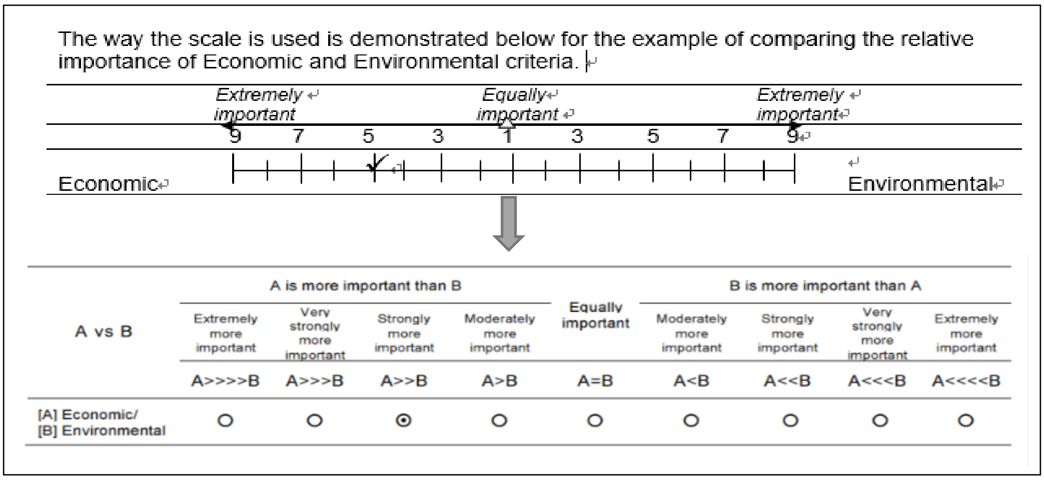


Figure 3.3 Example of criteria weighting question

3.3.3 Pilot study and formal web-based survey

The survey is initially designed in a paper version and tested within a group of 10 researchers working at UCL's Institute of Environmental Design and Engineering. Three feedback questions were individually asked when they returned the survey:

1. How long did it take you to complete the survey?
2. Did you find any questions ambiguous or difficult to answer?
3. Is there any difficulty in understanding the method doing criteria weighting?

All the participants in the pilot study thought that the questions are well developed and generally easy to understand, but a total of 43 pairwise comparisons might take a long time to answer and thus affect the number of returns. They suggested that a clear and concise explanation of technical criteria in the criteria tree is provided.

Based on the feedback, the survey has been improved by providing definitions for the technical criteria of compatibility and flexibility. The paper version survey is then designed into a formal web-based survey using survey design tools. Google form is used for the English version, and a survey design tool called "Sojump" (www. sojump.com) is used for the Chinese version. Survey links are generated and sent to all professional groups. The survey questionnaire is shown in Appendix C.

The data collection took approximately two months for each country. For the UK, the survey circulation and data collection were conducted from November-2015 to January-2016. For China, this was from January-2016 to February-2016. All the data collected were organised in the format of an Excel sheet for further statistical analysis. By extracting all the data from Excel spreadsheets, criteria weights can be calculated and further analysis is conducted using the following methods.

3.4 Data analysis

Data analysis is used to interpret data and draw conclusions from the data. *Descriptive statistics* will be used for the quantitative data analysis in this research, which is to describe the main features of a collection of data in quantitative terms. The relevant strategies include frequencies, percentages, and means for presenting descriptive findings. In this research, descriptive statistics are used to measure the sample size and response rate of the questionnaires, and analyse the statistical characteristics of collected samples from UK and China. The descriptive statistics can help to analyse the behaviour differences of UK experts and Chinese experts when selecting the green technologies for building retrofits.

AHP method, as one of the MCDM methods, is used to calculate criteria weights through the following three steps a) to c). The mathematical theory of AHP method can be found in Chapter 2 and the calculation is conducted with the assistance of MATLAB software.

a) The composition of matrices of pairwise comparison (MPC);

b) The consistency checking for MPC;

c) The criteria weights derivation using AHP method (Konidari and Mavrakis, 2007).

This 3-step process is applied to each response and expert groups. The geometric mean of individuals' judgements is used for the calculation of criteria weights for expert groups. Aczél and Saaty (1983) have shown that the geometric mean is uniquely appropriate for combining individual judgements because of its preservation of the property of the judgement matrix.

Based on the criteria weights derived from the AHP method, inferential analysis method is used to further analyse the differences of criteria weights between expert groups by using formula (3-1). Three levels are applied: "Large difference" (>50%), "Medium difference" (20%~50%) and "Small difference" (<20%).

$$Weights\ difference = \frac{Absolute\ value\ (w_i - w_j)}{1.000/n} \times 100\% \qquad (3\text{-}1)$$

Where w_i is the criteria weight given by expert group i, w_j is the criteria weight given by expert group j, n is the dimensions of pair-wise comparison matrix, $1.000/n$ is the average criteria weights for MPC with n dimensions.

Qualitative data analysis is used as a method to collect propositions or verify theories based on qualitative data (Taylor and Bogdan, 1984). The interpretation of qualitative information means "attaching significance to what was found, making sense of findings, offering explanations, drawing conclusions, extrapolating lessons, making inferences, considering meanings, and otherwise imposing order on an unruly but surely patterned world" (Patton, 2002: 480). In this research, this method is used to analyse the responses to the open question about criteria tree. All the responses will be collected and listed in their original texts. Based on this theory and the purpose of designing this open question, the suggestion on the reorganisation of criteria tree will be highlighted.

3.5 Case study

Case study is the empirical inquiry into the real-life context of the research work and can be regarded as an observational study (Yin, 2003). In this research, the method of *case study* is applied for the framework demonstration. Through real case study, the benefits and limitations of the proposed framework can be identified. The feasibility of the framework application into real cases can be analysed and suggestions on framework use and further development can be summarised. In this research, the proposed framework will be applied into an old academic building with the potential of retrofitting. The technology selection and evaluation will be carried out by steps, and the final results will be compared with retrofit suggestions proposed by a consultancy report. Through the comparison, the values and limits of the framework can be drawn from the findings.

In this research, the default weighting values will be the important contributions to the knowledge. Different sets of default weighting values will be applied in different scenarios. Through scenario analysis, the overall scores of the technology performance can be compared. To identify the key criteria that can influence the technology ranking, sensitivity analysis is conducted. Through sensitivity analysis, different scenarios with different weighting values can be helpful to observe the impact on final alternative rank (Syamsuddin, 2013). Erkut and Tarmcilar (1991, p.65) have summarised sensitivity analysis in relation to weights as:

1) "What if the weight of one criterion is changed from w_i to $w_i(1+p)$?
2) For which set of values of the weights will a particular alternative have the highest final ranking?
3) How sensitive is the final selection result to the changes in the weighting values?
4) What is the smallest change in the weights that will result in a change of the selected alternative?"

Considering there are two criteria included on each level in this study, the sensitivity analysis for two criteria is selected to be discussed. For the case with two criteria, the weight values of one criterion can be changed (increased or decreased) by a degree, and the sum of weights for these two criteria should remain as one. The final value of alternative i is given as below, which is a function of the single variable w_1.

$$V_i = w_1 x_{i1} + w_2 x_{i2} = w_1 x_{i1} + (1 - w_1) x_{i2} = (x_{i1} - x_{i2}) w_1 + x_{i2} \quad (3\text{-}2)$$

Chapter 4 Framework Development

4.1 Overview

Existing buildings can improve their overall sustainable performance by incorporating green technologies or cost-effective technical measures. Comprehension of building and technology characteristics and a multi-criteria assessment of counterpart alternatives are essential for the selection of right green technologies. Without matching up building and technology characteristics and a multi-criteria assessment for potential alternatives, the integration of green technology may not yield desired improvements in sustainable performance. Thus, an integrated assessment framework of green technology selection for non-domestic building retrofits was developed and is presented in this chapter. This framework is to provide a logical structure for identifying retrofit opportunities in existing buildings and evaluating potential alternatives against sustainability triple bottom lines and technical criteria. The framework is designed in such a way that it can be applied to multiple types of non-domestic buildings. It can assist project stakeholders who intend to retrofit buildings effectively and reasonably identify the optimal technology. These project stakeholders can be:

- Building owners;
- Real-estate developers and investors;
- Facility managers, energy managers and building operators;
- Architects, designers and planners.

The generic assessment framework of green technology consists of multiple phases, including:

- Site and building survey
- Potential technology listing
- Technology screening
- Technology evaluation

These four phases are developed in order to identify opportunities and limitations of existing buildings, understand green technology characteristics, check and screen technology from a broad perspective on the project level and evaluate technologies against multiple criteria with MCDM methods. Green technology evaluation with MCDM methods is divided into four steps:

- Criteria development
- Criteria weighting
- Technology scoring
- Results synthesis

The flow chart of the framework is shown in Figures 4.1 and 4.2.

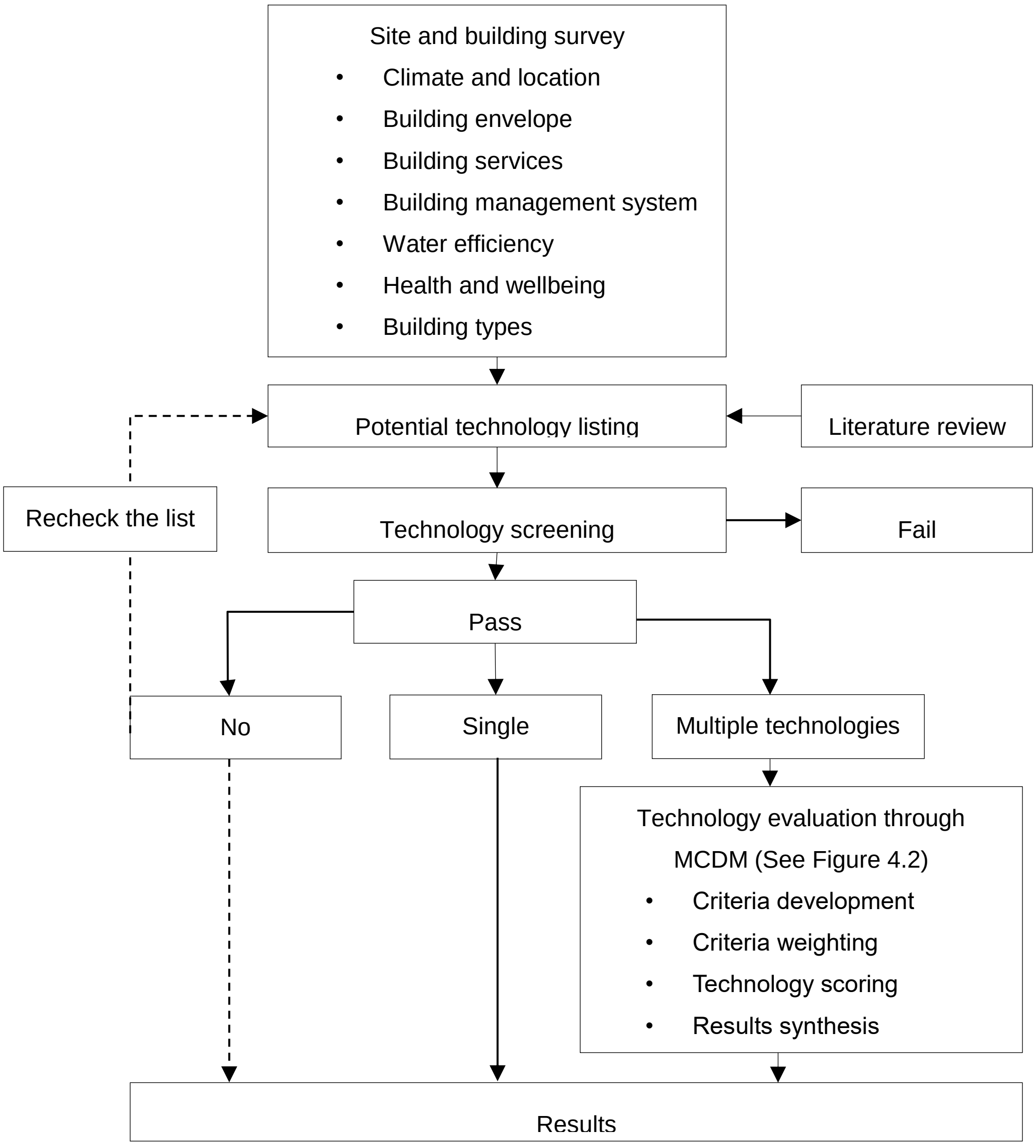


Figure 4.1 The generic assessment framework of green technology selection

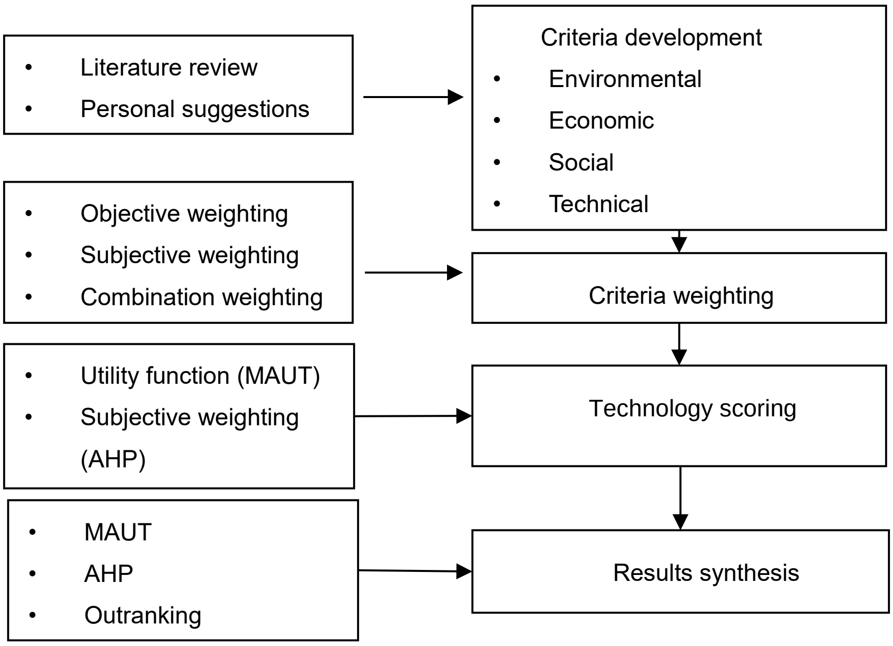


Figure 4.2 Technology evaluation with MCDM methods

4.2 Site and Building Survey

The purpose of the site and building survey is to collect information describing current building characteristics and its performance in terms of energy conservation, water efficiency as well as health and wellbeing improvement. This building-specific information such as such as geographic location, building type, size, age, occupancy schedule, operation and maintenance, energy sources, building fabric, services systems, etc. relates to the selection of the potential green technologies (Ma *et al.*, 2012). We categorised this information into the following types and the reasons why they have been selected are explained:

- Climate and location
- Building envelope
- Building services
- Building management system
- Water efficiency
- Health and wellbeing

Information about climate, such as temperature and precipitation, inform the heating or cooling requirements (CIBSE Guide F, 2012). The location information informs the feasibility of green technologies, such as wind turbines (Sara, 2011) and Ground Source Heat Pump (CIBSE TM51, 2013). Information about building envelope, including orientation, number of floors, footprint type, construction material, window/wall ratio, cavity wall, roofs and windows (CIBSE Guide F, 2013), plays a key role in determining heating and cooling requirements of buildings, natural lighting and ventilations, as well as levels of comfort (CIBSE Guide F, 2013). By investigating this information, the potentials of improving the building performances through green technologies can be identified. Building services, such as fuels and energy end-use categories of space heating, space cooling, ventilation, lighting, domestic water and appliances (CIBSE TM51, 2013), are suggested to investigate in the site and building survey. By understanding the status of building services, the suggestions of building performance improvement can be proposed. Building

Management Systems (BMS) checking can be used to reduce energy consumption and enable an effective monitoring and good control of internal comfort conditions for the building occupants (CIBSE Guide H, 2009). Water efficiency is an important aspect of achieving sustainability in the building performance, and the options for reducing water demand, supplying water efficiently and for use of rainwater or treatment and reuse of water are suggested to check their possibility (CIBSE Guide L, 2007). Health and wellbeing is also an important aspect in the delivery of green buildings. By referring to the LEED rating system (USGBC, 2016) and the WELL Building Standard (USGBC, 2014), the health and wellbeing category are proposed and this category of information is suggested to include physical health and mental health. Information about physical health is suggested to refer to indoor environmental health (ASHREA Handbook-HVAC Applications, 2013), which include indoor air quality, thermal comfort, visual comfort and acoustic comfort.

All information is organised into different levels, from general to specific. Following these levels, retrofit opportunities and corresponding green technology can be identified. The information is also coded to enable us to demonstrate the application of relevant information in a compact way.

4.2.1 Climate and location

Information about climate (CL) informs heating or cooling requirements since temperature conditions and weather variations have strong effects on buildings' energy requirement for heating or cooling. Cooling degree days (CDD) and heating degree days (HDD) are used to evaluate climate impact on building energy usage. Location (LO) information helps to identify the limitation for green technology applications. Both climate and location can inform whether or not it would be possible to integrate solutions based on renewable energy (ANSI/ASHRAE STANDARD 169, 2013).

In Table 4.1, Climate (CL) is at Level 1 categorized into five types: Tropical (CL.1), Dry (CL.2), Temperate (CL.3) and Polar (CL.4). Tropical climate (CL.1) is characterised by high temperatures and relative humidity as well as a high level of precipitation. Dry climate (CL.2) is characterised by high temperature with little precipitation. Temperate climate (CL.3) is characterised with the relatively moderate temperatures and is further described at Level 2 as having lower HDD (CL.3.1) or having lower CDD (CL.3.2). The continental climate of having lower HDD (CL.4.1) is further classified at Level 3 as having a high percentage of sunny days (CL.3.1.1) and having a lower percentage of sunny days (CL.3.1.2) at Level 3. Polar climate (CL.4) is characterised by low temperatures.

Location (LO) is categorised into three types at Level 1: Urban (LO.1), Semi-urban (LO.2) and Rural (LO.3). Urban (LO.1) is further described at Level 2 as high density (LO.1.1) and low density (LO.1.2). Both Semi-urban and Rural have two level 2 sub-categories: Coastal (LO.2.1) or Inland (LO.2.2).

Implications for green technology selection through checking the information of climate and location formally used in the framework are presented below. These implications are mainly drawn from the Appendix A: Green technology characteristics. They are coded to be consistent with the notes of Table 4.1.

1) When the building is located in a tropical (hot and humid) or dry (arid) climate, efficient cooling technologies should be considered. Since sunny days prevail in such climates, solar PV should also be considered (Pester and Crick, 2013);

2) When the building is located in a temperate climate, passive solutions such as improving envelope thermal performance, daylight and/or natural ventilation optimisation should be considered (Omrany and Marsono, 2016);

3) When the building is located in a temperate climate with cooling degree days being much longer than heating degree days, efficient cooling solutions should be given priority over heating solutions. When the building is located in a temperate climate with cooling degree days being less than heating degree days, efficient heating solutions should be given priority over cooling solutions (ANSI/ASHRAE STANDARD 169, 2013);

4) When the building is located in a temperate climate with cooling degree days being much more than heating degree days, as well as having a high percentage of sunny days, solar PV can be considered (Pester and Crick, 2013);

5) When the building is located in a polar climate, efficient heating technologies have to be considered;

6) When the building is located in an urban area with high-density population, green technologies requiring space and/or planning permission might not be feasible. For such locations, wind turbines and Ground Source Heat Pump (GSHP) may not be feasible (CIBSE TM51, 2013). Heating systems with biomass boilers might also be problematic due to the requirement of biomass supply (CIBSE AM15, 2014);

7) When the building is located in semi-urban and rural places, biomass boilers can be considered since biomass is more likely available in such areas (CIBSE AM15, 2014); GSHP can be also considered due to space availability (CIBSE TM51, 2013);

8) When the building is located in coastal places in semi-rural or rural areas, wind turbines may be feasible since wind speed may be likely to reach the technical requirement and on-shore installation can be a possibility (Ledo, Kosasih and Cooper, 2011).

Table 4.1 Hierarchical Information for Climate and Location (CL& LO)

		Level 1	Level 2	Level 3
Climate and Location (CL&LO)	Climate (CL)	1. Tropical (Hot and humid) (CL.1)		
		2. Dry (arid) (CL.2)		
		3. Temperate	1. Cooling Degree Days are much larger than Heating Degree Days. (CL.3.1)	1. High percentage of sunny days (CL.3.1.1)
				2. Low percentage of sunny days (CL.3.1.2)
			2. Cooling Degree Days are smaller than Heating Degree Days. (CL.3.2)	
		4. Polar (CL.4)		
	Location (LO)	1. Urban (LO.1)	1. High density (LO.1.1)	
			2. Low density (LO.1.2)	
		2. Semi-urban(LO.2)	1.Coastal (LO.2.1)	
			2. Inland (LO.2.2)	
		3. Rural (LO.3)	1. Coastal (LO.3.1)	
			2. Inland (LO.3.2)	

Notes:

- CL.1/CL.2: Efficient cooling technologies should be considered first.
- CL.3: Passive solutions should be considered, such as daylight use and natural ventilation.
- CL.3.1: Efficient cooling solutions should be given more priority over heating solutions.
- CL.3.2: Efficient heating solutions should be given more priority over cooling solutions.
- CL.3.1.1: Solar PV should be considered.
- CL.4: Heating technologies have to be considered.
- LO.1.1: Wind turbines, Ground Source Heat Pump (GSHP) and biomass boilers may be not feasible.
- LO.2/LO.3: Biomass boilers and GSHP should be considered.
- LO.2.1/LO.3.1: Wind turbines can be considered.

4.2.2 Building envelope (BE)

Building envelope, as the boundary between the conditioned interior of the building and the outdoors, plays a key role in determining heating and cooling requirements of buildings, natural lighting and ventilations, as well as levels of comfort (Lee *et al.*, 2002). Building envelope, which is defined in a broader perspective, includes information about orientation, number of floors, footprint type, construction material, window/wall ratio, cavity wall, roofs and windows (CIBSE Guide F, 2013). These factors are proposed due to their impacts on building performance.

Information included in Building Envelope (BE) includes 10 sub-categories at Level 1: Orientation (BE.1), Number of floors (BE.2), Footprint type (BE.3), Construction material of the roof (BE.4), Window/wall ratio (BE.5), Non-cavity wall (BE.6), Cavity wall (BE.7), Roof (BE.8), Single glazed windows (BE.9) and Double glazed windows (BE.10). Orientation (BE.1) is categorised into four types at Level 2: North (BE.1.1), South (BE.1.2), East (BE.1.3) and West (BE.1.4). Figure 4.3 has demonstrated these four types. Number of floors (BE.2) is described at Level 2 as High-rise (BE.2.1) and Normal (BE.2.2). Footprint type (BE.3) has three subcategories at level 2: Deep plan (BE.3.1), Narrow plan (BE.3.2) and Courtyard plan (BE.3.3). Construction material (BE.4) is categorised into three types at level 2: Lightweight (BE.4.1); Medium-weight (BE.4.2); Heavyweight (BE.4.3). Window/wall ratio (BE.5) has three subcategories at level 2, including Small (BE.5.1), Medium (BE.5.2) and High (BE.5.3). Cavity wall (BE.7) is described at Level 2 as: With insulation (BE.7.1) and No insulation (BE.7.2). Roofs (BE.8) is described at Level 2 as Flat (BE.8.1) and Pitched(BE.8.2). Both Single glazed windows (BE.9) and Double glazed windows (BE.10), have two subcategories: Operable (BE.10.1) and Fixed (BE.10.2).

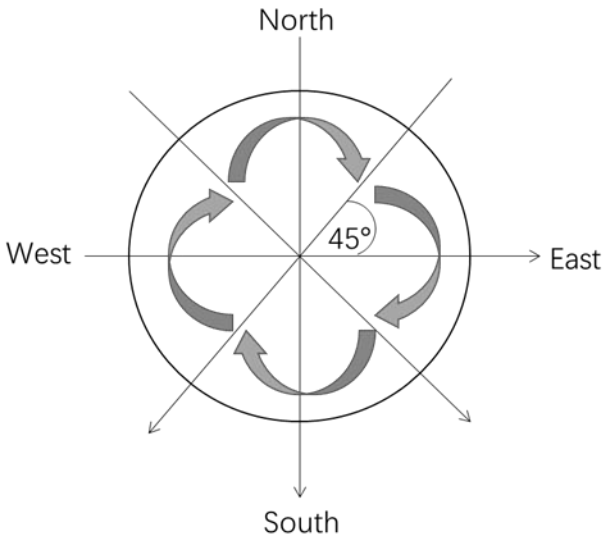


Figure 4.3 Eight types of orientation

Implications for green technology selection through checking building envelope information are explained as below (corresponding to the notes below Table 4.2):

1) If the building is narrow plan or courtyard plan, natural ventilation should be considered (Bryan 2010);
2) If the building roof is constructed with lightweight materials, structural reinforcing is required for the installation of solar PV (Arup, n.d.), wind turbines (Ledo, Kosasih and Cooper, 2011) or green roof (Hui, 2013) ;
3) If percentage of glazing in the building is medium or large, daylight optimisation and lighting control should be considered (Didwania and Mathur, 2011);
4) If the wall of the building is a non-cavity wall, the possibility of insulation on the (external and internal side should be checked (Hall and Nicholls, 2008). External insulation is not possible for heritage building and internal insulation is not preferable if the building inner space needs to be preserved (Hall and Nicholls, 2008);
5) If the wall of the building is cavity wall and without any insulation, insulation has to be considered (Hall and Nicholls, 2008);
6) For the building with unopenable windows, operable windows should be considered to make use of natural ventilation (National Institute of Building

Sciences, 2016).

Table 4.2 Hierarchical Information for Building Envelope (BE)

	Level 1	Level 2
Building Envelope (BE)	1. Orientation(BE.1)	1. North(BE.1.1) 2. South (BE.1.2) 3. East (BE.1.3) 4. West (BE.1.4)
	2. Number of floors (BE.2)	1. High-rise (BE.2.1) 2. Normal (BE.2.2)
	3. Footprint type (BE.3)	1. Deep plan(BE.3.1) 2. Narrow plan (BE.3.2) 3. Courtyard plan (BE.3.3)
	4. Construction material of the roof (BE.4)	1. Lightweight (BE.4.1) 2. Medium weight (BE.4.2) 3. Heavyweight (BE.4.3)
	5. Window/wall ratio (BE.5)	1. Small (BE.5.1) 2. Medium(BE.5.2) 3. High (BE.5.3)
	6. Non-cavity Wall (BE.6)	1. External insulation (BE.6.1) 2. Internal insulation (BE.6.2)
	7. Cavity wall (BE.7)	1. With Insulation(BE.7.1) 2. No insulation (BE.7.2)
	8. Roofs (BE.8)	1. Flat (BE.8.1) 2. Pitched(BE.8.2)
	9. Single glazed windows(BE.9)	1. Operable (BE.9.1) 2. Fixed (BE.9.2)
	10. Double glazed window (BE.10)	1. Operable (BE.10.1) 2. Fixed (BE.10.2)

Notes:

- BE.3.2/BE.3.3: Natural ventilation should be considered.
- BE.4.1: Structural reinforcing is required if Solar PV, wind turbine or green roof are considered.
- BE.5.2/BE.5.3: Daylight optimisation and lighting controls should be considered.
- BE.6: If insulation is not available, external or internal insulation should be checked for its feasibility.
- BE.7.2: Insulation has to be considered.
- BE.9.2/BE.10.2: Operable windows should be considered to make use of natural ventilation

4.2.3 Building Services (BS)

Building services surveying is to identify the energy source, energy end-use and the states of control systems. The major energy end-use categories for non-domestic buildings can include space heating, space cooling, ventilation, lighting, domestic water and appliances. More information about the energy end-use for different building types is presented in Appendix B. Through understanding the status of systems which provide for these energy end uses, retrofit opportunities through green technologies or technical measures can be more accurately identified. The selected information for building services are mainly from the CIBSE Guide F, “Energy efficiency in buildings” (CIBSE, 2004).

Information included in Building Services (BS) is categorised into five types at Level 1: Energy source (BS.1), Heating (BS.2), Ventilation (BS.3), Cooling (BS.4) and Lighting (BS.5). Energy source (BS.1) is further categorised into five types at Level 2: Coal (BS.1.1), Oil (BS.1.2), Gas (BS.1.3), Electricity(BS.1.4) and Renewable sources (BS.1.5); for the Renewable sources (BS.1.5), there are soar energy(BS.1.5.1), wind energy(BS.1.5.2) and biomass(BS.1.5.3); Heating (BS.2) is further categorised into three types at Level 2 as Hot water (BS.2.1), Air (BS.2.2) and Electrical (BS.2.3). Heating with air is further categorised into two systems at Level 3: Central system (BS.2.2.1) and Local system (BS.2.2.2). Ventilation (BS.3) is categorised into two types at Level 2 as Natural (BS.3.1) and Mechanical (BS.3.2). Mechanical system (BS.3.2) is further described at Level 3 as Heat recovery (BE.3.2.1) and Variable speed control (BE.3.2.2). Cooling (BS.4) is categorised into two types at Level 2 as Central system (BS.4.1) and Local system (BS.4.2). Central system (BS.4.1) is further described into two types at Level 3 as All air (BS.4.1.1) and Air/water (BS.4.1.2); Local system is further described into two types at Level 3 as localised control (BS.4.2.1) and under BMS control (BS.4.2.2). Controls are listed at Level 4 for the central system and the local system. Lighting (BS.5) has three subcategories at Level 2 as Conventional incandescent lamps (BS.5.1), Compact Fluorescent lamps (BS.5.2) and LEDs (BS.5.3). These three types of lighting all have three types of lighting controls at Level 3, as Manual control, Timer control and Occupancy sensor.

Implications for green technology selection through checking building services information are explained as below (corresponding to the notes below Table 4.3):

1) When the energy source is coal, oil, gas, and/or electricity, renewable energy or less carbon intensive solutions should be considered. For example, gas-fired boilers can be replaced into biomass boilers or CHP (CIBSE AM15, 2014);
2) Localised controls for heating systems can help to improve energy efficiency. In buildings, where individual heating units are available in each room, localised control systems such as thermostatic control, manual control or on/off control should be considered (Muniak, 2015);
3) Energy saving measures for mechanical ventilation systems can be considered, including heat recovery and variable speed control (Mardiana-Idayu and Riffata, 2012);
4) There are two main types of energy efficient light bulbs. Compact Fluorescent Lamps (CFLs) and Light Emitting Diodes (LEDs). CFLs are a cost-effective option for most general lighting requirements. LEDs are available to fit both types of fittings and are particularly good for replacing spotlights and dimmable lights (Dubois *et al.*, 2015). They are more efficient than CFLs;
5) Individual control of lights can save 40% lighting end-use energy (Galasiu *et al.*, 2007). Lighting controls can also extend the calendar life of lighting lamps, creating a longer interval between lamp replacements and savings on maintenance materials and labour costs.

Table 4.3 Hierarchical Information for Building Services (BS)

	Level 1	Level 2	Level 3	Level 4
Building Services (BS)	1. Energy source (BS.1)	1. Coal (BS.1.1)		
		2. Oil (BS.1.2)		
		3. Gas (BS.1.3)		
		4. Electricity (BS.1.4)		
		5. Renewable sources (BS.1.5)	1. Solar energy (BS.1.5.1) 2. Wind energy (BS.1.5.2) 3. Biomass (BS.1.5.3)	
	2. Heating (BS.2)	1. Hot water (BS.2.1)	1. Manual control (BS.2.1.1)	
		2. Air (BS.2.2)	1. Central system (BS.2.2.1)	1. Automatic central control (BS.2.2.1.1)
			2. Local system (BS.2.2.2)	1. Localised manual control (BS.2.2.2.1)
		3. Electrical (BS.2.3)	1. Manual control (BS.2.3.1)	
	3. Ventilation(BS.3)	1. Natural (BS.3.1)		
		2. Mechanical(BS.3.2)	1. Heat recovery (BS.3.2.1) 2. Variable speed control (BS.3.2.2)	
	4. Cooling (BS.4)	1. Central system(BS.4.1)	1. All air (BS.4.1.1) 2. Air/water (BS.4.1.2)	
		2. Local system(BS.4.2)	1. Localised manual control (BS.4.2.1)	

			2. BMS control (BS.4.2.2)
	5. Lighting (BS.5)	1. Conventional incandescent lamps (BS.5.1)	1. Manual control (BS.5.1.1) 2. Timer control (BS.5.1.2) 3. Occupancy sensor(BS.5.1.3)
		2. Compact Fluorescent lamps (BS.5.2)	1. Manual control (BS.5.2.1) 2. Timer control(BS.5.2.2) 3. Occupancy sensor(BS.5.2.3)
		3. LEDs (BS.5.3)	1. Manual control (BS.5.3.1) 2. Timer control(BS.5.3.2) 3. Occupancy sensor(BS.5.3.3)

Notes:

- BS1.1/BS1.2/BS1.3/BS1.4: Renewable sources should be considered.
- BS2: For different types of heating systems, heating controls should be considered.
- BS 3.2: Energy saving measures should be considered for mechanical ventilation.
- BS 5.1: Energy efficient lighting should be considered.
- BS.5.1/BS.5.2/BS.5.3: Lighting controls can be considered.

4.2.4 Building Management System (BMS)

Information about Building Management System (BMS) is categorised into two levels (CIBSE Guide H, 2009). Level 1: Separate (BMS.1) and Integrated (BMS.2). For the separate system (BMS.1), it can be Lighting control only (BMS.1.1) or HVAC only (BMS.1.2) For these individual systems, the possibility to integrate them should be checked. Table 4.4 shows the hierarchical information for BMS.

Table 4.4 Hierarchical information for Building Management System (BMS)

	Level 1	Level 2
Building Management System (BMS)	1. Separate system for lighting and/or HVAC (BMS.1)	1. Lighting control only (BMS.1.1)
		2 Heating, Ventilation and Air-conditioning (HVAC) only (BMS.1.2)
	2 Integrated BMS (BMS.2)	

Note: BMS.1: To check whether there is an opportunity to integrate individual systems as an integrated Building Management system.

4.2.5 Water Efficiency (WE)

Water Efficiency (WE) can be achieved through Water saving (WE.1) and Water recycling (WE.2) (BioRegional and Association for Conservation of Energy, n.d.). Green measures for water efficiency include Spray/aerating/sensor/ time turn-off taps (WE.1.1); Dual, low flush toilet (WE.1.2); Waterless urinal (WE.1.3); and Meter installation (WE.1.4). Green measures for water recycling (WE.2) include Grey water recycling (WE.2.1) or Rainwater harvesting (WE.2.2) can be checked. Table 4.5 shows a hierarchical information for water efficiency.

Table 4.5 Hierarchical information for water efficiency (WE)

	Level 1	Level 2
Water Efficiency (WE)	1. Water saving (WE.1)	1. Spray/aerating/sensor/ time turn-off taps (WE.1.1) 2. Dual, low flush toilet(WE.1.2) 3. Waterless urinal(WE.1.3) 4. Meter installation (WE.1.4)
	2. Water recycling(WE.2)	1. Grey water recycling (WE.2.1) 2. Rainwater harvesting (WE.2.2)

Notes:

- WE.1: To check whether water saving measures on level 2 have been applied or more measures can be considered.
- WE.2: To check whether there is an opportunity to recycle water.

4.2.6 Health and Wellbeing (HW)

Health and Wellbeing (HW) is increasingly becoming an important concern for building performance improvement. Health and wellbeing (HW) include Physical health (HW.1) and Mental health (HW.2).

Physical health (HW.1) is suggested from three aspects (ASHREA Handbook-HVAC applications, 2013): Indoor air quality (HW.1.1); Thermal comfort (HW.1.2); Visual comfort (HW.1.3); Acoustic comfort (HW.1.4). Two indicators are suggested for Indoor air quality (HW.1.1): Concentration of CO_2 (HW.1.1.1) and Concentration of TVOC (HW.1.1.2) (ASHREA Handbook-HVAC applications, 2013). Visual comfort is suggested to measure in three levels: Low (HW.1.3.1), Medium (HW.1.3.2) and high (HW.1.3.3) (HSG 38, 2010). Low level is for the activity of movement of people, machines and vehicles; Medium level is for the activity of work requiring the perception of detail; A high level of illuminance is for the activity of work that requires the perception of fine detail. Table 4.6 shows a hierarchical information for Health and Wellbeing.

Table 4.6 Hierarchical Information for Health and Wellbeing (HW)

	Level 1	Level 2	Level 3	Level 4
Health and Wellbeing (HW)	1. Physical health (HW.1)	1. Indoor air quality (HW.1.1)	1. Concentration of CO_2 (HW1.1.1)	
			2. Concentration of TVOC (HW1.1.2)	
		2. Thermal comfort (HW.1.2)		
		3.Visual comfort (HW.1.3)	1. Average illuminance (lux) (HW.1.3.1)	1. Low 20-50 (HW.1.3.1.1)
				2. Medium 100(HW.1.3.2.2)
				3. High 200-500(HW.1.3.3.3)
			2. daylight (HW.1.3.2)	
		4. Acoustic comfort (HW1.4)		
	3. Mental health (HW.2)			

Notes:

- HW.1.1: To check whether two indicators of indoor air quality, including Concentration of CO_2 (HW1.1.1) and Concentration of TVOC (HW1.1.2) is monitored or not.
- HW1.3.1: To check whether visual comfort has reached a preferable level.
- HW1.3.2: To check the possibility of daylighting.

4.2.7 Building type

By checking information about climate and location, building envelope, building services, building management system, water efficiency, as well as health and wellbeing, potential green technologies can be proposed. Relevant references are provided for the technology proposal. More details about green technology characteristics can be found in Appendix A. At the same time, operational characteristics of non-domestic buildings can also inform the suitability of green technology selection. These operational characteristics mainly refer to building function, occupancy hours and energy use patterns, etc (See

Appendix B). By cross referencing Appendix A and B, the following provides suggestions of green technologies for different building types:

1) Offices and the large schools would usually have a large demand for electricity for lighting and appliances (CIBSE TM46, 2008), and as a result, lighting controls and/or supply of electricity from PV system should be considered.
2) Hotels, with swimming pools, have a large and continuous heat demand. Solar thermal can be considered (CIBSE TM22, 2006).
3) Higher education campuses have multiple buildings and have a continuous demand for heat and electricity, can consider CHP (CIBSE TM46, 2008). Multiple buildings can be connected to a district scheme to balance heat and electricity.
4) Hospitals with A&E, operating 24/7, CHP might be suitable for heat and electricity (CIBSE AM12, 2013).

4.3 Technology Screening

After a critical review of benefits and limitations of potential green technologies in relation to existing building operational characteristic, a screening process is suggested as a next step prior to the multi-criteria evaluation of technologies.

Screening criteria are suggested on three levels: technology, building, and community. Specific criteria include the maturity of technology and its supply chain, compliance with building design regulations, planning permission and social acceptance. We suggest to conduct this green technology screening after the site and building survey and potential technology listing to save unnecessary work in the technology evaluation. In technology screening, we suggest to first consider the technology maturity and its supply chain to meet the essential requirements of technology application. Then we suggest to check whether these technologies comply with building regulations. On the community level, we suggest to consider planning permission for some technologies, such as ground source heat pump. When necessary, social acceptability towards potential green technologies are also suggest to check. The three levels are shown in Figure 4.4 and more information for each level of screening criteria is also provided.

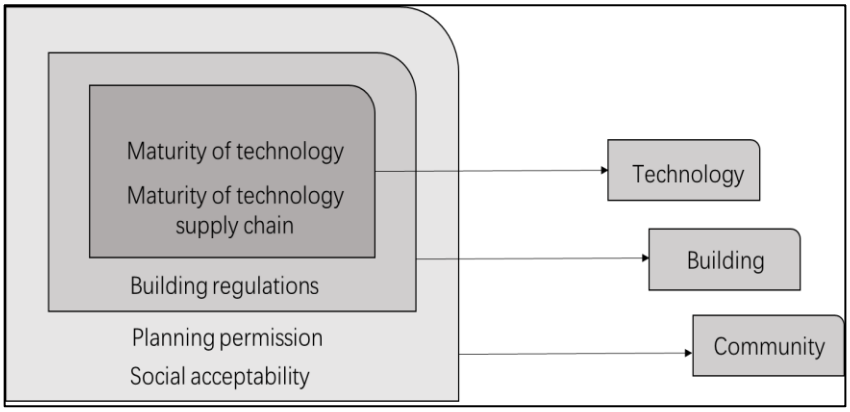


Figure 4.4 Suggested Screening criteria on different levels

A variety of renewable energy technologies is available at different stages of the development cycle, as indicated in Table 4.7. This table shows the global status, but the maturity of technology can be varied in different countries.

Table 4.7 Maturity of selected green technologies (Source: IEA, 2011)

Technology	Demonstration	Commercialisation
Solar PV	PV system -3rd generation	PV crystalline and thin-film
Solar thermal		Solar water heaters
Biomass	Thermal gasification	Anaerobic digestion
		Co-firing
		Modern boilers and stoves
Geothermal	Enhanced geothermal	Conventional geothermal
Wind		Offshore wind
		Onshore wind

The maturity of the technology supply chain can ensure a normal operation of green technologies. The supply chain includes technology provision, equipment manufacturing, distribution, as well as repair and maintenance. The maturity of technology supply chain is to ensure normal operation of green technologies.

On the building level, selected retrofit technologies or solutions must meet the relevant technical requirements in the Building Regulations and they must not make other fabric, services and fittings less compliant than they were before. Building Regulations set standards for the design and construction of buildings to ensure the safety and health for people in buildings. Examples of the England building regulations for selected green technologies are summarised in Table 4.8.

Table 4.8 Building regulation requirements for selected green technologies (Source: London Borough of Camden, 2013)

Green technology	Building regulations
Solar PV & Solar heating systems	Part A (Structural safety) - need to confirm the roof can take the weight of panels Part G (Sanitation, Hot Water Safety and Water Efficiency) – when altering hot water system Part J (Combustion appliances and Fuel Storage systems) – when altering boiler system Part P (Electrical safety)
Ground source heat pumps	Part E (Resistance to sound) Part G (Sanitation, Hot Water Safety and Water Efficiency) – when altering hot water system Part P (Electrical safety)
Air source heat pumps	Part E (Resistance to sound) Part G (Sanitation, Hot Water Safety and Water Efficiency) – when altering hot water system Part P (Electrical safety)
Biomass heating system Combined heat and power system	Part B (Fire safety) Part E (Resistance to sound) Part F (Ventilation) - Extraction flues should be positioned away from air intake vents and open-able window Part G (Sanitation, Hot Water Safety and Water Efficiency) – when altering hot water system Part J (Combustion appliances and Fuel Storage systems) – when altering boiler system Part P (Electrical safety)
Wind turbine	Part A (Structural safety) Part K (Protection from falling) Part P (Electrical safety)

On a community level, the particular type of buildings or buildings that are located in a conservation area may not receive planning permission for certain solutions or you may need to choose particular solutions.

4.4 Technology Evaluation with MCDM methods

After technology screening, there can be two outcomes, one single technology or multiple technologies remaining. For multiple technologies, comparison and ranking are suggested to conduct using MCDM methods. This decision making process with MCDM methods contains four steps: criteria development, criteria weighting, technology scoring and results synthesis.

4.4.1 Criteria development

A robust selection of green technologies takes account of multiple criteria. These criteria can be technical, such as capacity requirements, spatial requirements, reliability, and flexibility; economic, such as capital cost, operating cost and maintenance cost; environmental such as carbon reduction and energy saving potential; and social such as occupant health and safety and employment creation. These criteria can influence the decision makers' goal and be reflected as different priorities, which may be represented as criteria weights in decision support systems.

The criteria collection can be conducted through literature review, survey, interviews, or a combination of these methods. (Pan *et al.*, 2012). We have taken the approach of the literature review, and complied the list of criteria. By reviewing the existing research on criteria development, researchers (Sheikh and Kocaoglu, 2011; Huang *et al.*, 2012) suggest the criteria should be collected comprehensively to cover the economic, environmental, social and technical performance. Economic criteria are suggested to include capital cost and operation and maintenance (O&M) cost (Zainab *et al.*, 2013; Collier *et al.*, 2013), installation time (Zainab *et al.*, 2013; Collier *et al.*, 2013), payback period (Huang *et al.*, 2005), and available incentives (Nelms *et al.*, 2007). Environmental criteria can refer to consumption of resources and environmental impacts (Collier *et al.*, 2013). The social criteria are classified into organisation mission and welfare (Collier *et al.*, 2013), human health and safety, and employment creation (Odhiambo and Wekesa, 2010). Technical criteria can incorporated the criteria of technology efficiency (Wang *et al.*, 2009), the complexity of implementation (Nelms *et al.*, 2007), the service life (Odhiambo and Wekesa, 2010) and safety (Huang *et al.*, 2012).

Based on the suggestions from existing research and guided by the sustainability's triple bottom line, an integrative AHP hierarchy with multiple criteria is here proposed and presented in Figure 4.5 (Si *et al.*, 2016). The structure is informed by the individual criteria attributes and their interrelationships (Ibáñez-Forés *et al*., 2014; Yu *et al.*, 2015). This criteria tree is suggested in a comprehensive way of evaluating and comparing green alternatives. In rea cases, decision makers can adopt fewer criteria based on their goals, limitations and availability of data. In this case, the criteria tree may be slimmed down to a simplified version.

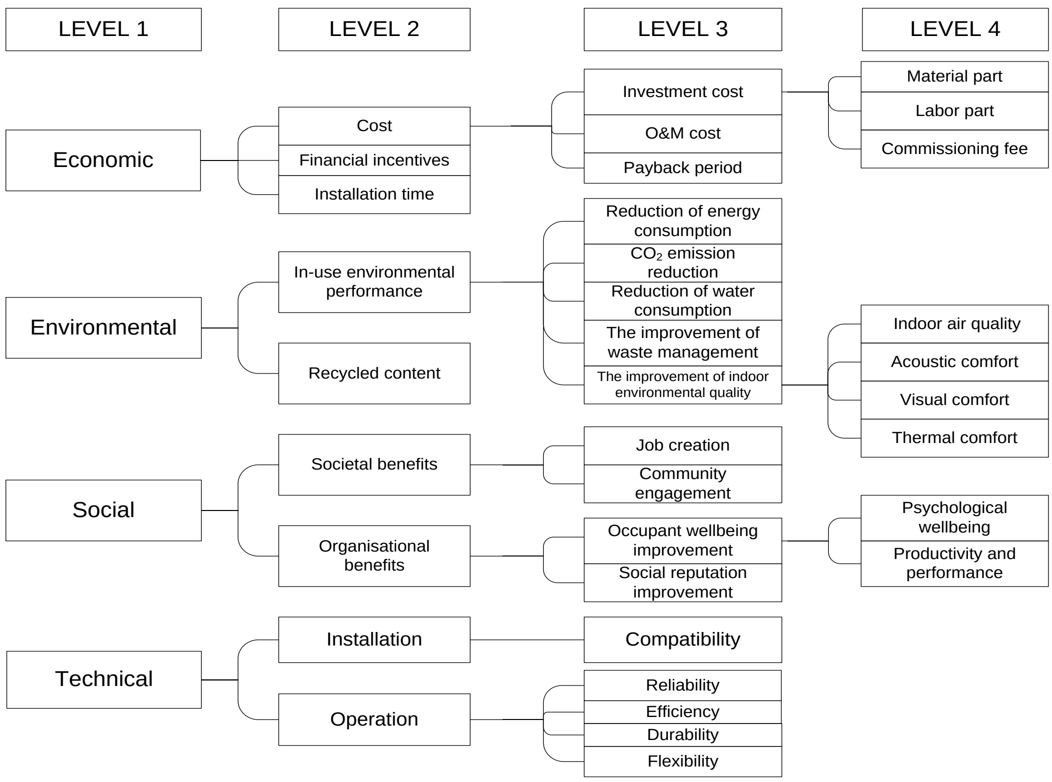


Figure 4.5 Proposed multi-criteria tree (Si *et al.*, 2016)

4.4.2 Default criteria weighting

After establishing the set of criteria, weights must be assigned to reflect on their relative importance. Criteria weighting is one of the critical steps in the MCDM process that can influence the final ranking of the results. Criteria weighting can be influenced by stakeholder perspectives and country contexts.

