

Sustainable Retrofitting of Existing Residential Buildings at Community scale in China



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Abstract

Rapid urbanisation in China is leading to significant demands for energy and resources. China's urban housing is therefore facing the following problems: on the one hand, due to the acceleration of urbanisation and improvement of living standards, there is a rising trend in new housing developments. On the other hand, many residential buildings in cities in China are below modern standards of energy performance, sustainability, or liveability, and they need to be improved.

The aim of this research is to investigate the retrofit projects in Wales, UK, to explore the retrofitting of existing residential buildings at the community scale in Beijing, China, to find out how and to what extent the retrofit technologies and processes can be transferred from the UK to China, and the most suitable, sustainable, cost-effective combination of retrofit strategies to improve energy efficiency and sustainability. This is achieved through a holistic method based on qualitative research and simulation research including a literature review, case studies, on-site surveys, interviews, and modelling for the Chinese case studies.

There are three stages in this research: first is to investigate low carbon housing retrofitting projects in Wales in the UK across environmental, economic and social aspects, to find out how and to what extent those technologies and processes can be transferred to China. Second is to investigate the retrofitting progress and development in China and explore the optimal retrofit solutions for different types of Chinese residential buildings at both building and community scale. The last stage looks at the research outcomes, addressing the multiple social and economic benefits, to provide suggestions and guidance for retrofitting residential buildings in China to create a high-quality living environment.

The UK case study reviews seven retrofit projects. The findings show that most of the large-scale retrofit projects in the UK mainly conduct elemental retrofit, which uses one or two retrofit measures with relatively low cost, and can generally reduce energy

consumptions and CO₂ emissions of 10% to 30%. Meanwhile, there are some examples of deep retrofit in the UK at small scales, but the retrofit costs tend to be relatively expensive so that large-scale deep retrofit has not been considered to be financially available. Now the UK starts to look at multiple benefits of retrofit relating to issues like fuel poverty alleviation and job creation.

From the case study in China, it is found that the fabric retrofit could reduce up to 54% of the gas consumption due to less heating demand with improved building envelop, while the electricity use can be significantly reduced through installing solar PV to the roof and the south facade above the third floor, with reductions of 82.2% to 90.9% for high-rises, and 168.8% to 179.2% for mid-rises and multi-storeys. The best retrofitting results can be achieved by applying the highest specification of the 'whole-house' approach, which combines fabric, system, and renewable retrofit measures, with annual CO₂ emissions reductions of 75.6% to 80.6% for high-rises, and 104.7% to 105.2% for multi-storey and mid-rise buildings. The retrofit costs are ranging from 597.9 CNY/m² to 1365.1 CNY/m², and the payback years are between 10.4 to 12.6 years. Moreover, older buildings have more retrofitting potentials in energy savings and CO₂ emissions reduction. In addition, there could be added benefits at the community scale, across economic and social aspects such as energy bill reduction, health improvement and job creation.

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Chapter 1 Introduction

1.1. Research Background

Today, more than 54% of the world's population lives in cities, and this percentage is likely to increase to 66% by 2050 (United Nations 2014). With a large number of the rural population moving into urban areas, these areas are under significant pressure to meet the needs of expanding the population. In the meanwhile, cities are responsible for approximately 75% of the world's total energy consumption and 80% of global greenhouse gas emissions (United Nations 2007).

Chinese cities are home to more than 50% of China's population. China is also one of the three countries experiencing the largest urban growth according to the World Urbanization Prospects by UN DESA's Population Division in 2014 (United Nations 2014). It is estimated that, if this rate maintains itself, there will be more than eight megacities, each with over 10 million people, by the year 2025 (Woetzel et al. 2009). China now has more large cities than ever before (Liu et al. 2014).

Rapid urbanisation in China is leading to significant demands for energy and resources. From 2000 to 2010, China's construction area has grown from 27.7 billion to 45.3 billion m² (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012). Currently, the energy consumption in China creates 4.6 tons of CO₂ emission per capita, accounting for 20.6% of the global total, which exceeds the global average value. For the past 20 years, the energy consumption of buildings in China has been increasing at more than 10% per year (Cai et al. 2009), and it may grow by an extra 70% from 2012 to 2050 if this trend continues (IEA & BERC 2015). In 2007, the building sectors accounted for 31% of total energy use in China. According to the current situation, the building energy consumption in cities is expected to reach above 35% of China's national energy consumption in 2020 (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012). Besides, China's building energy consumption is the second largest in the world after the United States, accounting for nearly 16% of the total energy consumption of buildings in the world in 2012 (IEA & BERC 2015).