In the decision making process, multiple stakeholders from different backgrounds of architecture, design, engineering, and planning may have contrasting opinions which can influence the final decision (Dangana *et al.*, 2013; Zainab *et al.*, 2013). Banville *et al.* (1998) describe a stakeholder as everyone with a vested interest in a problem that can either affect, be affected by or is both being affected by and affecting the problem. Rey (2004) has emphasized that varying stakeholder opinions have a great importance in the selection of the most suitable retrofit strategy, and collaboration between stakeholders is required. Bernstein and Russo (2009) have also indicated that conflicting stakeholder perspectives are the main barrier in the decision making of sustainable retrofit.

Criteria weighting can also be influenced by overarching national level of development. Huang *et al.* (2012) have found that in the China, green technology selection mainly emphasises microeconomic efficiency and contribution to industrial development under economy criteria; GHG emission reduction, contribution to the industrial development and land resources under environment and energy criteria; employment generation and technology safety under society criteria. By contrast, Luong *et al.* (2012) have found that green technology selection in the UK emphasises life cycle cost, government schemes, expenditure on energy and income from energy under economic criteria; resource usage by building, technology capacity and environmental impact under environment; direct impacts of technology under social criteria; performance of the system, durability, flexibility and adaptability under technical criteria.

Criteria weighting can be collected through the professional survey. As indicated before that criteria weighting can be influenced by varying stakeholder opinions in relation to their professional background and overarching national level of development. The survey design and data collections methods have been described in Chapter 3. There are 35 responses from the UK industry and 33 responses from Chinese industry. The response rate is 4.6% for the UK industry and 16.5% for the Chinese industry. After the consistency checking, there are 25 valid responses from the UK industry and 29 valid responses from the Chinese industry. The survey responses and criteria weighting results are explained as below.

1) *Survey responses*

Question 1: What is your background?

☐ Architecture ☐ Design ☐ Engineering ☐ Planning

☐ Others, please specify______________

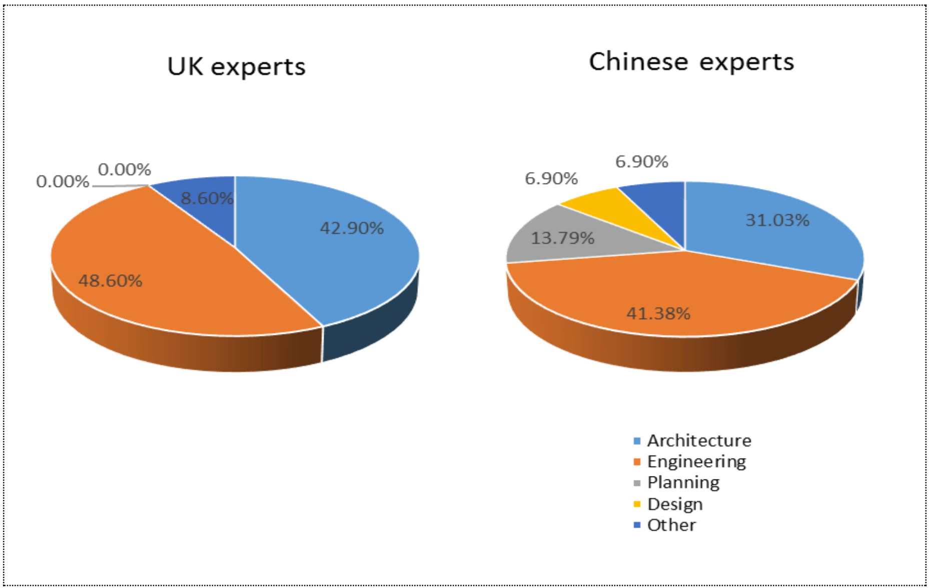


Figure 4.6 Backgrounds of survey respondents

It can be found from Figure 4.6, the UK respondents are from the backgrounds of Architecture, Engineering, and Others. Other backgrounds, according to the responses, include Design of supply chain for green building materials and service, and Ecology. There is no respondent from the background in Planning and Design.

Question 2: Which of the following can best describe your expertise?

☐ Façade engineering ☐ Structure engineering ☐ Mechanical, Electrical, and Plumbing

☐ Lighting design ☐ Facility management ☐ Energy analysis

☐ Ecology ☐ LEED or BREEAM Certification ☐ Sustainability consulting

☐ Others, please specify_____________

Figure 4.7 shows the respondents' expertise distribution. The dominant groups are those have the expertise in structure engineering and façade engineering for both Chinese and UK expert groups.

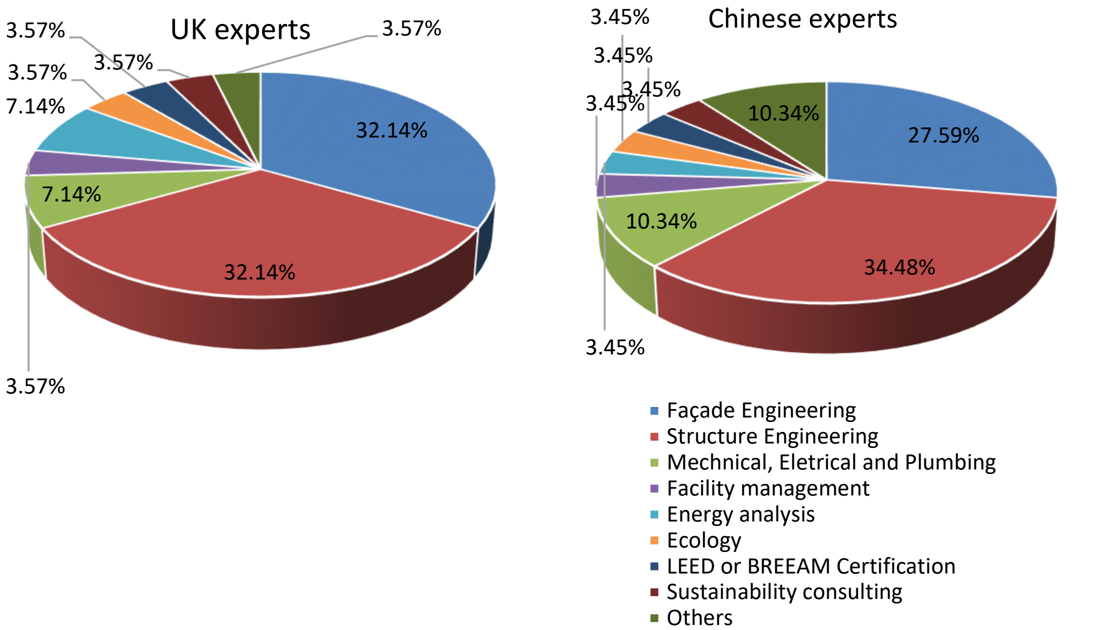


Figure 4.7 Expertise of the respondents

Question 3: How many years of working experience do you have in the built environment field?

The responses to Question 3 for both national groups are presented in Figure 4.8.

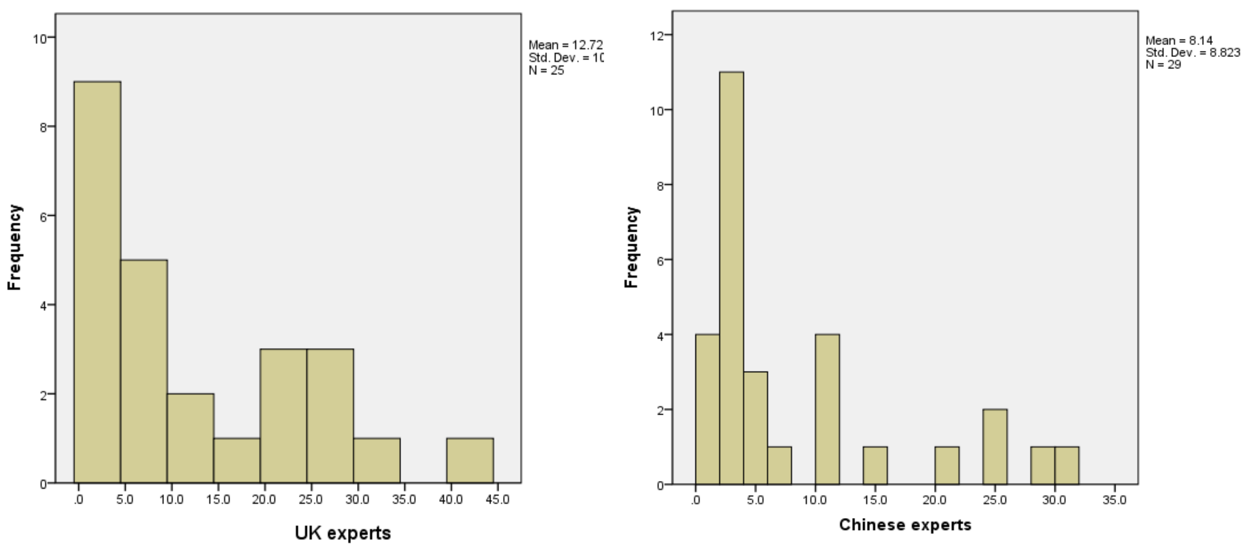


Figure 4.8 Distribution of working years of the respondents in the built environment

Question 4: How many retrofit projects have you participated in so far (approximately)?

From the answers to Question 4 presented in Figure 4.9, it can be concluded that the respondents from both national groups have reasonable experience with retrofit projects.

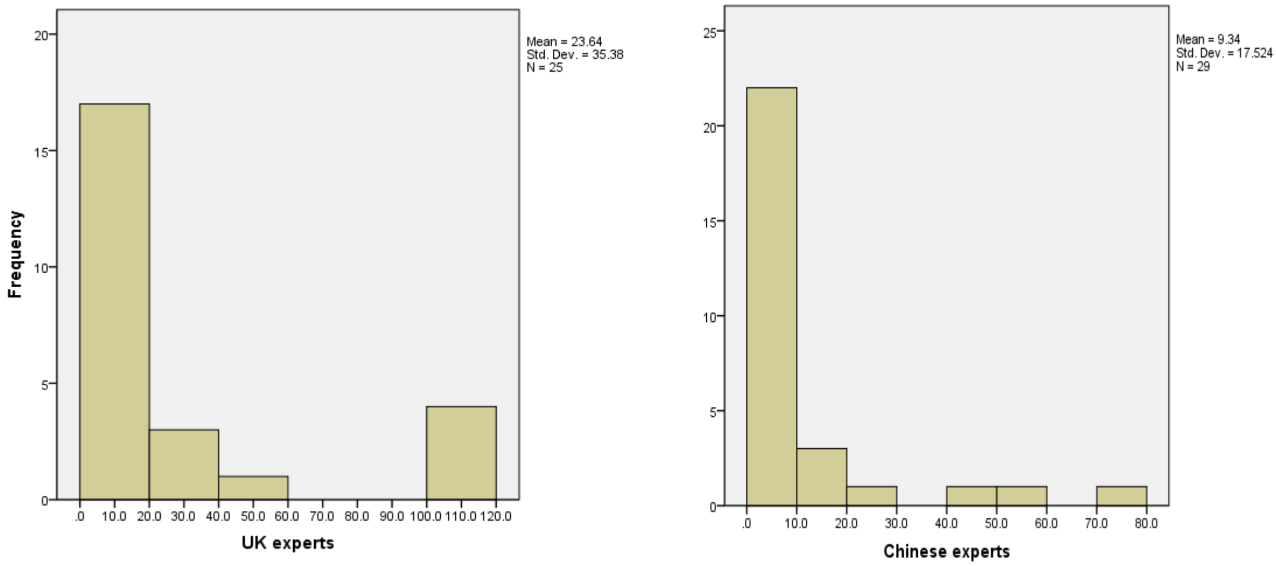


Figure 4.9 Distribution of the number of retrofit projects respondents who have participated

Question 5: What were the most frequent client requirements for the retrofit projects? (Tick all that apply).

☐ To reduce operational cost ☐ To increase asset value ☐ To improve energy performance

☐ To improve water efficiency☐ To improve occupant well-being ☐ To improve building durability

☐ To conserve fabric (heritage building)☐ To improve building safety & security

☐To improve corporate sustainability

☐ Others, please specify________________________

The responses to Question 5 presented in Figure 4.10 can illustrate the difference between the most frequent client requirements in the UK and China. The selection percentages of the client requirements are shown in Figure 4.10. In the UK, the most frequent client requirements are "to reduce the operational cost", "to improve energy performance" and "to increase asset value". In China, the most frequent client requirements are "to reduce operational cost", "to improve building safety and security", and "to improve occupant well-being". Reducing operational cost appears to be dominant client requirements in retrofit projects in both the UK and China.

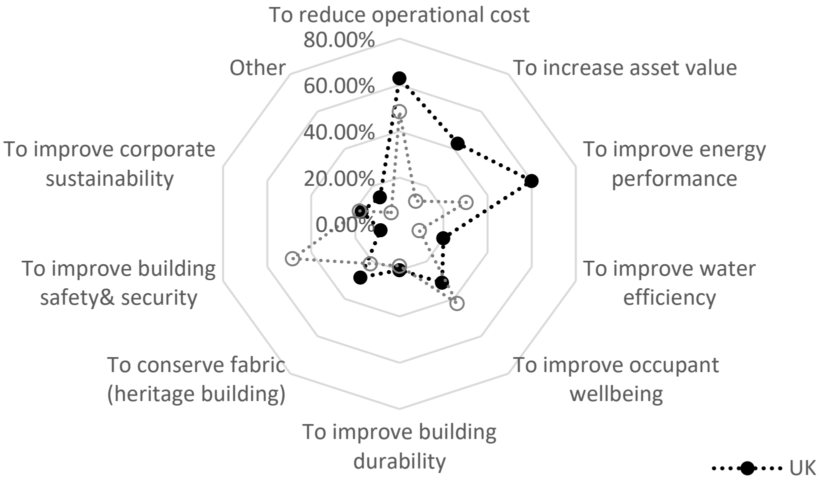


Figure 4.10 The most frequent client requirements in UK and China

Question 6: What were the most commonly used green technologies/solutions in these retrofit projects? (Tick all that apply).

☐ Enhanced wall insulation ☐ Enhanced glazing ☐ Solar shading
☐ Energy efficient lighting ☐ Lighting controls (occupancy sensors and timers)
☐ Task lighting ☐ Day Lighting sensors
☐ Pumps and/or fans retrofit ☐ Mechanical ventilation with heat recovery
☐ Insulation around hot water tanks and pipes (for HAVC system)
☐ Solar hot water ☐ Biomass boiler ☐ Heating control upgrades
☐ Water efficiency fittings ☐ Rainwater harvesting ☐ Green roof
☐ Combined Heat and Power ☐ Solar PV ☐ Ground Source Heat
☐ Building automation system ☐ Others, please specify______________________

The results presented in Figure 4.11 shows that in the UK, the most commonly used green technologies are Energy efficient lighting, Enhanced wall insulation, and Enhanced glazing; in China, the most commonly used green technologies are Enhanced wall insulation, Energy efficient lighting and Solar hot water. The results also indicate control technologies including Heating control upgrades, Daylighting sensors, Pumps and/or fans retrofit and Water efficiency fittings are not frequently used in the retrofit projects both in the UK and China. However, the Building automation system has been given considerable attention during retrofit projects in China.

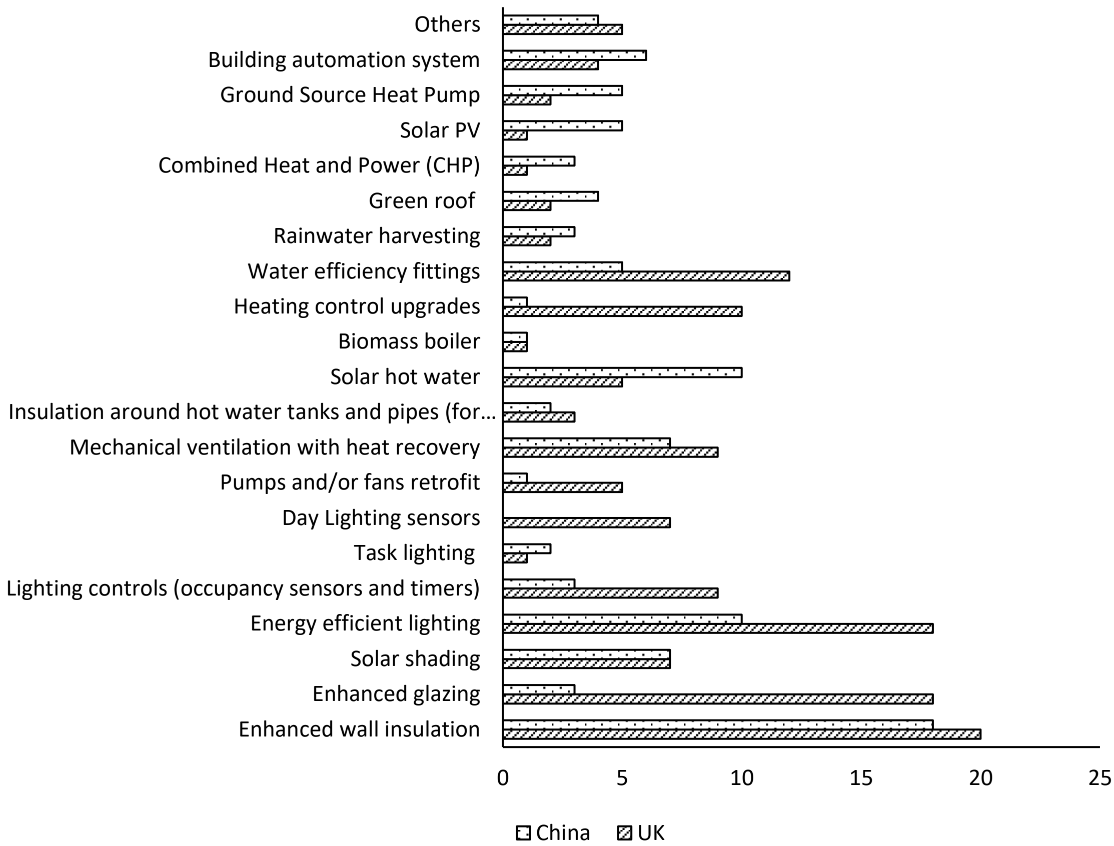


Figure 4.11 Comparison of the most commonly-used green technologies from UK and China

The next group of questions, as explained in Survey Design, was used to familiarise the respondents with the proposed criteria tree but also to allow for its future development.

Question 7: Is there any criterion you want to add to the Criteria tree?

Replies from UK experts and Chinese experts to the open question are summarised in Table 4.9 and Table 4.10 respectively. Suggested criteria include two types: those with similar meaning to the proposed criteria in the multi-criteria tree and those different from the proposed criteria. Suggestions of these criteria will be discussed against the literature review. The reason why the proposed criteria tree has not included these criteria will be also explained.

The most detailed answer from the UK expert group was received from respondent No. 1 who suggested revising the environmental criteria by incorporating the criteria of impacts on construction materials, ecosystem impacts and site impacts into Level 2. The criterion of recycled content is suggested to reorganise into Level 3 and other criteria of local material and low-carbon footprint are suggested to include at the same level. This respondent has emphasised the importance of impacts of construction materials, which corresponds to the fundamental aim of sustainable practice in terms of best resource consumption of energy, material, and water. No.1 respondent also suggested the other criteria of ecosystem impacts and site impacts to emphasise the concern about site pollution reduction from construction activities, with ecological care on biodiversity protection. The suggestion of No.1 respondent on the revision of environmental criteria is shown in Figure 4.12.

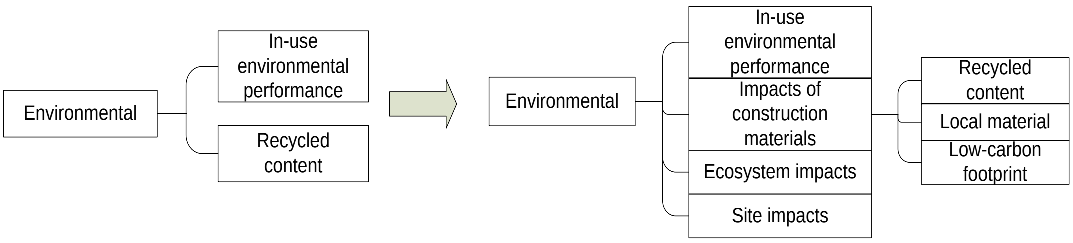


Figure 4.12 No.1 respondent opinion on environmental criteria category

Table 4.9 The potential criteria suggested by UK experts

No.	Background	Expertise	Suggestions on the criteria tree
1	Architecture	Sustainability consulting	For Environmental, I would add a Level 2 criteria called "Impact of construction materials", in which "Recycled content" could be a Level 3 criteria, and other Level 3 criteria could be "Local materials", "Low-carbon footprint materials", etc. I think using the right materials and re-using 'waste' materials in a creative way should be encouraged, if we want to minimise the amount of waste and the carbon footprint of producing new materials. For instance, if you need to take down a brick wall on a construction site, do it manually, save the bricks and reuse them on the same project, if possible, I would also add another two Level 2 criterion for Environmental: Ecosystem impacts and Site impacts - both of which should contain criteria related to the projects' impacts on the site and surroundings.
2	Architecture	Building design	Under environmental I would suggest prolonging life of existing building fabric should be considered as well as recycling.
3	Engineering	Sustainability consulting	For Environmental criteria please refer to LCA For Economic criteria please refer to LCC
4	Architecture	Sustainability consulting	Health. In terms of materials VOCs, etc.
5	Engineering	Sustainability consulting	Productivity Operational performance
6	Architecture	Architecture	A few categories that fit under various headings are off-site manufacture and modular construction. This assists in reducing cost, better H&S, quality control, environmental benefits etc.

7	By education and engineer and consultant - I was responsible for developing a supply chain of green/ecological building materials and services	Sustainability consulting	Level 0 should be explicitly stated ie. The requirement for redevelopment in the first place and the acceptance criteria that have been selected by the commissioning client. All your stated "criteria" generally are a fall-out of a design/construction process and are "technical" values and are not the drivers themselves. Furthermore, a large number of elements are not known until after design and tendering have been completed. Your tree is an aid to post-rationalisation and not a decision making aid.
8	Architecture	Sustainability consulting	Environmental (embodied carbon) Economic (impact on value of property) Installation (availability of skilled labour) Operation (usability)
9	Architecture	LEED or BREEAM Certification	Regulatory. Speculative clients usually are only worried about meeting planning or Building Regulations!
10	Engineering	Sustainability consulting	Social: reducing fuel poverty
11	Ecologist	Ecology	Environmental might include flood management, biodiversity
12	Architecture	Environmental Specification & Knowledge sharing	Healthy (Environmental) Resourceful (Environmental) [Recycled below this] Appropriate (Technical) Competency (Technical) Effective (Technical) [Efficiency below this] Biodiversity (Environmental) and many more but my 15 minutes is up.

By analysing the above 12 responses to open questions for additional criteria suggestion, several findings are summarised:

1） For the environmental criteria, it has been found that *ecosystem impacts* or s*ite impacts* have been proposed by several experts, which has shown industry professionals have started to pay attention to building impacts on a broader perspective. In addition, the embodied energy and carbon footprint of materials have also been stressed.

2） For the economic criteria, *added values on building* through the integration of green technology have been proposed. This is an important criterion when choosing green technology. We have not included this criterion in the proposed criteria tree because we are focused on the technology attributes not on the benefits the technology may bring to the whole building. We consider the cost and installation time as two criteria for economic performance of technologies.

3） For the social criteria, reducing fuel poverty has been proposed, which is a criterion from a much higher level. In the proposed criteria tree, we consider social criteria on the benefits for organisation and occupants.

4） For the technical criteria, industry experts have provided many suggestions. However, the majority of the suggestions have vague meanings. We have been careful to identify criteria for the technical category and provided clear explanations for these criteria.

Table 4.10 The potential criteria suggested by Chinese experts

No.	Background	Expertise	Suggestions on the criteria tree
1	Architecture	Façade engineering	Technical (intelligent technology application)
2	Design	MEP	Environmental (Ecosystem impacts)
3	Engineering	Structure engineering	Operation(Security) Social (the change of façade)

There are three responses received from Chinese experts for the open question. Compared to responses from UK experts, there are limited responses collected from Chinese experts. This could be due to the reason that green retrofit of existing buildings is common in the UK, but in China, this topic is not popular and widely discussed. However, some findings can be drawn from these responses. The criterion of ecosystem impacts has been proposed, with a similar opinion from UK experts. For Chinese experts, it can be found that for technical criterion, they have paid more attention to the security issue.

2) Default criteria weights

In the next section of the survey, the respondents were first asked to rank the importance of all level one criteria: *Environmental*, *Economic*, *Social*, and *Technical*. They were then asked to rank criteria at the next level within each individual group. For example, at Level 2 below *Economic* criterion, experts were asked to rank the criteria of *Cost*, *Financial incentives* and *Installation time*. The same process was repeated for all levels of the existing criteria three. All responses received were tested for consistency. For example, if the *Economic* criterion is weighed more important than the *Environmental* criterion, and the *Environmental* criterion is weighed more important than the *Social* criterion, there should be the *Economic* criterion is more important than the *Social* criterion. This judgment is considered to be consistent. Instead, if the *Social* criterion is weighted more important than the *Economic* criterion, the judgement is inconsistent. The number of matrices of pairwise comparison (MPC) for each level that passed consistency checking is listed in Appendix D Table 1. The consistency ratio is listed in Appendix D Table 2. The default weights for all levels of criteria by expert groups from the UK and China are shown in Table 4.11.

The number of MPC that passed consistency checking is limited which is typical when the criteria weighting has been conducted in a web-based survey as opposed to semi-interviews or workshop when consistent judgements from participants can be easier to manage (Pan *et al*., 2012; Zaniab *et al*., 2013). When the criteria weighting is conducted through Expert Choice, a software professionally designed for AHP method, a reminder of inconsistency can be triggered. The number of MPC that can pass consistency checking may be adjusted when using a different CR threshold value. In this study, we adopted a standard CR threshold value of 0.10 which has been widely used as a measure of the consistency checking of AHP applications in the literature.

Table 4.11 The default criteria weights assigned by different expert groups from UK and China

Criteria	Sub-criteria	UK All	China All	UK Architects	China Architects	UK Engineers	China Engineers	UK Others	China Planning	China Design	China Others
Level 1	Economic	0.296	0.190	0.173	0.250*	0.326	0.189	0.512	0.531	0.461	0.164
	Environmental	0.279	0.290	0.303	0.250*	0.289	0.282	0.147	0.233	0.113	0.345
	Social	0.185	0.181	0.303	0.250*	0.152	0.248	0.194	0.134	0.286	0.246
	Technical	0.240	0.338	0.220	0.250*	0.234	0.282	0.147	0.102	0.140	0.246
Level 2 (Economic)	Cost	0.465	0.467	0.405	0.515*	0.504	0.333	0.630	0.481	0.400	0.397
	Financial incentives	0.304	0.226	0.405	0.097*	0.234	0.333	0.177	0.389	0.354	0.302
	Installation time	0.231	0.306	0.189	0.388*	0.262	0.333	0.193	0.130	0.246	0.302
Level 2 (Environmental)	In-use environmental performance	0.665	0.577	0.646	0.539	0.670	0.590	0.721	0.634	0.594	0.500
	Recycled content	0.335	0.423	0.354	0.461	0.330	0.410	0.279	0.366	0.406	0.500
Level 2 (Social)	Societal benefits	0.521	0.543	0.545	0.567	0.534	0.528	0.318	0.568	0.447	0.619
	Organisational benefits	0.479	0.457	0.455	0.433	0.466	0.472	0.682	0.432	0.553	0.381
Level 2 (Technical)	Installation	0.475	0.525	0.452	0.580	0.506	0.516	0.401	0.516	0.540	0.291
	Operation	0.525	0.475	0.548	0.420	0.494	0.484	0.599	0.484	0.46	0.709
Level 3 (Cost)	Investment cost	0.251	0.342	0.183	0.427	0.333	0.300	0.240	0.383	0.365	0.473
	O&M cost	0.375	0.433	0.409	0.427	0.333	0.412	0.548	0.331	0.339	0.211
	Payback period	0.375	0.225	0.409	0.146	0.333	0.288	0.212	0.286	0.296	0.316

Level 3 (In-use environmental performance)	Reduction of energy consumption	0.233	0.245	0.295*	0.275	0.175*	0.225	0.805	0.735	0.537	0.156
	CO_2 emission reduction	0.186	0.161	0.143*	0.163	0.221*	0.231	0.023	0.067	0.223	0.060
	Reduction of water consumption	0.271	0.211	0.187*	0.190	0.355*	0.231	0.066	0.124	0.087	0.201
	The improvement of waste management	0.189	0.187	0.187*	0.221	0.175*	0.146	0.071	0.041	0.071	0.233
	The improvement of IEQ	0.122	0.196	0.187*	0.151	0.074*	0.168	0.036	0.032	0.082	0.349
Level 3 (Societal benefits)	Job creation	0.561	0.536	0.646	0.598	0.469	0.527	0.709	0.695	0.516	0.309
	Community engagement	0.439	0.464	0.354	0.402	0.531	0.473	0.291	0.305	0.484	0.691
Level 3 (Organizational benefits)	Occupant wellbeing improvement	0.657	0.574	0.680	0.601	0.643	0.545	0.634	0.695	0.518	0.709
	Social reputation improvement	0.343	0.426	0.320	0.399	0.357	0.455	0.366	0.305	0.482	0.291
Level 3 (Operation)	Reliability	0.359	0.239	0.301	0.250	0.385	0.228	0.683	0.672	0.179	0.357
	Efficiency	0.259	0.25	0.250	0.250	0.256	0.249	0.106	0.150	0.264	0.289
	Durability	0.202	0.262	0.316	0.250	0.151	0.274	0.149	0.121	0.264	0.219
	Flexibility	0.180	0.250	0.133	0.250	0.208	0.249	0.061	0.057	0.293	0.135
Level 4 (Investment cost)	Material part	0.400	0.332	0.507	0.510	0.299	0.289	0.473	0.564	0.306	0.375
	Labour part	0.310	0.376	0.186	0.245	0.460	0.429	0.316	0.248	0.347	0.426

	Commissioning fee	0.290	0.292	0.307	0.245	0.241	0.281	0.211	0.188	0.347	0.199
Level 4 (The improvement of IEQ)	Indoor air quality	0.248	0.206	0.257	0.155	0.246	0.250	0.300	0.544	0.441	0.524
	Acoustic comfort	0.152	0.211	0.144	0.139	0.153	0.250	0.173	0.239	0.295	0.096
	Visual comfort	0.184	0.305	0.168	0.367	0.181	0.250	0.228	0.138	0.129	0.216
	Thermal comfort	0.416	0.278	0.431	0.340	0.420	0.250	0.300	0.080	0.135	0.164
Level 4 (Occupant wellbeing improvement)	Psychological wellbeing	0.538	0.543	0.574	0.551	0.528	0.557	0.432	0.568	0.537	0.500
	Productivity and performance	0.462	0.457	0.426	0.449	0.472	0.443	0.568	0.432	0.463	0.500

* means the singular response that has passed the consistency checking.

The default weights for Level 1 criteria in relation to a stakeholder background is presented in Figures 4.13 and 4.14 for the UK and Chinese experts respectively.

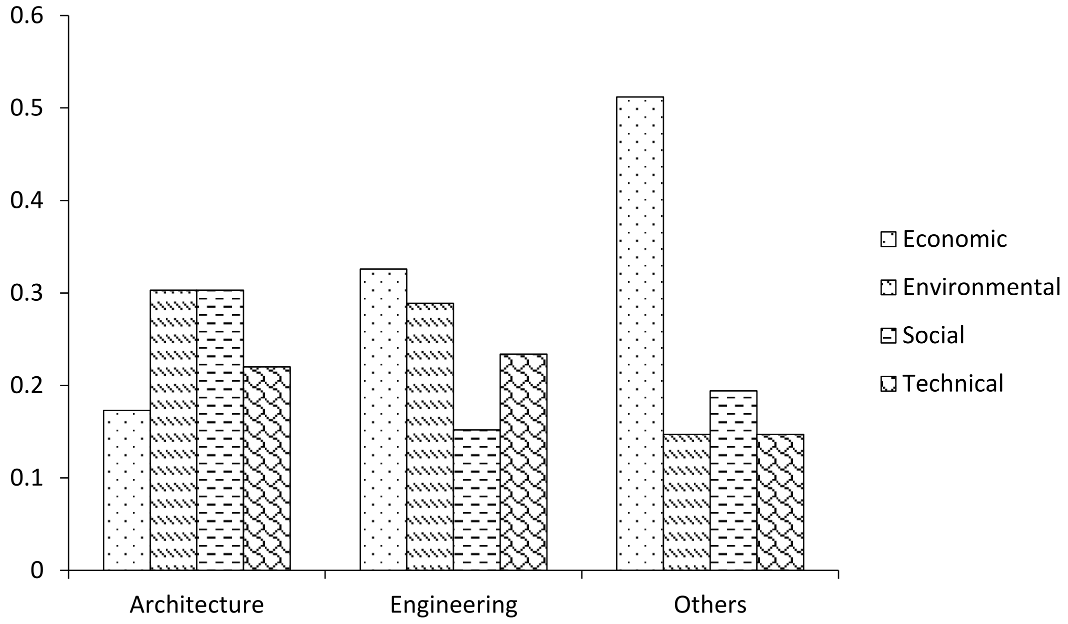


Figure 4.13 Comparison of Level 1 criteria by expert groups from different backgrounds in the UK

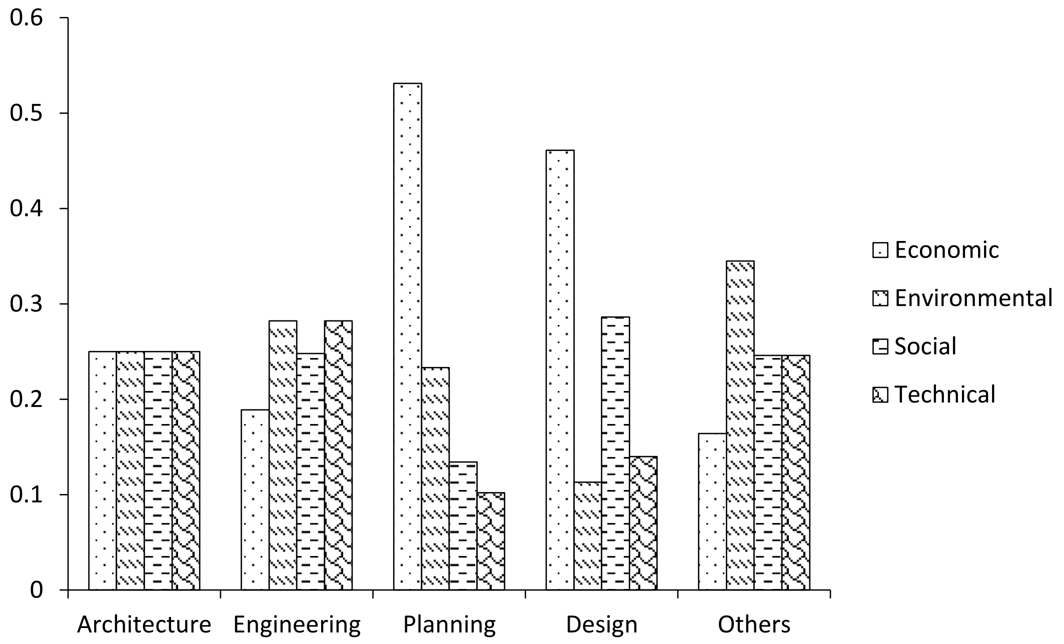


Figure 4.14 Comparison of Level 1 criteria by expert groups from different backgrounds in China

In the UK, for Level 1 criteria, the architect group have assigned weighting factors to the four criteria, from highest to lowest, as *Environmental* and *Social*, *Technical* and *Economic* criteria. It can be concluded that architects group regard *Environmental* and *Social* as the most important criteria for green technology evaluation. They regard the *Economic* criterion as the least important criterion. The engineer group have assigned weighting factors to these criteria, from highest to lowest, as *Economic*, *Environmental*, *Technical* and *Social*. It can be concluded that the engineer group, who are holding different opinions from the architect group, regard the *Economic* criterion as the most important criterion. The expert group from other backgrounds regard the *Economic* criterion as the most important criterion as well. They think the *Social* criterion as the second most important criterion and the other two criteria can be taken with the same importance.

In China, for Level 1 criteria, the architect group have given equal weighting factors to all the four criteria. The engineer group hold an opinion that *Environmental* and *Technical* criteria can be treated as the most important criteria, with the same weighting factors. The *Social* criterion should be the taken as a much more important criterion compared to the *Economic* criterion. Expert groups from backgrounds of planning and design think the *Economic* criterion as the most important criterion. The expert group from the background of design think highly of the *Social* criterion compared to the planning group. The expert group from other backgrounds think the *Environmental* criterion as the most important criterion and the *Economic* criterion as the least important criterion. They have assigned the same weighting factors to the *Social* and *Technical* criteria.

The default weights for Level 2 criteria in relation to a stakeholder background is presented in Figures 4.15 and 4.16 for the UK and Chinese experts respectively.

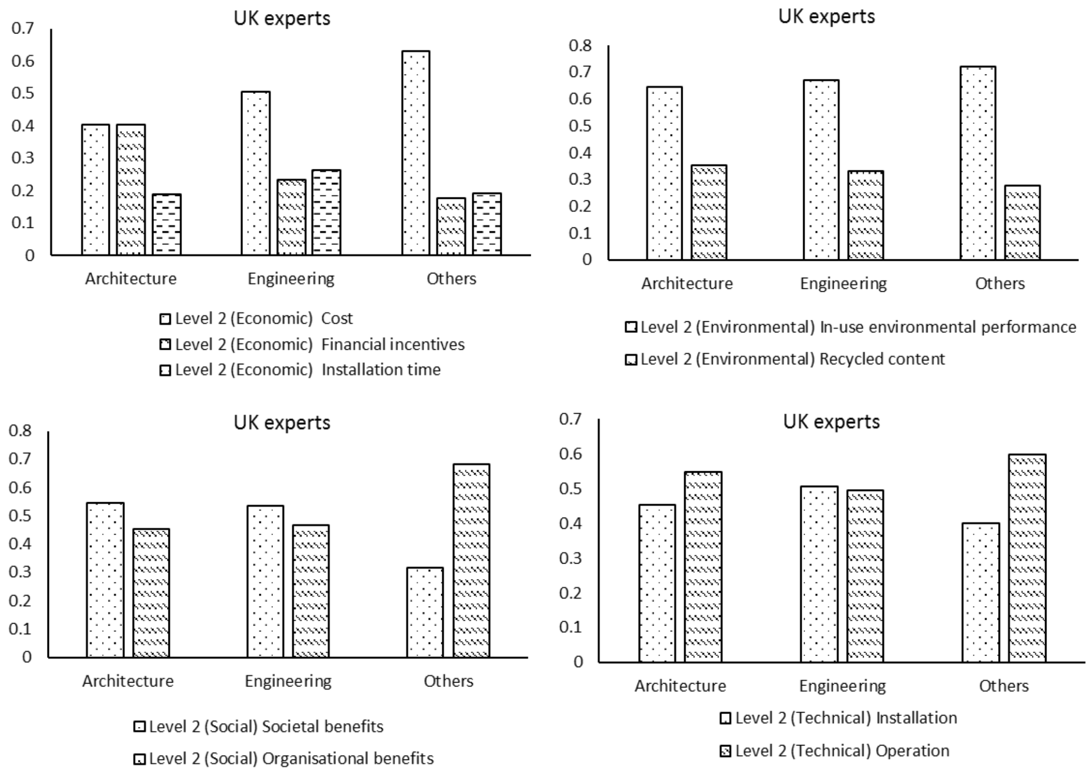


Figure 4.15 Comparison of Level 2 criteria by expert groups from different backgrounds in the UK

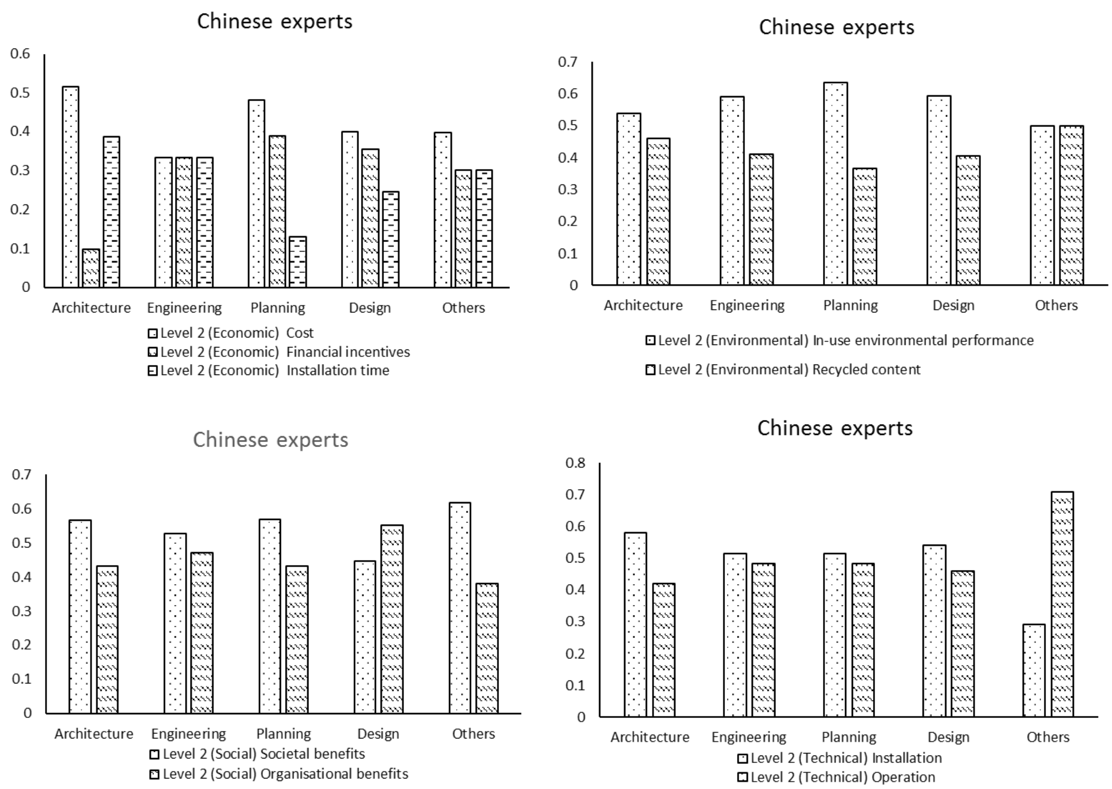


Figure 4.16 Comparison of Level 2 criteria by expert groups from different backgrounds in China

In the UK, for Level 2 criteria, all background groups agree that under the *Economic* category, *Cost* is the most important criterion. *Financial incentive* has been weighed higher than *Installation time* by the architect group. Under the *Environmental* category, all background groups think *In-use environmental performance* is much more important than *Recycled content*. Under the *Social* category, the criterion of *Societal benefit*s has been weighted higher than *Organizational benefits* by the architect group and the engineer group. The expert group from other backgrounds think oppositely. Under the *Technical* category, the architect group and the expert group from other backgrounds think *Operation* is more important.

In China, for Level 2 criteria, under *Economic*, all background groups agree that under the *Economic* category, *Cost* is the most important criterion. Under the *Environmental* category, all background groups think *In-use environmental performance* is much more important than *Recycled content*. Under the *Social* category, the criterion of *Societal benefits* has been weighted with higher values than *Organizational benefits* by the all expert group except for the design group. Under the *Technical* category, all groups think *Installation* is slightly more important than *Operation*, except for the expert group from other backgrounds.

The default weights for Level 3 criteria in relation to a stakeholder background is presented in Figures 4.17 and 4.18 for the UK and Chinese experts respectively.