China's urban housing is facing several problems. On the one hand, due to the acceleration of urbanisation and the improvement of living standards, there is a rising trend in new housing development. On the other hand, many residential buildings in cities in China are below modern standards of energy performance, sustainability, and liveability, and they need to be improved. At the same time, a large number of building stocks have been demolished, resulting in a waste of resources, environmental pollution and social conflict.

After the beginning of Reform and Opening Up Policy in 1978, China's economy began to grow at a rapid rate, and the speed of housing construction has also accelerated significantly. However, at that time, most of the houses were built to meet people's basic living needs, and the building standards could not keep up with the speed of construction, resulting in hidden risks to building quality. Therefore, the current retrofitting of existing housing in China is mainly focusing on building stocks completed 20 to 30 years ago. Most of them use a basic elemental retrofit strategy, such as improving wall insulation or changing single glazing to double. 90% of these projects are led by the government, and the implementation process has not yet been done in a clear, systematic and unified way.

To solve the current retrofit problems in China and achieve the new national carbon targets made in 2012, it is significant to consider many aspects of China's current retrofit scheme and explore more suitable, sustainable, and effective ways to implement the retrofit process.

In the UK, the retrofitting of urban housing has been practised for some time, and the retrofit scales up in recent years. Also, the 'whole-house approach' which includes a broader range of low carbon measures, has gradually been introduced in recent years. Thus, although there are many differences in context, scale, housing systems, and regulatory patterns, between the two countries, transferring the retrofit process and retrofit technology from the UK to China will provide valuable suggestions for implementation approaches and improvement of the existing housing retrofit process.

1.2. Research Aims, Questions and Objectives

1.2.1. Research Aims

The aim of this research is to investigate the retrofit projects in Wales, UK to explore the retrofitting of existing residential buildings at the community scale in Beijing, China to find out how and to what extent the retrofit technologies and processes can be transferred from the UK to China, and the most suitable, sustainable, cost-effective combination of retrofit strategies to improve energy efficiency and sustainability. This will be divided into three parts. The first part will investigate the current low carbon housing retrofit projects in Wales, the UK in environmental, social and economic aspects to find out how and to what extent these technologies and processes can be transferred to China. The second part will explore the optimal retrofit solutions for different types of China's residential buildings sustainably. This will improve the existing cities. The final part will discuss the social and economic aspects of the research outcomes to provide suggestions and guidance for retrofitting residential buildings on the community scale in China to create a high-quality living environment.

1.2.2. Research Questions

To address the research aim, five research questions are posed:

1. What is 'Sustainable retrofit'? What are the reasons and drivers of sustainable retrofit?
2. How is the sustainable retrofit developed in the UK? What are the processes, implement methods, technologies, financial schemes, and multiple benefits of low carbon retrofit in the UK in practice?
3. What are the problems and challenges of current housing retrofit in China? To what extent can the UK's experiences be transferred to China?
4. What strategies can be gathered from this research to improve the existing housings and communities in China?

5.How can the research outcomes be applied in practice to create a high quality living environment?

1.2.3.Research Objectives

In order to achieve the research aim and answer each of the research questions, the objectives to be achieved in this research are outlined below:

- 1.To identify the definition, development, reason and importance of sustainable retrofit;
- 2.To explore the UK's retrofit methods, implement processes, technologies, financial schemes, and multiple benefits through the examination of practical projects;
- 3.To discover the problems of the current retrofitting of existing residential buildings in China to find out the gap between the UK and China;
- 4.To identify the most suitable, sustainable, cost-effective retrofit approaches in transferring the technologies and processes from the UK to China to improve existing housings and communities;
- 5.To discuss research outcomes with more social, economic aspects and multiple benefits to provide suggestions and guidance for retrofitting residential buildings in China to create a high quality living environment.