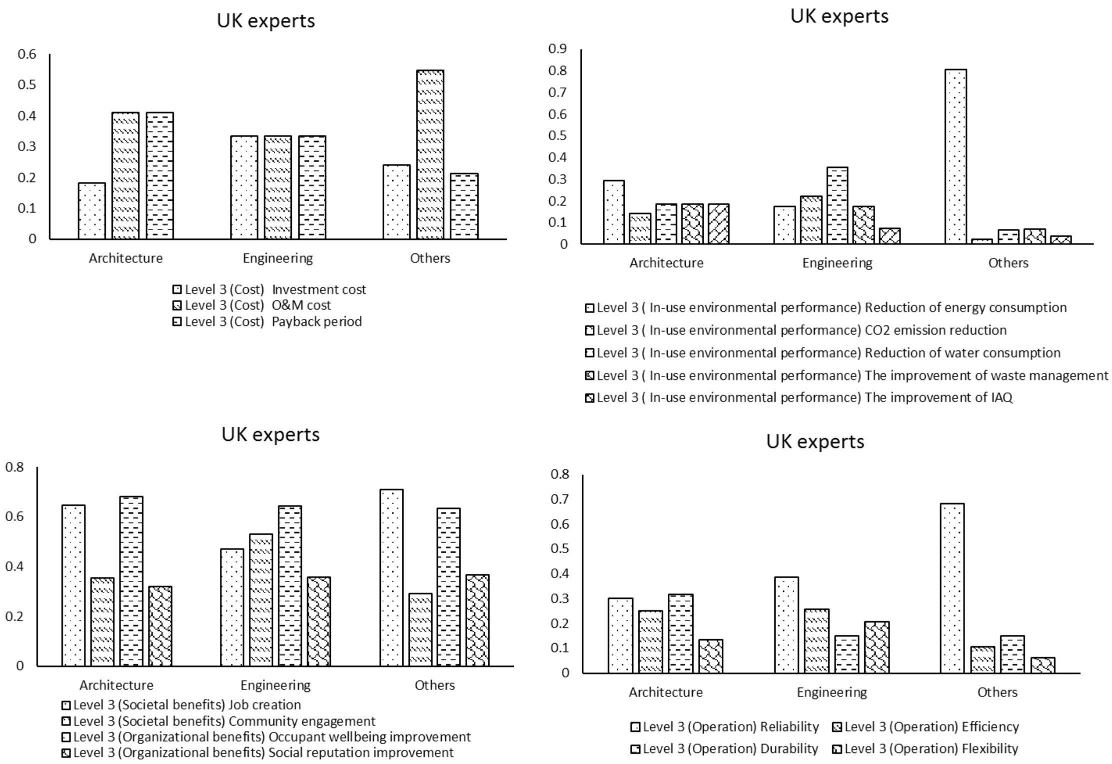


Figure 4.17 Comparison of Level 3 criteria by expert groups from different backgrounds in the UK

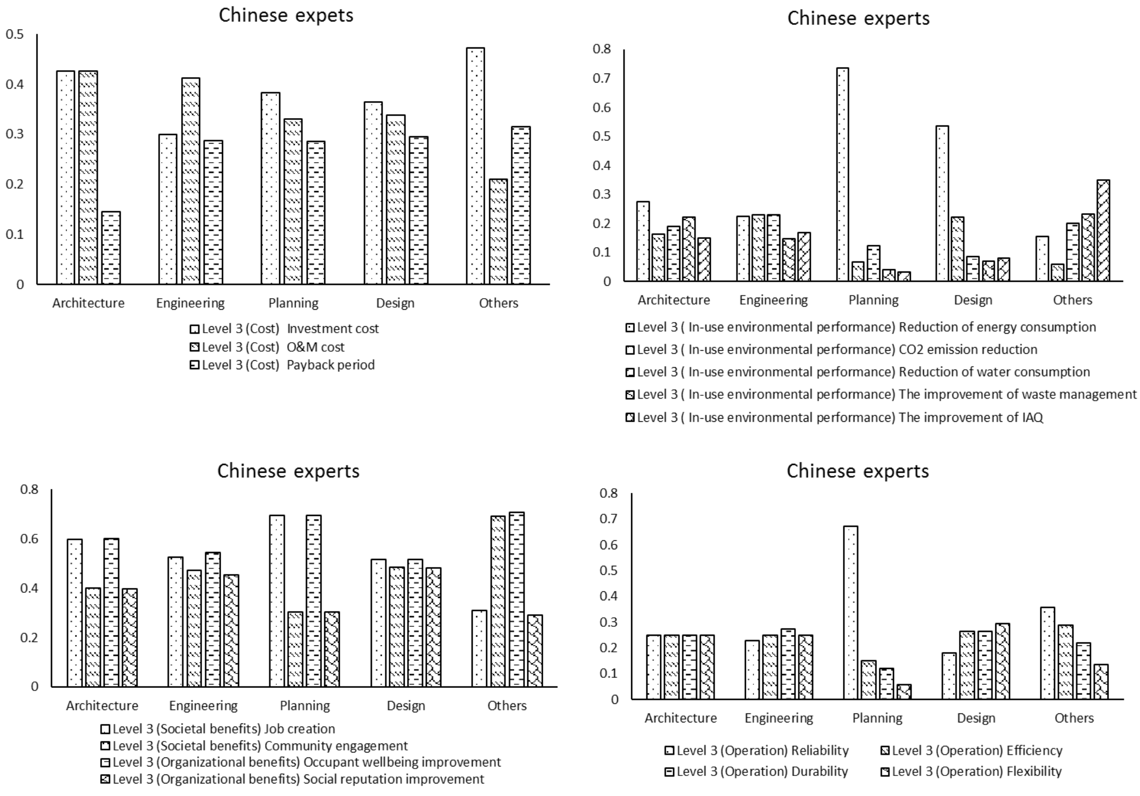


Figure 4.18 Comparison of Level 3 criteria by expert groups from different backgrounds in China

In the UK, for Level 3 criteria, under *Cost*, the architect group have assigned the same weighting factors to the criteria of *O&M cost* and *Payback period*. The engineer group have assigned equal weights to all three criteria under *Cost*. The expert group from other backgrounds think *O&M cost* should be the most important criterion under *Cost*. Under *In-use environmental performance*, the architect group think *Reduction of energy consumption* is the most important criterion, and the engineer group alternatively thinks *Reduction of water consumption* should be the most important criterion. Under *Societal benefits*, *Job creation* is much more important than *Community engagement*, shared by all expert groups. Under *Organisational benefits*, *Occupant wellbeing improvement* is more important than *Social reputation improvement* for all expert groups. Under *Operation*, the architect group think *Durability* should be the most important criterion. Other expert groups think *Reliability* should be the most important criterion.

In China, for Level 3 criteria, under *Cost*, the architect group thinks *Investment cost* and *O&M cost* should be treated with the same importance. The engineer group think *O&M cost* could be more important than *Investment cost* and *Payback period*. Other expert groups including the planning group, design group and experts from other backgrounds agree that *Investment cost* should be the most important criterion. Under *In-use environmental performance*, expert groups from the backgrounds of architecture and planning claim that the importance of *Reduction of energy consumption* override other sub-criteria. The engineer group have assigned with close weighting factors to the criteria of *Reduction of energy consumption*, *CO_2 emission reduction* and *Reduction of water consumption*. The expert group from other backgrounds think *the Improvement of IAQ* should be the most important topic. For *Societal benefits*, all the expert groups except the group from other backgrounds think *Job creation* is much more important than *Community engagement*. For *Organisational benefits*, all expert groups think *Occupant wellbeing improvement* is more important than *Social reputation improvement*. Under *Operation*, different expert groups hold different opinions on the relative importance of the four sub-criteria. The architect group think all sub-criteria should be treated with the same importance. The engineer group think *Durability* should be the most important criterion.

The planning group and the expert group from other backgrounds think *Reliability* is the most important criterion. The design group think *Flexibility* should be the most important criterion.

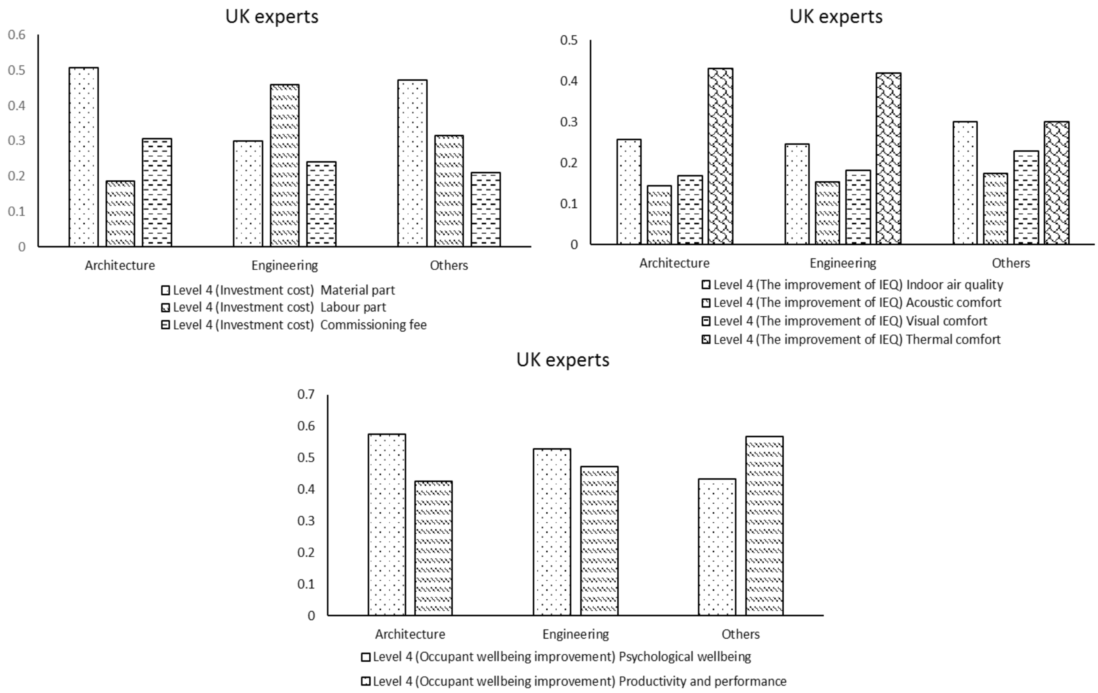


Figure 4.19 Comparison of Level 4 criteria by expert groups from different backgrounds in the UK

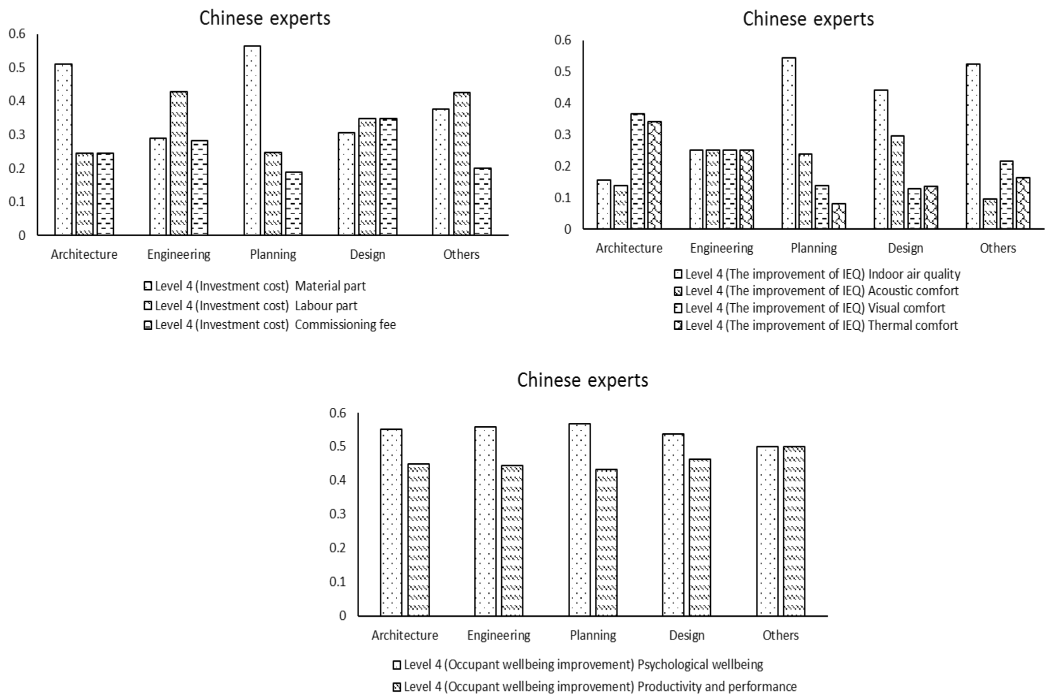


Figure 4.20 Comparison of Level 4 criteria by expert groups from different backgrounds in China

The default weights for Level 4 criteria in relation to a stakeholder background is presented in Figures 4.19 and 4.20 for the UK and Chinese experts respectively.

In the UK, for level 4 criteria, the architect group and the expert group from other backgrounds think the most important criterion should be the *Material part*. The engineer group think the most important criterion should be *Labour part*. For the sub-criteria of *the Improvement of IEQ*, all the expert groups think the most important criterion should be *Thermal comfort*. *Indoor air quality* has been also emphasised by all the expert groups. Under *Occupant wellbeing improvement*, all expert groups except for the expert group from other backgrounds think *Psychological wellbeing* is much more important than *Productivity and performance*.

In China, for level 4 criteria, the architect group and planning group think *Material part* should be the most important criterion. Other expert groups tend to take *Labour part* as the most important criterion. Under *The improvement of IEQ*, all expert groups hold varying opinions about the most important subtopic. The architect group think *Visual comfort* should be the most important criterion. The engineer group consider all the sub-topics with the same importance. The expert group from backgrounds of planning, design and others all think *Indoor air quality* should be the most important criterion. Under *Occupant wellbeing improvement*, the majority of experts think *Psychological wellbeing improvement* is more important than *Productivity and performance*. The expert group from other backgrounds think these two criteria could be treated with the same importance.

3) Comparison of criteria weights between the UK and China

As the previous section shows, there is a difference of criteria weighting by experts from different countries: the UK and China. The comparison of criteria weighting by the same expert group originally from different countries can show varying opinions towards green technology selection in different geographical locations. Criteria weighting comparison will be conducted for three expert groups: all expert group, architect group and engineer group between the UK and China. The difference of criteria weights between expert groups is categorised into three levels: “Large difference” (>50%), “Medium difference" (20%~ 50%) and "Small difference" (<20%). The values of the difference are listed in Table 3 in Appendix D.

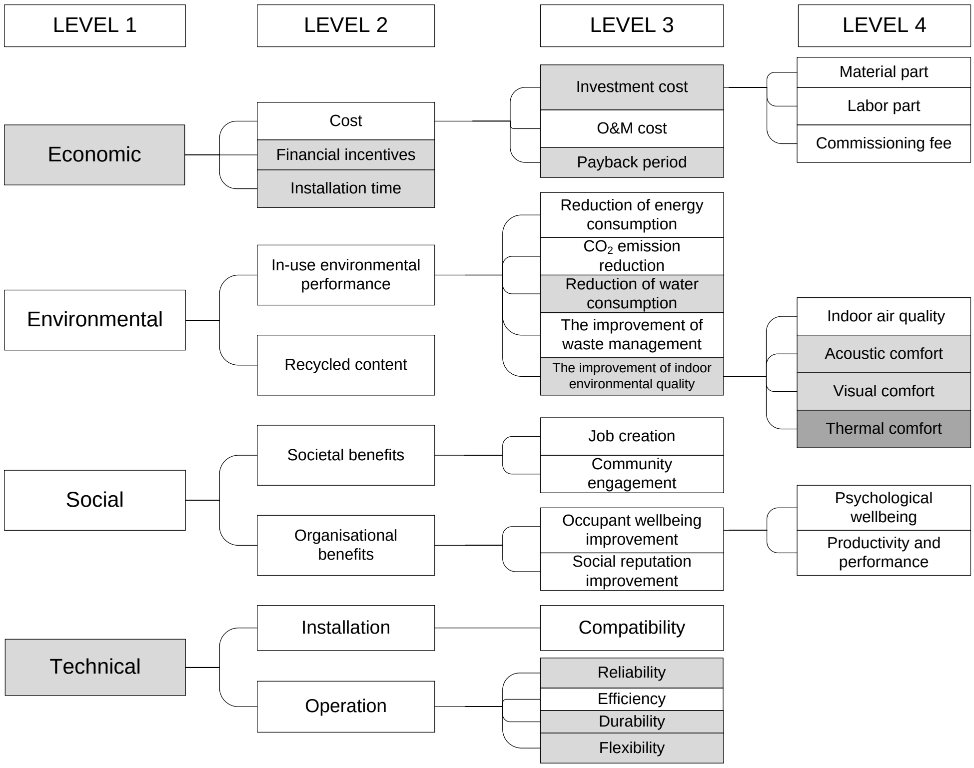


Figure 4.21 Difference of Criteria weighting for all expert groups

Note: "Large difference" (>50%) (dark grey); "Medium difference" (20%~ 50%) (light grey); "Small difference" (<20%) (No shading)

The difference of criteria weighting by all expert groups in the UK and China (see Figure 4.21) can be summarised as:

1) On Level 1, UK experts appear to be more concerned with the overall *Economic* performance of green technologies, while Chinese experts put more emphasis on their overall *Technical* performance.

2) On Level 2, experts have different opinions about *Financial incentives* and *Installation time* which belong to the *Economic* criterion. UK experts think the availability of *Financial incentives* that can support technology adoption is much more important. Chinese experts, contrastively, regard *Installation time* is much more important.

3) On Level 3, differences are found in criteria relating to *Cost*, *In-use environmental*

performance, and *Operation*. The Chinese experts think *Investment cost* is the most important criterion, while UK experts think it is less important than the other two sub-criteria under *Cost*. The experts from UK and China have distinct opinions on the relative importance of five topics of *In-use environmental performance*. The UK experts think *Reduction of water consumption* as the most important, but *the Improvement of Indoor Environmental Quality (IEQ)* is the least important, while Chinese experts think these two topics are of similar importance. Additionally, experts from the two countries have different opinions for most of the sub-criteria for *Operation*. The UK experts think highly of technology *Reliability* but the Chinese experts emphasise *Durability.*

4) On Level 4, experts have varying opinions mainly around two criteria: *Visual comfort* and *Thermal comfort*. The UK experts think *Thermal comfort* is their first concern and the Chinese experts regard *Visual comfort* as their first concern and *Thermal comfort* as the second one.

The difference of criteria weighting by the architect groups in the UK and China (see Figure 4.22) can be summarised as:

1) On Level 1, results show that architect groups from the two countries have different opinions about *Economic*, *Environmental*, and *Social* criteria. Compared to equally weighting by the Chinese architect group, the UK architect group have paid more attention to the *Environmental* and *Social* criteria.
2) On Level 2, a criteria weights difference exists for all the criteria except for sub-criteria under the *Social* aspect. Criteria with large weighting difference are *Financial incentives* and *Installation time*. *Financial incentives* are weighed much higher by the UK architects than the Chinese architects.
3) On Level 3, the criteria with medium to large difference are the same as the criteria identified for all the groups. The criteria with a large difference are *Investment cost* and *Payback period*. The UK architects are more concerned about *Payback period* while Chinese architects are more concerned about *Investment cost*.
4) On Level 4, criteria weights difference is mainly identified for *the Improvement of IEQ*. *Visual comfort* is identified as the criterion with a large difference between countries.

This difference showed that Chinese architects are more concerned about *Visual comfort* under *the Improvement of IEQ*.

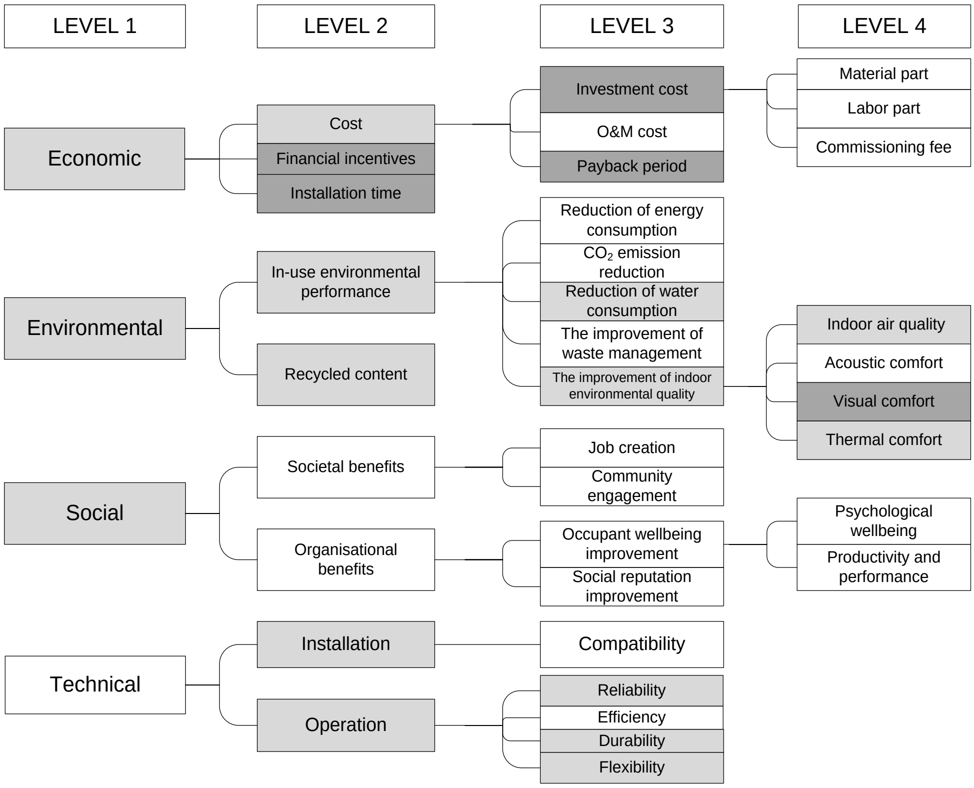


Figure 4.22 Difference of Criteria weighting for the architect groups

Note: "Large difference" (>50%) (dark grey); "Medium difference" (20%~ 50%) (light grey); "Small difference" (<20%) (No shading)

The difference of criteria weighting by the engineer group in the UK and China (see Figure 4.23) can be summarised as:

1) On Level 1, the results show that the engineer groups have different opinions towards *Economic* and *Social* criteria. The UK engineer group are more concerned about the *Economic* criterion, with a contrast that the Chinese engineer group has paid more attention to the *Social* criterion.
2) On Level 2, criteria weights differences are mainly identified for *Cost*, *Financial incentives* and *Installation time*. The engineer groups have a large difference in *Cost*. The UK engineers give more emphasis to *Cost* than Chinese engineers.
3) On Level 3, a large difference in criteria weighting has been identified for *Reduction of water consumption* and *Reliability*. Results show that the UK engineers assign more

weights to *Reduction of water consumption* than Chinese engineers. They also emphasise on technology *Reliability* under *Operation*.

4) On Level 4, the UK engineer group think *Thermal comfort* should be given the first priority.

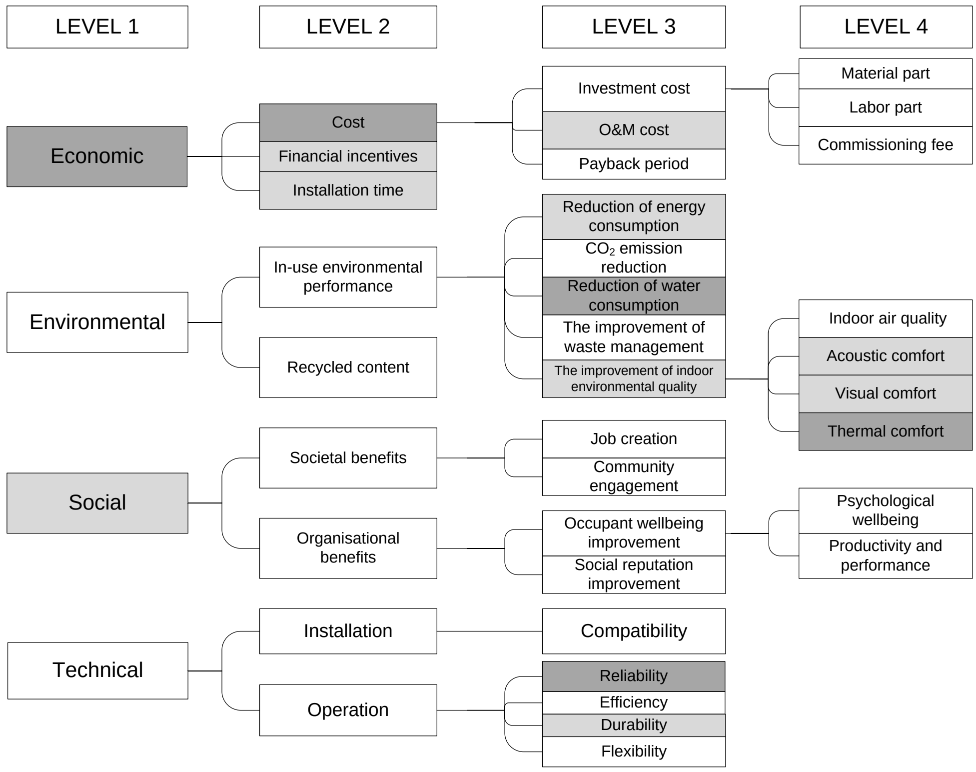


Figure 4.23 Difference of Criteria weighting for the engineer groups

Note: "Large difference" (>50%) (dark grey); "Medium difference" (20%~ 50%) (light grey); "Small difference" (<20%) (No shading)

Criteria weights comparison between expert groups in the two countries indicates criteria preferences of expert groups when they are selecting the optimal technology for building retrofits. Generally speaking, the UK experts place more emphasis on the *Economic* criteria, more specifically sub-criteria of the *Cost* and *Financial incentives* for green technology. Chinese experts, in contrast, are more concerned about the *Technical* criteria. This difference between UK and China is supported by results of the most frequent client requirements. In the UK, they are "to reduce operational cost" and "to increase asset value". Comparatively, in China, the most frequent client requirement is found to be "to improve building safety and security".

Under *In-use environmental performance*, experts from the two countries regard *Reduction of water consumption* and *Reduction of energy consumption* as the most important topics, but UK experts currently tend to give slightly more emphasis to water than energy efficiency. When it comes to *The improvement of IEQ*, the UK experts think *Thermal comfort* is the first concern, but Chinese experts regard *Visual comfort* as their first concern.

4.4.3 Technology scoring

After evaluation criteria are developed and criteria weights are identified, technology scoring regarding individual criterion should be conducted. Technology performance regarding multi-criteria can be measured in quantitative units and in the scale, depending on the criteria attributes. A comprehensive listing of performance measures is outlined in Table 4.12. It should be noted that this table is just a suggestion of technology scoring, and the scoring scale and the measuring unit of specific criteira can be adjusted in the real cases.

The method of MAUT is used in scale measurement. The principle of MAUT is when minimum and maximum points, as well as, measuring function are defined, so interval points can be assigned accordingly. The basic utility function is a linear function. Following this approach, the maximum and minimum points of qualitative data are listed in Table 4.12. For the criteria which are measured in No, Possible and Yes, values have been correspondingly assigned as 0, 0.5 and 1. For the criteria which are measured in five scales, such as “strongly agree, somewhat agree, neutral, somewhat disagree, strongly disagree”, values have been assigned as 2, 1, 0, -1 and -2. The negative sign for this is used to indicate the negative performance of the green technology regarding the specific criterion.

Table 4.12 Suggestions of data collections for technology scoring

Category	Criteria	Sub-criteria and their descriptions	Measuring units	Min	Max	Data
Economic	Cost	Capital cost- How much is the capital cost?	£			
		O&M cost- How much is the annual cost of operation and maintenance cost	£			
		Payback period -How long is the capital cost paid back by saving? (<2 years, 2-5years, >5 years)	Years	>5 years (point -1)	<2 years (point 1)	
	Financial incentives	Are there any financial incentives available for the technology adoption?	Yes/No	0	1	
	Installation Time	Time of installation -How long does the technology take for installation (<1 week, 1-4 weeks, 1-3 months, 3-6 months, > 6 months)	Scale	>6 months (point -2)	<1 week (point 2)	
Environmental	In-use environmental performance	Reduction of energy consumption- how much is annual saving of energy consumption?	kWh			
		Reduction of water consumption? -how much is the annual	Litres/flush			

	saving of water consumption?			
	Waste management- Can the technology improve the efficiency of waste management? (strongly agree, somewhat agree, neutral, somewhat disagree, strongly disagree)	Scale	strongly disagree (point -2)	strongly agree (point 2)
	Indoor air quality improvement- To what extent does the potential technology improve the indoor air quality? (worsens, slightly worsens, does not change, slightly improves, improves)	Scale	Worsens (-2)	Improves (2)
	Acoustic comfort improvement- To what extent does the potential technology improve the acoustic environment? (worsens, slightly worsens, does not change, slightly improves, improves)	Scale	Worsens (-2)	Improves (2)
	Visual comfort improvement- To what extent does the potential technology improve the acoustic environment? (worsens, slightly worsens, does not change, slightly improves, improves)	Scale	Worsens (-2)	Improves (2)
	Thermal comfort improvement- To what extent does the potential technology improve the thermal comfort? (worsens, slightly worsens, does not change, slightly improves, improves)	Scale	Worsens (-2)	Improves (2)

	Recycled content	Whether there is any opportunity to recycle the technology component when disposal? (No, Possible (0.5), Yes)	Scale	No (0)	Yes (1)
Social	Job creation	Can the technology help to increase relevant job positions for the society? (No, Possible (0.5), Yes)	Scale	No (0)	Yes (1)
	Community engagement	Can the technology help to increase the opportunity for community engagement? (No, Possible (0.5), Yes)	Scale	No (0)	Yes (1)
	Social reputation improvement	Can the potential technology help to improve the social reputation of the organization? (No, Possible (0.5), Yes)	Scale	No (0)	Yes (1)
	Psychological wellbeing	To what extent does the potential technology improve the psychological well-being of occupants (worsens, slightly worsens, does not change, slightly improves, improves)	Scale	Worsens (-2)	Improves (2)
	Productivity and performance	To what extent does the potential technology improve the productivity and performance of occupants (worsens, slightly worsens, does not change, slightly improves, improves)	Scale	Worsens (-2)	Improves (2)
Technical	Installation	Compatibility- Can the technology be installed with the compatibility of existing building components? (strongly agree, somewhat agree, neutral, somewhat disagree, strongly	Scale	Strongly disagree (-2)	Strongly agree (2)

		disagree)			
		Reliability- How much percentage of time can the technology function with no errors?	%	Scale	
		Efficiency- How much is the efficiency of the technology?	%	Scale	
	Operation	Durability- How long is the lifetime of the technology?	Years		
		Flexibility- Can the technology be flexible for system upgrading? (strongly agree, somewhat agree, neutral, somewhat disagree, strongly disagree)	Scale	Strongly disagree (-2)	Strongly agree (2)

4.4.4 Result synthesis

Combining criteria weighting and individual technology scores, integrated technology performance scores can be calculated. Based on the integrated scores, the ranking of all potential alternatives will be obtained. By changing weight values allocation to different criteria, technology ranking will be changed. Scenario analysis based on different weight values can inform decision makers which technology could be the optimal technology when they put the priority to particular evaluation criteria.

With the weight values of the criteria and the technology performance scores regarding individual criterion, the integrated performance scores V_i of each technology were calculated using the linear additive function (4-2):

$$\mathrm{V}_i = \omega_i x_i \quad \text{, where} \sum \omega_i = 1 \qquad \text{(4-2)}$$

where ω_i is the weight value of criterion i, x_i is the corresponding technology performance scores, and V_i is the IPS calculated for criterion i. The global scores of technologies are calculated using the equation (4-3):

$$\text{Global scores} = \sum V_i \qquad \text{(4-3)}$$

Chapter 5 Framework application

5.1 Overview

To investigate the effectiveness of a proposed framework of green technology selection in existing buildings, a case study has been conducted. The Pearson building at UCL (University College London) is selected as a case study building (Figure 5.1). This building represents a fairly typical higher education building. Apart from staff offices, there are some teaching rooms and lecture theatres on the upper floors (including a video conferencing suite) and laboratories in the basement. The building opens at 8am with laboratories closing at 5pm but the staff and students essentially have 24-hour access to the building. This building was originally constructed from solid stone in 1919 with further extensions in the 1980s and was refurbished in 2005. Unlike new buildings, which can easily incorporate state-of-the-art energy efficient technologies to achieve current requirements in building energy efficiency, these old university buildings usually have their intrinsic characteristics in comparison to new ones and perform poorly in terms of energy efficiency.

Figure 5.1 Case study building (Source: UCL Estate, n.d.)

The UCL has been working on a Carbon Management Strategy and its Implementation Plan since 2008 (UCL, 2011). The target set is 10% reduction of

2005/2006 carbon emission baseline by 2013. The 2008 Strategy has involved multiple stakeholders:

- The Environmental Sustainability Action Group: mainly based within the Estates Division, also with stakeholder representations from other support services, Green Champions, and students. Its role is to implement the university's environmental sustainability initiatives.
- The Environmental Sustainability Steering Group: a formal consultative committee with academic, non-academic and student representations. They are responsible for wider consultation and approval of the issues reported by the Environmental Sustainability Action Group.
- Estates Management Committee: with the President and Provost of the university as the chair, Director of Estates Division and Dean of Faculty of Social and Historical Sciences as the members. The Committee is to provide oversight and strategic support to the plan development, monitor the progress of the carbon reduction against agreed targets and sign off any amendments or new strategies prior to submission to the council for approval.

The Strategy Implementation plan identified the case study building as a showcase for exploring potential solutions as well as operational problems in delivering energy efficiency improvements across the campus. The UCL Sustainability Team, belonging to the Environmental Sustainability Steering Group, has engaged a certified building consultancy firm to conduct an energy survey for the case building in September 2008 and propose further energy saving solutions. The full consultancy report is presented in Appendix E. In this chapter, the framework-based technology listing will be compared with the one from the consultancy report. The methodology of the framework demonstration is illustrated in Figure 5.2.

Step 1: Case study identification

Step 2:Framework application

- Site and building survey
- Green technology listing
- Technology screening
- Technology evaluation with MCDM methods

Step 3: Analysis and discussion

- Selected technology list comparison between framework application and consultancy report
- Green technology ranking by applying different weighting values
- Sensitivity analysis of weighting values

Figure 5.2 The methodology of framework application

As part of this testing process, the sensitivity analysis of the proposed default weighting values will also be conducted.

5.2 Site and Building Survey

The consultancy report identified energy saving opportunities in the areas of lighting, pumps, insulation, cooling, building management system, small power/equipment, and water saving. The results from this professional survey will be compared with the results obtained from the site and building survey using the proposed framework.

The Site and building survey is to collect basic information to investigate building retrofit opportunities in sustainability topics, including energy conservation, water efficiency as well as health and wellbeing improvement. Information is suggested to collect in the aspects of:

- Climate and location
- Building envelope
- Building services
- Building management system
- Water efficiency
- Health and wellbeing

Climate and location

The case study building is located in central London, a high-density location. The climate in London is categorised as continental, with heating degree days longer than cooling degree days. This information can provide implications for green technology selection, which is demonstrated in Figure 5.3.

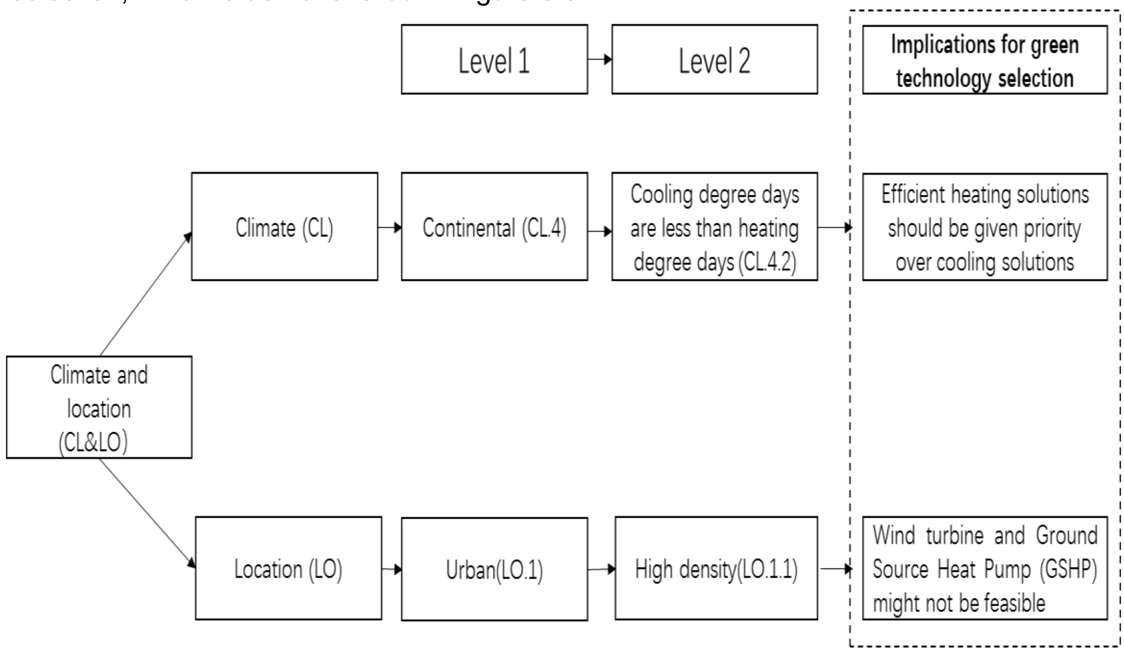


Figure 5.3 Information collection for Climate and Location and implications for green technology

Building envelope

The building is oriented to the East with the possibility of applying a PV system. The building has five floors including the basement. This building was constructed from solid stone and cavity wall insulation is not possible for this type of construction. The case building has a pitched roof on top of it, under which the air conditioning units are installed.

There is still roof space that can house additional systems, like a PV system or green roof. Windows facing Street side (West) of the building have been fitted with secondary glazing. Windows facing the Quad side (East) are single-glazed and can be upgraded. The building has a medium window/wall ratio. Based on this, daylighting optimisation and lighting controls should be considered. The same information collection process for building envelope and implications for green technologies is shown in Figure 5.4.

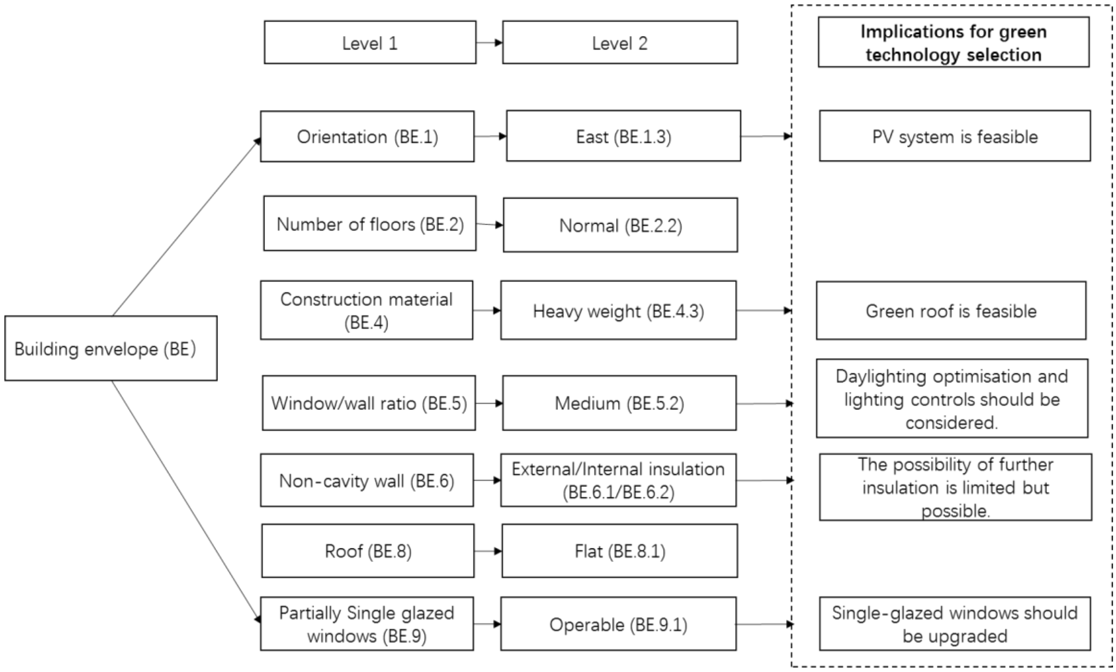


Figure 5.4 Information collection for Building envelope and implications for green technology selection

Building services

The heat and electricity for the building are supplied by a university-owned Combined Heat and Power (CHP) plant. There is no natural gas consumed on site. As the pumps of the CHP plant also operate through electricity, ensuring that electricity is coming from the renewable sources is highly recommended. The heat in the building is supplied via a meter and distributed through radiators with thermostatic Radiator Valves (TRVs).

Ventilation is provided via Air Handling Units (AHU). There are three AHUs in this building. Checking whether or not in AHU systems have Variable speed control is highly recommended.

Cooling is supplied via Fan Coil Units (FCU), which are manually controlled. Investigating centralised control via BMS is recommended.

For lighting, conventional incandescent lamps and less efficient compact fluorescent lamps are installed. Efficient lighting, occupancy sensors, and lighting controls are highly recommended.

The information collection for building services and implications for green technologies is shown in Figure 5.5.

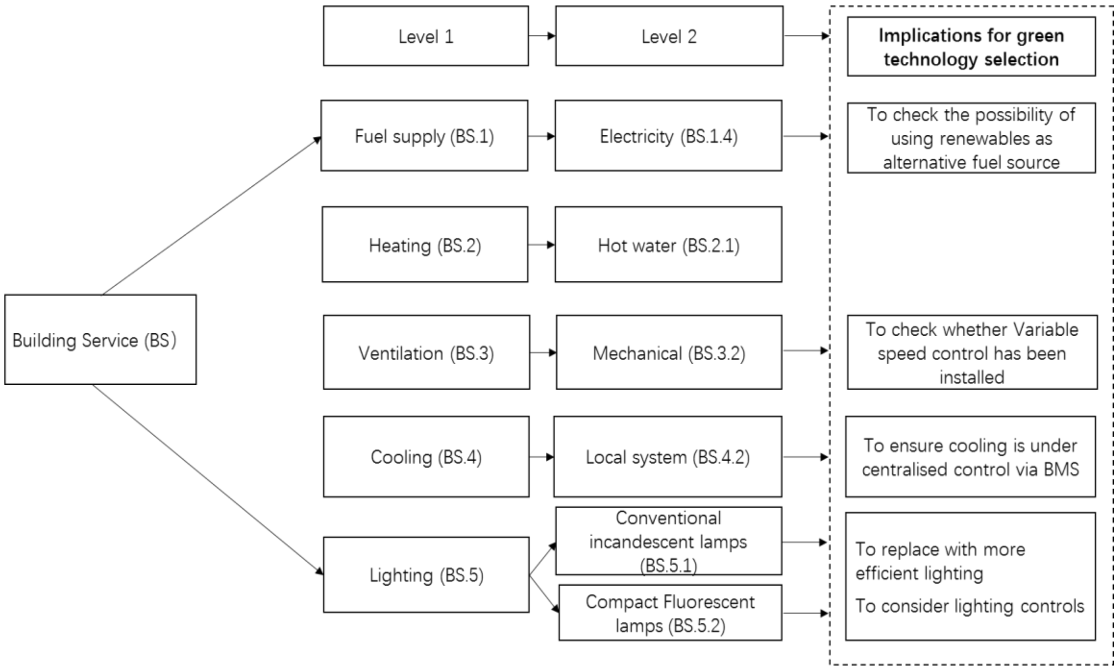


Figure 5.5 Information collection for Building services and implications for green technology selection

Building management system

A Building Management System (BMS) is a central computerised system for managing and operating systems within a building. BMS in Pearson building incorporates controls for heating, cooling and ventilation, and it is suggested to check the opportunity of being extended to incorporate lighting, security, access and fire systems.

Water efficiency

Water is used on the site in the laboratories, as well as for the toilets, the small kitchen areas and for cleaning. The installations were single-flush units in the toilets. The taps in the toilets and the labs are manually controlled and are suggested to replace with low flow taps. Water recycling measures, such as rainwater harvesting and grey water recycling are recommended to consider. Although there is no apparent space currently available in the building, spaces can be possibly provided in the future for housing water tanks, making these options viable.

Health and wellbeing

Health and wellbeing include both physical health and mental health. For mental health improvement, the feasibility of daylighting optimisation should be further checked.

Information collection for BMS, Water efficiency, Health and wellbeing and implications for green technologies are shown in Figure 5.6.

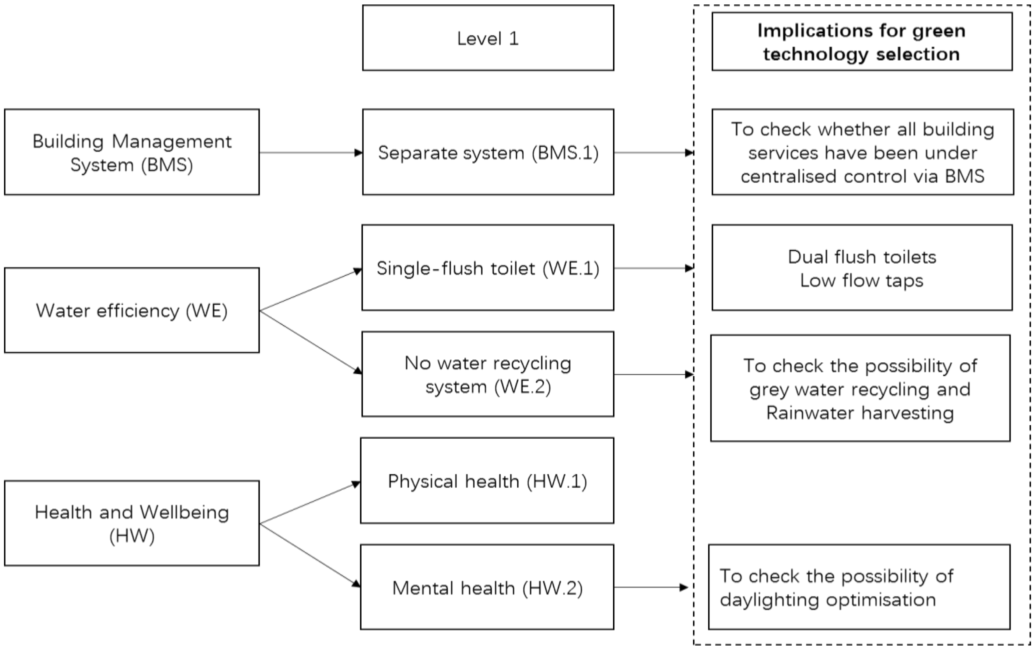


Figure 5.6 Information collection for BMS, Water efficiency, Health and wellbeing and implications for green technology

The professional survey conducted by the building consultancy firm has more detailed observations for building services. Ventilation was controlled under a building management system (BMS) but it does not work effectively. AHU 1 and AHU 2 have been found operating the whole day without installation of variable speed controls. FCUs for cooling are found connected to the BMS, however, FCU zones 1 and 2 were set to manual, not under BMS control. The survey has revealed that the stairwell lights operate all day, a passive infrared sensor (PIR sensor) was suggested to install in the staircases. PIRs could, therefore, be installed in staircases to reduce lamp operation and energy use. The PIR sensor was found in most classrooms and lecture theatres, but their sensitivity should be further improved. One lecture theatre was noticed consuming a significant amount of lighting and would reduce energy consumption through the installation of a lighting timer. The consultancy firm also received occupants' complaints about overheating, which is also another evidence indicating that the BMS for the Pearson building does not work effectively.

5.3 Potential technology listing and screening

Based on Site and building survey phase of the proposed framework and its implications for green technology selection, potential technologies can then be listed. These technologies are suggested to screen through a series of filters on different levels: technology level, building level, and community level, which are proposed and discussed in Section 4.3 of the Chapter 4.

In this real case study, most of the proposed green technologies and their supply chains are mature in central London. On the building level, we mainly concern the requirements when installing these technologies to the buildings. On the community level, we consider the planning regulations for these technologies. If the technologies can not satisfy the planning requirements, they will be screened out. The list of technologies that can pass the screening process is shown from Figure 5.7.