1.3.Research Scope and Focus

This research focuses on the retrofitting of existing residential buildings in Beijing on a community scale. The main research object is a typical 'gated community' which consists of many multi-storey flats and a small number of high-rise flats. These flats were commonly built from the 1980s to 2000s in China. Most of them are below modern standards in both sustainability and liveability, and they need to be improved. Four case studies have been chosen to examine the different retrofit solution combinations in detail. As retrofitting has been practised in the UK for some time,

seven cases in Wales have been surveyed to study the experience relating to policy, technologies, processes, implementation, management, financial schemes and multiple benefits. Besides this, broader aspects have been covered, including fuel poverty, health improvement, potential saving, and job creation etc. to generate a holistic sustainable retrofit approach and to identify optimal solutions for improving existing residential buildings and communities in China.

1.4.Thesis Structure

This thesis consists of eight chapters.

Chapter 1 introduces the research background, including the current situation and problems of urban housing in China, as well as the research aim, questions, objectives, and scope. It then outlines the structure and framework of the research.

Chapter 2 is the literature review. It begins with an overview of essential understandings of the ‘retrofit’, and analyses the drivers and reasons for retrofitting. It then discusses under what conditions it is better to retrofit an existing building or to demolish and build a new one. Following this, the key elements influencing sustainable retrofit are presented. Delineation is then made of the concept of “sustainability”, which contains the development of sustainability, the definition across social, environmental and economic aspects, and sustainability at the community and urban levels. This is joined by a discussion of the development of sustainable retrofitting in China including the background, built environment, current situation, and challenges of existing residential building retrofit in China. Next, a comparison of five aspects sustainable retrofitting in the UK and China is given, including energy use and target, retrofit policy, retrofit measures, implementation process, and financing. Finally, a description of fuel poverty, thermal comfort, and human health is presented.

Chapter 3 provides an overview of the research methods employed, the analytical framework developed, and case study selection in this research. It begins with a review of several traditional research methods for architecture research, then is

followed by descriptions of the research methods chosen in this research. The next section introduces the building energy modelling development and the modelling software adopted in this research. Following this, the research framework and the simulation process flowchart are presented. Lastly, the method's limitations are discussed.

Chapter 4 presents the case studies of seven housing retrofitting projects in Wales. Each project begins with a description of the basic information, followed by a summary of the work outcomes. Then, the main points of the project are extracted. The UK's low carbon housing retrofit processes, implementation methods, technologies, financial schemes and multiple benefits are investigated. After this, the primary outcomes and lessons learned are discussed.

Chapter 5 provides the interviews conducted in three cities in northern China in June 2015 and December 2017 in Xi'an. It begins with the introduction of the interview procedure and the detail information of the interviewees, and continues by listing the initial questions for the interviewees. Then, multiple issues extracted from the interview results are interpreted and discussed. After this, the outcome of the interviews is summarised.

Chapter 6 focuses on the case studies in Beijing, China. It begins with an introduction of the climate in Beijing. Following this, the interior conditions and input parameters for simulation are presented. Next, the four cases selected in this research are introduced. This is joined by the detailed introduction of the location, architectural layout, construction data, and service system of each case. Then, the retrofit packages of different measures are selected for simulation. After that, the simulation results for before and after retrofitting for each case are analysed and compared. Finally, the four cases are compared in terms of energy demand, supply, CO₂ emissions, cost and savings.

Chapter 7 contains the energy simulation of the four Chinese cases in community scale and broader related issues. It starts with the simulation of four communities before and after the retrofit. Then, a comparison are made and the effect of different retrofit measure combinations is evaluated. After this, comparisons are made between the

four communities and two different scales. Lastly, the social, environmental and economic aspects of improving existing communities in China through sustainable housing retrofit are analysed and discussed.

Finally, **Chapter 8** presents the main conclusions of this research. Then, the implications of research outcomes, the limitations of this research, and recommendations for future research are discussed. This chapter closes with a short conclusion to the thesis.

1.5. Research Method and Framework

1.5.1. Research Method

This research adopts a holistic method based on qualitative research and simulation research, including a literature review, site surveys, interviews, case studies and modelling. Then, an inductive approach is applied to analyse and summarise the research outcome.

1.5.2. Research Framework

Figure 1.1 shows the framework of this research. Firstly, a literature review is conducted relating to six aspects of sustainability and retrofitting in Chapter 2. This is followed by the research method in Chapter 3. Then case studies of seven Welsh retrofitting projects are presented in Chapter 4. Chapter 5 presents the interviews in China. Chapter 6 and Chapter 7 focus on the simulation of retrofitting existing residential buildings in China at both the building and community scales. The last chapter concludes with the research outcomes.