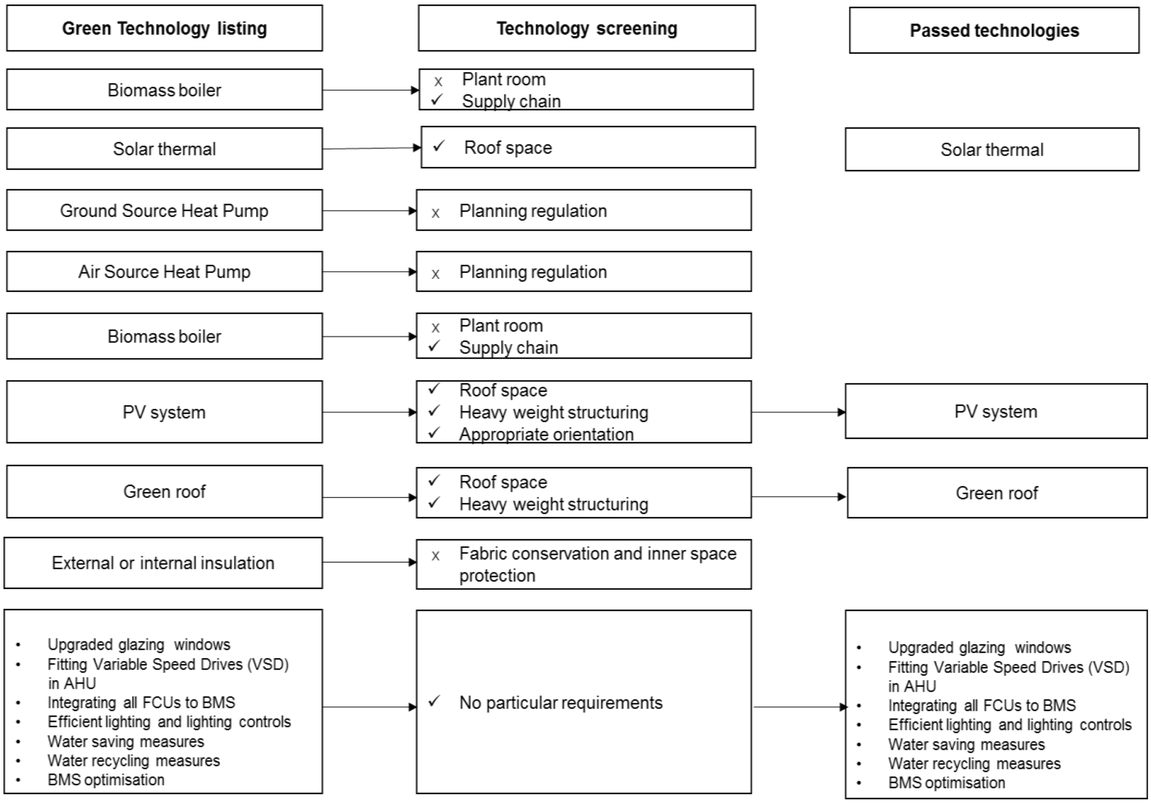


Figure 5.7 Green technology listing and screening

The technology listing suggested in the consultancy report is presented in Table 5.1. The consultancy firm has considered green technologies, including biomass boiler, solar thermal collectors, solar PV, green roof and rainwater harvesting system, but have excluded them from further considerations due to the particular reasons. The biomass boiler was excluded due to no heating plant in the building. Because the electricity and heat requirements of the Pearson building are supplied by a Combined Heat and Power scheme, the biomass boiler may not be feasible for this individual building. However, using the biomass as the energy source of the Combined Heat and Power scheme can be a possibility. This fact is less likely to be supported by the proposed framework, which is considered as a limitation of the proposed framework. The proposed framework is potentially designed for individual buildings, which normally have electricity and heat supply on site.

Solar thermal was excluded by the consultancy firm due to no water storage on site. This can be an option if additional storage room can be provided. Moreover, the roof space for solar thermal installation is sufficient.

Solar PV has been excluded due to shading and cost. However, if the decision making process is based on a broader sustainability perspective, there is no reason to exclude solar PV, especially as the building orientation is favourable.

Green roof has not been considered by the consultancy firm. Through the site and building survey in the proposed framework, a green roof can be an option and technical requirements can be satisfied by the building.

Water saving measures, such as rainwater harvesting system, have been excluded due to no apparent space for a housing water collection tank. This can be an option if additional space can be provided.

Green technologies, wind turbine and GSHP, have been directly excluded by the consultancy firm due to the same reasons stated in the proposed framework.

The same suggestions are suggested both by the proposed framework and the consultancy firm for the performance improvement in building envelope, HVAC equipment, lighting, BMS, and water saving. The specific technologies are listed in Table 5.1.

Table 5.1 Comparison of green technology listing results by the framework and by the consultancy firm

Theme	Green technologies suggested by the framework	Green technologies suggested by the consultancy firm	Comparisons of the two suggestions
Efficient heating solutions	Biomass boiler	Excluded	× No heating plant in the building (provided by the consultancy firm)
	Solar thermal	Excluded	× No water storage on site (provided by the consultancy firm)
Renewable sources	PV system	Excluded	× Unshaded roof space available (provided by the consultancy firm) × Not a cost-effective technology (provided by the consultancy firm)
Roof space available and heavy structured roof	Green roof	Not considered at all	
Building envelope	Single glazing windows should be upgraded	Secondary glazing on all single-glazed windows	✓ The two suggestions are same
HVAC equipment	Fitting Variable Speed Drives in AHU	Fitting Variable Speed Drives (VSD) in AHU	✓ The two suggestions are same
	Integrating all Fan Coil Units (FCUs) with Building Management System (BMS)	Integrating Fan Coil Units (FCUs) with Building Management System (BMS)	✓ The two suggestions are same

Lighting	Efficient lighting and lighting controls	Replacing 50W halogen spotlights with 30W halogen lamps Passive Infrared Sensor (PIRs) in stairwells Lighting timer installed in the lecture theatre G22 T8 lamps replacement with T5 lamps	✓	The two suggestions are same
BMS	BMS optimization	Extending the monitoring system to AM&T system Optimizing BMS	✓	The two suggestions are same
Water efficient systems	Rainwater harvesting system	Excluded	×	No apparent space available in the building or basement to house the collection tank (provided by the consultancy firm)
	Water saving measures	Low flush toilets Low flow taps	✓	The two suggestions are same

5.4 Technology evaluation with MCDM method

As the consultancy report considered only *Economic* criteria and *Energy saving potential*, the proposed framework will have to be adjusted. Under *Economic* criteria, the report only identified the *Cost* and the *Payback period*. The consultancy firm did not provide data for the development of social criteria regardless of the fact that the main stakeholder, the University, recognises the close link between the Carbon Management Strategy and wider sustainability agenda. The criteria considered in the consultancy report are marked as grey within the full proposed criteria tree in Figure 5.8.

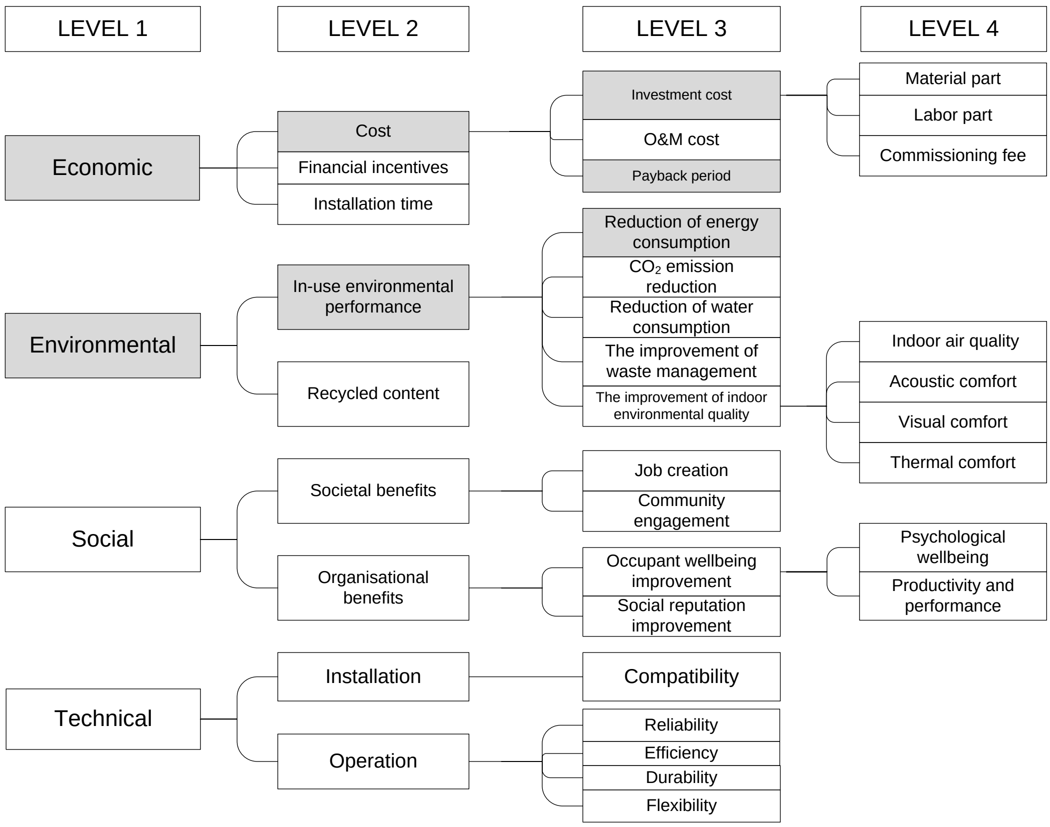


Figure 5.8 Selected evaluation criteria for the case study

In order to investigate the influence of stakeholder perspectives on the criteria weighting, three scenarios have been developed using default weighting values assigned by all the UK experts, UK architects and UK engineers.

1) Default weighting values suggested by all the UK experts at level 1 are 0.279 for

Economic, 0.296 for *Environmental*, 0.185 for *Social* and 0.240 for *Technical*. Given that no *Social* and *Technical* criteria were considered in the consultancy report, by averaging the default weighting values for these two criteria, *Economic* criterion and *Environmental* criterion were assigned with the weight values of 0.4915 and 0.5085 respectively. For the level 3 sub-criteria of *Cost* and *Payback period*, weighting values are assigned as 0.4375 and 0.5625 by adding the averaged weighting value for O&M cost of 0.375 to each. The method of weighting value allocation is a standard practice, which has been used in relevant research (Wang *et al.* 2009). The application of default criteria weights to criteria used in the consultancy report is shown in Figure 5.9.

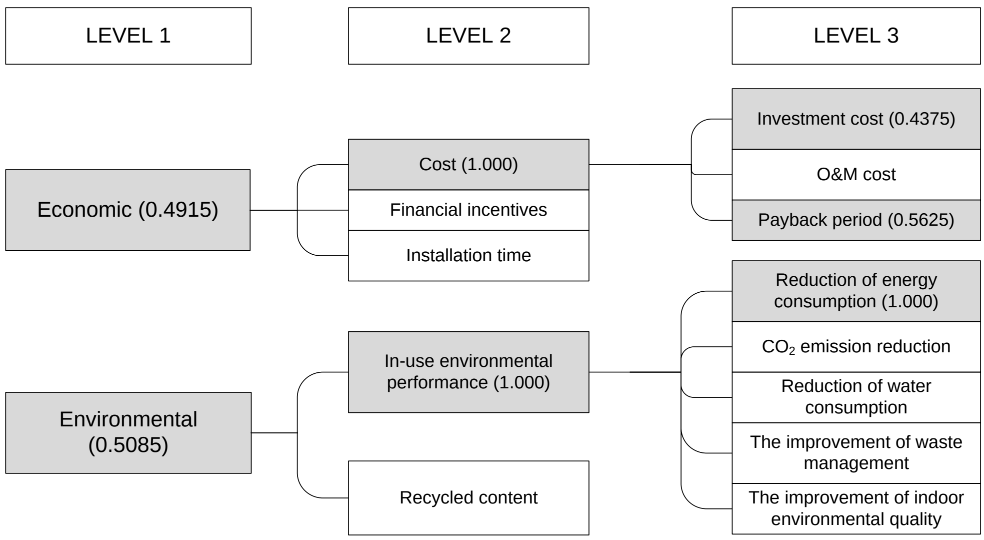


Figure 5.9 Criteria weighting by all the UK experts

2) Default weighting values suggested by the UK architects for level 1 criteria are: 0.303 for *Economic*, 0.173 for *Environmental*, 0.303 for *Social* and 0.220 for *Technical*. Following the same weight distribution as in the example for all the UK experts, the weights for scenario 2 are presented in Figure 5.10.

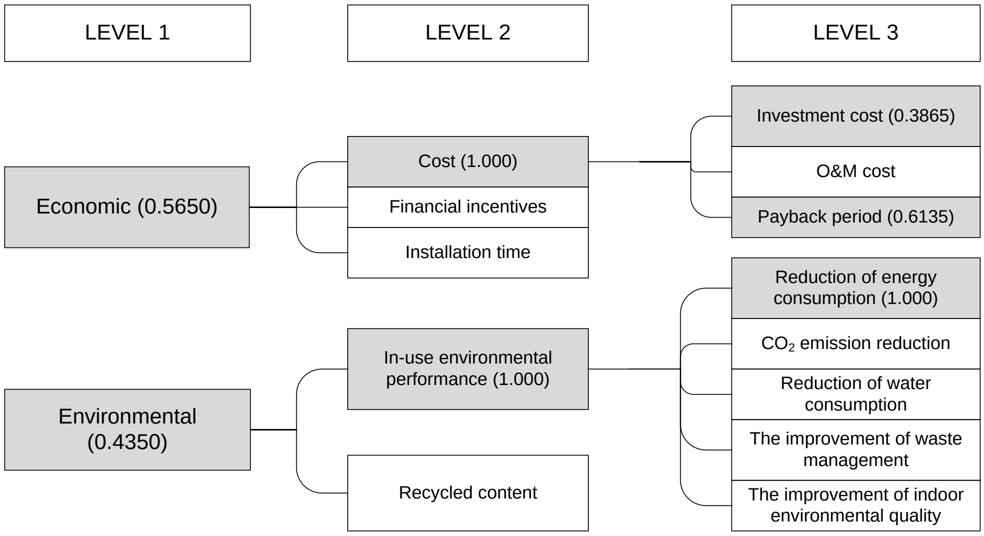


Figure 5.10 Criteria weighting by the UK architects

3) Default weighting values suggested by the UK engineers for level 1 criteria are 0.289 for *Economic*, 0.326 for *Environmental*, 0.152 for *Social* and 0.234 for *Technical*. The weights for criteria used in the consultancy report are presented in Figure 5.11.

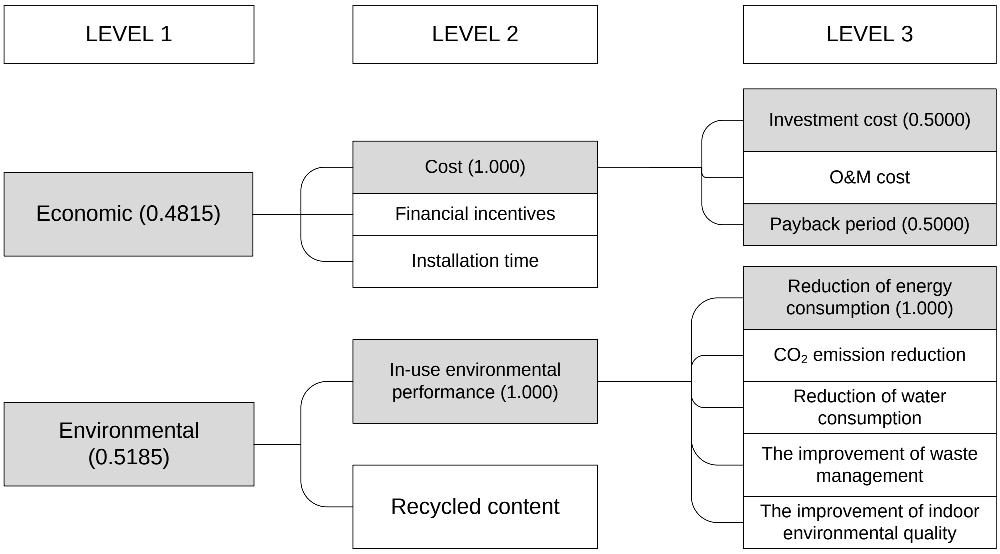


Figure 5.11 Criteria weighting by the UK engineers

Combined with technologies which have passed the screening process and data availability, the final list of technologies and their performance data regarding individual criterion are shown in Table 5. 2.

The technology performance in terms of the criteria of annual energy saving, investment cost and payback period is compared in pairs. The quotients of the pair comparisons will be mapped as equivalent to expert opinions of relative importance of criteria using Saaty's 1-9 scale (Wang *et al*., 2009). For example, the annual energy saving achieved by T8 lamps replacement with T5 lamps (C5) of 378kWh/yr (quotient A), can be compared to energy saving of Fitting Variable Speed Drives (VSD) in AHU (C6) of 24090kWh/yr (quotient B). The comparison results of these two data is the quotient of A versus B, which is equal to value of A divided by value of B. Same for the cost and payback period, the investment cost of Temperature control on AHU (C8) of £640 (quotient A), can be compared to the investment cost of Extending the monitoring system to AM&T system (C9) of £15500 (quotient B); the payback period of Extending the monitoring system to AM&T system (C9) of 4.9 years (quotient A), can be compared to the payback period of Optimizing BMS (C10) of 2.4 years (quotient B). The quotient results can span over a wide numerical range, such as the range of quotients for energy saving performance spanned from 1.20 to 77.50. It should be noted that the 1-9 scale assignment will be decided depending on the specific range of the quotients.

The relative importance (pairwise comparison) scale developed by Saaty (1990) was adopted to map all the quotients into 1-9 scale. If the technology performance of alternative A has a great value than that of alternative B, their pair-wise comparison results by using 1-9 scale will be greater than 1. Otherwise, the pair-wise comparison results are less than 1. In the matrices of pair comparisons (MPC), the pair-wise comparison of B to A is the reciprocal value of the A to B. For example, the investment cost (IC) of alternative C6 is 8.18 times greater than C5. Depending the whole distribution of all the quotient results, this value of 8.18 is mapped as the equivalent of 4 by using 1-9 scale. The reciprocal value is 1/4, which means that C5 is 1/4 of C6 in investment cost. This is how to deal with the quantitative data when using the AHP methods, which is to normalise the quantitative data and mapped them as the equivalents to the experts' opinions in 1-9 scale (Wang *et al.* 2009).

Tables 5.3 to 5.5 are the matrices of pair comparisons (MPC) of annual energy saving, investment cost and payback period, respectively. The MPC of annual energy saving has 10 columns and 10 rows. Due to no cost and zero payback period for C7, the MPC of economic criteria have 9 columns by 9 rows. The analysis of C7 is conducted separately.

Table 5.2 The list of alternative energy-saving technologies

Categories	Energy saving technologies	Code	Annual energy saving (KWh)	Investment cost (£)	Payback period (yrs)
Fabric	Secondary glazing on all single-glazed windows	C1	20160	11200	16
Lighting	Replacing 50W halogen spotlights with 30W halogen lamps	C2	1800	298	0.8
	Passive Infrared Sensor (PIRs) in stairwells	C3	1845	200	0.8
	Lighting timer installed in the lecture theatre G22	C4	1620	240	1.2
	T8 lamps replacement with T5 lamps	C5	378	440	8
HVAC equipment	Fitting Variable Speed Drives (VSD) in AHU	C6	24090	3601	1.5
	Integrating all Fan Coil Units (FCUs) with Building Management System (BMS)	C7	19250	0	0
	Temperature control on AHU	C8	8760	640	0.8
Management	Extending the monitoring system to AM&T system	C9	46033	15500	4.9
	Optimizing BMS	C10	18413	3000	2.4

Table 5.3 Relational scoring of alternative technologies regarding annual energy saving (AES)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1.00	0.25	0.25	0.25	0.14	1.00	1.00	2.00	1.00	1.00
C2	4.00	1.00	1.00	1.00	0.33	2.00	3.00	2.00	5.00	3.00
C3	4.00	1.00	1.00	1.00	0.33	2.00	3.00	2.00	5.00	3.00
C4	4.00	1.00	1.00	1.00	0.33	4.00	4.00	2.00	6.00	3.00
C5	7.00	3.00	3.00	3.00	1.00	8.00	7.00	5.00	9.00	7.00
C6	1.00	3.00	0.50	2.00	0.13	1.00	1.00	0.50	1.00	1.00
C7	1.00	0.33	0.33	0.25	0.14	1.00	1.00	0.50	2.00	1.00
C8	0.50	0.50	0.50	0.50	0.20	2.00	2.00	1.00	2.00	1.00
C9	1.00	0.20	0.20	0.17	0.11	1.00	0.50	0.50	1.00	0.50
C10	1.00	0.33	0.33	0.33	0.14	1.00	1.00	1.00	2.00	1.00

Table 5.4 Relational scoring of alternative technologies regarding the investment cost (IC)

	C1	C2	C3	C4	C5	C6	C8	C9	C10
C1	1.00	0.14	0.13	0.14	0.17	0.33	0.20	1.00	0.33
C2	7.00	1.00	1.00	1.00	1.00	5.00	2.00	8.00	5.00
C3	8.00	1.00	1.00	1.00	2.00	5.00	3.00	9.00	5.00
C4	7.00	1.00	1.00	1.00	2.00	5.00	3.00	9.00	5.00
C5	6.00	1.00	0.50	0.50	1.00	4.00	1.00	7.00	4.00
C6	3.00	0.20	0.20	0.20	0.25	1.00	0.25	3.00	1.00
C8	5.00	0.50	0.33	0.33	1.00	4.00	1.00	6.00	4.00
C9	1.00	0.13	0.11	0.11	0.14	0.33	0.17	1.00	0.25
C10	3.00	0.20	0.20	0.20	0.25	1.00	0.25	4.00	1.00

Table 5.5 Relational scoring of alternative technologies regarding payback period (PP)

	C1	C2	C3	C4	C5	C6	C8	C9	C10
C1	1.00	9.00	9.00	8.00	2.00	7.00	9.00	3.00	6.00
C2	0.11	1.00	1.00	1.00	0.14	1.00	1.00	0.17	0.33
C3	0.11	1.00	1.00	1.00	0.14	1.00	1.00	0.17	0.33
C4	0.13	1.00	1.00	1.00	0.17	1.00	1.00	0.25	0.50
C5	0.50	7.00	7.00	6.00	1.00	5.00	7.00	1.00	3.00
C6	0.14	1.00	1.00	1.00	0.20	1.00	1.00	0.33	1.00
C8	0.11	1.00	1.00	1.00	0.14	1.00	1.00	0.17	0.33
C9	0.33	6.00	6.00	4.00	1.00	3.00	6.00	1.00	2.00
C10	0.17	3.00	3.00	2.00	0.33	1.00	3.00	0.50	1.00

5.5 Result synthesis

All the relative technology scores can be calculated through the MPC above (Afshari, Mojahed and Yusuff, 2010). Combined with the weights, the integrated performance scores (IPS) of each technology can be calculated with the equation (5-1):

$$\mathrm{V}_i = \sum_i \omega_i x_i \quad , \text{where} \sum \omega_i = 1 \qquad (5\text{-}1)$$

where ω_i is the weight of criterion i, x_i is the corresponding technology performance score, and V_i is the IPS calculated for criterion i.

The global scores of technologies can be calculated using the equation (5-2):

Global scores =IPS for AES +IPS for IC*+ IPS for PP * (5-2)

Due to the impacts of cost and payback period are opposite to that of energy saving potential to technology performance scores, the MPCs of these two criteria have been transposed to calculate the technology performance scores (CS* and PP* mean the transposed matrices of cost and payback period). The MPCs have all passed the consistency checking.

An example is given here to explain the above equation. For example, in the UK all expert scenario, Economic criterion and Environmental criterion were assigned with the weight values of 0.4915 (ω_1) and 0.5085 (ω_2) respectively. For the level 3 sub-criteria of Cost and Payback period, weighting values are assigned as 0.4375 (ω_{21}) and 0.5625(ω_{22}) The IPS for AES is 0.5085*0.140=0.0712; The IPS for IC is 0.4915*(0.4375*0.264)=0.057; The IPS for PP is 0.4915*(0.5625*0.017)=0.005; the global score of technology C1 is 0.0172+0.057+0.005=0.13. The results for technology ranking regarding individual criterion are shown in Table 5.6.

Table 5.6 Relative scores of alternative technologies regarding individual criterion

Code	The score for AES	Ranking for AES	The score for IC	Ranking for IC	The score for PP	Ranking for PP
C1	0.140	4	0.264	2	0.017	9
C2	0.034	10	0.030	7	0.180	1
C3	0.034	9	0.026	8	0.180	1
C4	0.033	8	0.026	9	0.160	4
C5	0.015	6	0.041	6	0.028	8
C6	0.160	1	0.133	3	0.138	5
C7	0.137	5	-	-	-	-
C8	0.084	2	0.051	5	0.180	1
C9	0.225	7	0.299	1	0.040	7
C10	0.137	3	0.129	4	0.080	6

The results for technology ranking regarding the global scores of three scenarios are listed in Table 5.7.

Table 5.7 Global scores and technology ranking for three scenarios

Code	UK all experts		UK Architects		UK Engineers	
	Global score	Final ranking	Global score	Final ranking	Global score	Final ranking
C1	0.13	4	0.13	4	0.14	4
C2	0.07	7	0.08	7	0.07	7
C3	0.07	8	0.08	8	0.07	8
C4	0.07	9	0.07	9	0.06	9
C5	0.03	10	0.03	10	0.03	10
C6	0.15	3	0.15	3	0.15	3
C7	-	1	-	1	-	1
C8	0.11	6	0.11	6	0.10	6
C9	0.19	2	0.17	2	0.20	2
C10	0.12	5	0.12	5	0.12	5

The final rankings of individual technology for different scenarios are the same. The top three technologies are listed in Table 5.8. Integrating all Fan Coil Units (FCUs) with Building Management System (BMS) (C7) has the overall ranking of 1, where the cost and the payback period has the highest priority. On the other hand, extending the monitoring system to AM&T system (C9) has a better energy saving potential but lower priorities for other criteria. Fitting Variable Speed Drives (VSD) in AHU (C6) gives the highest priority to the energy saving potential but poor performance in terms of annual costs and payback period.

Table 5.8 Top three ranking technologies

Technology	Ranking for AES	Ranking for IC	Ranking for PP	Final ranking
Integrating all Fan Coil Units (FCUs) with Building Management System (BMS) (C7)	5	1	1	1
Extending the monitoring system to AM&T system (C9)	7	1	7	2
Fitting Variable Speed Drives (VSD) in AHU (C6)	1	3	5	3

In contrast, the least favourable technologies are listed in Table 5.9. Both Passive Infrared Sensor (PIRs) in stairwells (C3) and Lighting timer installed in the lecture theatre G22 (C4) have poor performance in annual energy saving and investment cost but have a good performance in payback period, especially for C3. T8 lamps replacement with T5 lamps (C5) has a relatively good performance in both annual energy saving and investment cost but a poor performance in payback period.

Table 5.9 The Less desirable technologies

Technology	Ranking for AES	Ranking for IC	Ranking for PP	Final ranking
Passive Infrared Sensor (PIRs) in stairwells (C3)	9	8	1	8
Lighting timer installed in the lecture theatre G22 (C4)	8	9	4	9
T8 lamps replacement with T5 lamps (C5)	6	6	8	10

5.6 Sensitivity analysis

Technology ranking is dependent on the weights assigned to the evaluation criteria. Small changes could cause major changes of the final results. Since these weights are usually based on highly subjective judgments, the stability of the ranking under varying criteria weights has to be tested (Chang *et al*., 2007). For this purpose, sensitivity analysis can be performed based on scenarios that reflect alternative future developments or different views on the relative importance of the criteria. Through increasing or decreasing the weight of individual criterion, the resulting changes of results and their ranking can be observed. Sensitivity analysis therefore can provide information on the stability of the ranking. If the ranking is highly sensitive to small changes in the criteria weights, a careful review of the weights is recommended (Chang *et al*., 2007). When weight value has been changed for one criterion, other criteria change accordingly, reflecting the relative nature of the weights, i.e., the total weights have to add up to 100%.

Following this approach, sensitivity analysis has been conducted. Through sensitivity analysis, different scenarios with different weighting values can be helpful to observe the impact on final alternative rank (Syamsuddin, 2013). Erkut and Tarmcilar (1991, p.65) have summarised sensitivity analysis in relation to weights as:

5) "What if the weight of one criterion is changed from w_i to $w_i(1+p)$?
6) For which set of values of the weights will a particular alternative have the highest final ranking?
7) How sensitive is the final selection result to the changes in the weighting values?
8) What is the smallest change in the weights that will result in a change of the selected alternative?"

Considering there are two criteria included on each level in this study, the sensitivity analysis for two criteria is selected to be discussed. For the case with two criteria, the weight values of one criterion can be changed (increased or decreased) by a degree, and the sum of weights for these two criteria should remain as one. The final value of alternative i is given as below, which is a function of the single variable w_1.

$$V_i = w_1 x_{i1} + w_2 x_{i2} = w_1 x_{i1} + (1 - w_1) x_{i2} = (x_{i1} - x_{i2}) w_1 + x_{i2} \quad (5\text{-}3)$$

From the existing research of AHP method and its sensitivity analysis, the percentage in weighting values change is between 25% to 35% (Chang *et al.*, 2007). The middle value of 30% is adopted for individual criterion changes. Changes of criteria weighting values for three scenarios are shown from Table 5.10 to 5.12.

Table 5.10 Changes of criteria weighting values for all the UK expert scenario

Level	Criteria	Default weighting values	Economic Increased by 30%	Environmental Increased by 30%	Cost Increased by 30%	Payback increased by 30%
Level 1	Economic	0.5085	0.6611	0.3611	0.5085	0.5085
	Environmental	0.4915	0.3390	0.6390	0.4915	0.4915
Level 3	Investment cost	0.4381	0.4381	0.4381	0.5695	0.2695
	Payback period	0.5619	0.5619	0.5619	0.4305	0.7305

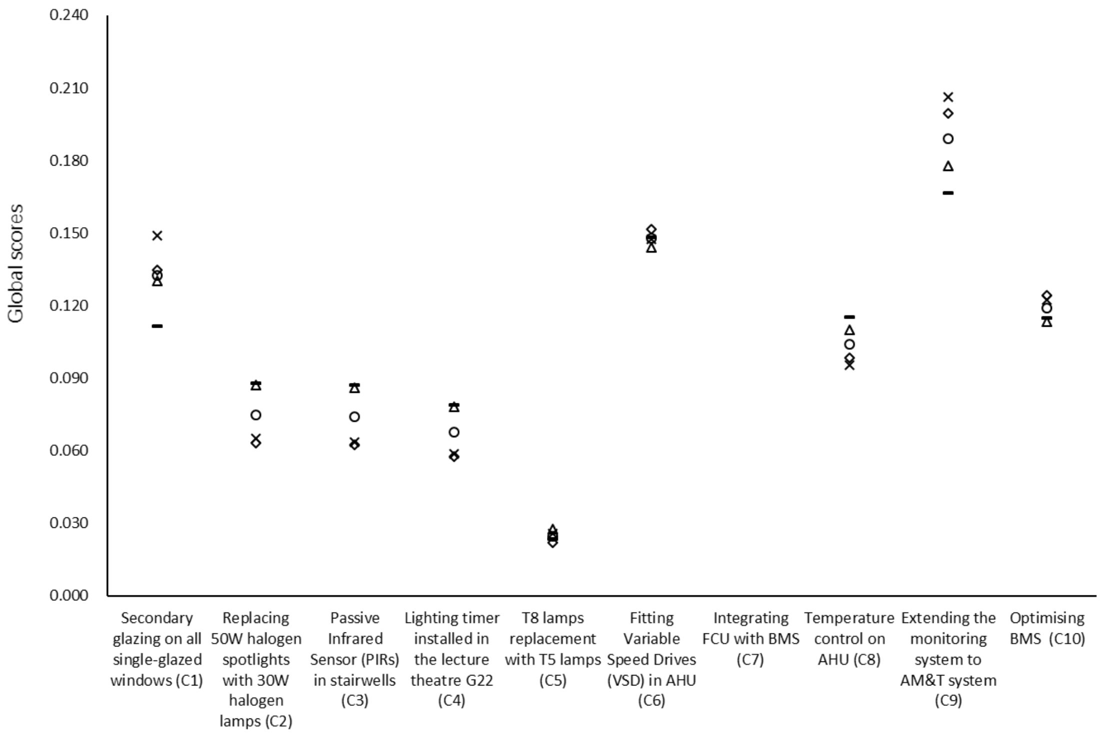
Table 5.11 Changes of criteria weighting values for the UK architect scenario

Level	Criteria	Default weighting values	Economic Increased by 30%	Environmental Increased by 30%	Cost Increased by 30%	Payback increased by 30%
Level 1	Economic	0.4349	0.5654	0.2654	0.4349	0.4349
	Environmental	0.5651	0.4346	0.7346	0.5651	0.5651
Level 3	Investment cost	0.3871	0.3871	0.3871	0.5032	0.2032
	Payback period	0.6129	0.6129	0.6129	0.4968	0.7968

Table 5.12 Changes of criteria weighting values for the UK engineer scenario

Level	Criteria	Default weighting values	Economic Increased by 30%	Environmental Increased by 30%	Cost Increased by 30%	Payback increased by 30%
Level 1	Economic	0.6740	0.3740	0.5185	0.5185	0.6740
	Environmental	0.3260	0.6260	0.4815	0.4815	0.3260
Level 3	Investment cost	0.5000	0.5000	0.6500	0.3500	0.5000
	Payback period	0.5000	0.5000	0.3500	0.6500	0.5000

The influence of weights changes to the global scores in presented in Figures 5.12 to 5.14 for different scenarios.

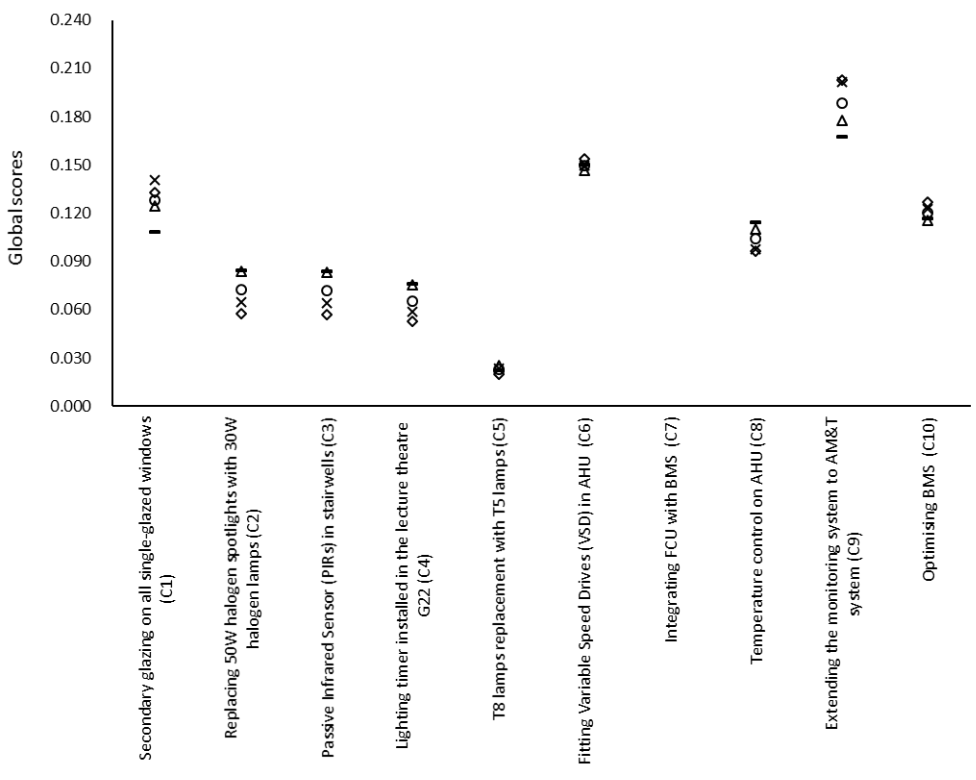


○ Default scenario △ Economic criterion increased by 30% ◇ Environmental criterion increased by 30% ×Cost criterion increased by 30% —Payback period criterion increased by 30%

Figure 5.12 Global scores change of technology alternatives when individual criterion weight increased by 30% in all the UK expert scenario

In the all UK expert scenario, with the change of weighting values of the economic criterion and environmental criterion, changes in global scores can be identified for efficient lighting solutions and lighting controls (include replacing 50w halogen spotlights with 30w halogen lamps, passive infrared sensors in stairs, lighting timer installed replacement in the lecture theatre G22) and extending the monitoring system to AM&T system. With the change of weighting values of cost criterion, changes in global scores can be identified for the above-mentioned technologies, secondary glazing on the single-glazed windows and temperature control on AHU. With the change of weighting values of the payback period, noticeable changes in global scores have been identified for the majority of technologies except for the T8 lamps replacement with T5 lamps, fitting variable speed drives in AHU and optimising BMS.

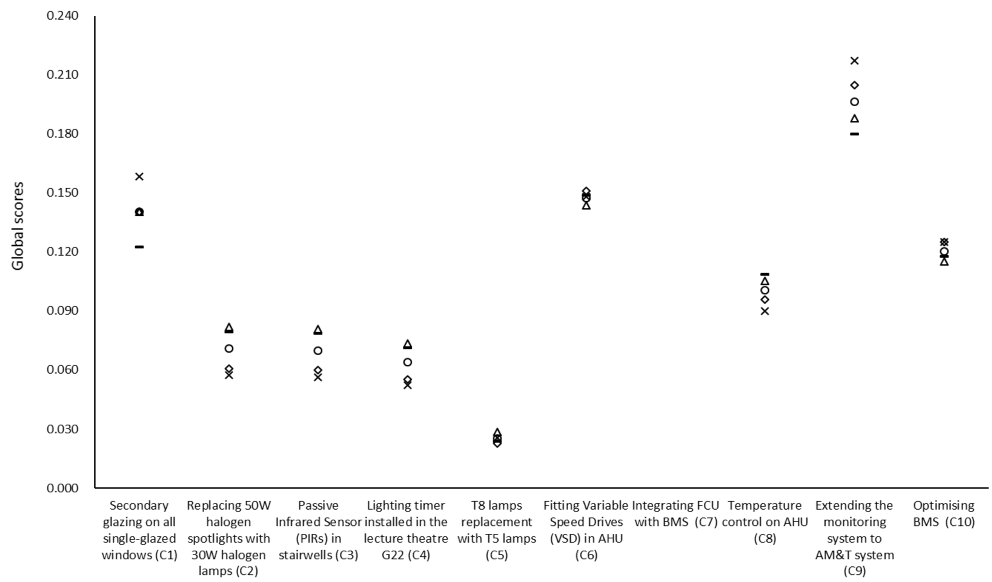
Technology ranking has been changed when changing the weighting values of cost criterion and payback period criteria too. When changing the weighting values of cost criterion, the global score of secondary glazing on all single-glazed windows is increased by 12.45%, which makes this technology rank higher as 3rd choice and accordingly the previous 3rd technology of fitting VSDs in AHU ranked as 4th choice. When changing the weighting values of payback period criterion by 30%, the global scores of the majority of technologies changed, which has caused a significant change in the ranking. In Table 5.13, the technologies of temperature control on AHU and optimising BMS have ranked higher compared to the UK all expert default scenario. Technologies of secondary glazing on all single-glazed windows and fitting VSDs in AHU ranked lower compared to the UK all expert default scenario. The technology ranking changes due to the changes of criteria of cost and payback period in the all UK expert scenario is shown in Table 5.13.



○ Default scenario △ Economic criterion increased by 30% ◇ Environmental criterion increased by 30%
×Cost criterion increased by 30% —Payback period criterion increased by 30%

Figure 5.13 Global scores of technology alternatives when individual criterion weight increased by 30% for the UK architect scenario

In the UK architect scenario, with the change of weighting values of economic criterion and environmental criterion, changes in global scores can be identified for efficient lighting solutions and lighting controls (include replacing 50w halogen spotlights with 30w halogen lamps, passive infrared sensors in stairs, lighting timer installed replacement in the lecture theatre G22) and extending the monitoring system to AM&T system, which is the same as the UK all experts scenario. With the change of weighting values of cost criterion and payback period criterion, changes in global scores can be identified for the majority of technologies except for the T8 lamps replacement with T5 lamps, fitting variable speed drives in AHU and optimising BMS. Technology ranking has been changed when changing the weighting values of economic criterion, environmental criterion and cost criterion. Compared to the default scenario, when changing these three criteria, the 4th and 5th technologies in default scenario, which are respectively Optimizing BMS and Secondary glazing on all single-glazed windows, have shifted their ranking. When changing the weighting values of the payback period criterion by 30%, the global scores of the majority of technologies changed, which leads to a change in technology ranking: secondary glazing on all single-glazed windows has dropped to 6th technology, and 5th technology and 6th technology, which are respectively optimising BMS and temperature control on AHU, have ranked as 4th and 5th technologies. The technology ranking changes due to the changes of criteria of cost and payback period in the UK architect scenario is shown in Table 5.14.



○ Default scenario △ Economic criterion increased by 30% ◇ Environmental criterion increased by 30% ×Cost criterion increased by 30% —Payback period criterion increased by 30%

Figure 5.14 Global scores of technology alternatives when individual criterion weight increased by 30% for the UK engineer scenario

In the UK engineer scenario, with the change of weighting values of economic criterion and environmental criterion, changes in global scores can be identified for efficient lighting solutions and lighting controls (include replacing 50W halogen spotlights with 30W halogen lamps, passive infrared sensors in stairs, lighting timer installed replacement in the lecture theatre G22) and extending the monitoring system to AM&T system, which is the same as the all UK expert scenario and UK architects scenario. With the change of weighting values of criteria of cost and payback period, changes in global scores can be identified for the majority of technologies except for the T8 lamps replacement with T5 lamps, fitting VSD in AHU and optimising BMS. Technology ranking remains the same and has been influenced by criteria weighting change. The technology ranking changes due to the changes of criteria of cost and payback period in the UK architect scenario is shown in Table 5.15.

Table 5.13 Global scores and technology ranking when criteria weighting change in all the UK expert scenario

Technology alternatives	All the UK expert default scenario		Economic criterion weight increased by 30%		Environmental criterion weight increased by 30%		Cost criterion weight increased by 30%		Payback period criterion weight increased by 30%	
	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking
Secondary glazing on all the single-glazed windows	0.133	4	0.130	4	0.135	4	0.149	**3**	0.111	**6**
Replacing 50W halogen spotlights with 30W halogen lamps	0.075	7	0.087	7	0.063	7	0.065	7	0.088	7
Passive Infrared Sensor (PIRs) in stairwells	0.074	8	0.086	8	0.062	8	0.064	8	0.087	8
Lighting timer installed in the lecture theatre G22	0.068	9	0.078	9	0.057	9	0.059	9	0.079	9
T8 lamps replacement with T5 lamps	0.025	10	0.028	10	0.022	10	0.026	10	0.024	10
Fitting Variable Speed Drives (VSD) in AHU	0.148	3	0.144	3	0.151	3	0.148	4	0.148	5

Integrating FCU with BMS		1		1		1		1		1
Temperature control on AHU	0.104	6	0.110	6	0.098	6	0.096	6	0.1152	3
Extending the monitoring system to AM&T system	0.189	2	0.178	2	0.200	2	0.206	2	0.1667	2
Optimizing BMS	0.119	5	0.114	5	0.124	5	0.122	5	0.1148	4

Table 5.14 Global scores and technology ranking when criteria weighting change in the UK architect scenario

Technology alternatives	The UK architect default scenario		Economic criterion weight increased by 30%		Environmental criterion weight increased by 30%		Cost criterion weight increased by 30%		Payback period criterion weight increased by 30%	
	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking
Secondary glazing on all single-glazed windows	0.128	5	0.125	**4**	0.133	**4**	0.141	**4**	0.108	**6**
Replacing 50W halogen spotlights with 30W halogen lamps	0.072	7	0.084	7	0.057	7	0.065	7	0.084	7
Passive Infrared Sensor (PIRs) in stairwells	0.072	8	0.083	8	0.057	8	0.064	8	0.084	8
Lighting timer installed in the lecture theatre G22	0.066	9	0.075	9	0.053	9	0.059	9	0.076	9
T8 lamps replacement with T5 lamps	0.023	10	0.025	10	0.020	10	0.024	10	0.022	10

Fitting Variable Speed Drives (VSD) in AHU	0.150	3	0.147	3	0.154	3	0.149	3	0.150	3
Integrating FCU with BMS		1		1		1		1		1
Temperature control on AHU	0.104	6	0.110	6	0.096	6	0.098	6	0.114	**5**
Extending the monitoring system to AM&T system	0.188	2	0.177	2	0.203	2	0.202	2	0.168	2
Optimising BMS	0.121	4	0.116	**5**	0.127	**5**	0.123	**5**	0.117	**4**

Table 5.15 Global scores and technology ranking when criteria weighting change in the UK engineer scenario

Technology alternatives	The UK engineer default scenario		Economic criterion weight increased by 30%		Environmental criterion weight increased by 30%		Cost criterion weight increased by 30%		Payback period criterion weight increased by 30%	
	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking	Global scores	Ranking
Secondary glazing on all single-glazed windows	0.140	4	0.140	4	0.140	4	0.158	4	0.123	4
Replacing 50W halogen spotlights with 30W halogen lamps	0.071	7	0.082	7	0.061	7	0.057	7	0.079	7
Passive Infrared Sensor (PIRs) in stairwells	0.070	8	0.081	8	0.060	8	0.056	8	0.078	8
Lighting timer installed in the lecture theatre G22	0.064	9	0.073	9	0.055	9	0.052	9	0.071	9
T8 lamps replacement with T5 lamps	0.025	10	0.028	10	0.023	10	0.026	10	0.024	10

Fitting Variable Speed Drives (VSD) in AHU	0.147	3	0.144	3	0.151	3	0.148	3	0.149	3
Integrating FCU with BMS		1		1		1		1		1
Temperature control on AHU	0.100	6	0.105	6	0.096	6	0.090	6	0.109	6
Extending the monitoring system to AM&T system	0.197	2	0.188	2	0.205	2	0.217	2	0.180	2
Optimizing BMS	0.120	5	0.115	5	0.125	5	0.125	5	0.118	5

5.7 Summary

This chapter has applied the proposed framework into a real-case building. By conducting three phases of site and building survey, green technology listing and technology screening, a list of green technologies has been identified. The result of this list of green technology has been compared with the results from the industry report. It has been found that this case building still has potential opportunities to integrate with green technologies, such as solar PV, solar thermal and water harvesting system. Without applying the framework to list and screen green technology in a systematic approach, potential green technologies are too quick to be excluded. However, the limitations of the proposed framework have been identified as well. Since the framework is designed for non-expert users to generally investigate the potentials of building retrofits, some detailed problems such as control problems are not easy to identify with framework.

Technology evaluation with MCDM methods has been conducted for green technologies with available data. Technology ranking has been identified through MCDM methods. To investigate the sensitivity of result changes by changing criteria weighting values, different scenarios are developed and the sensitivity analysis has been performed. It has been found that in all the UK expert scenario, changes of criteria weighting for cost and payback period can lead to technology ranking changes. In the UK architect scenario, changes of weighting values for all criteria can lead to technology ranking changes. In the UK engineer scenario, there is no change in technology ranking due to criteria weighting changes.

Chapter 6 Conclusions and future works

This chapter concludes the thesis and presents its contributions to the knowledge. It also discusses the limitations of the study and offers guidance to the future research.

6.1 Achievement of the research objectives

The aim of this research was to investigate green retrofit of non-domestic buildings by developing an integrated assessment framework of green technology selection. In order to achieve this aim, five objectives were developed and outlined in the introductory chapter. The following explains how these objectives have been achieved through the research.

The first objective was “to cross reference green technologies specifications against operational characteristics of different non-domestic building types”. A detailed analysis of the green technologies against operational characteristics of different non-domestic buildings types has informed the development of the framework, more specifically in its site and building survey part. Below the information tables in site and building survey, there are suggestions on green technology listing based on the building characteristics, which are mainly proposed by referring to Appendix A. At the same time, how the building types can inform the green technology selection is also explained in Section 4.2.7, which is proposed by referring to Appendix B. In Chapter 5 where the application of the proposed framework on existing HE building, it was demonstrated that the energy performance of this building can be improved through green technologies of upgraded glazing windows, Fitting VSD in AHU, integrating all FCUs to BMS, Daylighting optimisation and Lighting controls, BMS optimisation, PV system, Solar thermal and Green roof. Water efficiency of the building can be improved with Water saving measures and Water recycling measures.

The second objective was “to develop an integrated framework of green technology selection phase by phase by including proposing technologies, screening technologies and evaluating technologies". This objective was achieved by proposing a conceptual framework in Chapter 4. The framework was designed with multiple phases: site and building survey, technology listing and screening, and technology evaluation with MCDM methods. The proposed framework, different from previous frameworks in existing research, has focused on the green technology selection and has provided practical guidance on how to carry out the selection. In the Site and Building Survey (Section 4.2), the information describing current building characteristics and its performance in terms of energy conservation, water efficiency as well as health and wellbeing improvement was suggested to collect. The implications of potential green technologies against the operational characteristics was presented. With a list of potential green technologies, technology screening process (Section 4.3) was suggested to further check technologies' feasibility on three levels: technology, building and community. For the case of multiple technologies left after the Screening Process, MCDM methods with four steps (Section 4.4) were recommended to evaluate and rank the technologies. With reference to the default multiple criteria tree, default weighting factors and technology scoring methods, the technology ranking can be achieved and the optimal technologies and the less desirable ones can be identified.

The third objective was "to propose a default multi-criteria tree covering sustainability criteria and technical criteria". This objective has been achieved in Section 4.4.1 in the Chapter 4. Building upon sustainability's triple bottom line, an integrative AHP hierarchy with multiple criteria was proposed and presented in Figure 4.6. The proposed criteria tree was based on existing literature findings and its structure was informed by individual criteria attributes and interrelationships. The proposal of this criteria tree can provide decision makers with the possibility to evaluate and compare green technologies in a broader perspective. In reality, decision makers can adopt fewer criteria based on their goals, limitations and availability of data, and employ a simplified version of the criteria tree.

The fourth objective was "to suggest default weighting values for proposed multiple criteria and methods to use these values". This objective was achieved in Section 4.4.2 of the Chapter 4. With the identification that criteria weighting can be influenced both by stakeholder perspectives and overarching national level of development, industry surveys were designed and distributed to collect the subjective weighting factors assigned by stakeholders from different backgrounds in the UK and China. By using the AHP method and processing the data in the Matlab, default weighting factors were proposed and listed in Table 4.12. Comparisons of weighting factors for criteria on different levels between expert groups in the individual country and between the two countries have been conducted (Section 4.4.2.3). It has been found that the UK experts have placed more emphasis on economic criteria, while Chinese experts are more concerned about technical criteria. The finding is consistent with the survey results of the most frequent client requirements in the two countries, which are "to reduce operational cost" and "to increase asset value" in the UK, and "to improve building safety and security" in China.

The fifth objective was "to illustrate the use of each phase of the framework through real case study and make a scenario analysis by applying different sets of weighting values". This objective was achieved in the Chapter 5. A Higher Education building located in the area of high urban density and with the climate of heating degree days are more than cooling degree days, was selected as a case study building to investigate the effectiveness of a proposed framework of green technology selection in existing buildings. In real life scenario in which relevant stakeholders in charge of the case building retrofit have appointed external consultancy to the survey and suggest technical solutions. Their suggested solutions have been compared with the technology results achieved from the proposed framework.

With the available data for economic and environmental criteria, the listed green technologies were further evaluated and ranked using MCDM methods. The optimal technologies and less desirable technologies were identified. Three scenarios were developed for the case building by applying different sets of default weighting factors. With a further sensitivity analysis, the stability of the technology ranking has been checked for these three scenarios and the criteria that can influence the technology ranking have been identified for all the UK expert scenario and UK architect scenario. In all the UK expert scenario, changes of criteria weighting for cost and payback period can lead to technology ranking changes. In the UK architect scenario, changes of weighting values for all criteria can lead to technology ranking changes.

6.2 Contributions of the research

The research contributions of these research are summarised into three aspects as follows.

A contribution to the theoretical understanding of green retrofit as a multi-criteria decision making process: Developing an integrative selection framework of green technology for non-domestic buildings

Although the literature review identified many available theoretical models for building retrofits, these frameworks lack in the provision of practical suggestions on how to propose suitable green technologies and screen unsuitable ones against the operational characteristics of existing buildings. Moreover, the integration of multi-criteria analysis in green technology evaluation is still limited in existing research. Compared to technology evaluation, which is the focus of existing research, other essential phases, such as technology screening, are rarely discussed. In contrast, the proposed framework has been designed with the highlights of the investigation of potentials and limitations of existing buildings to integrate green technologies through the site and building survey, screening and checking the feasibility of potential technologies on multiple levels, and evaluating and ranking green technologies with MCDM methods.

A development of default multiple criteria tree for green technology selection

The research has made a contribution by proposing a default multiple criteria tree for green technology selection. From the literature review, the single-criteria analysis, such as the Cost Benefit Analysis is still dominant. In order to maximise the possibility of the evaluation of green technologies with multiple criteria, a default multiple criteria tree in the sense of overall thinking of sustainability has been suggested. Multiple criteria were proposed from the perspectives of environmental, economic, social and technical. Decision makers can adopt some of them and employ a simplified version of the criteria tree based on their goals. The suggestion of the multiple criteria tree can facilitate the technology evaluation with MCDM methods.

The investigation into stakeholder perspectives and national context's influence on weighting values

The research has contributed, at least to some extent, to the understanding of stakeholder perspectives and country contexts' influence on criteria weighting. As criteria weights can directly influence the ranking order of alternatives and the final results, the selection which takes into account stakeholder perspectives and country development is essential. Based on the proposed multiple criteria tree, criteria weights were collected from industry professionals through the surveys for UK and China (Table 4.12). With reference to the default weighting factors, the framework users can balance the stakeholders' opinions and optimise their sustainability goals in the decision-making process.

6.3 Limitations of the study and recommendations of the future research

In this study, the web-based surveys using the AHP method were designed to collect the subjective weighting factors for the proposed criteria. Valid responses were required from the industry experts who have working experience in the building retrofit. To maximise the sample size, a multi-stage sampling method has been utilised and three months have been allowed for data collection. There are 25 valid responses collected from the UK industry and 29 valid responses collected from the Chinese industry. The limited number of responses could be contributed to the reasons: 1) the web-based surveys are easy to be ignored and the number of qualified respondents may be affected; 2) the pilot study has revealed that the number of the responses could also be affected due to a tiresome work of 43 pairwise comparisons required in the survey. In the future work, the approach of the paper-version surveys will be considered and the surveys will be circulated into the targeted industry companies in person. By taking this approach, the qualified respondents who have working experience in building retrofits are more easily to identify and the direct communications with the experts can increase the response rate. In addition, the AHP method can be explained to the experts more clearly and the pairwise comparisons with consistent results are more likely to achieve. It could be expected that in this approach, the time spent on the individual respondent would be relatively long, but the validity of each response is more likely to manage and the total number of the valid responses may be increased.

Apart from the limitations of the survey, intrinsic limitations also exist for the AHP method. A portion of the survey responses using the AHP method was checked inconsistent, with consistency ratios > 0.1. However, this inconsistency seems not to be unusual in making paired comparisons, just as in thinking, people do not have the intrinsic logical ability to always be consistent. Existing research has shown that the use of AHP requires substantial beforehand training and the usage could be explained in semi-interviews or workshops, where consistent judgements from participants are much easier to manage. Meanwhile, by organising the workshops, the method of using the proposed criteria tree and default weighting factors for the real-life cases could be also explained to the participated stakeholders.

Alternatively, the AHP method can be implemented through the Expert Choice, a software professionally designed for the method, a reminder of inconsistency will be triggered for users and more consistent results can be received. By identifying the limitations of the research design and the AHP method, future works could be conducted in the way that the survey of criteria weighting is designed with the assistance of the Expert Choice. With more consistent results achieved through the software, a validation of criteria weights could be further carried out. In the validation process, the Pearson correlation test can be conducted between the weights elicited through the Expert Choice software and the weights proposed through the web-based surveys, and the correlation coefficient between these two results can be calculated. Criteria weights with the low correlation coefficient will be identified and validated.

Due to the time limits, the framework has been demonstrated through only one building, a HE building in this research. More case studies of using the framework into other types of non-domestic buildings could be conducted in the future. With more case study demonstrations, the effectiveness of the framework can be further tested and subsequently refined.

Through the application of the proposed framework into real case study, benefits and limitations of the framework have been identified. The proposed framework has improved the understanding of building retrofits and decision-making capabilities of decision makers when they are faced with green building technologies. However, it has shown that the framework is more capable of providing technology suggestions generally, helping decision makers to identify the retrofit potential of the existing buildings and drawing their attention on improving the building performance in multiple aspects of building performance. When it comes to more detailed technology suggestions, such as optimising the set-up and improving the control systems, additional in-depth survey into buildings may be needed. This limitation also clarifies the potential users of the proposed framework, who are non-expert users with the intention of retrofitting the buildings towards sustainability.

In addition, the framework is initially proposed to enhance the understanding of selecting green technologies with multiple criteria decision making (MCDM) method. In this conceptual framework, we have tried to propose a logical decision making process with multiple steps connected. In the technology screening process, we have proposed the screening criteria on three levels of technology, building and community. In the technology evaluation process, we have proposed the evaluation criteria from four perspectives: economic, environmental, social and technical, in accordance with sustainability goal and technology requirements. In real cases, the screening criteria and evaluation criteria may be adjusted. For example, when there is a financial budget, potential green technologies with investment cost exceeding the financial budget limits could be screened out. This limitation helps to clarify this framework is initially proposed as a logical structure for applying sustainability concepts and selecting green technologies with consideration of multiple criteria. In the real-life operation, the framework may need to be adjusted to satisfy the requirements of potential users and take account of real-life conditions.

References

Aczél, J. and Saaty, T.L. (1983). Procedures for synthesizing ratio judgements. *Journal of mathematical Psychology*, *27*(1), pp.93-102.

Adetunji, I.O. (2006). Sustainable construction: a web-based performance assessment tool (Doctoral dissertation).

Afshari, A., Mojahed, M. and Yusuff, R.M. (2010). Simple additive weighting approach to personnel selection problem. *International Journal of Innovation, Management and Technology*, *1*(5), p.511.

Alajmi, A. (2012). Energy audit of an educational building in a hot summer climate. *Energy and Buildings*, *47*, pp.122-130.

Amor, R. ed. (1998). Product and process modelling in the building industry: proceedings of ECPPM'98-the second European. *Conference on Product and Process Modelling in the Building Industry, BRE, UK, 19-21 October 1998*. Building Research Establishment.

Amaratunga, D., Baldry, D., Sarshar, M. and Newton, R. (2002). Quantitative and qualitative research in the built environment: application of "mixed" research approach. *Work study*, *51*(1), pp.17-31.

Andersen, P. D., Bonou, A., Beauson, J. and Brøndsted, P. (2014). Recycling of wind turbines. In H. Hvidtfeldt Larsen, & L. Sønderberg Petersen (Eds.), DTU International Energy Report 2014: Wind energy — drivers and barriers for higher shares of wind in the global power generation mix. (pp. 91-97). Technical University of Denmark.

Anastaselos, D., Giama, E. and Papadopoulos, A.M. (2009). An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. *Energy and Buildings*, *41*(11), pp.1165-1171.

ASHRAE Handbook-HVAC Applications (2011). Available at:
https://www.ashrae.org/standards-research--technology/research

ANSI/ASHRAE STANDARD 169 (2013). Available at:

https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwi7_IqBipfSAhUmxVQKHTLsCWkQFggcMAA&url=https%3A%2F%2Fwww.ashrae.org%2FFile%2520Library%2Fd ocLib%2FStdsErrata%2F169-2013ErrataSheet_1-24-2016.pdf&usg=AFQjCNH1Lh21cDW380xadpBZNOvVnWnINA

Ardente, F., Beccali, M., Cellura, M. and Mistretta, M. (2011). Energy and environmental benefits in public buildings as a result of retrofit actions. *Renewable and Sustainable Energy Reviews*, 15: 460-470.

Ardilly, P. and Tillé, Y. (2006). *Sampling methods: Exercises and solutions*. Springer Science & Business Media.

Banville, C., Landry, M., Martel, J.M. and Boulaire, C. (1998). A stakeholder approach to MCDA. *Systems Research and Behavioral Science*, *15*(1), pp.15-32.

Belton, V. and Pictet, J. (1997). A framework for group decision using a MCDA model: sharing, aggregating or comparing individual information?. *Journal of decision systems*, *6*(3), pp.283-303.

Benayoun, R., Roy, B. and Sussman, N. (1966). Manual de reference du programme electre. Note de synthese et Formation, 25.

Berardi, U. (2012). Sustainability assessment in the construction sector: rating systems and rated buildings. *Sustainable Development*, *20*(6), pp.411-424.

Bernstein, H.M. and Russo, M.A. (2009). Green Building Retrofit and Renovation: Rapidly Expanding Market Opportunities through Existing Buildings, Smart Market Report.

Bilgen, S. (2014). Structure and environmental impact of global energy consumption. *Renewable and Sustainable Energy Reviews*, 38: 890-902.

Bragança, L., Mateus, R. and Koukkari, H. (2010). Building sustainability assessment. *Sustainability*, *2*(7).

Brannen, J. (2005). Mixing methods: The entry of qualitative and quantitative approaches into the research process. *International journal of social research methodology*, *8*(3), pp.173-184.

BRE(2016). BREEAM In-Use International. Technical Manual. Available at： http://www.breeam.com/filelibrary/Technical%20Manuals/SD221_BIU_International_2015_Re-issue_V2.0.pdf.

BRE (2015). Washington Plaza, Paris. Available at: http://www.breeam.com/index.jsp?id=799

BRE (2015). Morelands Rooftop, London. Available at: http://www.breeam.com/index.jsp?id=798

Bryan, T. (2010). *Construction technology: analysis and choice* (2rd ed.). Chichester: Wiley-Blackwell

Bryman, A., Becker, S. and Sempik, J. (2008). Quality criteria for quantitative, qualitative and mixed methods research: A view from social policy. *International Journal of Social Research Methodology*, *11*(4), pp.261-276.

Carbon Trust (2009). Building the future, today. Available at: https://www.carbontrust.com/media/77252/ctc765_building_the_future__today.pdf.

Chang, C.W., Wu, C.R., Lin, C.T. and Chen, H.C. (2007). An application of AHP and sensitivity analysis for selecting the best slicing machine. *Computers & Industrial Engineering*, *52*(2), pp.296-307.

Chen, Y., Yu, J. and Khan, S. (2010). Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. *Environmental Modelling & Software*, *25*(12), pp.1582-1591.

Chidiac, S.E., Catania, E.J.C., Perry, H.L., Morofsky, E. and Foo, S. (2009). Computational tools for selecting energy conservation measures for retrofitting existing office buildings. Canadian Journal of Civil Engineering, 40: 445-459.

Chidiac, S.E., Catania, E.J.C., Morofsky, E. and Foo, S. (2011). Effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings. *Energy*, 36: 5037-5052.

Collier, Z.A., Wang, D., Vogel, J.T., Tatham, E.K. and Linkov, I. (2013). Sustainable roofing technology under multiple constraints: a decision-analytical approach. *Environment Systems and Decisions*, *33*(2), pp.261-271.

Cobanoglu, C., Warde, B. and Moreo, P.J. (2001). A comparison of mail, fax and web-based survey methods. *International journal of market research*, *43*(4), pp.441-452.

Committee on Climate Change (CCC) (2010) The Fourth Carbon Budget: Reducing Emissions through the 2020s. December, CCC, London.

Creswell, J.W. (2013). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.

Dahlen, P. and Bolmsjö, G.S. (1996). Life-cycle cost analysis of the labor factor. *International Journal of Production Economics*, *46*, pp.459-467.

Dangana, Z., Pan, W. and Goodhew, S. (2013). A decision making system for selecting sustainable technologies for retail buildings. *Energy and the Built Environment Proceedings*.

Department of Health. (2015). The Health and Social Care Act 2008: code of practice on the prevention and control of infections and related guidance. Available at:

https://www.gov.uk/government/publications/the-health-and-social-care-act-2008-code-of-practice-on-the-prevention-and-control-of-infections-and-related-guidance

Didwania, S. and Mathur, J. (2011). Optimisation of window-wall ratio for different building types. Available at:
https://www.researchgate.net/profile/Srijan_Didwania/publication/259921312_OPTIMIZATION_OF_WINDOW-

WALL_RATIO_FOR_DIFFERENT_BUILDING_TYPES/links/0c96052e8be7617c6e000000.pdf

Dodgson, J.S., Spackman, M., Pearman, A. and Phillips, L.D. (2009). Multi-criteria analysis: a manual. Available at: http://eprints.lse.ac.uk/12761/1/Multi-criteria_Analysis.pdf

Dubois, M.C., Bisegna, F., Gentile, N., Knoop, M., Matusiak, B., Osterhaus, W. and Tetri, E., (2015). Retrofitting the electric lighting and daylighting systems to reduce energy use in buildings: a literature review. *Energy Research Journal*, *6*(1), p.25.

Dyer, R.F. and Forman, E.H. (1992). Group decision support with the analytic hierarchy process. *Decision support systems*, *8*(2), pp.99-124.

Edwards, W. and Von Winterfeldt, D. (1986). Decision analysis and behavioural research. Cambridge: Cambridge University Press

EIA (2016). Annual Energy Outlook 2016. Available at: http://www.eia.gov/outlooks/aeo/

Erkut, E. and Tarimcilar, M. (1991). On sensitivity analysis in the analytic hierarchy process. *IMA Journal of Management Mathematics*, *3*(1), pp.61-83.

European commission (2012). Energy Efficiency Directive (2012/27/EU). Available at: http://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficiency-directive.

Fishburn, P.C. (1967). Methods of estimating additive utilities. *Management science*, *13*(7), pp.435-453.

Fowler Jr, F.J. (2013). *Survey research methods*. London: Sage publications.

Galasiu, A.D.; Newsham , G.R.; Suvagau, C. and Sander, D.M. (2007). Energy saving lighting control systems for open-plan offices: a field study. Available at: http://www.mcclungfoundation.org/-/media/files/mcclung/research%20papers/energysavinglightingcontrolsystems.pdf

Geothermal Heat Pump Association of New Zealand. (n.d.). The schematic of Ground Source Heat Pump. Available at:

https://www.google.co.uk/search?q=The+schematic+of+Ground+Source+Heat+Pump&tbm=isch&imgil=qU7ltzkN5YORdM%253A%253BKH_TxTKHWweTOM%253Bhttp%25253A%25252F%25252Fwww.nzgeothermal.org.nz%25252Fghanz_heatpumps.html&source=iu&pf=m&fir=qU7ltzkN5YORdM%253A%252CKH_TxTKHWweTOM%252C_&usg=__5ivhD89c9FYwIIxJH_lpFxPH2aA%3D&biw=1147&bih=577&ved=0ahUKEwjq3cjwn_HQAhUH3CwKHekwCS0QyjcIJw&ei=E_RPWKqILYe4swHp4aToAg#imgrc=qU7ltzkN5YORdM%3A

Ghani, A.A. (2014). Experimental Research Methods for Students in Built Environment and Engineering. In *MATEC Web of Conferences* (Vol. 10, p. 01001). EDP Sciences.

Ghunmi, L.A., Zeeman, G., Fayyad, M. and van Lier, J.B. (2011). Grey water treatment systems: A review. *Critical reviews in environmental science and technology*, *41*(7), pp.657-698.

Gillham, B. (2000). *Case study research methods*. London: Bloomsbury Publishing.

Greenwood, D.J. and Levin, M. (1998). Action research, science, and the co-optation of social research. *Studies in cultures, organizations and societies*, *4*(2), pp.237-261.

Guo Y.J. (2007). *System synthetical evaluation theory, methods and application*. Beijing: Science Press.

Hair, J.F., Anderson, R.E., Tatham, R.L. and Black, W.C. (1998). Multivariate Data Analysis(ed.) Prentice Hall. *Upper Saddle River, NJ*, *166*.

Hall, K and Nicholls, R. (2008). The green building bible (4th ed). Llandysul: Green Building Press.

Huang, I.B., Keisler, J. and Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: ten years of applications and trends. *Science of the total environment*, 409(19), pp.3578-3594.

Hwang, C.L., Paidy, S.R., Yoon, K. and Masud, A.S.M. (1980). Mathematical programming with multiple objectives: A tutorial. *Computers & Operations Research*, *7*(1), pp.5-31.

Ibáñez-Forés, V., Bovea, M.D. and Pérez-Belis, V. (2014). A holistic review of applied methodologies for assessing and selecting the optimal technological alternative from a sustainability perspective. *Journal of Cleaner Production*, *70*, pp.259-281.

IEA (2011). *Deploying renewables. Best and Future Policy Practice*. Available at: https://www.iea.org/publications/freepublications/publication/Deploying_Renewables2011.pdf

IEA (2012). *Transition to Sustainable Buildings-Strategies and Opportunities to 2050.* Available at: https://www.iea.org/media/training/presentations/etw2014/publications/Sustainable_Buildings_2013.pdf (Accessed: 7 June 2015).

Ilesanmi, A.O. and Egbe, M. (2013). Sustainable Innovations in Building Design: The Courtyard and Veranda Concepts in Nigeria. In *AEI 2013: Building Solutions for Architectural Engineering* (pp. 594-603). ASCE.

IPCC (2014). *Climate Change 2014: Mitigation of Climate Change.* Available at: https://www.ipcc.ch/report/ar5/wg3/

ISO (2006). 14040: 2006. *Environmental management–Life cycle assessment–Principles and framework*.

Jahan, A., Mustapha, F., Sapuan, S.M., Ismail, M.Y. and Bahraminasab, M. (2012). A framework for weighting of criteria in ranking stage of material selection process. *The International Journal of Advanced Manufacturing Technology*, *58*(1-4), pp.411-420.

James, M. and Card, K. (2012). Factors contributing to institutions achieving environmental sustainability. *International Journal of Sustainability in Higher Education*, *13*(2), pp.166-176.

Keeney, R.L. (1996). Value-focused thinking: Identifying decision opportunities and creating alternatives. *European Journal of operational research*, *92*(3), pp.537-549.

Klotz, L. and Horman, M. (2009). Counterfactual analysis of sustainable project delivery processes. *Journal of Construction Engineering and Management*, *136*(5), pp.595-605.

Kolokotsa, D., Diakaki, C., Grigoroudis, E., Stavrakakis, G. and Kalaitzakis, K. (2009). Decision support methodologies on the energy efficiency and energy management in buildings. *Advances in Building Energy Research*, *3*(1), pp.121-146.

Konidari, P. and Mavrakis, D. (2007). A multi-criteria evaluation method for climate change mitigation policy instruments. *Energy Policy*, *35*(12), pp.6235-6257.

Lapinski, A.R., Horman, M.J. and Riley, D.R. (2006). Lean processes for sustainable project delivery. *Journal of Construction Engineering and Management*, *132*(10), pp.1083-1091.

Langston, C. ed. (2008). *Sustainable practices in the built environment*. Routledge.

Lee, E., Selkowitz, S., Bazjanac, V., Inkarojrit, V. and Kohler, C. (2002). High-performance commercial building façades. Lawrence Berkeley National Laboratory.

Linkov, I. and Ramadan, A.B. (2004). *Comparative risk assessment and environmental decision making* (Vol. 38). Springer Science & Business Media.

Linkov, I. and Moberg, E. (2012). Multi-criteria Decision Analysis: Environmental Applications and Case Studies. USA: CRC Press.

London Borough of Camden. (2013). Retrofitting Planning Guidance. Available at: https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjkgKSlk_DQAhVlF8AKHa78ACcQFggcMAA&url=https%3A%2F%2Fwww.camden.gov.uk%2Fccm%2Fcms-service%2Fdownload%2Fasset%3Fasset_id%3D3166890&usg=AFQjCNEsaSCsJ4gxqi2-wKjcpN4pdT_PJA&sig2=Z9hnncDbxCiBMcLo9FkXgw

Løken, E. (2007). Use of multicriteria decision analysis methods for energy planning problems. *Renewable and Sustainable Energy Reviews*, *11*(7), pp.1584-1595.

Luong, S., Liu, K. and Robey, J. (2012). Sustainability Assessment Framework for Renewable Energy Technology. *Technologies for Sustainable Built Environment Centre. Reading: Informatics Research Centre*, pp.1-8.

Ma, Z., Cooper, P., Daly, D. and Ledo, L. (2012). Existing building retrofits: Methodology and state-of-the-art. *Energy and buildings,* 55, pp.889-902.

Mardiana-Idayu, A. and Riffat, S.B., 2012. Review on heat recovery technologies for building applications. *Renewable and Sustainable Energy Reviews*, 16(2), pp.1241-1255.

Mafakheri, F., Dai, L., Slezak, D. and Nasiri, F. (2007). Project delivery system selection under uncertainty: Multicriteria multilevel decision aid model. *Journal of Management in Engineering*, *23*(4), pp.200-206.

Menassa, C.C. and Baer, B. (2014). A framework to assess the role of stakeholders in sustainable building retrofit decisions. *Sustainable Cities and Society*, *10*, pp.207-221.

Mickaityte, A., Zavadskas, E.K., Kaklauskas, A. and Tupenaite, L. (2008). The concept model of sustainable buildings refurbishment. *International Journal of Strategic Property Management*, *12*(1), pp.53-68.

Miles, M.B. and Huberman, A.M. (1994). *Qualitative data analysis: An expanded sourcebook*. Sage.

Miller, D.W. and Starr M.K. (1969). Executive Decisions and Operations Research, Prentice-Hall, Inc.,Englewood Cliffs, NJ.

Mintzberg, H., Raisinghani, D. and Theoret, A. (1976). The structure of" unstructured" decision processes. *Administrative science quarterly*, pp.246-275.

Mohsen, M.S. and Akash, B.A. (1997). Evaluation of domestic solar water heating system in Jordan using analytic hierarchy process. *Energy Conversion and Management*, *38*(18), pp.1815-1822.

Modell, S. (2009). In defence of triangulation: a critical realist approach to mixed methods research in management accounting. *Management Accounting Research*, *20*(3), pp.208-221.

Muniak, D.P. (2015). A proposal for a new methodology to determine inner authority of the control valve in the heating system. *Applied Energy*, *155*, pp.421-433.

National Institute of Building Sciences (2016). Natural Ventilation. Available at: https://www.wbdg.org/resources/natural-ventilation

Nelms, C.E., Russell, A.D. and Lence, B.J. (2005). Assessing the performance of sustainable technologies for building projects. *Canadian Journal of Civil Engineering*, *32*(1), pp.114-128.

Nelms, C.E., Russell, A.D. and Lence, B.J. (2007). Assessing the performance of sustainable technologies: a framework and its application. *Building Research & Information*, *35*(3), pp.237-251.

Norris, G.A. and Marshall, H.E. (1995). *Multi-attribute decision analysis method for evaluating buildings and building systems*. Building and Fire Research Laboratory, National Institute of Standards and Technology.

NSW Office of Environment and Heritage (2001). *National Australian Built Environment Rating System(NABERS)*. Available at: https://nabers.gov.au/public/webpages/home.aspx

Odhiambo, J. and Wekesa, B. (2010). A framework for assessing building technologies for marginalised communities. *Human Settlements Review*, p.59.

Omrany, H. and Marsono, A.K. (2016). Optimization of building energy performance through passive design strategies. British Journal of Applied Science & Technology, 13(6), pp.1-16.

Oreszczyn, T. and Lowe, R. (2010). Challenges for energy and buildings research: objectives, methods and funding mechanisms. *Building Research & Information*, *38*(1), pp.107-122.

Pan, W., Dainty, A.R. and Gibb, A.G. (2012). Establishing and weighting decision criteria for building system selection in housing construction. *Journal of Construction Engineering and Management*, *138*(11), pp.1239-1250.

Papadatos, N. and Xifara, T. (2013). A simple method for obtaining the maximal correlation coefficient and related characterizations. *Journal of Multivariate Analysis*, *118*, pp.102-114.

Ravetz, J.(2008). State of the stock — What do we know about existing buildings and their future prospects? *Energy Policy*, 36(12), pp.4462–4470.

Pirlot, M. (1997). A common framework for describing some outranking methods. *Journal of Multi‐Criteria Decision Analysis*, *6*(2), pp.86-92.

Pöyhönen, M. and Hämäläinen, R.P. (1998). *On Attribute Weighting in Value Trees*. Helsinki University of Technology, Systems Analysis Laboratory.

Pohekar, S.D. and Ramachandran, M. (2004). Application of multi-criteria decision making to sustainable energy planning—a review. *Renewable and sustainable energy reviews*, *8*(4), pp.365-381.

Rey, E. (2004). Office building retrofitting strategies: multi-criteria approach of an architectural and technical issue. *Energy and Buildings*, *36*(4), pp.367-372.

Richardson, G.R. and Lynes, J.K. (2007). Institutional motivations and barriers to the construction of green buildings on campus: A case study of the University of Waterloo, Ontario. *International Journal of Sustainability in Higher Education*, *8*(3), pp.339-354.

Roberts, S. (2008). Altering existing buildings in the UK. *Energy policy*, *36*(12), pp.4482-4486.

Rongxi, Z., Jianrong, X. and Dayi, H. (2009), June. Approach of determining interval entropy weight based on the subjective preference of decision-maker and its application.

In Proceedings of the 21st annual international conference on Chinese control and decision conference (pp. 5969-5972). IEEE Press.

Sara L.W. (2011). Building mounted wind turbines and their suitability for the urban scale—A review of methods of estimating urban wind resource. *Energy and Buildings.* 43: 1852-1862.

Saaty, T.L. (1980). The Analytic Hierarchy Process. New York: McGraw-Hill

Saaty, T.L. (1989). Group decision making and the AHP. In *The Analytic Hierarchy Process* (pp. 59-67). Springer Berlin Heidelberg.

Saaty, T.L. (1990). How to make a decision: the analytic hierarchy process. *European journal of operational research*, *48*(1), pp.9-26.

Saaty, T.L. (2000). *Fundamentals of decision making and priority theory with the analytic hierarchy process* (Vol. 6). Rws Publications.

Senthil Kumaran, D., Ong, S.K., Tan, R.B. and Nee, A.Y.C. (2001). Environmental life cycle cost analysis of products. *Environmental Management and Health*, *12*(3), pp.260-276.

Sev, A. (2009). How can the construction industry contribute to sustainable development? A conceptual framework. *Sustainable Development*, *17*(3), pp.161-173.

Sheikh, N. and Kocaoglu, D.F. (2011) A comprehensive assessment of solar photovoltaic technologies: literature review. In *2011 Proceedings of PICMET'11: Technology Management in the Energy Smart World (PICMET)* (pp. 1-11). IEEE.

Si, J., Marjanovic-Halburd, L., Nasiri, F. and Bell, S. (2016). Assessment of building-integrated green technologies: A review and case study on applications of Multi-Criteria Decision Making (MCDM) method. *Sustainable Cities and Society*, *27*, pp.106-115.

Simon, H.A.(1977). The logic of heuristic decision making. In *Models of discovery* (pp. 154-175). Springer Netherlands.

Sutter, C. (2003). *Sustainability check-up for CDM projects*. Diss., Eidgenössische Technische Hochschule ETH Zürich, Nr. 15332, 2003.

Syamsuddin, I. (2013). Multicriteria Evaluation and Sensitivity Analysis on Information Security. *arXiv preprint arXiv:1310.3312*.

Taylor, S. J. and Bogdan, R. (1984) *Introduction to Qualitative Research Methods: The Search for Meaning*, 2nded. John Wiley, New York.

The Building and Construction Authority, Singapore (Singapore, BCA). (2015). The BCA Green Mark Scheme. Available at: https://www.bca.gov.sg/GreenMark/green_mark_buildings.html

Turban E. and Aronson J. E. (2001) Decision support systems and intelligent systems. New Yersey: Prentice Hall.

UNEP (2015). *Annual Report 2015*. Available at: http://web.unep.org/annualreport/2015/en/index.html

UNEP Sustainable Building & Climate Initiative (UNEP-SBCI) (2009). *Buildings and Climate Change: Summary for Decision-Makers.* Available at: http://www.unep.org/sbci/pdfs/SBCI-BCCSummary.pdf

University College London (2008). *Carbon Management Plan.* Available at: https://www.ucl.ac.uk/transforming-ucl/pdfs/ucl-carboon-management-plan

U.S. Green Building Council. (U.S.GBC) (2009). *LEED for Existing Buildings: Operations & Maintenance.* Available at: http://www.usgbc.org/Docs/Archive/General/Docs3617.pdf

U.S. Energy Information Administration (U.S.EIA) (2016). *Annual Energy Outlook 2016.* Available at: http://www.eia.gov/outlooks/aeo/

Wang, J.J., Jing, Y.Y. and Zhang, C.F. (2009). Weighting methodologies in multi-criteria evaluations of combined heat and power systems. *International Journal of Energy Research*, *33*(12), pp.1023-1039.

Xing, Y.G., Hewitt, N. and Griffiths, P. (2011). Zero carbon buildings refurbishment – a hierarchical pathway. *Renewable and Sustainable Energy Reviews*, 15: 3229–3236.

Ye, Y.C., Ke, L.H. and Huang, D.Y. (2006). *System synthetical evaluation technology and its application*. Beijing: Matellurgical Industry Press

Yin, R. K. (2003). *Case Study Research: Design and Methods*, 3rd ed., Sage, Thousand Oaks, California.

Yu, W., Li, B., Yang, X. and Wang, Q. (2015). A development of a rating method and weighting system for green store buildings in China. *Renewable Energy*, *73*, pp.123-129.

Yudelson, J. (2010). *The green building revolution*. London: Island Press.

Zainab, S., Pan, W., Goodhew, S. and Fuertes, A. (2013). Stakeholders perspective on sustainable technology selection to achieve zero carbon retail buildings. *Management*, *1219*, p.1229.

Zardari, N.H., Ahmed, K., Shirazi, S.M. and Yusop, Z.B. (2015). Research Methodology and Results. In *Weighting Methods and their Effects on Multi-Criteria Decision Making Model Outcomes in Water Resources Management* (pp. 69-100). Springer International Publishing.

Zeng, G., Jiang, R., Huang, G., Xu, M. and Li, J. (2007). Optimization of wastewater treatment alternative selection by hierarchy grey relational analysis. *Journal of. Environmental Management*, 82 (2): 250-259

Zeiler, W., Vissers, D., Maaijen, R. and Boxem, G. (2014). Occupants' behavioural impact on energy consumption: 'human-in-the-loop' comfort process control. *Architectural Engineering and Design Management*, *10*(1-2), pp.108-130.

Appendix A Green Technology Characteristics

As defined in the introduction chapter, the following are referred to as green technologies:

1) PV system
2) Solar thermal
3) Wind turbine
4) Biomass boiler
5) Combined Heat and Power
6) Ground Source Heat Pump
7) Air Source Heat Pump
8) Green roof
9) Water efficiency systems (including water saving systems and water recycling system)

Considering multiple considerations normally involved in above technologies, we suggest discussing these green technologies from four perspectives, assisting decision makers to understand green technology characteristics from:

1. Design considerations.

Design considerations provide the basic working principles of green technologies, bringing the attention of decision makers to the requirements of technology installation and operation into buildings.

2. Financial considerations.

Financial considerations provide the installation costs and O&M costs of the technologies, and recommend potential financial incentives whenever available.

3. Environmental considerations (Environmental impacts during operation and recycling opportunities).

According to the assessment categories suggested in the green building environmental assessment systems, such as BREEAM in-use International, energy efficiency and wastes have to be considered. To encourage and recognise the implementation of policies and systems that reduce waste production and improve levels of segregation and recycling.

4. Planning permission and building regulation.

Some of green technologies installation into existing buildings requires planning permission or building control approval. Advice is given as to whether permissions might be needed.

A.1 PV Systems

PV systems generate electricity in the way that when light energy strikes the solar cell, electrons are knocked loose from the atoms in the semi-conductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current, which is the electricity.

There are two basic commercial module technologies available in the market: crystalline solar cell and thin-film solar cell. The working principle of a solar cell is shown in Figure A.1. The components of a PV system are shown in Figure A.2. The performance of a PV system can be influenced by the geographic location and orientation of a building, the tilt and shading of a building surface for PV arrays (Pester and Crick, 2013). A PV system can reach the optimum performance with solar array facing south, but can also reach desirable performance facing east and west. A PV system is suitable for both rural and urban areas where sunshine is sufficient.

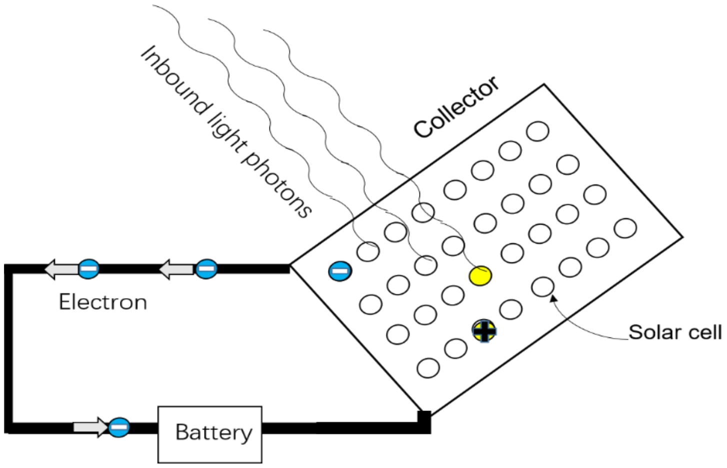


Figure A.1 Working principle of solar cell (Source: Advanced Energy Solutions. Inc., n.d.)

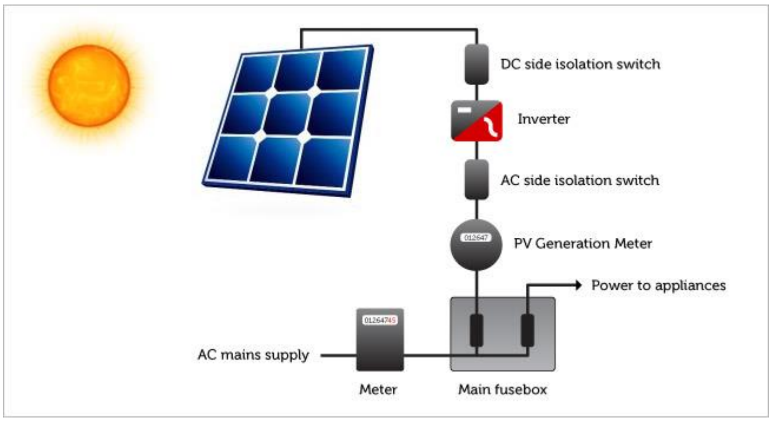


Figure A.2 The schematic of a Solar PV system (Source: WeatherEnergy, n.d.)

A.1.1 Design considerations

A PV system can be roof-mounted, which has the following design considerations (Arup, n.d.):

1) Enough rooftop space is required and different sizes of PV modular can be selected to fit the space and meet the energy demand;

2) A Roof-mounted system can reach a desirable performance by adjusting the orientation and tilt of PV modules;

3) A Building survey is required to ensure the roof top can carry the additional load.

A PV system can also be integrated into the building structure, referred to as Building

Integrated Solar Photovoltaics (BIPV), establishing a symbiotic relationship between the architectural design, functional properties and economic regenerative energy conversion. PV modules replace conventional construction materials, taking over the function that these would otherwise perform. When designing a BIPV system, a compromise must be reached between the requirements of yield optimisation and those of the architectural environment (Odersun, 2011)

Example of roof-mounted PV and BIPV is shown in Figure A.3.

Figure A.3 (a) 1st LEED PARKING GARAGE: Santa Monica Civic Centre (Inhabitat.com, 2008); (b) Future Business Centre (FBC), Cambridge, with BIPV (Cambridge Network, 2013)

A.1.2 Financial considerations

NERL (2016) has provided a summary of Installed cost, O&M cost and lifetime for PV systems (See Table A.1). The actual costs of a PV system for the particular installation is dependent on the system specification and selection. With technology development, PV cost has seen an increasing decrease globally. The USA has also seen consistent PV cost reductions, with installed system costs decreasing by 10-14% from 2010-2011, 6%-14% from 2011-2012, and by 12%–15% from 2012–2013 (Arup, n.d.).

PV system installation can receive benefits from Feed-in tariffs, which can provide a major incentive to installers of all renewable electricity technologies. The installers can receive both the generation tariff (a fixed income for every kilowatt hour of electricity generated from the renewable sources) and the export tariff (an additional fixed income for every kilowatt hour of electricity sold to the grid). The mechanism has been considered as the best policy tool for the faster and lower-cost deployment of renewables, which is demonstrated by Germany's world leadership in renewable energy. (Pester and Crick, 2013).

Table A.1 Installed cost, O&M costs and lifetime of PV systems (Source: NREL, 2016)

Technology Type	Mean installed cost ($/kW)	Installed cost Std. Dev. (+/- $/kW)	Fixed O&M costs ($/kW-yr)	Fixed O&M costs Std. Dev. (+/- $/kW-yr)	Lifetime (yr)	Lifetime Std. Dev. (yr)
PV <10 kW	3897	889	21	20	33	11
PV 10–100 kW	3463	947	19	18	33	11
PV 100–1,000 kW	2493	774	19	15	33	11

A.1.3 Environmental considerations

Compared with conventional energy sources, there are low environmental impacts caused by a PV system. There are no carbon emissions produced during systems' operation. A PV system can be recycled at the end of life (Pester and Crick, 2013). Thin-film PV systems normally have much lower embodied energy than crystalline silicon systems. Some types of thin-film PV systems may have toxic materials (Pester and Crick, 2013).

A.1.4 Planning permission and building regulations

Planning permission might be required for a PV system when the building is located in a conservation area. It is recommended to check whether planning permission is required or not.

A.2 Solar Thermal

Solar thermal systems collect heat from the sun and transfer this heat to a fluid that is retained within a sealed circuit linking the solar collector to the hot water storage vessel.

The fluid is then circulated to meet energy needs within a building. Major components of solar thermal systems include collectors, storage tank, pumps, and controls (See Figure A.4). There are basically two types of collectors: evacuated tubes and flat plate collectors. Evacuated tubes are generally better performing. Flat plate collectors can be more desirable because they are less visually intrusive, cheaper and more robust. A regular maintenance is required every five years for solar thermal systems and a well-maintained system can last over 25 years (BioRegional and Association for the Conservation of Energy, n.d.).

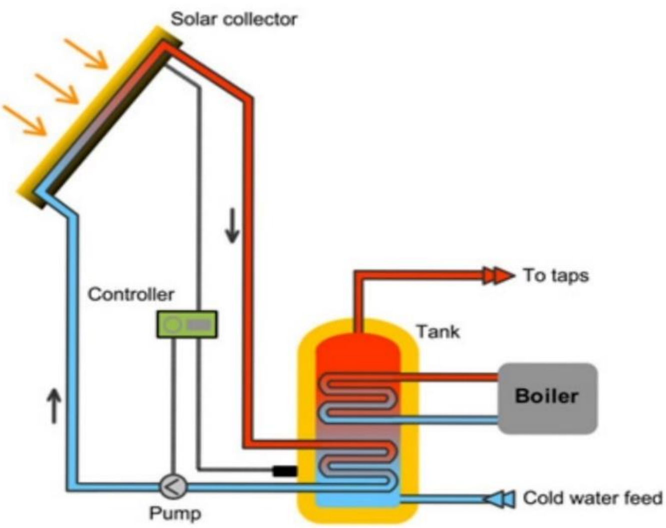


Figure A.4 The schematic of a solar thermal system (Source: CELTIC Renewable Energy, n.d.)

A.2.1 Design considerations

The crucial question for a solar thermal system is correctly sizing the system based on hot water demand assessment for summer. A solar thermal system is not suitable for buildings that are unoccupied in summer, such as schools. Instead, the system can be a good option for hotels (with swimming pools) or hospitals with a large demand for hot water. An example of a solar thermal application into a hospital is shown as Figure A.5.

Figure A.5 Princess Alexandra Hospital in England with Solar thermal collectors (Princess Alexandra Hospital, n.d.)

A.2.2 Financial considerations

The cost of a solar thermal system depends on the type and size of the installation, but would be typically around £500/m^2–£1200/m^2 (Thorne, 2014). A small office would use around 4m^2 of roof space, which will cost around £4000. Approximately £400 per year will be saved and additional money can be gained from incentives (BioRegional and Association for Conservation of Energy, n.d.). In the UK, solar thermal installation can benefit from the Renewable Heat Incentive (RHI) for non-domestic buildings, which works in a similar way to Feed-in Tariffs. The costs of solar thermal technologies are provided in Table A.2.

Table A.2 Installed cost, O&M costs and lifetime of Solar Thermal Technologies (Source: NREL, 2016)

Technology Type	Mean installed cost ($/$ft^2$)	Installed cost range (+/- $/$ft^2$)	O&M costs	Lifetime (yr)
Flat plate & Evacuated tube	$162	$91	0.5 to 1.0 % initial installed cost	31

A.2.3 Environmental considerations

Solar thermal systems typically produce heat at rates of 450 kWh/m^2 or more per annum for flat-plate collectors and 550 kWh/m^2 per year for evacuated tubes, with resultant annual carbon savings of 100–110 $kgCO_2/m^2$ and 130–140 $kgCO_2/m^2$, respectively, when compared with gas-fuelled systems (Thorne, 2014). When solar thermal collectors are towards the end of their service life, the glass in the tubes, which is made of borosilicate, cannot be recycled. The copper tubes and aluminium fins can be recycled. None of the components is hazardous or toxic (Contemporary energy, n.d.).

A.2.4 Planning permission and building regulations

Solar systems for non-domestic buildings are classed as ‘permitted development’ and therefore do not require full planning permission. Each building and installation is required to be considered individually; therefore, consultation with the planning authority is required.

A.3 Wind Turbine

Wind turbine works in the way that when the blades start moving, they spin a shaft that leads to a generator. The generator consists of a conductor, such as a coiled wire, that is surrounded by magnets. The rotating shaft turns the magnets around the conductor and generates an electrical current. The wind turbine diagram is shown as Figure A.6.

A.3.1 Design considerations

The energy of wind turbines is generated through rotation of large blades driven by wind and the conversion of mechanical power into electricity. The stronger the wind, the more electricity is produced. It is not recommended installing building mounted turbines in urban areas, due to low wind speeds, high turbulence intensity and perception of potentially high levels of aerodynamic noise generated by the turbines (Ledo, Kosasih and Cooper, 2011). However, there is the possibility of applying wind turbines on high-rise buildings (Blackmore, 2010). An example of wind turbines on high-rise buildings is shown in Figure A.7.

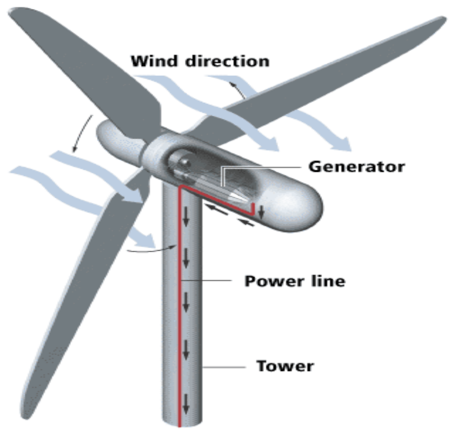


Figure A.6 The schematic of a wind turbine (Source: Engineers Garage, n.d.)

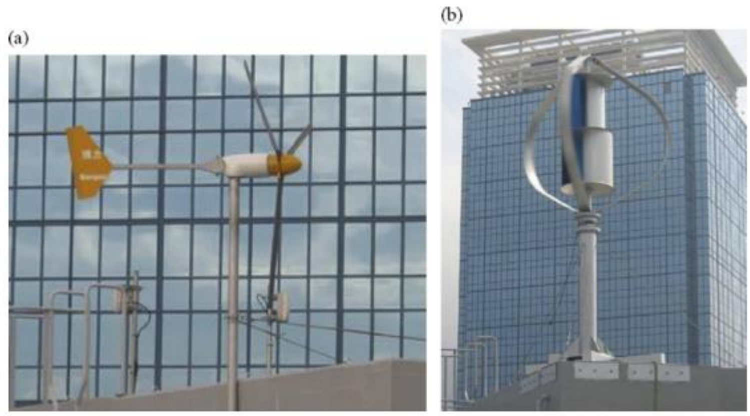


Figure A.7 (a) 1 kW horizontal-axis, and (b) 1.5 kW vertical-axis small wind turbines on the roof of EMSD headquarters building of Hong Kong (Source: Lu and Ip, 2009)

A.3.2 Financial considerations

The costs for a utility scale wind turbine range from about $1.3 million to $2.2 million per MW of nameplate capacity installed. Most of the commercial-scale turbines installed today are 2 MW in size and cost roughly $3-$4 million (Windustry, 2016). Other costs can include:

1) Wind resource assessment and site analysis;

2) Permitting and interconnection studies;

3) Utility system upgrades, transformers, protection and metering equipment;

4) Insurance;

5) Operations, warranty, maintenance and repair;

6) Legal and consultation fees.

Maintenance checks are essential every few years, and generally cost around £100 to £200 per year depending on the turbine size. A well-maintained turbine should last more than 20 years, but with the inverter replaced at some stage during this time, at a cost of £1,000–£2,000 (Energy Saving Trust, 2016). Wind turbines are eligible for Feed-in Tariffs and a tariff for each kWh of electricity generated by the system can be gained.

A.3.3 Environmental considerations

During operation, wind turbines may cause negative impacts including (Greening and Azapagic, 2013):

1) Noise affecting nearby residents;
2) Shadow flicker irritating for human eyes;
3) Visual impact of the development on the landscape;
4) Bird collisions

When wind turbines are at the end of their service life, most materials of wind turbines can be recycled. The recycling rates and disposal routes for wind turbine components are shown in Table A.3.

Table A.3 Recycling rates and disposal routes for wind turbine components (Source: Andersen *et al.*, 2014, p.95)

Material	Recycling/Disposal rate (%)	Disposal method
Ferrous high alloy	98	Recycling
Ferrous metal	95	Recycling
Steel	-	Recycling
Aluminum and aluminum alloys	95	Recycling
Copper, magnesium, nickel, zinc and their alloys	98	Recycling
Precious metals and other non-ferrous metals and alloys	98	Recycling
Plastics, rubber and other organic materials	100	Incineration with energy recovery

Material	Recycling/Disposal rate (%)	Disposal method
Electronic	50	Recycling with energy recovery
Batteries	100	Recycling
Concrete, bricks etc.	64	Landfill
Sand and gravel	0	Remains in the ground after wind farm is dismantled
Blades	95	Landfill or recycling
Remaining materials	-	Incineration or landfill

A.3.4 Planning permission and building regulations

The installation, alteration or replacement of a building mounted wind turbine is considered as permitted development.

A.4 Biomass Boilers

Biomass is the name given to any organic matter which is derived from plants, that is plant and animal materials such as wood from forests, crops, seaweed, material left over from agricultural and forestry processes, and organic industrial, human and animal wastes. Biomass is a general term which includes plant biomass and zoomass or animal biomass. Sources of biomass are shown in Figure A.8. A biomass boiler is to burn biomass providing energy to power central heating and hot water boilers.

Figure A.8 The sources of biomass (Source: Asian Productivity Organization(APO), 2010)

A biomass boiler works in the way that wood pellets or chips are fed into a storage hopper, and the automated system feeds fuel from the hopper into the biomass furnace. The energy produced is absorbed into a heat exchanger. Then the heat exchanged feeds into the hot water tank, supplying hot water and heating. This is shown in Figure A.9. An example of biomass boiler installation is shown in Figure A.10.

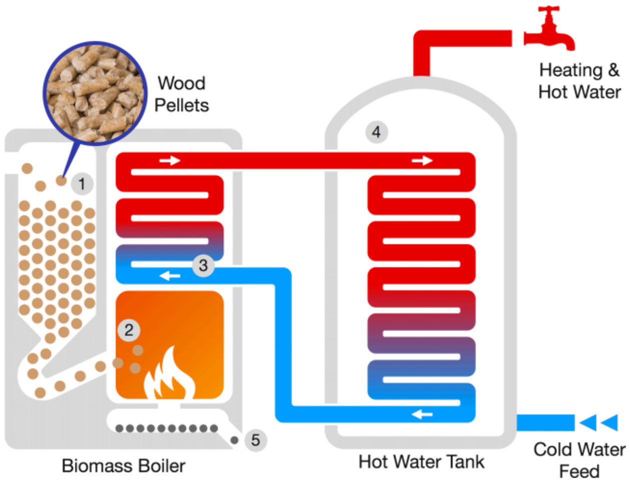


Figure A.9 The schematic of a biomass boiler (Source: Green energy advice team, n.d.)

Figure A.10 Biomass boiler installation with wood pellet burner at Nayland Primary School, Suffolk (Source: Nayland Primary School, n.d.)

A.4.1 Design considerations

The type of system best suited to a particular application depends on many factors, including: availability and cost of each type of biomass (e.g. chip, pellet or logs), competing fuel cost (e.g. fuel oil and natural gas), thermal peak and annual load, building size and type, space availability, operation and maintenance (O&M) staff availability, and local emissions regulations (CIBSE AM15, 2014).

It is recommended to keep the wood chips clean and safe. Wood chips can have self-ignition or spontaneous combustion, when stored for long periods of time. The probability of spontaneous combustion increases as pile size increases, due to the decreasing surface area-to-mass ratio (CIBSE AM15, 2014).

A.4.2 Financial considerations

The capital costs for biomass heating systems are significantly higher than the costs for fossil-fuel plants, but savings on fuel use reduce the cost of energy over time. An automatically fed pellet boiler costs between £9,000 and £21,000, including cost on installation, fuels and fuel storage (Energy Saving Trust, n.d.). For users who select biomass on the Biomass Suppliers List, additional economic benefits can be gained. O&M costs of biomass heating systems are predominately the costs of fuel and labour. Cost for a Wood-Fired Heat System is listed in Table A.4. A well-operated and maintained wood chip-fired heating system should require 2 to 5 hours of O&M per week during the heating season.

Table A.4 Installed cost, O&M costs and lifetime of the Wood-Fired Heat System (Source: NREL, 2016)

Technology Type	Mean installed cost ($/kW)	Fixed O&M costs ($/kW)	Lifetime (yr)	Fuel and/or water cost ($/kWh)
Biomass wood heat	575	98	32	0.03

A.4.3 Environmental considerations

Carbon dioxide is the main emission of biomass combustion. The carbon dioxide emitted when wood is burned is the same amount that is absorbed by the plants when they are growing. As long as the fuel is sourced locally, much lower emissions can be achieved compared to fossil fuel combustion (Energy Saving Trust, n.d.).

Other principal emissions from biomass boilers include: the gas phase emissions of carbon monoxide (CO), water vapour and nitric oxide (NO), nitrogen dioxide (NO_2) collectively known as NO_x, and particulate matter including salts, soot, condensable organic compounds and volatile organic compounds (CIBSE AM15, 2014).

A.4.4 Planning permission and building regulations

Biomass heating systems are deemed permitted developments. In conservation areas and world heritage sites it is not permitted development when a flue is required to be installed outside buildings.

A.5 Combined Heat and Power

Combined Heat and Power (CHP), also known as cogeneration, is the energy system that can generate heat and electricity in the same process. The main power part is electricity and waste heat is reclaimed for space heating or domestic hot water use. The most common type for CHP applications is the system based on a spark ignition reciprocating gas engine directly driving a generator to produce electrical power. Figure A.11 shows a spark ignition reciprocating gas engine.

The main components of a CHP unit based on spark-ignition gas engine technology include prime mover, fuel system, generator, heat recovery system, cooling system, combustion and ventilation air systems, exhaust gas silencer and chimney, control system and enclosure. Selection of the prime mover, the engine to drive the generator, depends on thermal and electrical loads and power quality requirements (CIBSE AM12, 2013). There are four types of prime mover: gas turbines, micro-turbines, reciprocating engines and fuel cells. Gas turbines are commonly used in large hospitals because of their light weight, quick start-up and size; micro-turbines are smaller than gas turbines, particularly useful for CHP projects that require scalability; a reciprocating engine creates power from spark-ignited or compressed-ignited engines. These engines are good for small-scale CHP systems and they are useful as backup energy systems for their quick start-up attributes. Fuel cells are relatively new to commercial CHP use.

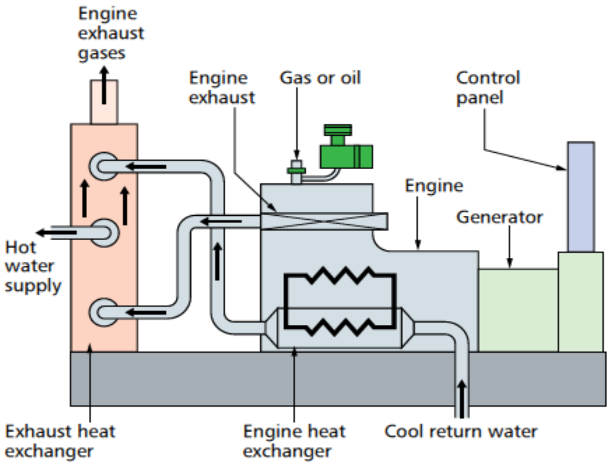


Figure A.11 The schematic of a gas-engine CHP system (CIBSE AM12, 2013, p.5)

A.5.1 Design considerations

CHP is suitable for buildings that have a significant and continuous heat demand throughout the day and the year. These buildings can include hospitals, hotels with swimming pools and university buildings (CIBSE AM12, 2013). Less commonly-used CHP applications can be offices with an extended occupancy into the evening, museums that need to maintain stable temperature/humidity conditions and retail stores with extended operating hours. A regular maintenance is required for CHP. Staff training may be required for CHP operation and maintenance.

A.5.2 Financial considerations

The installed cost for most CHP technologies consists of the total equipment cost plus installation labour and materials, engineering, project management, and financial carrying costs during construction. Non-fuel Operation and Maintenance (O&M) costs typically include routine inspections, scheduled overhauls, preventive maintenance, and operating labour. O&M costs are comparable for gas turbines, gas engines, steam turbines, and micro-turbines, and only a fraction higher for fuel cells. Table A.5 provides reference on costs for CHP with different prime movers.

Table A.5 Installed cost and O&M costs of the CHP technology with different prime movers (Source: National Institute of Building Science (NIBS), 2016)

Costs	Gas Turbine	Micro-turbine	Reciprocating Engine	Steam Turbine	Fuel Cell
Installed Cost ($/kW)	1,200 to 3,300	2,500 to 4,300	1,500 to 2,900	670 to 1,100	5,000 to 6,500
Non-fuel O&M Costs ($/kWh)	0.009 to 0.013	0.009 to 0.013	0.009 to 0.025	0.006 to 0.01	0.32 0.038

A.5.3 Environmental considerations

CHP systems have a higher whole-system efficiency than individual heating or electricity generation systems. With less fuel consumed, greenhouse gases and air pollutions can be reduced. If combined with renewable fuels, such as biogas and biomass, CHP systems can produce fewer emissions than the systems using traditional fuels.

Table A.6 Typical emissions from CHP systems (Source: DECC, 2008)

CHP system type	Gas turbine with heat recovery boiler	Gas turbine with heat recovery boiler and back-pressure steam turbine	Compression ignition engine with heat recovery boiler	Lean-burn spark ignition engine with heat recovery boiler
Fuel type	Natural gas	Natural gas	Natural gas	Natural gas
Emissions in g/kWh of electrical power produced				
CO_2	610	510	570	500
NO_x	1.1	0.9	5-10	3

A.5.4 Planning permission and building regulations

The equipment, installation and testing of a CHP system must comply with the relevant standards in building regulations. Building regulations also apply to other aspects of the work such as electrical installation and plumbing work. The Guide of *Low or Zero Carbon Energy Sources: Strategic Guide (LZC)* sets out the factors to be considered for the purposes of calculating the potential of a micro-CHP system in buildings to contribute towards lowering the carbon dioxide emissions of a building in order for it to meet the compliance requirements of Part L.

Planning permission is not normally required when installing a CHP system in a building if the work is all internal. If the installation requires a flue outside, however, it will need to check permission requirements.

A.6 Ground Source Heat Pump

Ground Source Heat Pump (GSHP) systems are electrically powered space heating and cooling technologies that take advantage of the earth’ s relatively constant temperature to provide heat for the building. GSHP systems work optimally in climate regimes where heating and cooling are relatively balanced. The basic elements of a ground source heat pump system are the heat pump itself, the ground loop and the distribution system (CIBSE TM51, 2013). Each one of them is a separate closed circuit (the ground loop can be established as an open loop, although this is not its most common configuration), but this does not mean they work independently. Both the ground loop and the distribution system are connected to the heat pump, with which they exchange heat (CIBSE TM51, 2013). This is shown in Figure A.12.

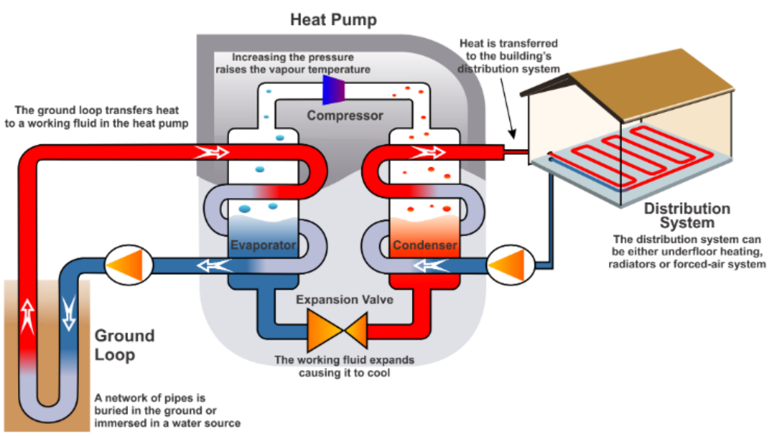


Figure A.12 The schematic of Ground Source Heat Pump (Source: Royal Mechanical LLC, n.d.)

A.6.1 Design considerations

GSHP systems can be deployed effectively in heating-dominated or cooling-dominated climates. Building function is probably the single most important factor in determining whether significant energy savings can be achieved with GSHP systems. GSHP systems are best suited for large loads such as commercial buildings and schools (Hillesheim and Mosey, 2014).

GSHP system design consideration falls into two categories: interior building design and exterior loop field design. Interior building design considerations include the knowledge of a building's peak loads and cumulative load profile, the type of interior heating and cooling distribution system, and the building's envelope condition (Hillesheim and Mosey, 2014). Exterior loop field considerations include configuration type and loop size. The configuration can be vertical or horizontal, which is constrained by parameters such as thermal conductivity, thermal diffusivity, and in situ temperature. A horizontal loop requires sufficient ground space and the land available for trenches should be twice the size of the heated area (Hillesheim and Mosey, 2014). If sufficient space for horizontal loops is not available, drilling boreholes for a vertical loop becomes an option. A series of boreholes takes the collector pipe straight down into the ground rather than horizontally. Drilling can be an expensive exercise due to the complex geology across much of the country. General considerations for various loop-field configurations are listed in Table A.7.

Table A.7 Design considerations for various loop-field configurations (Source: Hillesheim and Mosey, 2014)

Loop configuration	Consideration
Horizontal	1. Installation depth (including frost depth and seasonal temperature changes) 2. Land availability and infrastructure
Vertical	1. Depth (based on subsurface parameters) 2. Spacing (minimum of 20 ft)

A.6.2 Financial consideration

The installation cost of GSHP depends on loop type and system size. Horizontal closed loops are generally less expensive to install than vertical closed loops, since drilling equipment is far more expensive to hire and operate (CIBSE TM51, 2013).

Table A.8 Installed cost, O&M costs and lifetime of Ground Source Heat Pump (Source: NREL, 2016)

Technology Type	Mean installed cost ($/ton)	Installed cost range (+/-$/ton)	O&M costs	Lifetime (yr)	Fuel and/or water cost ($/ton)
Ground Source Heat Pump	7765	4632	$109 +/- $94	38	397

A.6.3 Environmental considerations

The main environmental risks associated with GSHP include (Energy Agency, 2011): 1) All GSHP systems can result in undesirable temperature changes in the ground; 2) Closed loop systems may contain thermal transfer fluids which are toxic and may cause pollution if they leak. When GSHP has reached the end of its life, it is important to make sure all boreholes and wells are responsibly decommissioned.

A.6.4 Planning permission and building regulations

Installation of either a ground source or air source heat pump will have to comply with Building Regulations. The installation of a ground source heat pump is usually considered to be permitted development, not needing an application for planning permission.

A.7 Air Source Heat Pump

Air source heat pumps (ASHP) upgrade low temperature heat from the air outside to a higher temperature that can be used for space or water heating, using electricity to power the process. Air source heat pumps exploit solar energy to limit the demand for electricity, but are generally less energy efficient than ground source heat pumps.

A typical ASHP works as follows (The Scottish government, 2010) : the fan draws air into the heat pump and passes it over the evaporator which contains refrigerant gas at a very low temperature; the refrigerant gas absorbs heat from the outside air; the compressor compresses the refrigerant gas, which raises its temperature; the condenser causes the refrigerant gas to condense to its liquid form, transferring the heat through a coil to the heating system; the liquid refrigerant is passed, through a drying filter to collect any excess moisture, to the expansion valve; the expansion valve lowers the refrigerant pressure and the refrigerant liquid returns to the evaporator; the heat is transferred to the heating system through a coil within a thermal store (a hot water storage cylinder or buffer tank). Figure A.13 illustrates the working principle of an ASHP system.

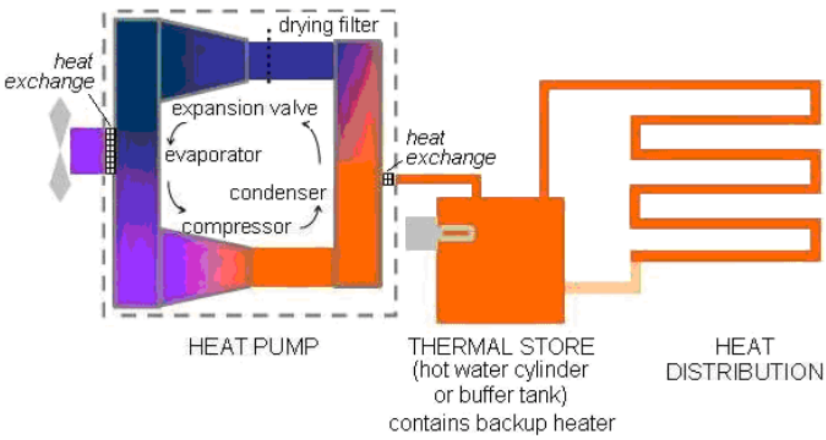


Figure A.13 The schematic of an Air Source Heat Pump system (Source: The Scottish government, 2012, p.6)

A.7.1 Design considerations

Air source heat pumps can be used for space heating or domestic hot water and space cooling in non-domestic buildings. There are two types of air-source heat pump heating systems:

1) Air-to-air which supplies and circulates warm air to heat a building;
2) Air-to-water which supplies heat for space heating through radiators or an underfloor system, and may also supply hot water.

In the air-to-air system, the heat pump is normally located externally and an indoor fan circulates the warm air produced by the heat pump. In the air-to-water system, the heat produced raises the water temperature in a storage tank that is circulated through underfloor heating or radiator. Figure A.14 shows an example of ASHP system.

Figure A.14 An example of ASHP system (Korrie Renewables, n.d.)

A.7.2 Financial considerations

The main advantage of air-source heat pumps over ground-source heat pumps is their lower installation cost. A ground-source heat pump requires a network of underground coils that is used to extract heat from the ground. By comparison, air-source heat pumps extract the heat directly from the outside air and so avoid these potential problems. The cost of a typical ASHP system is around £7,000 to £11,000 (Energy Saving Trust, 2016). Operation costs vary depending on the condition of building insulation and the temperature aiming to reach. The common range of annual running cost is £400 to £500 (GreenMatch, 2016). ASHP is expected to operate for 20 years or more and regular maintenance is suggested (Energy Saving Trust, 2016).

A.7.3 Environmental considerations

The most obvious environmental benefits a heat pump offers the end user is perhaps the complete avoidance of local emissions from combustion. The indirect emissions from a heat pump are dependent on the efficiency of the plant generating the electricity. The biggest concern about ASHP is the safety of the refrigerant. ASHP has an environmental risk associated with refrigerant leak. HFC contained within the heat pump has the potential to damage the environment. In addition to leakage that occurs during operation, losses will occur at the demolition of the appliance. The impact of these losses on the environment will depend on the refrigerant in use. The refrigerants have no ozone depletion potential, but they are contributing to global warming and should therefore be used with care (Forsén, 2005).

A.7.4 Planning permission and building regulations

From 1 December 2011 the installation of an air source heat pump on domestic premises is considered to be permitted development, not needing an application for planning permission. Installation of ASHP will have to comply with the building regulations.

A.8 Green Roof

Green roof systems are living vegetation installed on roofs and can provide many environmental and social benefits for buildings achieving low-carbon and high performance (Hui, 2013). A green roof is generally comprised of a waterproofing membrane, growing medium and the vegetation layer. Other components of green roofs can include a root barrier layer, drainage layer and an irrigation system.

A.8.1 Design considerations

There are generally two types of green roofs, intensive and extensive (See Figure A.15). Intensive roofs have a deeper substrate layer to allow deeper rooting plants to survive. Extensive roofs have a much thinner and lighter soil layer with low level planting, typically sedum or lawn, which are lightweight in structure. Sedum is common and suitable for using as a plant on an extensive green roof (Hui, 2013). Sedum can store water in their leaves, leaving them highly drought resistant.

A green roof on existing buildings through retrofit projects is an important consideration for urban cities, since existing buildings have a large stock (Castleton *et al.*, 2010). Owners of commercial and academic buildings can repair or refurbish a roof during a building lifetime without planning permission. For existing buildings, green roof design can be limited to the loading capacity of the existing roof (Hui, 2013). The current structural loading and building requirements may limit the growing medium depth and type of vegetation. Additional rooftop water points and new drainage points may be required to be installed.

Figure A.15 Examples of extensive and intensive green roofs
Left: Extensive green roof Right: Intensive green roof（Source: Hui, 2013）

A.8.2 Financial considerations

Capital cost and O&M cost of a green roof are different depending on countries. The costs of an extensive green roof system were estimated between £60 and £100/m^2 by the Green Roof Centre (2010). The supply and installed costs of green roof for public buildings retrofits in Manchester were around £65/m^2, which was provided by consultants Drivers Jonas Deloitte (2009). The cost of an extensive green roof system in the Ethelred estate, Kennington, was £179/m^2(Lambeth council, 2009). Depending on the above real-world evidence, a reasonable estimate of an extensive green roof system would cost £150/m^2 (at 2010 prices).

A.8.3 Environmental considerations

A green roof can offer buildings and surrounding environment many benefits:

(1) To reduce the heat flux and solar reflectivity, which can help to cool the building in the summer and warm the building in the winter;

(2) To absorb water to decrease storm accidents in heavy rain, helping to reduce the pressure on the urban drainage systems (Mentens, Raes and Hermy, 2006; Stovin, Dunnett and Hallam, 2007);

(3) To improve urban air quality and purify the surrounding air which will be beneficial to human health (Yang, Yu and Gong, 2008);

(4) To increase environmental service value by providing habitat for birds or invertebrates (Köhler, 2003);

(5) To absorb some noise, acting as an acoustic muffler;

A.8.4 Planning permission and building regulations

The installation of a green roof is to be permitted development, not needing an application for planning permission. Building regulations are required if the following activities are carried out:

1) Structural alterations
2) Replacing/ repairing more than 25 percent of the roof area
3) The removal or alteration to any roof elements could affect how the roof works and cause movement to occur.

A.9 Water Efficiency Systems

Water efficiency systems are categorised into water saving systems and water recycling systems as below.

A.9.1 Water Saving Systems

In a building, washing and toilet flushing consume the largest part of total water consumption. Methods of reducing water use can be applied to taps, toilets and urinals. Measures for minimising water use through taps include using self- closing taps, using taps with a reduced flow rate, and isolating the entire water supply to the washroom when it is vacant.

Water saving measures for toilets include: vacuum toilets and composting toilets. Unlike the traditional toilets, which carry away the waste with a large amount of water, vacuum toilets are driven by air pressure not by gravity force in traditional systems. Benefits of this system include: (1) less diameter of pipe work, making it less expensive and simpler to accommodate in the building; (2) no extract ventilation pipes required in the toilet; (3) more flexibility of system design; (4) easy removal of large objects, preventing serious blocking of pipes. The drawback of a vacuum toilet is the electricity required to operate the vacuum pumps.

For urinals, hydraulic systems and detector/ solenoid valve systems can be employed to restrict flushing of the urinals to within occupancy hours (Proença and Ghisi, 2013).

A.9.2 Water Recycling Systems

Water recycling systems can be operated through grey water and rain water. Grey water is the water originally coming from potable mains supply, used for washing, bathing, washing dishes or clothes. Grey water contains chemicals, organic suspended solids, and contaminants, such as fat and grease. These things should be passed through some elementary treatment before reuse. Soil can be used to filter grey water for garden use, but may have the risk of destroying the structure from chemical ingredients contained in grey water (Ghunmi *et al*., 2011). A rain water system is a better choice for garden watering. Rainwater is relatively clean when it is falling through the sky, although it will pick up some air pollution. Economic incentives are available for rain water systems, such as Enhanced Capital Allowance scheme, from which, 100% capital allowances can be claimed in the first year on this sustainable water use investment. Conceptual diagram of rain water harvesting and grey water reusing are respectively shown in Figure A.16 and Figure A.17.

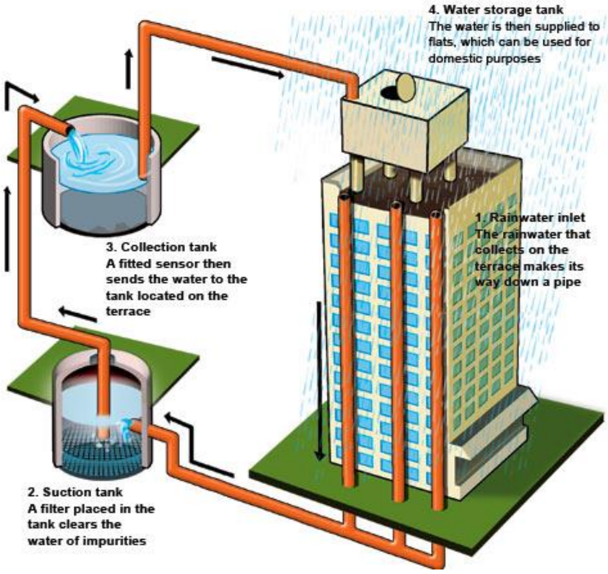


Figure A.16 Roof-top Rainwater harvesting concept (Source: Icon homz, n.d)

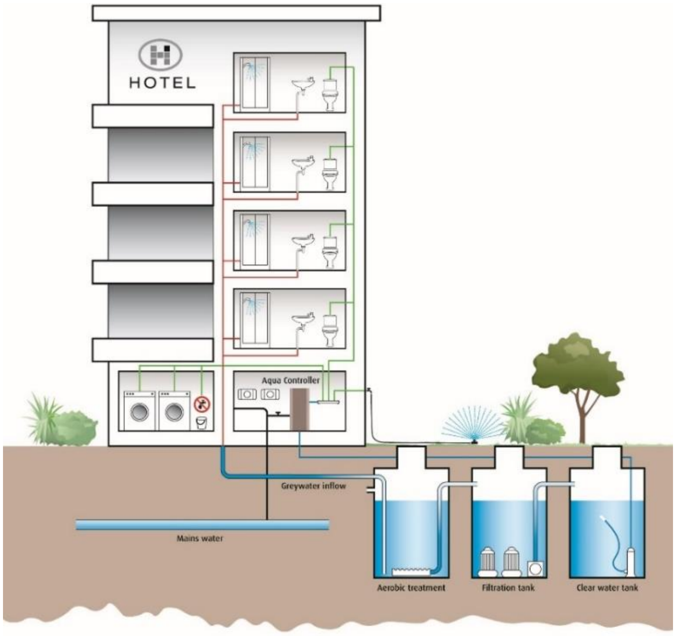


Figure A.17 Grey water reusing concept (Source: Waterscan, 2014)

References of Appendix A

Advanced Energy Solutions. Inc. (n.d.). Working principle of solar cell. Available at: http://aessolar.com/Resources/howpvworks.htm.

Andersen, P.D., Bonou, A., Beauson, J. and Brøndsted, P. (2014). Recycling of wind turbines. *DTU International Energy Report 2014*, pp.91–98. Available at: http://orbit.dtu.dk/files/102458629/DTU_INTL_ENERGY_REP_2014_WIND_91_97.pdf

Arup (n.d.) Five minute guide to rooftop solar PV. Available at: http://publications.arup.com/publications/f/five_minute_guide_to_rooftop_solar_pv

Asian Productivity Organization (APO) (2010). Reusing biomass waste in industrial boilers for energy recovery. http://www.apo-tokyo.org/ biomassboiler/D0 online-resources.htm.

BioRegional and Association for Conservation of Energy (n.d.). Retrofitting: A guide for non-residential buildings. Available at: http://www.hertslink.org/buildingfutures/content/migrated/obdocs/pdfs/retrofitnonres.pdf

Blackmore P. (2010) Building-mounted micro-wind turbines on high-rise and commercial buildings. Available at: https://www.brebookshop.com/details.jsp?id=325406

Cambridge Network (2013). Future Business Centre. Available at: https://www.cambridgenetwork.co.uk/news/fbc-integrates-polysolar-innovation/

Castleton, H.F., Stovin, V., Beck, S.B.M. and Davison, J.B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and buildings*, *42*(10), pp.1582-1591.

CELTIC Renewable Energy (n.d.). Solar Heating-webpage. Available at: http://eco2solar.co.uk/solar-heating/

CIBSE AM15(2014). Biomass heating. Available at: http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I76dAAC

CIBSE AM12(2013) Combined heat and power for buildings. Available at: http://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I7nsAAC

CIBSE TM51(2013). Ground source heat pumps. Available at: http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7f4AAC

Contemporary energy. (n.d.). Solar Thermal Panels for Heating Water. Available at: http://contemporaryenergy.co.uk/

DECC (2008). A detailed guide for CHP developers – Part 3. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/345173/Part_3_CHP_Environmental.pdf

Drivers Jonas Deloitte (2009). Greater Manchester Green Roof Programme- Guidance Document.

Energy Agency (EA) (2011). Environmental good practice guide for ground source heating and cooling. Available at: http://www.gshp.org.uk/pdf/EA_GSHC_Good_Practice_Guide.pdf

Energy Saving Trust (2016). Renewable Energy_ Electricity _ Wind turbines. Available at: http://www.energysavingtrust.org.uk/domestic/wind-turbines

Energy Saving Trust (n.d.). Biomass. Available at: http://www.energysavingtrust.org.uk/renewable-energy/heat/biomass

Energy Saving Trust (2016). Renewable Energy _ Heat_ Air source heat pump. Available at: http://www.energysavingtrust.org.uk/renewable-energy/heat/air-source-heat-pumps

Engineers Garage. (n.d.). The schematic of wind turbines. Available at: https://www.engineersgarage.com/articles/what-is-a-windmill-design?page=3

Forsén, M. (2005). Heat Pumps Technology and Environmental Impact. Available at: http://ec.europa.eu/environment/ecolabel/about_ecolabel/reports/hp_tech_env_impact_aug2005.pdf

Ghunmi, L.A., Zeeman, G., Fayyad, M. and van Lier, J.B. (2011). Grey water treatment systems: A review. *Critical reviews in environmental science and technology*, *41*(7), pp.657-698.

Greening, B. and Azapagic, A. (2013). Environmental impacts of micro-wind turbines and their potential to contribute to UK climate change targets. *Energy*, 59, pp.454-466.

Green energy advice team (n.d.). The schematic of a biomass boiler. Available at: http://geat.org.uk/biomass-boilers/

GreenMatch (2016). The running costs of Heat pumps. Available at: http://www.greenmatch.co.uk/blog/2014/08/the-running-costs-of-heat-pumps

Hillesheim M. and Mosey G. (2014). Technical Feasibility Study for Deployment of Ground-Source Heat Pump Systems: Portsmouth Naval Shipyard— Kittery, Maine. Available at: http://www.nrel.gov/docs/fy15osti/62353.pdf

Hui, S.CM. (2013). Guidelines for the design and application of green roof system. Available at: http://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I7oLAAS

Icon homz (n.d). *Roof-top Rainwater harvesting concept.* Available at: https://iconinfrashelters.wordpress.com/tag/rainwater-harvesting-2/

Inhabitat.com (2008). Santa Monica Civic Center. Available at: http://inhabitat.com/first-leed-certified-parking-garage/

Korrie Renewables (n.d.). An example of ASHP system. Available at: http://www.korrie-renewables.co.uk/heatpumps

Köhler, M. (2003), May. Plant survival research and biodiversity: Lessons from Europe. In *First Annual Greening Rooftops for Sustainable Communities Conference, Awards and* Trade Show (pp. 20-30).

Lambeth Council (2009). Ethelred Estate—the green roof revolution. Available from: http://www.lambeth.gov.uk/Services/HousingPlanning/Planning/EnvironmentalIssues EXTRA.htm.

Ledo, L., Kosasih, P.B. and Cooper, P. (2011). Roof mounting site analysis for micro-wind turbines. Renewable Energy, 36(5), pp.1379-1391.

Lu, L. and Ip, K.Y. (2009). Investigation on the feasibility and enhancement methods of wind power utilization in high-rise buildings of Hong Kong. *Renewable and Sustainable Energy Reviews,*13(2), pp.450–461. Available at: http://www.sciencedirect.com/science/article/pii/S1364032107001530

Mentens, J., Raes, D. and Hermy, M. (2006). Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?. *Landscape and urban planning*, *77*(3), pp.217-226.

National Renewable Energy Laboratory (NREL) (2016). Installed cost, O&M cost and lifetime of PV systems. Available at: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

National Renewable Energy Laboratory (NREL) (2016). Installed cost, O&M cost and lifetime of Solar Thermal Technologies. Available at: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

National Renewable Energy Laboratory (NREL) (2016). Installed cost, O&M cost and lifetime of the Wood-Fired Heat System. Available at: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

National Institute of Building Science (NIBS) (2016). Installed cost and O&M costs of the CHP technology with different prime movers. Available at: https://www.wbdg.org/resources/combined-heat-and-power-chp

National Institute of Building Science (NIBS) (2016). Installed cost, O&M costs and lifetime of Ground Source Heat Pump. Available at: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

Nayland Primary School (n.d.). Biomass boiler installation with wood pellet burner at Nayland Primary School, Suffolk. Available at: http://www.bghn.co.uk/docs/files/Case%20studies/OLD%20Nayland_Primary_School_case%20study.pdf

Odersun (2011). Manual for BiPV Projects. Available at: https://www.ntnu.no/wiki/download/attachments/40800075/Odersun-BiPV-Download.pdf?version=1&modificationDate=1326906420000

Pester, S. and Crick, F. (2013). Performance of photovoltaic systems on non-domestic buildings. Available at: https://www.brebookshop.com/samples/327258.pdf

Princess Alexandra Hospital (n.d.). Princess Alexandra Hospital in England with Solar thermal collectors. Available at: http://rcp.net.au/services/project-management/princess-alexandra-hospital/#!prettyPhoto

Proença, L.C. and Ghisi, E. (2013). Assessment of potable water savings in office buildings considering embodied energy. *Water Resources Management*, *27*(2), pp.581-599.

Royal Mechanical LLC (n.d.). The schematic of Ground Source Heat Pump. Available at: http://www.royalmechanicalllc.com/geothermal-heatpump.php

Stovin, V., Dunnett, N. and Hallam, A. (2007), June. Green roofs–getting sustainable drainage off the ground. In *6th International Conference of Sustainable Techniques and Strategies in Urban Water Mangement* (Novatech 2007), Lyon, France, pp. 11-18.

Thorne A. (2014). Solar thermal systems: key factors for successful installations. Available at: http://www.book-me.net/read/solar-thermal-systems-key-factors-for-successful-installations.pdf

The Green Roof Centre (2010). Cost of Green Roof. Available from: http://www.thegreenroofcentre.co.uk/pages/faq.html

The Scottish Government (2010). Low carbon equipment and building regulations – A guide to safe and sustainable construction Available at: http://www.gov.scot/Resource/Doc/217736/0097150.pdf

Waterscan (2014). Grey water reusing concept. Available at: http://water-recycling-harvesting.co.uk/tag/grey-water-recycling/

Weather Energy (n.d.). The schematic of a Solar PV system. Available at: http://www.weatherenergy.co.uk/solar-photovoltaic/how-it-works

Windustry (2016). How much do wind turbines cost?. Available at: http://www.windustry.org/how_much_do_wind_turbines_cost

Yang, J., Yu, Q. and Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric environment*, *42*(31), pp.7266-7273.

Appendix B Building Operational Characteristics

B.1 Overview

Non-domestic buildings include multiple building types. The classification of non-domestic buildings is discussed by a range of energy benchmarking methods, such as guides provided by UK Energy Efficiency office (EEO), the Energy Consumption Guides (ECON Guides or ECGs) by the Carbon Trust, the Energy Assessment and Reporting Method by the Chartered Institute of Building Services Engineers (CIBSE TM22, 2006), Energy Benchmark System developed by Asia-Pacific Economic Cooperation (APEC) and building use classification suggested by the Commercial Buildings Energy Consumption Survey (CBECES). By referring to these methods, five general types of non-domestic buildings are selected to discuss in this chapter. These buildings are:

1) Office buildings
2) Hotels
3) Schools (including primary schools and secondary schools)
4) Higher education buildings (or university buildings)
5) Hospitals (inpatient with A&E)

The above types of non-domestic buildings will be discussed from the following perspectives:

1. Building function

   This is to provide a general introduction about what the building is designed for and what the main occupants are inside the building.

2. Annual occupancy hours

   Buildings that are occupied for a longer time are likely to consume more energy than those occupied for a shorter time. According to CIBSE TM46 (2008), definitions of annual occupancy hours are provided:

a) The number of hours per year that the number of recorded occupants exceeds 25% of the nominal maximum occupancy;

b) The number of hours per year that the premises are fully open to the public according to published opening hours.

3. Energy end use

   Understanding the energy end use of different types of buildings can help to identify what the main energy consumer is. Energy end use is categorised into heating, cooling and ventilation (HVAC), lighting, domestic hot water and appliances.

4. Health and safety requirements

   Health and safety requirements of a particular type of buildings should be checked. This information could be used for proposing potential green technology to improve health and safety requirements of buildings.

B.2 Office Buildings

B.2.1 Building function

Office buildings are buildings where clerical and administrative work activities are carried out. An office building should provide flexible and technologically-advanced working environments that are safe, healthy, comfortable, durable, aesthetically-pleasing, and accessible. It must be able to accommodate the specific space and equipment needs of the tenant. Special attention should be paid to the selection of interior finishes and art installations, particularly in entry spaces, conference rooms and other areas with public access. Office buildings can be classified into four types: naturally ventilated cellular, naturally ventilated open-plan, air-conditioned, standard and air-conditioned, prestige (CIBSE ECG19, 2005). An example of typical working place in office buildings is shown in Figure B.1.

Figure B.1 An example of office building (Source: Iser, 2016)

B.2.2 Occupancy hours

The reference occupancy hours per year for general office buildings are 2040hrs (CIBSE TM46, 2008). The U.S. Environmental Protection Agency's ENERGY STAR Portfolio Manager has surveyed office buildings in the USA (EPA, 2012) and operating hours are reported in the range of 40-120 hrs/week with a median value of 60 hrs/week.

B.2.3 Energy end use

Building services in office buildings include space heating, lighting, space cooling, water heating, office equipment and others. The distribution of energy consumption in U.S. office buildings is shown in Figure B.2.

From Figure B.2, it can be found that the main energy consumer in U.S. office buildings is lighting and space heating. Energy efficient measures for lighting can include high-efficiency lighting, lighting controls and occupancy sensors. Localized control is a good measure not only to save energy, but can also provide employees with opportunities for personal control. Daylighting can be also used for saving energy and improving occupant wellbeing (The Association for the Conservation of Energy, 2003).

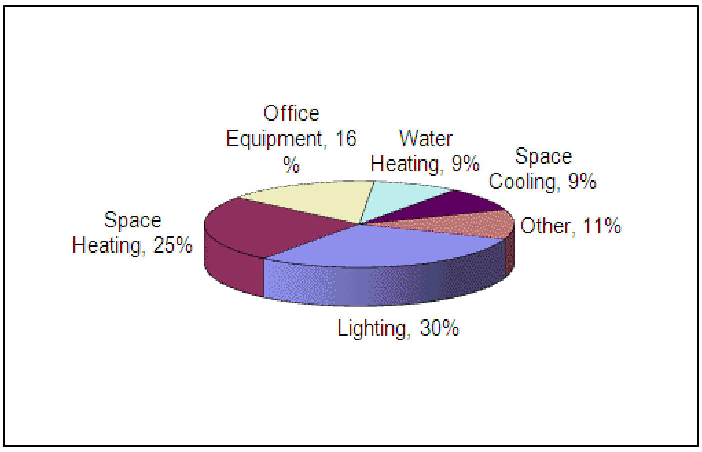


Figure B.2 Office buildings energy usage (U.S. average) by building services

(Source: University of California, 2007)

In the UK, office buildings are further categorised into four types with standards and building services: naturally ventilated cellular, naturally ventilated open-plan, air-conditioned standard and air-conditioned prestige. Energy use indices (EUIs), which are expressed as annual energy use per square meters of treated floor area, is used to compare the energy use difference. Figure B.3 shows EUIs for good practice and typical examples for these four office types.

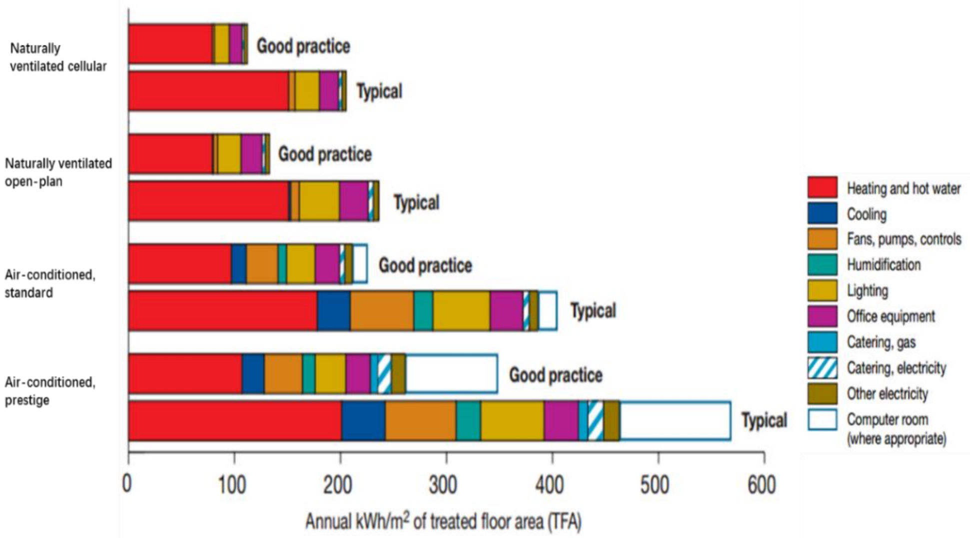


Figure B.3 EUIs for good practice and typical examples of the four office types

(Source: CIBSE ECG19, 2005)

B.2.4 Health and safety requirements

The principal legislation concerning offices is the Workplace (Health, Safety and

Welfare) Regulations 1992 (Health and Safety Executive (HSE), 2013). This legislation covers all workplaces and deals with specifics such as lighting, ventilation/air quality, thermal comfort, noise, and fire safety standards, etc. Different activities require different levels of light, and more local controls can increase job satisfaction in open plan offices (HSE HSG38, 1997). For thermal comfort, extremes of temperature can put physiological stress on an individual. Lack of control of the temperature of a workplace can lead to job dissatisfaction and increased incidence of stress and long term sickness absence (HSE, 2016). In addition, exposure to high levels of noise can increase individual experience of stress (HSE, 2016).

B.3 Hotels

B.3.1 Building function

Hotels are to provide lodging, meals and other services to guests (See example in Figure B.4). There are three categories of hotels: luxury, business, small (CIBSE TM22, 2006).

Figure B.4 An example of hotel with swimming pools (Dona Filipa Hotel, 2015)

B.3.2 Occupancy hours

Hotels always operate 24 hours and energy in hotel buildings is frequently consumed 24 hours a day, year-round regardless of whether or not the room is occupied.

B.3.3 Energy end use

Energy consumption for hotels is mainly for heating rooms, cooling rooms, lighting, hot water use and other energy consuming activities by guests, catering, and swimming pools. A breakdown of average energy end-use for hotels is shown as Figure B.5.

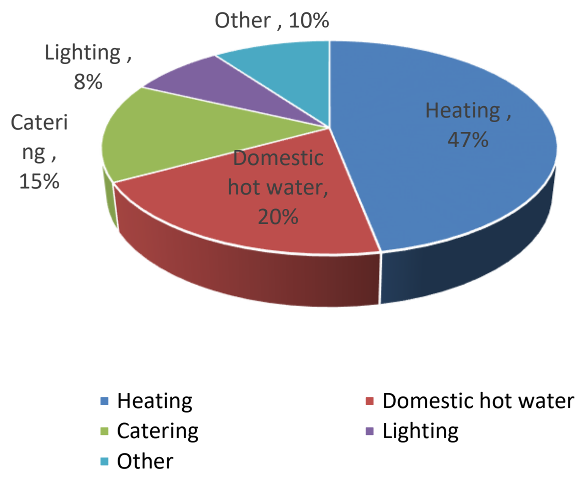


Figure B.5 Energy end-use for hotels (Source: CIBSE ECG36, 1997)

Figure B.5 shows that air conditioning for space heating and cooling is the largest energy consumer in hotels, accounting for over half a portion of the total consumption (56%). Services such as catering and laundry also account for a considerable share of energy consumption. Other studies have stated that domestic hot water can be the main energy consumer, which can account for 15% of the total energy demand (Hotel Energy Solutions, 2011). Lighting can fluctuate between a range of 12-18% and up to 40% of a hotel's total energy consumption, depending on the category of the establishment (Hotel Energy Solutions, 2011). Energy consumption can be influenced by a range of operational parameters, such as operating schedules for different functional facilities in hotels, the number of facilities, services offered etc.

B.3.4 Health and safety requirements

Given that there is no health and safety regulation specifically for hotels, general suggestions are listed and recommended to be considered through all phases of a building's life cycle (NIBS, 2015). The suggestions relevant to occupant health and safety can include:

- Ensure electrical safety from turn-over through Operations and Maintenance. Modifications must be in conformance with life safety codes and standards and be documented.
- Eliminate exposure to hazardous materials (e.g., volatile organic compounds) and formaldehyde, and lead and asbestos in older buildings.
- Provide good indoor air quality and adequate ventilation.

B.4 Schools

B.4.1 Building function

Schools can be elementary schools or secondary schools. Generally, secondary schools have higher total energy consumption than primary schools (CIBSE ECG73, 1993). This is explained by secondary schools having longer operating hours and a larger number of students, as well as more widespread use of electrical equipment in ICT, science, sports and crafts lessons.

B.4.2 Occupancy hours

The reference occupancy hours per year for general office buildings are 1400hrs (CIBSE TM46, 2008).

B.4.3 Energy end use

Five specific factors influence energy (CIBSE ECG73, 1993), including occupancy level, additional facilities (swimming pools and sports halls), extended hours of use and the size of schools. A breakdown of energy use and energy cost in a typical school are respectively shown in Figure B.6. HVAC and domestic water heating constitutes the major portion of energy consumption. Upgrading or installing component parts of an HVAC system can reduce energy consumption. Measures of saving energy for water heating include insulating hot water storage tanks and choosing the most effective heat source to generate hot water (Carbon Trust, 2012).

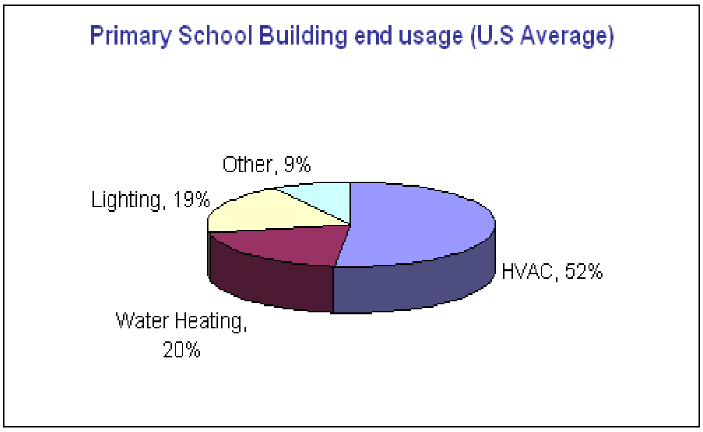


Figure B.6 Primary school building energy end usage (U.S Average) (Source: University of California, 2007)

B.4.4 Health and safety requirements

Health and safety in a school is about taking a sensible and proportionate approach to ensure the premises provide a healthy and safe place for all who use them, including the school workforce, visitors and pupils. Key elements of a health and safety policy regarding buildings may include (Department for Education, 2014):

1) Control of hazardous substances;
2) Maintenance (and, where necessary examination and testing) of plant and equipment such as electrical equipment, local exhaust ventilation, pressure systems, gas appliances, lifting equipment and glazing safety;
3) Fire safety, including testing of alarms and evacuation procedures.

To minimise the risks above, Health and Safety Executives for the UK have published a health and safety checklist for the classroom, which is suggested to check for buildings.

B.5 Higher Education Buildings

B.5.1 Building function

Higher education buildings are more complex than school buildings. It can have a mix of spaces for different use, including study rooms, lecture rooms, library, leisure centres, refectories, residential accommodation and science or biomedical laboratories. Representative space types and their characteristics of higher education buildings are shown in Table B.1.

Table B.1 Representative space types and their characteristics (Source: CIBSE ECG54, 1997.p.6)

Generic space type	Areas covered	Occupancy characteristics
Teaching	Classrooms Tutorial areas Seminar rooms	Variable occupancy pattern, some transient periods but generally medium- to long-term use
Research	Laboratories Workshops	Variable occupancy pattern Potential for high process loads
Lecture hall	Lecture theatres Halls	Dense occupancy for mid- to short-term. Large room volumes with mechanical ventilation and additional specialist electrical loads
Library	Resource centres Reading rooms	Long-term occupancy, some at high density. Increasing use of computer terminals along with traditional book-based study
Office	Administration Department offices	Mainly cellular space with single occupancy. Natural ventilation and local control much in evidence
Catering	Central kitchen Refectories, Canteens Common rooms Bars	Staff areas tend to be long-term, low-density occupancy whilst the public spaces are subject to transit use which can be high density
Recreational	Sports halls Swimming pools	Large volume spaces with occasional short-term high-density occupancy as well as more regular low-density use
Residential	Study bedrooms En-suite bathrooms Shared ablutions and catering facilities	Domestic usage pattern with long-term local occupancy of some areas

B.5.2 Occupancy hours

The reference data of occupancy hours per year for light use public and institutional buildings are 2040hrs per year (CIBSE TM46, 2008).

B.5.3 Energy end use

In higher education buildings, energy consumption is mainly for space heating, water heating and lighting. Typical university building in the US has the following consumption profile (University of California, 2007), shown in Figure B.7.

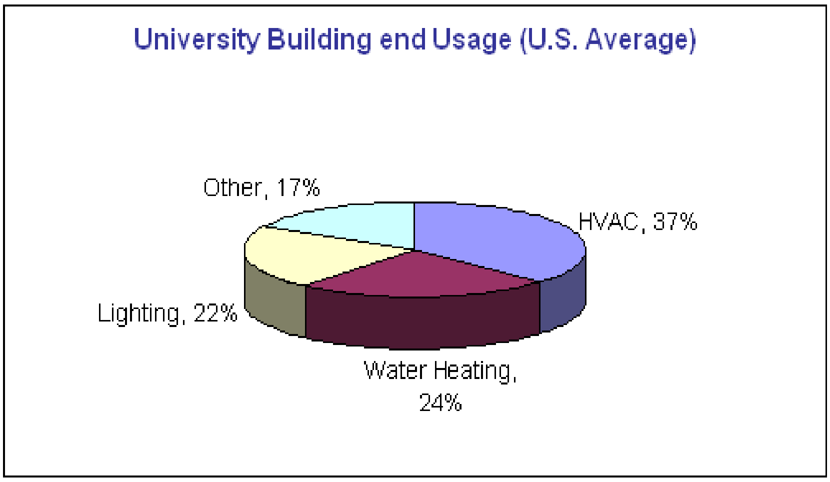


Figure B.7 University building energy end usage (U.S Average) (Source: University of California, 2007)

Following energy conservation measures can be considered for higher education buildings (CIBSE ECG54, 1997):

1) Replacing windows with double glazing with low emissivity glass and specifying triple glazing on north facing can offer further energy savings. High performance glass with a coating can be taken, which allows more daylight but reduces heat gains from direct sunlight (CIBSE ECG54, 1997).

2) Recovering heat from exhaust air. The measure of recovering heat from exhaust air is to re-circulate a proportion of the exhaust air along with fresh air to maintain air quality (CIBSE ECG54, 1997).

3) Full air conditioning should be checked whether required or not. Full air conditioning is only considered for the control of humidity. Natural ventilation should be considered if it is unavailable and possible (CIBSE ECG54, 1997).

4) Lighting is recommended to be optimised according to space use purposes and

occupancy time. Low energy lighting can generally save energy. For instance, upgrading any ‘standard’ tungsten light bulbs to compact fluorescent lamps (CFLs), produce less unwanted heat and last 8-10 times longer; upgrading to LEDs can use up to 80% less energy and provide around 50,000 hours of use (CIBSE ECG54, 1997). Lighting controls can be applied. They can be time switches with a manual override for teaching areas, occupancy sensors in intermittently occupied spaces or an override for quiet activities such as examinations and educational activity.

5) For higher education buildings with on-site high and constant heat demands throughout the year, it is beneficial to connect multiple buildings within a district heating scheme (CIBSE ECG54, 1997). This scheme uses a sizeable heat source, like a large centralized boiler plant to heat a number of discrete premises. For education buildings with swimming pools, residential accommodations or other research equipment, this scheme can be very effective.

B.5.4 Health and safety requirements

Health and safety requirements for higher education buildings can refer to the requirements stated for schools in B.4.4. Apart from control of hazardous substances, maintenance of plant and equipment and the check of the fire safety, the management of sickness absence has been emphasised for higher education buildings. Guidance for this be found in “Managing sickness absence in the public sector. A joint review by the Ministerial Task Force for Health, Safety and Productivity and the Cabinet Office Cabinet Office, DWP and HSE 2004” (HSE,2004).

B.6 Hospitals

B.6.1 Building function

Hospitals are the most complicated non-domestic buildings due to multiple services to provide and a range of occupancy patterns. Hospitals always have a range of services to provide and functional units to support these services. The basic form of a hospital can have functions as below:

1) bed-related inpatient functions
2) diagnostic and treatment functions
3) administrative functions
4) service functions (food, supply)
5) research and teaching functions

B.6.2 Occupancy hours

Hospitals have varying working hours from Monday to Friday. The A&E departments of hospitals, however, normally operate 24 hours each day.

B.6.3 Energy end use

Health care buildings, compared to other types of non-domestic buildings, consume the highest amount of energy per unit floor area. The average end use of energy in the U.S. hospital building can be classified as (University of California, 2007): Water heating (28%), Space heating (23%), office equipment (16%), Lighting (16%) and other (27%), which is shown in Figure B.8. It can be found that hot water uses the biggest energy consumer for hospital buildings. A solar water heating system can be considered and system sizing should be given more consideration to avoid the system breaking due to oversizing. Space heating or cooling can be improved by installation of Variable Speed Drivers for an air conditioning system or replacing with more efficient boilers or chillers.

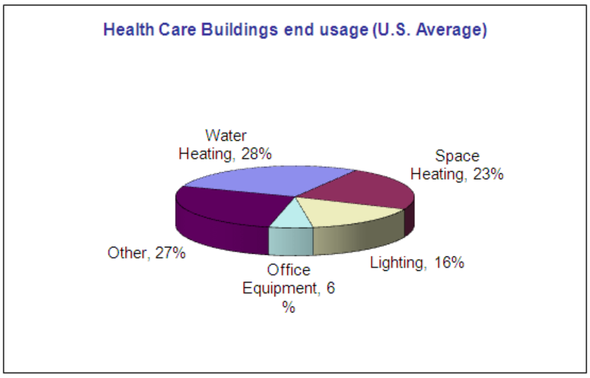


Figure B.8 Energy end use in hospitals (U.S. Average) (Source: University of California, 2007)

B.6.4 Health and safety requirements

Hospital buildings should follow the general principles given in the “The Health and Social Care Act 2008: Code of Practice on the prevention and control of infections and related guidance “(the HCAI Code of Practice). This code of practice set outs how hospitals comply with requirements for cleanliness and infection control.

B.7 Summary

This appendix provides a review about building operational characteristics on building function, occupancy hours, energy end use, as well as health and safety requirements. Decision makers who intend to retrofit existing buildings are recommended to understand their buildings from these four aspects. By understanding the characteristics of building function, occupancy hours and energy end use, existing buildings’ energy use pattern and main energy consumer can be identified. This can help decision makers to identify targeted building services and to propose effective technologies for these services. For particular building services for typical types of buildings, there are some green technologies available. This could be one point to match up building operational characteristics and green technologies.

Moreover, understanding health and safety requirements of non-domestic buildings can help decision makers to pay attention to health and safety issues when they propose potential green technologies. In the previous chapter, it was also suggested checking whether building regulations should be compliant when choosing green technologies. This could be the other point matching green technology characteristics with building operation.

How to investigate building characteristics through survey to identify opportunities of integrating green technologies to improve building performance has explained in detail in the site and building survey of the proposed framework. Following the survey, implications for green technology selection by checking building characteristics will be listed and explained. In green technology listing of the framework, potential green technologies for typical building types will be highlighted.

References of Appendix B

Carbon Trust (2012). Schools - Learning to improve energy efficiency. Available at: https://www.carbontrust.com/media/39232/ctv019_schools.pdf

CIBSE ECG 73 (1993). Saving Energy in schools. Available at: http://www.cibse.org/getmedia/082e52c7-b87a-404d-a4d1-68d0e8e0cf20/ECG73-Saving-Energy-in-Schools.pdf.aspx

CIBSE ECG 36 (1997). Energy Efficiency in Hotels – a Guide for Owners and Managers. Available at: http://www.cibse.org/getmedia/070252ba-cd5e-4b74-ba0b-4bb51e8d55c2/ECG36-Energy-Efficiency-in-Hotels-a-Guide-for-Owners-and-Managers.pdf.aspx

CIBSE ECG 54 (1997). Energy efficiency in further and higher education-cost-effective low energy buildings. Available at: http://www.cibse.org/getmedia/f944f3e0-e047-4c62-af85-43f02533f2de/ECG54-Energy-Use-in-Further-Higher-Education-Buildings.pdf.aspx

CIBSE ECG19 (2005). Energy Use in Offices. Available at: http://www.cibse.org/getmedia/7fb5616f-1ed7-4854-bf72-2dae1d8bde62/ECG19-Energy-Use-in-Offices-(formerly-ECON19).pdf.aspx

CIBSE TM22 (2006). Energy Assessment and Reporting Methodology. Available at: http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7eWAAS

CIBSE TM46 (2008). Energy benchmarks. Available at: http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7evAAC

CIBSE (2012). Energy efficiency. In buildings. Available at: http://www.cibse.org/Knowledge/knowledge-items/detail?id=a0q20000008I7oTAAS

Department of Education (2014). Health and safety: advice on legal duties and powers-For local authorities, school leaders, school staff and governing bodies. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/335111/DfE_Health_and_Safety_Advice_06_02_14.pdf

Dona Filipa Hotel (2015). An example of hotel with swimming pools. Available at: http://www.donafilipahotel.com/our-hotel/hotel-amenities/swimming-pool/

Environmental Protection Agency (EPA) (2012) Energy Use in Offices. Available at: https://www.energystar.gov/sites/default/files/tools/DataTrends_Office_20150129.pdf

Health and Safety Executive (HSE). (1997). HSG38: Lighting at work. Available at: http://www.hse.gov.uk/pubns/books/hsg38.htm

Health and Safety Executive (HSE). (2004). Managing sickness absence in the public sector. A joint review by the Ministerial Task Force for Health, Safety and Productivity and the Cabinet Office Cabinet Office, DWP and HSE 2004. Available at: http://megaslides.net/doc/1780887/healthy-workplace--healthy-workforce--better-business-del...

Health and Safety Executive (HSE). (2013). *Workplace health, safety and welfare. Workplace (Health, Safety and Welfare) Regulations 1992. Approved Code of Practice and guidance.* Available at: http://www.hse.gov.uk/pubns/books/l24.htm

Health and Safety Executive (HSE). (2016). Work related stress. Available at: http://www.hse.gov.uk/stress/

Hotel Energy Solutions (2011). Analysis on Energy Use by European Hotels: Online Survey and Desk Research, Hotel Energy Solutions project publications. Available at: http://hes.unwto.org/sites/all/files/docpdf/analysisonenergyusebyeuropeanhotelsonlinesurveyanddeskresearch2382011-1.pdf

Iser. A (2016). An example of office building. Available at: https://officesnapshots.com/2012/02/29/hospiras-new-open-plan-melbourne-office/

National Institute of Building Service (NIBS) (2016). Occupant Safety and Health. Available at: https://www.wbdg.org/design-objectives/secure-safe/occupant-safety-health

The Association for the Conservation of Energy (2003). Energy efficiency in offices: Assessing the situation. Available at: http://www.ukace.org/wpcontent/uploads/2012/11/ACE-Research-2003-05-Energy-Efficiency-in-offices-Assessing-the-situation-report1.pdf

University of California. (2007). Office Buildings end usage (U.S. Average). *Building Integration Tutorial*. Available at: http://www.apep.uci.edu/der/buildingintegration/2/BuildingTemplates/Office.aspx

University of California. (2007). Primary School Building end usage (U.S. Average). *Building Integration Tutorial*. Available at: http://www.apep.uci.edu/der/buildingintegration/2/BuildingTemplates/School.aspx

University of California. (2007). Health Care Buildings end usage (U.S. Average). *Building Integration Tutorial*. Available at: http://www.apep.uci.edu/der/buildingintegration/2/BuildingTemplates/Hospital.aspx

Appendix C Web-based Survey

Survey about green technology selection for non-domestic building retrofits

Introduction

Thank you for your interest in this survey. My name is Jin Si, an Erasmus PhD student at UCL. This survey is a part of my research, which explores decision-making process of green technology selection for non-domestic building retrofits.

Due to the fact that existing buildings comprise the largest segment of the built environment, low carbon retrofitting of existing buildings is vitally important if we are to improve the performance of our building stock. However, low carbon retrofit of non-domestic buildings is a multi-criteria decision making process, which can be influenced by economic, environmental, social and technical considerations.

This questionnaire is designed to collect your expert views on relative importance for multiple criteria when choosing green technologies. I would greatly appreciate if you could please spare less than 15 minutes to complete the survey. All the answers will be treated in absolute confidence and used for academic purposes only. No personal information is asked and no company name will be disclosed.

General Information

What is your background?

☐ Architecture ☐ Design ☐ Engineering ☐ Planning ☐ Others, please specify______________

Which following can best describe your expertise?

☐ Façade engineering ☐ Structure engineering ☐ Mechanical, Electrical and Plumbing

☐ Lighting design ☐ Facility management ☑ Energy analysis

☐ Ecology ☐ LEED or BREEAM Certification ☐ Sustainability consulting

☐ Others, please specify_____________

How many years of working experience do you have in the built environment field? ___________________

How many retrofit projects have you participated in so far (approximately)? _________________________

What were the most frequent client requirements for the retrofit projects? (Tick all that apply)

☐ To reduce operational cost ☐ To increase asset value ☐ To improve energy performance

☐ To improve water efficiency☐ To improve occupant wellbeing☐ To improve building durability

☐ To conserve fabric (heritage building)☐ To improve building safety & security

☐ To improve corporate sustainability ☐ Others, please specify________________________

What were the most commonly used green technologies/solutions in these retrofit projects? (Tick all that apply)

☐ Enhanced wall insulation ☐ Enhanced glazing ☐ Solar shading

☐ Energy efficient lighting ☐ Lighting controls (occupancy sensors and timers)

☐ Task lighting ☐ Day Lighting sensors

☐ Pumps and/or fans retrofit ☐ Mechanical ventilation with heat recovery

☐ Insulation around hot water tanks and pipes (for HAVC system)

☐ Solar hot water ☐ Biomass boiler ☐ Heating control

☐ Water efficiency fittings ☐ Rainwater ☐ Green roof

☐ Combined Heat and Power ☐ Solar PV ☐ Ground Source Heat

☐ Building automation system ☐ Others, please specify_______________________

Criteria development

The selection framework being currently developed uses the criteria tree with different levels shown below.

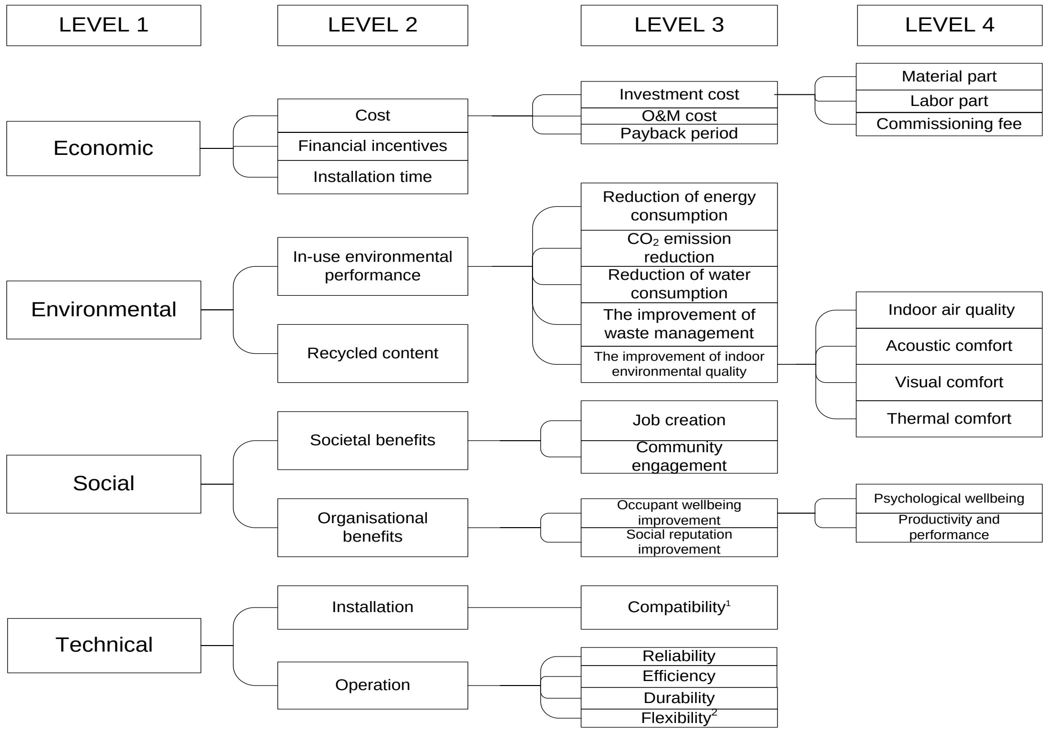


Figure 1 Evaluation criteria tree

1. Compatibility: The technology should be compatible with existing building systems.

2. Flexibility: The system units can be replaced without difficulties when the system upgrades.

Are there any criterion you want to add? If so, please also indicate its parent criterion on the existing tree. [For example: Environmental (Ecosystem impacts)]

Criteria weighting

The weighting method

Multiple criteria may differ in the importance when choosing green technologies. One of the approaches for the importance identification is to conduct a pair-wise comparison.

In the example of the pair-wise comparison table below, the positioning of tick symbol ⊙ indicates that Economic criterion is strongly more important than Environmental criterion.

A vs B	A is more important than B					B is more important than A			
	Extremely more important	Very strongly more important	Strongly more important	Moderately more important	Equally important	Moderately more important	Strongly more important	Very strongly more important	Extremely more important
	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
[A] Economic/ [B]Environmental	○	○	⊙	○	○	○	○	○	○

In the following example, the tick indicates Social criterion is very strongly more important than Economic criterion.

A vs B	A is more important than B				Equally important	B is more important than A			
	Extremely more important	Very strongly more important	Strongly more important	Moderately more important		Moderately more important	Strongly more important	Very strongly more important	Extremely more important
	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
[A]Economic/ [B] Social	○	○	○	○	○	○	○	⊙	○

Please now rate the relative importance of the proposed criteria the way you see it.

LEVEL 1

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Economic / Environmental	○	○	○	○	○	○	○	○	○
Economic / Social	○	○	○	○	○	○	○	○	○
Economic / Technical	○	○	○	○	○	○	○	○	○
Environmetal / Social	○	○	○	○	○	○	○	○	○
Environmental / Technical	○	○	○	○	○	○	○	○	○
Social / Technical	○	○	○	○	○	○	○	○	○

LEVEL 2: Economic

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Cost / Financial incentives	○	○	○	○	○	○	○	○	○
Cost / Installation time	○	○	○	○	○	○	○	○	○
Financial incentives / Installation time	○	○	○	○	○	○	○	○	○

LEVEL 2: Environmental

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
$\frac{\text{In} - \text{use environmental performance}}{\text{Recycled content}}$	○	○	○	○	○	○	○	○	○

LEVEL 2: Social

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
$\frac{\text{Societal benefits}}{\text{Organisational benefits}}$	○	○	○	○	○	○	○	○	○

LEVEL 2: Technical

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
$\frac{\text{Installation}}{\text{Operation}}$	○	○	○	○	○	○	○	○	○

LEVEL 3: Cost

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
$\frac{\text{Investment cost}}{O\&M\ cost}$	○	○	○	○	○	○	○	○	○
$\frac{\text{Investment cost}}{\text{Payback period}}$	○	○	○	○	○	○	○	○	○
$\frac{O\&M\ cost}{\text{Payback period}}$	○	○	○	○	○	○	○	○	○

LEVEL 3: In-use environmental performance

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Reduction of energy consumption / CO_2 emission reduction	○	○	○	○	○	○	○	○	○
Reduction of energy consumption / Reduction of water consumption	○	○	○	○	○	○	○	○	○
Reduction of energy consumption / The improvement of waste management	○	○	○	○	○	○	○	○	○
Reduction of energy consumption / The improvement of Indoor environmen quality	○	○	○	○	○	○	○	○	○
CO_2 emission reduction / Reduction of water consumption	○	○	○	○	○	○	○	○	○

CO_2 emission reduction / The improvement of waste management	○	○	○	○	○	○	○	○	○
CO_2 emission reduction / The improvement of Indoor environment quality	○	○	○	○	○	○	○	○	○
Reduction of water consumption / The improvement of waste management	○	○	○	○	○	○	○	○	○
Reduction of water consumption / The improvement of Indoor environment quality	○	○	○	○	○	○	○	○	○
The improvement of waste management / The improvement of Indoor environment quality	○	○	○	○	○	○	○	○	○

LEVEL 3: Societal benefits

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Job creation / Community engagement	○	○	○	○	○	○	○	○	○

LEVEL 3: Organisational benefits

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Occupant wellbeing improvement / Social reputation improvement	○	○	○	○	○	○	○	○	○

LEVEL 3: Operation

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Reliability / Efficency	○	○	○	○	○	○	○	○	○
Reliability / Durability	○	○	○	○	○	○	○	○	○
Reliability / Flexibility	○	○	○	○	○	○	○	○	○
Efficiency / Durability	○	○	○	○	○	○	○	○	○
Efficiency / Flexibility	○	○	○	○	○	○	○	○	○
Durability / Flexibility	○	○	○	○	○	○	○	○	○

LEVEL 4: Investment cost

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Material part / Labour part	○	○	○	○	○	○	○	○	○
Material part / Commissioning fee	○	○	○	○	○	○	○	○	○
Labour part / Commissioning fee	○	○	○	○	○	○	○	○	○

LEVEL 4: The improvement of Indoor environmental quality

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Indoor air quality / Acoustic comfort	○	○	○	○	○	○	○	○	○
Indoor air quality / Visual comfort	○	○	○	○	○	○	○	○	○
Indoor air quality / Thermal comfort	○	○	○	○	○	○	○	○	○

Acoustic comfort Visual comfort	○	○	○	○	○	○	○	○	○
Acoustic comfort Thermal comfort	○	○	○	○	○	○	○	○	○
Visual comfort Thermal comfort	○	○	○	○	○	○	○	○	○

LEVEL4: Occupant wellbeing improvement

A vs B	A>>>>B	A>>>B	A>>B	A>B	A=B	A<B	A<<B	A<<<B	A<<<<B
Psychological wellbeing Productivity and performance	○	○	○	○	○	○	○	○	○

Appendix D Consistency checking and Categorisation of criteria weights difference

Table D.1 Numbers of matrices of pairwise comparison (MPC) that have passed consistency checking

Level	Dimensions	UK				China					
		All Expert group	Architect group	Engineer group	Others group	All expert group	Architect group	Engineer group	Planning group	Design group	Others group
Level 1	4×4	14	4	9	1	4	1	2	0	0	1
Level 2 (Economic)	3×3	9	4	5	0	7	1	2	2	1	1
Level 3 (Cost)	3×3	4	2	2	0	9	3	4	1	0	1
Level 3 (In-use Environmental Performance)	5×5	2	1	1	0	9	3	4	1	0	0
Level 3 (Operation)	4×4	11	4	7	0	6	2	3	0	0	1
Level 4 (Investment cost)	3×3	9	4	4	1	10	3	6	0	0	1
Level 4 (The improvement of IEQ)	4×4	16	4	10	2	8	3	2	0	1	2

Table D.2 Consistency ratios of matrices for Group Weighting Values generation

Level	UK				China					
	All Expert group	Architect group	Engineers group	Others group	All Expert group	Architect group	Engineer group	Planning group	Design group	Others group
Level 1	0.002	0.004	0.002	0.003	0.012	0.000	0.013	-	-	0.079
Level 2 (Economic)	0.000	0.000	0.000	-	0.000	0.040	0.000	0.001	0.040	0.000
Level 3 (Cost)	0.000	0.000	0.000	-	0.002	0.000	0.001	0.006	-	0.032
Level 3 (In-use Environmental Performance)	0.042	0.084	0.049	-	0.004	0.006	0.002	0.073	-	-
Level 3 (Operation)	0.009	0.004	0.014	-	0.001	0.000	0.006	-	-	0.000
Level 4 (Investment cost)	0.000	0.001	0.000	0.000	0.000	0.000	0.000	-	-	0.000
Level 4 (The improvement of IEQ)	0.004	0.009	0.003	0.013	0.002	0.014	0.000	-	0.052	0.013

Table D.3 Categorisation of criteria weights difference by expert groups in the UK and China

Criteria	Sub-criteria	Criteria weights difference (%)			Criteria weights difference (In Levels)		
		All expert	Architect group	Engineer group	All expert	Architect group	Engineer group
Level 1	Economic	42.40	30.80	54.80	Medium	Medium	Large
	Environmental	4.40	21.20	2.80	Small	Medium	Small
	Social	1.60	21.20	38.40	Small	Medium	Medium
	Technical	39.20	12.00	19.20	Medium	Small	Small
Level 2 (Economic)	Cost	0.60	33.00	51.30	Small	Medium	Large
	Financial incentives	23.40	92.40	29.70	Medium	Large	Medium
	Installation time	22.50	59.70	21.30	Medium	Large	Medium
Level 2 (Environmental)	In-use environmental performance	17.60	21.40	16.00	Small	Medium	Small
	Recycled content	17.60	21.40	16.00	Small	Medium	Small
Level 2 (Social)	Societal benefits	4.40	4.40	1.20	Small	Small	Small
	Organisational benefits	4.40	4.40	1.20	Small	Small	Small
Level 2 (Technical)	Installation	10.00	25.60	2.00	Small	Medium	Small
	Operation	10.00	25.60	2.00	Small	Medium	Small
Level 3 (Cost)	Investment cost	27.30	73.20	9.90	Medium	Large	Small
	O&M cost	17.40	5.40	23.70	Small	Small	Medium
	Payback period	45.00	78.90	13.50	Medium	Large	Small
Level 3 (In-use environmental	Reduction of energy consumption	6.00	10.00	25.00	Small	Small	Medium

performance)	CO_2 emission reduction	12.50	10.00	5.00	Small	Small	Small
	Reduction of water consumption	30.00	1.50	62.00	Medium	Small	Large
	The improvement of waste management	1.00	17.00	14.50	Small	Small	Small
	The improvement of IEQ	37.00	18.00	47.00	Medium	Small	Medium
Level 3 (Societal benefits)	Job creation	5.00	9.60	11.60	Small	Small	Small
	Community engagement	5.00	9.60	11.60	Small	Small	Small
Level 3 (Organizational benefits)	Occupant wellbeing improvement	16.60	15.80	19.60	Small	Small	Small
	Social reputation improvement	16.60	15.80	19.60	Small	Small	Small
Level 3 (Operation)	Reliability	48.00	20.40	62.80	Medium	Medium	Large
	Efficiency	3.60	0.00	2.80	Small	Small	Small
	Durability	24.00	26.40	49.20	Medium	Medium	Medium
	Flexibility	28.00	46.80	16.40	Medium	Medium	Small
Level 4 (Investment cost)	Material part	20.40	0.90	3.00	Medium	Small	Small
	Labour part	19.80	17.70	9.30	Small	Small	Small
	Commissioning fee	0.60	18.60	12.00	Small	Small	Small
	Indoor air quality	16.80	40.80	1.60	Small	Medium	Small

Level 4 (The improvement of IEQ)	Acoustic comfort	23.60	2.00	38.80	Medium	Small	Medium
	Visual comfort	48.40	79.60	27.60	Medium	Large	Medium
	Thermal comfort	55.20	36.40	68.00	Large	Medium	Large
Level 4 (Occupant wellbeing improvement)	Psychological wellbeing	1.00	4.60	5.80	Small	Small	Small
	Productivity and performance	1.00	4.60	5.80	Small	Small	Small

1.0 INTRODUCTION

This document has been produced as part of the University College London's (UCL) ongoing commitment to improve the energy performance of its estate.

Situated in Bloomsbury, UCL is the largest of the institutions that make up the University of London. The physical estate of UCL comprises approximately 200 buildings (excluding residences) and has a total gross internal area of 294,970 m^2.

The energy budget including electricity, gas, oil, steam, heat and water exceeded £7,000,000 for 2006/07.

1.1 Objective of the Report

The purpose of this document is to provide an assessment of the current operational energy performance rating of the Pearson building. An outline of measures that may be taken to improve the efficiency and rating is included.

An energy survey was undertaken in September 2008 by N. Hadden and C. Hawkins, with assistance from UCL's Property Maintenance and Facilities Management team.

1.2 Site Details

The Pearson building has a floor area of 4,162m^2 over five storeys (including the basement).

The Pearson building is a stone building that was completely refurbished internally two and a half years ago.

The majority of the building is office space, with some meeting rooms, lecture theatres/ teachings spaces and laboratory areas. Laboratories are located in the basement areas, with teaching and offices on the upper floors. The building is predominantly for postgraduate and staff use with only two centrally booked rooms, and very little undergraduate teaching.

Even though a number of activities take place in the building, e.g. teaching areas, offices and laboratories, for the purpose of the DEC benchmark data, the whole building can be considered as a University Building.

The building is occupied by the Geography department and also houses part of the Earth Sciences department.

The heat requirements of the Pearson building are supplied by a Combined Heat and Power (CHP) scheme. The electricity is also supplied from the CHP. There is no gas consumed on site.

Some staff have reported that heating problems tend to occur in some areas of the building.

Hours of operation of the building
The building appears to operate as a standard office.

Area of the building	Occupied hours
All areas	Standard office: 8am – 7pm, Mon – Fri.

Laboratories are closed at 5pm. Staff and postgraduates may stay in the building after 5pm and to allow for varied working patterns, we have assumed a standard operating time finishing at 7pm.

Site staff commented that small numbers of staff habitually work varied hours, and may occupy the building later, in particular up until 9pm during weekdays.

It is assumed that the building operation during the weekend is limited, but that the building is occupied outside of term time (50 weeks assumed).

Planned works
There is a planned future upgrade to the North end of building. Although facades will be retained, this will link the adjacent Lewis building to the Pearson. This project is waiting for funding before it can be confirmed.

2.0 ENERGY & WATER CONSUMPTION PROFILE

Table 1 below outlines the total energy consumption and associated costs for the Pearson building for the period July 2007 – June 2008.

The electricity is supplied via a meter that also supplies the Wilkins building, the South Wing, the North Wing and 25 Gordon Street. The heat is supplied from a meter that also records supplies to the Katherine Lonsdale building and North Wing (Slade Building). There are no building-specific sub-meters that provide accurate energy consumption data for the Pearson building. The Pearson building's energy consumption has been apportioned based on a floor area weighting.

Table 1: Energy consumption and costs for July 2007 – June 2008

	kWh	Cost (£)	CO_2 (kg)
Electricity	493,048	48,073	169,401
Heat	427,616	15,420	61,457
Total	**920,664**	**63,493**	**230,858**

This report does not cover potential efficiency savings related to the operation of the CHP unit at Gower Street Heat and Power (GSHP), which is owned and operated by Utilicom.

As there is no metering on the site for individual areas in the building, the energy consumption of each area of the building is not defined. However, based on benchmark data[1] and estimated floor areas of each building use, the energy consumption per use has been estimated, as shown in Table 2.

Table 2: Estimated consumption per building use type

	Proportion of area	Proportion of energy
Office	87%	76%
Laboratory	5%	11%
Lecture Theatre	8%	14%

(Note: Proportion of energy appears to 101% due to rounding, 75.7%, 10.7%, 13.6%)

The 'bespoke' Typical and Best Practice energy benchmarks, based on the area weightings above, have been compared to the actual energy consumption for the building. As the Pearson building is heated via the heat network rather than onsite combustion of gas, it was necessary to adjust the benchmark data to show heat rather than gas in order to make a useful comparison.

It can be seen that the actual consumption is around 12% higher than the Typical Practice benchmark in Figure 2-1. The plot indicates that heat consumption is significantly higher, whereas the electricity consumption is lower than Typical Practice. This result is surprising; whilst it was noted during the site survey that the building

[1] CIBSE Guide F, Section 20

occupants regularly switch off unnecessary lighting, energy efficiency best practice was not necessarily evident in other areas of the building's operation. This result is most likely due to the floor-area weighted apportionment of electricity consumption, which is unlikely to be accurate and does not take into account the activities taking place in the buildings.

Figure 2-1: Comparison of energy consumption against Typical and Best Practice benchmarks

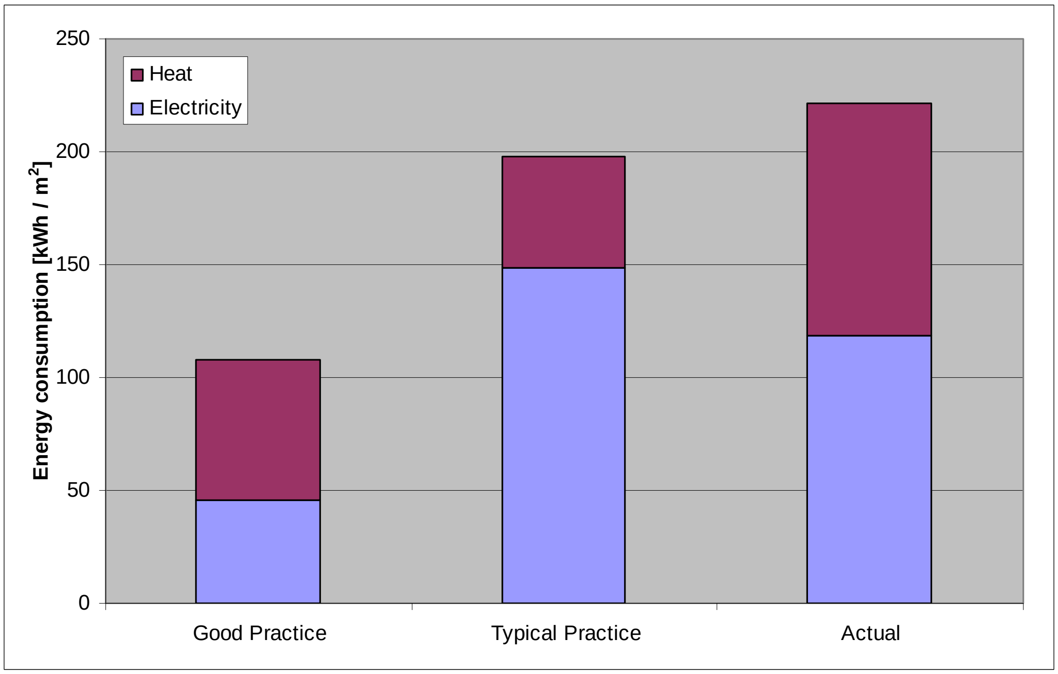


Figure 2-2 shows the equivalent CO_2 emissions, which are 8% lower than the Typical Practice benchmark value.

This is likely to be explained by the fact that, although the overall actual energy consumption is greater than Typical Practice in kWh terms, the ratio of electricity to heat consumption is lower for the actual data than for Typical Practice. As heat has a lower CO_2 factor than electricity, the total CO_2 emissions based on actual data is lower than the Typical Practice benchmark.

Figure 2-2: Comparison of CO_2 emissions against Typical and Best Practice benchmarks

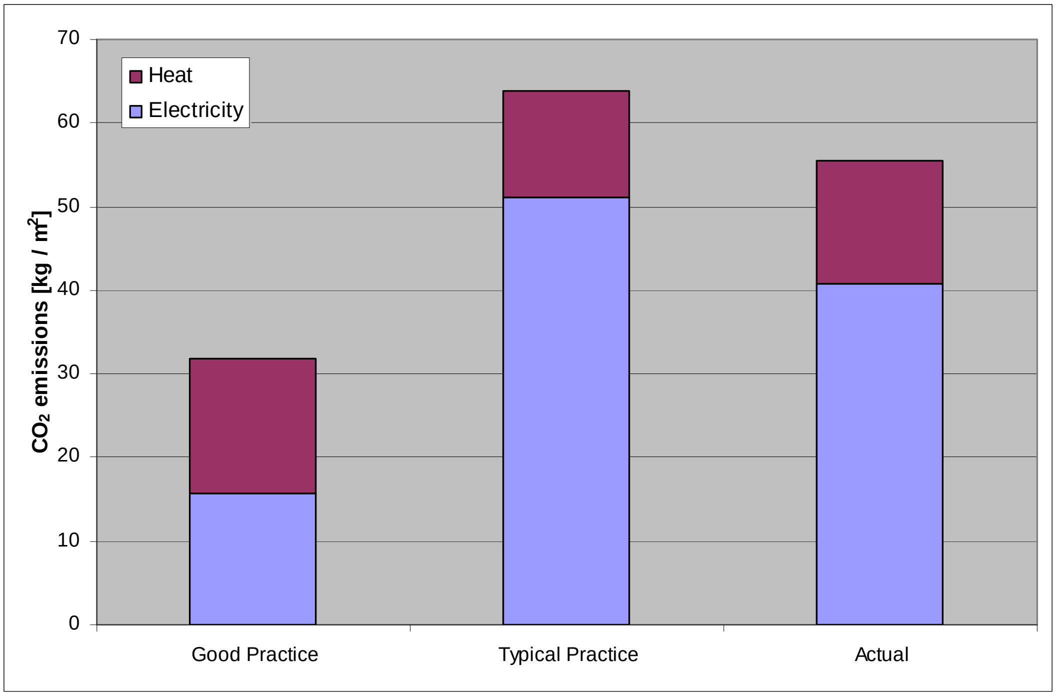


Table 3 indicates the utility costs per unit assumed in the calculations, based on the most recent billing data made available for the Pearson building. The unit cost was calculated based on a six-monthly average of the period January – June 2008.

Table 3: Assumed utility costs

	Cost (£)	Unit
Electricity	0.0971	kWh
Heat	0.0347	kWh
Water	1.3525	m^3

2.1 Electricity

Electricity is supplied to the building by the CHP operator, GSHP.

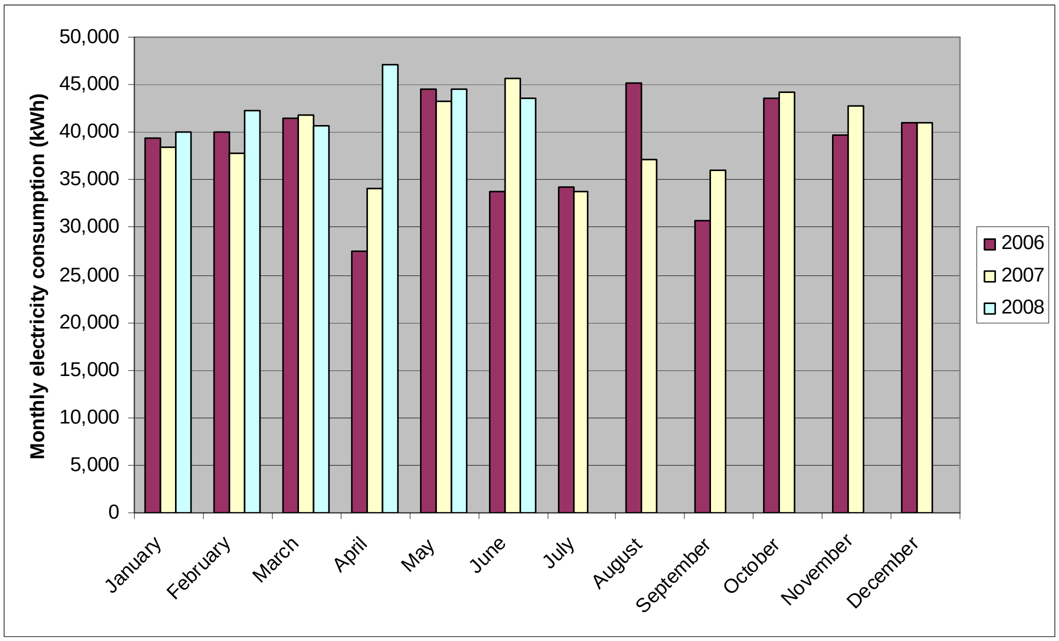
The electricity meter for this site supplies electricity to the Wilkins Building, North Wing, South Wing, 25 Gordon Street and the Pearson building. Monthly meter readings have been provided; the Pearson electricity consumption has been estimated by apportioning the electricity consumption between the five buildings based on floor area.

At the end of June 2008, the average cost per unit was 9.8p/kWh. This is the average cost per unit of electricity, including any standing and interest charges.

Without a breakdown of the individual cost elements that make up this bill, it is difficult to analyse the unit tariff. However, even with the charges additional to the consumption charge, this tariff seems to be in line with the typical market rate.

Figure 2-3 shows the monthly electricity consumption from July 2006 to June 2008 for the Pearson building.

Figure 2-3: Monthly electricity consumption (as billed)



Energy consumption appears relatively steady, but does have a small upward trend over time. The consumption in April 2008 was significantly higher when compared to April consumption in previous years. This may be worthwhile investigating (i.e. was this was due to an Easter holiday shutdown, or other increased usage?). The usage in April 2008, although high, is comparable to other months in 2008.

There is no half-hourly data available for the Pearson building.

2.2 Gas

There is no gas supply to the Pearson building.

2.3 Heat

Heat for space heating and domestic hot water (DHW) is supplied to the building from the GSHP scheme.

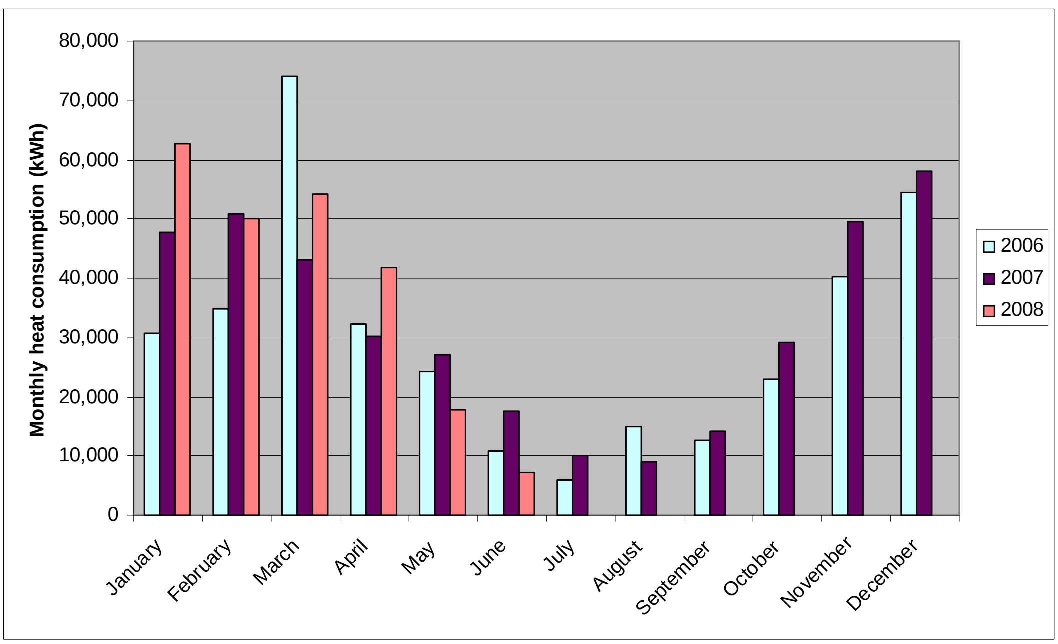
The heat supplied to this site is via a meter that supplies the Kathleen Lonsdale Building (KLB), North Wing and the Pearson buildings, but is not sub-metered. Monthly meter readings have been provided; the Pearson heat consumption has been estimated by apportioning the heat consumption between the Pearson, KLB and North Wing, based on floor area.

Figure 2-4 shows the estimated monthly heat consumption for Pearson. As would be expected; it is lower during the summer months than during the winter.

At the end of June 2008, the cost of heat consumed was charged at 9.3 p/kWh. This is the average cost per unit of heat, including any standing and performance charges. The performance charge is related to the quality of the heat provided by GSHP; where insufficient heat is supplied to the UCL buildings, a rebate is paid to UCL from GSHP.

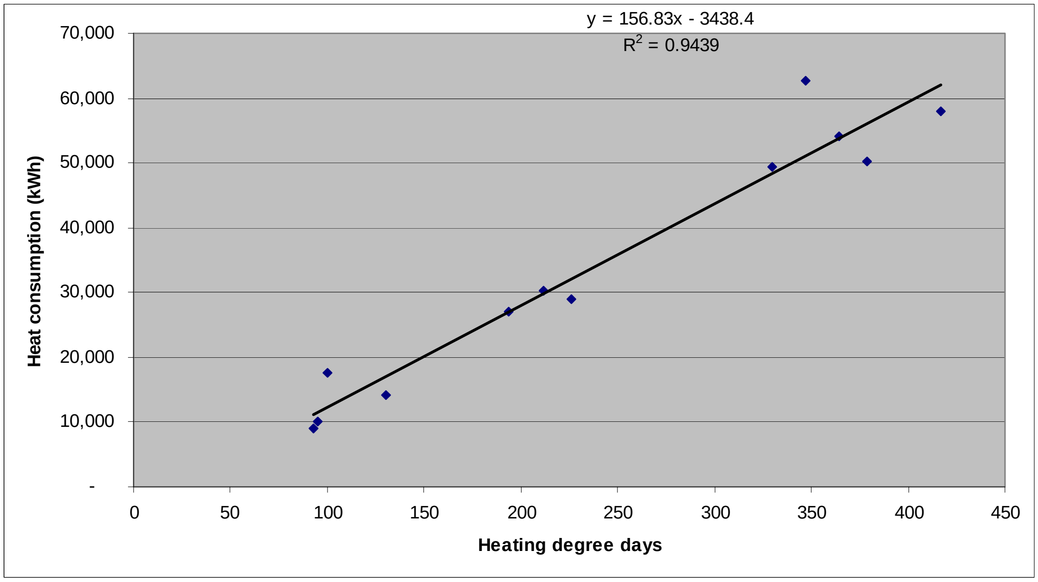
The unit cost of heat seems high compared to the current unit charge for a unit of gas. However, this tariff will take into account the CHP efficiency and the maintenance costs of the system. As the average unit cost also includes all charges, the fixed charges are a higher proportion of the overall cost when consumption is lower, i.e. during the summer months, and therefore the unit cost appears to be higher. The unit tariff for heat generated by the CHP unit should be regularly reviewed to ensure that UCL is getting best value from its contract with GSHP.

Figure 2-4: Monthly heat consumption



Weather is often one of the key factors affecting energy consumption in a building. It is possible to gauge how effectively the heating system adapts to fluctuations in weather in a graph comparing the amount of gas or heat used each month (in kWh) to the number of heating degree days (HDD) experienced for that time of year. The correlation between the two is shown in the form of a trend line. The plot for the Pearson building, using the most recent 12 months' data, is shown in Figure 2-5.

Figure 2-5: Heating degree day analysis



The point where the trend line intersects with the y-axis is the base load of heat consumption regardless of the external conditions. For Pearson, the trend line shows a negative. The result is skewed by the summer months where heating is completely shut off.

From the bar graph in Figure 2-4 we can estimate from mid-summer data that the building has a typical base-load of approximately 8,000 kWh, which can be attributed to DHW use in the building.

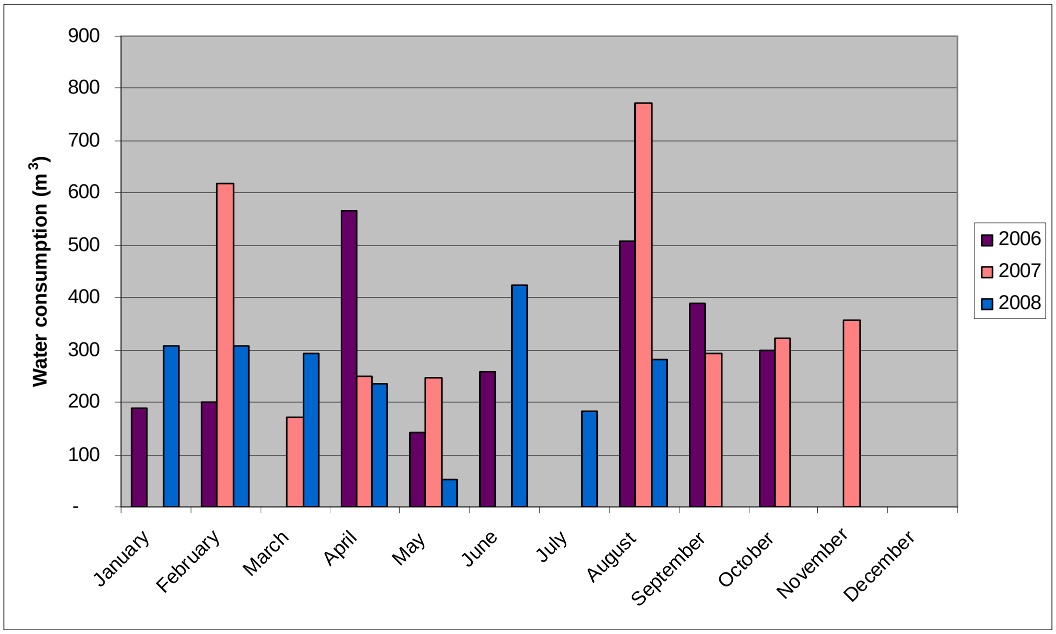
The correlation between the trend line and data points indicates how effectively the system reacts to changes in external conditions. The closer the correlation is to 1, the more effective the system. With a figure of 0.94, the graph would appear to indicate that there is a very good correlation between the operation of the system and the external temperature. Bearing in mind, however, that only 26% of the metered heat has been attributed to the Pearson building based on floor areas, it is not clear that this correlation is due to the consumption pattern of the Pearson building.

2.4 Water

Water is mainly used in the Pearson building for domestic purposes; being mostly office-type rooms. Laboratory areas in the basement may have additional consumption requirements.

Figure 2-6 shows the monthly water consumption for the Pearson building.

Figure 2-6: Monthly water consumption



The metering data provided for the previous years' water consumption shows that the meter readings have not always been undertaken on a regular, monthly basis.

Table 4 shows an analysis of estimated actual water consumption since 2006.

Table 4: Water consumption analysis, 2006 - 2008

	Annual water consumption (m^3)	Average Monthly Consumption (m^3)
2006	2,764	230
2007	2,875	240
2008	2,894 (projected)	241

There is little variation in consumption from year to year. This analysis has aimed to remove skewing of data, where four months' usage has been captured in February 2007. It is also interesting to note that the monthly consumption figures vary from month to month. This may also be explained by irregular meter readings.

Assuming a daily occupancy of 100 and using the 2007 data, the consumption per person is **28.7 m^3 / year**.

In the most recent version of the Building Research Establishment Environmental Assessment Method (BREEAM) for Offices, credits are awarded as follows:

- 1 credit where consumption is 4.5 - 5.5m^3 per person per year
- 2 credits where consumption is 1.5 - 4.4 m^3 per person per year
- 3 credits where consumption is <1.5 m^3 per person per year

It would be expected that the water consumption per capita in the Pearson building would be slightly greater than a typical office, due to the laboratory areas in the building. Also, the calculation is based on an estimate of building occupancy. There is, however, scope to identify measures to achieve a reduction in water consumption.

3.0 ENERGY MANAGEMENT

UCL is committed to a Carbon Management Strategy and Implementation Plan in order to reach a target of 10% reduction in CO_2 by 2013, with potential financial savings of more than £0.5 million over 5 years.

Without the co-operation and co-ordination of the Environmental Sustainability Steering Group, who developed the Strategy and Plan, and the UCL's Estates & Facilities Division (EFD), these targets will not be achieved. It is key that the correct energy management is developed on a building scale for the measures in the Strategy to be implemented.

This section of the report deals with energy management in the Pearson building. The estate-wide energy management will be covered in a separate report.

3.1 Building Services Rating

The current status of the building services present in the Pearson building was identified during the site survey. Each of the services has been reviewed and rated, based on the scale in Table 5, with the results shown in Figure 3-1.

Table 5: Building services ratings

Rating	Rating
1	Very poor
2	Requires significant improvement
3	Typical practice
4	Good but some improvement possible
5	Best practice

Figure 3-1: Current performance of the building

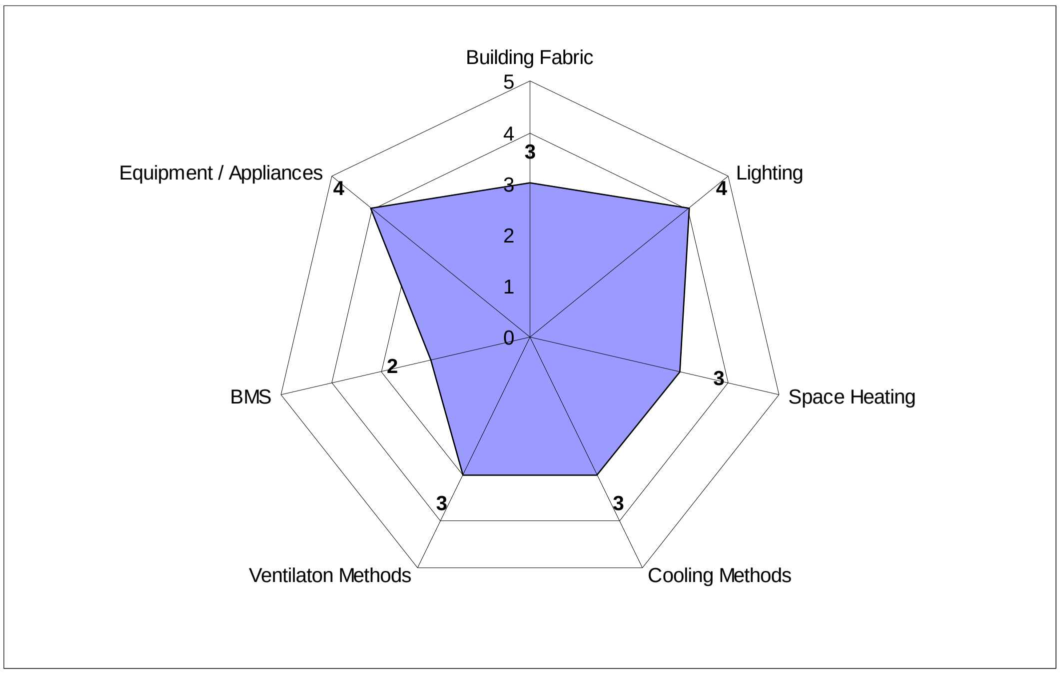


Figure 3-1 indicates that key area for improvement is optimising the building management system (BMS), but that all areas have opportunities for savings.

Recommendations for all of the areas indicated will be provided in detail in Section 4.0.

3.2 Carbon Management Rating

The Carbon Management matrix can be used to review the status of energy management, taking policy, organisation, training, performance measurement, communication and investment into account.

A matrix has been produced for UCL as a whole and can be viewed on the University's website[2]. The matrix shown in Figure 3-2 represents energy management on a building scale in the Pearson building only, rather than on a site-wide basis.

The coloured cells indicate where it is considered that the Pearson building currently stands. No rating has been selected for the 'Investment' stream, as it is understood that investment in energy projects comes centrally from the EFD rather than from internal Pearson Building funding.

Figure 3-2: Carbon Management in the Pearson building

Level	Policy*	Organising	Training	Performance Measurement	Communicating	Investment
5	Energy policy, Action Plan and regular review have active commitment of top management	Fully integrated into management structure with clear accountability for energy consumption	Appropriate and comprehensive staff training tailored to identified needs, with evaluation	Comprehensive performance measurement against targets with effective management reporting	Extensive communication of energy issues within and outside of organisation	Resources routinely committed to energy efficiency in support of business objectives
4	Formal policy but no active commitment from top management	Clear line management accountability for consumption and responsibility for improvement	Energy training targeted at major users following training needs analysis	Weekly performance measurement for each process, unit, or building	Regular staff briefings, performance reporting and energy promotion	Same appraisal criteria used as for other cost reduction projects
3	Un-adopted Policy	Some delegation of responsibility but line management and authority unclear	Ad-Hoc internal training for selected people as required	Monthly monitoring by fuel type	Some use of company communication mechanisms to promote energy efficiency	Low or medium cost measures considered if short payback period
2	An unwritten set of guidelines	Informal, mostly focused on energy supply	Technical staff occasionally attend specialist courses	Invoice checking only	Ad-Hoc informal contacts used to promote energy efficiency	Only low or no cost measures taken
1	No explicit energy Policy	No delegation of responsibility for managing energy	No energy related staff training provided	No measurement of energy costs or consumptions	No communication or promotion of energy issues	No investment in improving energy efficiency

The table above outlines carbon management for the Pearson building, rather than carbon management within the departments that occupy the building.

Further explanation will be provided in the following sections, with management recommendations that would improve the rating indicated in Section 3.6.

Key areas of note are:

- There is good departmental control and administration; however the occupying Geography department does not have responsibility for centrally booked rooms.

- Generally staff within the Pearson building were observed to be well schooled in management of lighting. Unusually there were no offices that were observed to

[2] http://www.ucl.ac.uk/youhavethepower/carbon-management/UCLSIP.pdf

be lit while unoccupied during the survey. This represents good practice by the building occupiers.

- However, all classrooms and lecture theatres that were unoccupied were found to have all lighting and equipment on.

- Some teaching rooms were also observed to have heating and cooling systems on at the same time.

- There is no facilities representative / building manager on the site; therefore there is no-one on site that the building occupants can contact should there be a 'problem' with the building, and no-one to take overall responsibility for energy use or energy-related matters on the site.

.

- The metering system currently in place does not allow the energy consumption in the Pearson building alone to be monitored.

3.3 Organisation

The Pearson building benefits from occupation by a Geography department that appears well organised, and staff who appear to appreciate energy efficiency issues. However, the department staff do not take responsibility for the building as a whole, or have authority over staff and students who use the centrally booked rooms.

We recommend that an energy team be formed (possibly comprising a building administrator and representatives of the departments using the building), supported by the Energy Section of the EFD, to meet regularly and review energy issues for the entire building. The Pearson building would benefit from an on-site energy manager with responsibility for the entire building.

The group might include staff that could assist with 'energy rounds' as part of their day to day duties e.g. ensuring lights are switched off at the end of the day. In particular for the lecture theatre and classroom areas.

As part of UCL's energy strategy, approximately 200 staff members volunteered to be departmental energy champions. Due to the setup of the departments, whereby a department could operate from a number of buildings, there is not necessarily an energy champion in each building; some buildings may have more than one energy champion, others none.

The Pearson building's energy team should include an energy champion, who has overall responsibility for the building (rather than departmental responsibility). Appointing an energy manager or champion to set and achieve energy and water reduction targets should enable the Pearson building to reduce its utility consumption and costs.

If the energy team has access to monthly consumption data, this will assist the team to systematically identify policies and action plans that are effective.

The team should meet with senior management regularly to review progress (at least monthly). Although this report recommends many technical energy saving opportunities, there also will be cost effective savings from awareness training for site staff and building occupants, including students. Engaging and motivating the building users is essential for changing energy consumption habits and reducing running costs.

Many of the staff who were in the building during the visit were very keen to talk about energy use in the building and also their experience of using the building in terms of comfort.

A number of building users noted that the building has suffered in the past from overheating. In particular hot air has been supplied to rooms in the summer. This results in Fan Coil Units (FCUs) being switched on for cooling. It would appear that where there was dissatisfaction in relation to building matters, the occupants were not aware of any way to feed this back to the EFD, even though an EFD help desk is in place. It would therefore be recommended that this opportunity for building users to comment on their environment be provided be promoted and that sufficient resource be provided for the EFD to respond to queries. This may result in savings through prompt investigation of any issues.

We would also recommend that consideration be given to a building small equipment log-book. A logbook would record any new equipment that comes on site; would ensure that any plug-in heaters and other inefficient appliances are known about, and allow the energy team to minimise their use as far as possible. Additionally, it would enable the internal energy team and the EFD's Energy Section to identify any causes for an increase in electricity consumption.

3.4 Training and Communication

Staff based in the building appeared to be knowledgeable about energy efficiency issues. However, a building energy team responsible for the building should identify the scope for a formal training programme for staff and building users.

A training programme should be drawn up that covers technical energy training for the building manager / administrator, as well a more general strategy to improve energy and awareness training, especially for transient building users that are leaving lights switched on in lecture theatre / classrooms. This is a key part of achieving low cost / no cost savings.

Unlike other buildings, posters encouraging energy efficiency were not noticed on display. Such campaigns can be effective, but need to be prominent and may need to be backed up by an awareness talk / training by a building manager or environmental champion. With the upcoming marketing campaign for energy efficiency that is due to take place at UCL, it is hoped that building occupant behaviour can be influenced in order to increase energy and resource efficiency.

The empowering of building occupants to take an active role in the energy saving strategy is an important part of controlling energy usage. By involving all occupants, the organisation's culture can be developed into a sustainable one. With a sustainable culture, the 30 to 40% of energy consumption that is at the control of the end user will not require expensive controls to mitigate the human factor in energy consumption.

Achievements and ongoing initiatives should be published regularly by the energy team, e.g. via notice boards, to assist in raising the profile of energy efficiency within the building. A noticeboard should ideally be placed in a highly visible area that will be seen by most staff entering the building. Some consideration should also be given to providing an incentive for building occupants to reduce the site's energy consumption.

3.5 Performance Measurement

There are two elements of performance measurement that are considered in this section: metering and billing.

3.5.1 Metering Recommendations

On the UCL estate, whilst some buildings' energy consumption is metered, for many buildings, the heat, gas or electricity may be supplied from an adjacent building and where there is a meter on site, it often supplies more than one building. It is difficult, and often impossible, to assess the energy performance of the buildings.

There is no sub-metering undertaken by the EFD Energy Section[3] to measure the energy consumption of the Pearson building. The heat is supplied via a meter that also serves the adjacent KLB and North Wing, and electricity also supplies the Wilkins building, North Wing, South Wing and 25 Gordon Street. Therefore, precise energy consumption data is not available.

Without metered data for the building, the energy inputs to the DEC have been estimated (apportioned related to building floor area). However, for more accurate DEC ratings, metered data would be required.

Furthermore, keeping track of energy consumption in the building can help to drive an energy reduction programme.

The EFD Energy Section is already operating a Monitoring System (using Systemlink software). This monitoring system should be used for bill verification and tracking site-wide energy consumption. In the case of UCL, where sub-metering for individual buildings and monthly data recording does not always take place, the software can also be used for bill apportionment; to split meter readings automatically (weighted by floor area) to provide energy consumption data for individual buildings and to divide consumption data over a number of months, where a reading relates to more than one month's consumption.

It is recommended that this monitoring system be extended to create an automated monitoring and targeting (aM&T) system and be implemented across the UCL estate. The aM&T can be used for bill verification, load shedding, plant optimisation and error reporting, resulting in a system that allows continuous optimisation and verification of energy use onsite. The functionality of the system is dependent on the level of metering.

The Pearson building contains some key plant. There are eight 19kW chillers and three Air Handling Units (AHUs). We would recommend that consideration is given to metering the on-site plant, as well as operational areas of the building (one meter per

[3] It has recently been discovered that there is some sub-metering of buildings undertaken by Electrical Services. At present, however, it is not clear which buildings are metered or which buildings the existing meters refer to. This data is not provided to the EFD Energy Section.

floor). This will identify energy use accurately, and allow benchmarking and control to optimise energy use.

Regular review (e.g. monthly) of the metered data would enable the Pearson energy team and the EFD Energy Section to identify when there is unusual energy consumption and to track the overall trend of energy use (year on year / seasonal averages etc.). The reviews would support in the setting of energy reduction targets and tracking the success of the measures implemented.

3.5.2 Efficiency Measures Identified

aM&T system				
Annual savings			Cost £15,500	Payback 4.9 Years
Energy 46,033 kWh	Cost £3,136	CO_2 11,543 kg		
Detail:	There is no metering of the energy consumption in the Pearson building, as the meters also serve other building and no sub-metering is in place.			
Rationale:	Precise energy consumption data for the Pearson building is not available. An aM&T system, in combination with an energy management programme, has shown to typically deliver energy savings in the region of 5-15%. The energy data would also enable a more accurate DEC rating to be established. (The indicative savings above assumes a 5% reduction in energy consumption.) It would be recommended that an aM&T system be implemented across the UCL estate.			
Risks:	None			
Next Step:	Identify appropriate locations for meter install. Obtain quote to link the meters back to main system.			

3.5.3 Billing Recommendations

The UCL EFD pays the utility bills for the whole estate; the individual buildings and departments are not required to pay a charge based on the energy and water consumed on the site.

As a result of this billing strategy, the building occupants have no impetus to consider the amount of energy used. With the current metering strategy, it is not possible in all cases to identify the energy and water consumption related to each individual building or individual departments within buildings (where more than one department occupy a building).

If a detailed aM&T system were to be implemented, it may then be possible to review the billing procedure for the estate whereby the bills could be split on a building, faculty or departmental basis. It is acknowledged that this would be a significant shift in billing procedure, which could prove to be challenging. However, a strategy where individual users take responsibility for utility consumption would be likely to result energy reduction benefits.

For high energy using buildings, it may be cost-effective to operate some loads whilst taking advantage of a lower night time tariff[4].

UCL have commissioned PCMG to audit their billing process, with a view to identify cost savings.

3.6 Summary of Recommendations

- Appoint an energy champion and form an energy team with responsibility for the entire Pearson building, to work with the Energy Section of the EFD and the wider university
- This energy team would identify and implement an energy action plan to reduce costs, and carbon emissions.
- Undertake a program of awareness training for building occupants (although building occupants already have good control over lighting, savings could be made in respect to heating / cooling)
- Install sub-metering for the Pearson building. This will allow benchmarking, and provide the ability for the energy team to manage energy on an ongoing basis.
- Extend the existing monitoring and targeting system for energy and water to create an estate-wide aM&T system and use this as a foundation for a costs and energy management program
- Review the current billing strategy at UCL.

[4] Only available to Grid-connected buildings, as there is a single 24h tariff for electricity generated by the CHP unit.

4.0 SURVEY RECOMMENDATIONS

This section outlines the findings of the site survey of the Pearson building.

A number of relatively low-cost energy saving measures have been identified, which could be implemented to reduce energy and water consumption at the Pearson building. These include opportunities in the areas of:

- Lighting
- Pumps
- Insulation
- Cooling
- Building Management System
- Small power / equipment
- Water saving

The tables throughout Section 4.0 illustrate the energy and water saving measures that could be implemented on the site to bring about cost savings.

The potential for incorporating low and zero carbon technologies is considered in Section 5.0.

A summary table, in the form of an Action Plan, is provided in Section 6.0.

4.1 Building Fabric

The building is constructed from stone. It would appear that the walls have a solid construction; cavity wall insulation would not be possible in this case.

Windows on the Gower Street side of the building have been fitted with secondary glazing. Windows on the Quad side are single-glazed.

4.1.1 Efficiency Measures Identified

Secondary glazing on all remaining windows				
Annual savings			Cost*	Payback*
Energy 20,160 kWh	Cost £700	CO_2 2,897 kg	£11,200	16 Years
Detail:	Fit secondary glazing to remaining single glazed windows.			
Rationale:	Where windows on the Pearson building are not secondary glazed, a significant proportion of the heat in the building will be lost through this area of the building fabric. Applying secondary glazing will improve the thermal properties of the window and therefore decrease the heat losses. Secondary glazing is a cost-effective way to improve windows' thermal properties. It may also reduce drafts, which can give the impression of under-heating to building occupants. This will also have additional benefits of reducing noise. The energy savings related to this measure are difficult to calculate without a more detailed study.			
Risks:	The application of secondary glazing should not prevent the windows from being opened for natural ventilation.			
Next Step:	Obtain a quote for secondary glazing.			

* Estimated install costs are anticipated to be between £60 and £100 / m^2 and are based on $140m^2$ glazed area. This would require confirmation.

4.2 Lighting

Improving the efficiency of the lamps used and installing appropriate lighting controls in some areas of the Pearson building will reduce electricity consumption.

A number of types of low energy light fittings were installed during the refurbishment of the Pearson building. The majority of the lamps in the building are T5 fluorescent tubes.

The stairwells in the Pearson building do not have natural light, and therefore require lighting while occupied for Health & Safety reasons. All floors of lighting are on one circuit. At present lights remain on all day during operational hours; however during the site survey the stairs were mainly unoccupied. Passive infra-red sensors (PIRs) could therefore be installed in staircases to reduce lamp operation and energy use. PIRs are already installed in toilet areas.

Classroom / Lecture theatre areas have trialled PIRs, but were unsuccessful as they lacked sensitivity. However, the lecture theatre G22 in particular uses a significant amount of lighting, and would benefit from a timer device to ensure that lights are switched off after use. The lecture theatre was observed unoccupied with lighting on during the survey.

A few T8 and high wattage Halogen lamps were noted through the building. It is possible to replace these lamps with lower Watt equivalents.

Where lamp upgrades are implemented that do not require new fittings, it is important to make sure that procurement policy reflects the change to the use of energy efficient lamps.

4.2.1 Efficiency Measures Identified

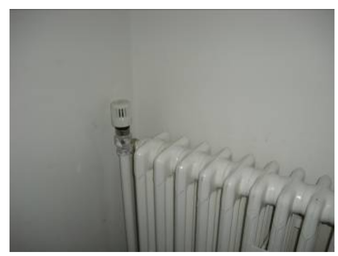
Replace 50W halogens with 30W lamps				
Annual savings			Cost £298	Payback 0.8 Years
Energy 1,800 kWh	Cost £380	CO_2 618 kg		
Detail:	Replace the existing halogen spotlights with lower wattage lamps.			
Rationale:	Lamp technology continues to evolve and Halogen lamps in the building may be replaced with newer equivalents that use fewer Watts.			
Risks:	None.			
Next Step:	Replace all lamps as part of a bulk lamp replacement.			

PIRs in stairwells				
Annual savings			Cost £200	Payback 0.8 Years
Energy 1,845 kWh	Cost £238	CO_2 634 kg		
Detail:	PIRs should be installed in each of the stairwells areas to ensure that lights are only operated when the stairwells areas are in use.			
Rationale:	It was observed during the site visit that lights were left on in the stairwells. A PIR sensor in each area would ensure that lights were only on for a defined period after movement is detected in the area.			
Risks:	The location of the PIRs and the timing of the lamp operation would have to be carefully considered to ensure that lights go on in time, and do not go off while there is someone in the staircase.			
Next Step:	Obtain a quote for PIR installation.			

Timer in the lecture theatre				
Annual savings			Cost £240	Payback 1.2 Years
Energy 1,620 kWh	Cost £201	CO_2 200 kg		
Detail:	Install a timer device to ensure that lights go off after the lecture theatre is unoccupied.			
Rationale:	Currently, building occupiers have no responsibility for these rooms. The room contains significant lighting, and it was observed to be lit while unoccupied.			
Risks:	The timer settings will need consideration to ensure that the product meets user requirements			
Next Step:	Consider user requirements, decide specification and obtain quote.			

Replace remaining T8 lamps with T5				
Annual savings			Cost £440	Payback 8.0 Years
Energy 378 kWh	Cost £55	CO_2 130 kg		
Detail:	Replace the existing T8 lamps and ballasts with lower wattage lamps and adapt fittings to fit T5 in T8 fitting.			
Rationale:	The 1200mm T8 lamps in the basement areas are rated at 36W. These can be replaced with 28W T5 lamps. The ballasts currently fitted may not accept the lower wattage lamps and so the ballasts may also be replaced.			
Risks:	Having to replace both the lamps and the ballasts may result in the payback being uneconomical; the solution above allows for a change to the fitting to accommodate a T5 lamp.			
Next Step:	Review requirements. If changing lamps is viable, replace all lamps as part of a bulk lamp replacement.			

4.3 Space Heating



Heat is supplied via a meter in the Katherine Lonsdale building. The heat in the building is distributed via radiators. The radiators have thermostatic radiator valves (TRVs).

Some of the building occupants complained of overheating in the offices. There may be potential to optimise the BMS and fan coil units (please see 4.4 and 4.7 for details).

Most pumps in the building have Variable Speed Drives (VSD) attached. There may be savings to be made by incorporating similar devices on two 11kW pumps that did not have VSDs.

It is also worth noting that there are several places where insulation for heating and DHW pipes has been damaged, or removed for maintenance and not replaced. It is recommended that where this is the case, insulation is replaced or repaired, although it is difficult to quantify the savings that will be generated.

Removable insulation jackets would be ideal for valves and flanges to allow access for maintenance.

4.3.1 Efficiency Measures Identified

Insulate the exposed heating pipes				
Annual savings			Cost £2,000	Payback n/a
Energy Unknown	Cost Unknown	CO_2 Unknown		
Detail:	There are some areas where pipes and valves are exposed. Insulating the pipes would reduce uncontrolled heat losses.			
Rationale:	The uninsulated pipes essentially act as 'mini radiators'; however, the heat losses cannot be controlled, for example by a TRV. Heat losses are difficult to quantify since there are many parts of the system with insulation that is partially damaged. However, insulating the pipes would prevent the heat from being distributed where it is not required thus reducing potential overheating in some areas. Installing removable insulation would allow future access for maintenance.			
Risks:	None			
Next Step:	Obtain a quote for pipe insulation			

Fit Variable Speed Drive to pumps				
Annual savings			Cost £3,601	Payback 1.5 Years
Energy 24,090 kWh	Cost £2,339	CO_2 8,277 kg		
Detail:	Connect the heating pumps to a VSD to allow the pumps to operate at a lower capacity when the demand is lower.			
Rationale:	The pumps currently operate at full rated capacity irrespective of the heating requirements in the building. Fitting a VSD to the VT circuit pumps would reduce energy consumption, as the pumps would require less energy when the demand for heating is lower. The heating demand could be linked to the pressure of the VT circuit, which would change as the TRVs adjust, or to indoor air temperature.			
Risks:	None.			
Next Step:	Obtain quite for supply and installation of inverters.			

4.4 Cooling Methods

Fan coil units (FCUs) for cooling are widely utilised in the Pearson building. FCUs are connected to the BMS, however it was found that FCU zones 1 and 2 were set to manual rather than BMS control.

4.4.1 Efficiency Measures Identified

Change Z1 & Z2 FCU settings to auto				
Annual savings			Cost £0*	Payback 0 Years*
Energy 19,250 kWh	Cost £1,869	CO_2 6,614 kg		
Detail:	Switch Zone 1 and 2 FCUs to BMS control			
Rationale:	Ensuring Zone 1 and 2 FCUs are controlled by the BMS will ensure that they are switched off while the building is unoccupied. At the time of the survey these were switched to manual. Although the department staff are environmentally aware, and may switch FCUs on and off appropriately, some teaching areas were observed with heating and cooling operating at the same time.			
Risks:	The FCUs were switched to manual control since the BMS was not optimised. The BMS must be optimised to ensure that the building is heated and/or cooled appropriately.			
Next Step:	Optimise BMS, and change setting on FCUs zones			

* The BMS will require optimisation for this to be possible – please see 4.7 for details

4.5 Ventilation Methods

The Pearson building has three AHUs. The presence of Fume Cupboards means that air is supplied to some parts of the building 24 hours a day.

During the site survey we identified that the BMS settings for AHU 1 and AHU 2 were set to 'hand'. AHU1 and AHU2 are on 24/7, and are not on timer control by the BMS. It should be possible to introduce a night-time set back that allows the AHUs to operate 24/7, but at reduced power (by utilising pressure sensors and VSDs). The rationale and savings for this are shown in more detail below in 4.5.1.

4.5.1 Efficiency Measures Identified

Night-time setback on AHU 1 & 2				
Annual savings			Cost £640	Payback 0.8 Years
Energy 8,760 kWh	Cost £851	CO_2 3,010 kg		
Detail:	Implement night-time setbacks for AHUs, providing ventilation as required for Fume Cupboards as required.			
Rationale:	AHU 1 and 2 are just ON. There may be significant savings if pressure sensors and VSDs are operational and automatic BMS control is provided. The savings shown represent a night-time setback from 2300-0500 hours.			

Night-time setback on AHU 1 & 2	
Risks:	The BMS needs to be optimised for this to be effective. Ensuring correct operation of Fume Cupboards is a Health & Safety issue.
Next Step:	Liaise with building occupiers regarding requirements and implement.

4.6 Humidification System

There is no humidification in the Pearson building.

4.7 Building Management System

A Building Management System (BMS) is a central computerised system for managing and operating systems within a building. A BMS usually incorporates controls for heating, cooling and ventilation, but can also be extended to incorporate lighting, security, access and fire systems. To manage energy use, the BMS can monitor various parameters in the building such as temperature, humidity, energy usage and occupancy patterns.

There is a perception that the BMS for the Pearson building does not work effectively. For example the FCUs for the laboratories have been set to manual, as they can get quite cold. One past cause of this problem (now rectified) was a faulty outside sensor for the BMS which read an incorrectly high reading. An optimisation exercise (to ensure operations are closely aligned with building use) can typically realise energy savings of up to 10%.

4.7.1 Efficiency Measures Identified

Optimise BMS				
Annual savings			Cost £3,000	Payback 2.4 Years
Energy 18,413 kWh	Cost £1,255	CO_2 4,617 kg		
Detail:	Conduct optimisation of BMS settings			
Rationale:	Ensuring effective control by the BMS is critical for energy efficiency. Building needs and uses must be matched with control of systems. For example, to ensure unnecessary systems are switched off, or run on reduced power, while the building is unoccupied. An effective BMS can also ensure that systems do not operate in conflict with each other; as mentioned in Section 4.4.1 some teaching areas were observed with heating and cooling operating at the same time.			
Risks:	Change of building use after optimisation, reducing effectiveness of exercise. One solution is to keep a log of the rationale behind settings, so that settings can easily be updated if any change of use occurs.			
Next Step:	Optimise BMS, and record rationale for settings.			

The example shows a smaller 2% saving, since aM&T savings and FCU savings are counted elsewhere (outlined in 3.5.2 and 4.4).

4.8 Appliances/Office Equipment

The use of appliances and office / laboratory equipment is an often overlooked use of energy. Office equipment in particular typically has low consumption per unit, but generally there are significant and increasing numbers of units. Controlling the use of these loads can be difficult.

Liquid crystal display (LCD) computer screens are used extensively in the building. An LCD screen typically consumes half the energy of a cathode ray tube (CRT), while also emitting less heat for air conditioning to overcome. It was pleasing to see that the computers in the Pearson building had flat screens. It is recommended to have PC monitors in power save mode. Building occupiers have confirmed that this is the case.

It is important to remember that any appliance that has a light, clock or power pack is using energy even when its core operation is not in use. This includes printers and computer or mobile phone power packs. Even if a laptop has been turned off for the night, the power pack is still consuming energy. All of these appliances contribute to a site's base load, and while the loads may be small, their continuous use soon adds up.

For office areas, it is important to make sure:

- All existing equipment that has a standby mode, such as photocopiers, printers, etc., has the standby mode enabled
- New equipment purchased has both a low energy rating and standby mode (where available), and that it is enabled
- Computers remain to have power down ability enabled (Note: According to building users power down is already enabled on all departmental PCs).

4.9 Water

Water is used on the site in the laboratories, as well as for the toilets, the small kitchen areas and for cleaning.

It was not possible to see the toilet cisterns, but the installations were single-flush units. It would be assumed that the cisterns have a volume of 7.5l / flush.

The taps in the toilets and the labs are manually controlled and may benefit from replacement with low flow taps.

The water consumption in the building could be reduced through the use of low-flush toilets (or installing devices to reduce the cistern capacity of the toilets) and low-flow taps or flow restrictors.

4.9.1 Water Efficiency Measures Identified

Water displacement devices (e.g. save a flush bag)			
Annual savings		Cost £80	Payback 1.2 Year
Cost £68	Volume 50 m^3		
Detail:	There are 21 toilets in the Pearson building. The fitting of a water displacement device in the cistern would displace a volume of water, generally 1l, per flush.		
Rationale:	In single-volume flush toilets, the volume of water that is held in the cistern is often in excess of the required amount for a satisfactory flush. The water displacement device will reduce the volume of water that will be flush each use.		
Risks:	None		
Next Step:	Purchase and install water displacement devices		

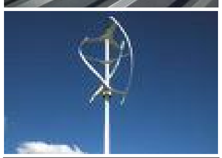
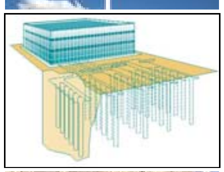
Tap flow restrictors			
Annual savings		Cost £500	Payback 1.7 Years
Cost £296	Volume 219 m^3		
Detail:	The device fitted into the tap head will reduce the volume of water that can pass through thus reducing water consumption. Calculations are based on reducing flow from 10 to 5 l/min.		
Rationale:	For hand washing, a constant flow rather than flow volume is important.		
Risks:	None.		
Next Step:	Purchase and install flow restrictors.		

5.0 OPPORTUNITIES FOR SUSTAINABLE TECHNOLOGIES

5.1 Low and Zero Carbon Technologies

Table 6 indicates the potential for the incorporation of low and zero carbon technologies on the site.

Table 6: Opportunities for the implementation of low and zero carbon technologies

Technology		Considered for the site?	Comment
Solar thermal collectors (ST) ***heat generation***		✘	• No water storage on site
Solar PV ***electricity generation***		✘	• Unshaded roof space available • Not at present a cost-effective technology
Wind turbines ***electricity generation***		✘	• The performance of small-scale turbines that are currently on the market is not proven • Structures on the roof area would result in turbulence to the air flow
Ground Source Heat Pumps (GSHP) ***heat generation***		✘	• Low-grade temperature of output water would not be compatible with the heating system for the building • No heating plant in the building
Biomass heating ***heat generation***		✘	• No heating plant in the building
Micro / Mini Combined Heat and Power (CHP) ***heat & electricity generation***		✘	• No heating plant in the building

5.1.1 Renewable Energy Opportunities Identified

There are no opportunities for the cost-effective implementation of renewable energy technologies in the Pearson building.

This conclusion should however be reviewed when any major refurbishment programme is undertaken.

5.2 Rainwater Harvesting

A rainwater harvesting system collects, filters and stores rain water, which is then used to displace mains water for uses such as toilet flushing and plant watering.

During the site visit, there was no apparent space available in the building or basement to house the collection tank. Rain water harvesting has therefore not been considered in this building. If significant refurbishment works are undertaken in future this may be a viable option.

6.0 ACTION PLAN

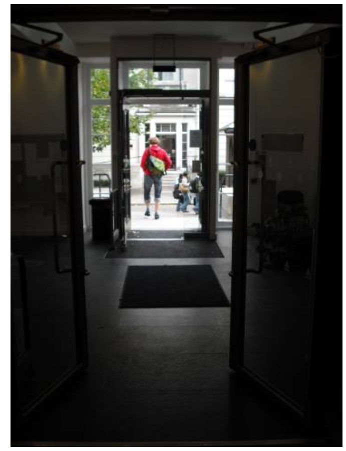
Table 7 provides a summary of measures recommended in Sections 3.0, 4.0 and 5.0. The table includes a column which should be completed by the EFD with next steps / target implementation dates in order to create an action plan for energy and water savings in the Pearson building.

Table 7: Summary of Recommended Measures

Recommendations	Estimated Annual Savings*[1] Elec. (kWh)	Gas or Heat (kWh)	Water (m^3)	Cost (£)	CO_2 (kg)	Est. cost (£)	Pay back (yrs)	Timescale for implementation
Projects with payback in under 2 years								
Change Z1, Z2 FCU settings from manual to auto*	19,250			1,869	6,614	0	0*	
Replace 50W halogens with 30W lamps	1,800			380	618	298	0.8	
PIRs on lighting in stairwells	1,845			238	634	200	0.8	
AHU1 & 2 night time set back	8,760			851	3,010	640	0.8	
Save a Flush Bag			50	68		80	1.2	
Light timer in lecture theatre	1,620			201	200	240	1.2	
Inverter Drives for 2 x 11kW pumps	24,090			2,339	8,277	3,601	1.5	
Flow Regulators			219	296		500	1.7	
Sub-total	***57,365***	***0***	***269***	***6,241***	***19,353***	***5,559***	***0.9***	
Projects with payback in 2 – 5 years								
BMS Optimisation	9,861	8,073		1,238	4,548	3,000	2.4	
Retrofit Push Tap			264	357		1,440	4.0	
Sub-total	***9,861***	***8,073***	***264***	***1,595***	***4,548***	***4,440***	***2.8***	
Energy management opportunities								
Continue with energy awareness campaign Appoint building energy champion to liaise with energy manager aM&T system	24,652	20,182		3,095	11,371	15,500	5.0	
Sub-total	***24,652***	***20,182***	***0***	***£3,095***	***11,371***	***£15,500***	***5.0***	
Total	**91,878**	**28,255**	**533**	**10,931**	**35,272**	**25,499**	**2.3**	

*[1]It should be noted that where the efficiency measures are not mutually exclusive, the overall savings may be lower.
*[2]BMS optimisation is required to change Z1, Z2 FCU settings to auto.

In addition to the measures indicated in the table, a number of further opportunities that could reduce the energy cost for the building or improve occupant comfort:



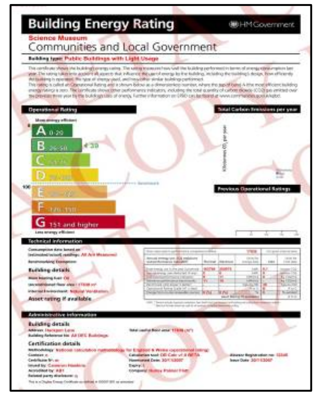
- Secondary glazing to reduce heat loss and drafts.
- Repair and install insulation, in particular on pipes in the building to improve occupant comfort.
- Consider heat loss in atrium area. Currently both sets of doors are open when people exit the building, leading to heat loss.
- Evolving light technology solutions:
    - Solutions are coming on to the market to allow lamps to be replaced with lower watt equivalents
    - Light manager software can reduce maintenance and running costs, (similar concept to BMS for lighting).

7.0 DISPLAY ENERGY CERTIFICATE ENERGY RATING ASSESSMENT

This section outlines the Display Energy Certificate (DEC) requirements for the Pearson building.

The European Energy Performance of Building Directive (EPBD): Article 7 requires each building to be in the possession of a certificate to show its energy rating.

A DEC shows an operational rating to convey the actual energy used by the building. Only public authorities or public institutions providing services traditionally associated with local or national Government and occupying a building must display a DEC. Other private occupants of the same building are not required to display a DEC.



Public authorities and institutions providing public services to a large number of people, who occupy space in a building with a total useful floor area greater than 1,000m^2, must display a valid DEC at all times and have a valid advisory report in their possession. The certificate requires updating each year, with a new advisory report required every 7 years.

A DEC assessment of the building has been carried out to provide a rating of how the Pearson building is currently performing.

7.1 Building Energy Ratings

Building Site

The total floor area of the Pearson building is 4,162 m^2. These are the parts that are conditioned and: either publicly accessible and over 1,000m^2 by area; or that are served by the same energy system as a publicly accessible area of over 1,000m^2.

Assigning a Reference Value (Benchmarking)

The benchmark used for the Pearson building is that for a University Campus, as outlined in the software. Where a building contains a number of building types, area-weighted benchmark figures are generated. The software adapts the composite benchmark based on the heating degree day data, period of energy data provided and special end uses, before comparing to actual figures. The benchmark is presented in Table 8.

Table 8: 'Typical' Benchmarks: Office

Category & Name	Energy Benchmarks Typical		CO_2 Benchmarks Typical		
	Electricity kWh/m^2	Fossil-thermal kWh/m^2	Electricity kgCO_2/m^2	Fossil-thermal kgCO_2/m^2	Total kgCO_2/m^2
University Campus	80	240	44.0	45.6	89.6

The A-G Display Rating

Dividing the actual rating by the University Campus benchmark returns an operational rating of **75**, based on **188** kWh/m^2, for a Display Energy Certificate (DEC) grade of ***'D'***. The DEC is shown in Appendix A.