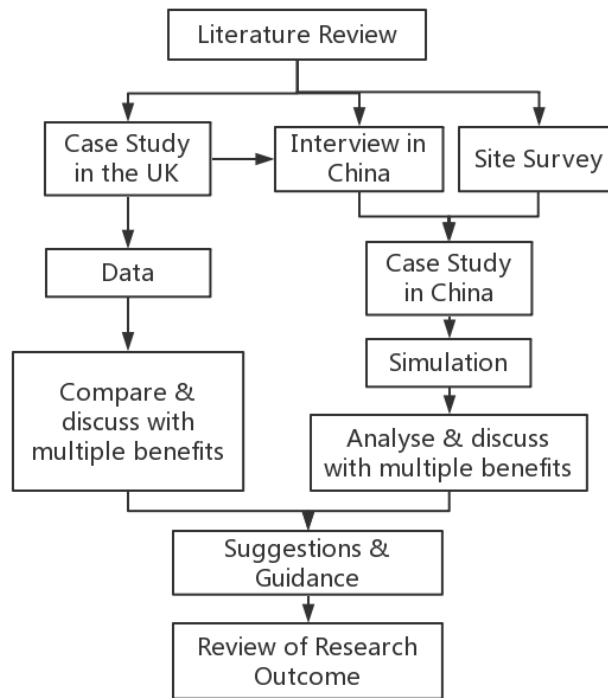


Figure 1.1 Research Framework

1.6. Summary

This chapter has introduced the basic information of this research including the research background, aims, questions, objectives, and scope. It then outlined the thesis structure, and finally the method and framework of this research have been presented.

Chapter 2 Literature Review

2.1. Introduction

One of the main components of achieving a more sustainable built environment is to improve the performance of the existing building stock by retrofitting to increase the energy efficiency and improve quality of life (Low Carbon Innovation Coordination Group 2012). However, most of the current retrofitting of residential buildings in China has failed to consider the sustainability issues and living quality of residents, which has led to multiple social and environmental problems, such as breaking up existing neighbourhood relationships, the loss of heritage and construction pollution (Plimmer al. 2008). Meanwhile, environmental problems are severe. According to the Asian Development Bank's report, less than 1% of China's 500 major cities meet the World Health Organisation's recommended air quality standards and seven of these cities rank among the ten most polluted cities in the world (Zhang & Crooks 2012). In recent years, environmental pollution in China, especially in the heating season, has driven both government and stakeholders to focus more on finding ways to reduce energy consumption and CO₂ emissions. Sustainable retrofitting should consider reducing energy demands, and consequently, reducing energy consumption and greenhouse gas emissions, as well as making the homes more pleasant to live.

This chapter reviews the existing literature related to the area of sustainability, retrofitting development and related issues including the policies, retrofitting technologies, implementation process, financial schemes, fuel poverty and multiple benefits of sustainable retrofitting in the UK and in China in order to achieve the research objective of 'identifying the definition, development, reason and importance of sustainable retrofit'. It begins with an overview of essential understandings of the 'Retrofit', then discusses the concept and development of 'Sustainability'. This is followed by presenting the development of sustainable retrofitting of existing residential buildings in China. After this, a comparison is made of five aspects of sustainable retrofit in the UK and China, including energy use and target, retrofit policy,

retrofit measures, implementation process, and financing. Finally, a description of fuel poverty, thermal comfort, and human health is provided.

2.2. Conceptualising the 'Retrofit'

2.2.1. Definition of 'Retrofit'

The original definition of the term 'retrofit' is 'to fit with a component or accessory not fitted during manufacture' (Soanes & Stevenson 2004). When it comes to architecture, generally, the term 'retrofit' is 'renovation that stretches beyond the norm to address sustainability matters' (Bernier et al. 2010). In terms of housing, 'retrofit' and other terms such as refurbishment, repair, renovation and restoration, etc. are all used to describe the building work to extend the useful lifetime of existing buildings (Baeli 2013).

Regarding 'Sustainable retrofit', Low Carbon Retrofit Toolkit (Rhoads 2010) defined it as 'incremental improvements to the building fabric and systems with the primary intention of improving energy efficiency and reducing carbon emissions'. It includes 'common measures such as top-up loft and cavity wall insulation, or more advanced measures such as improved air tightness combined with mechanical ventilation with heat recovery' (Bernier et al. 2010). Besides, retrofit should not only consider saving energy and reducing CO₂ emissions, but also improving the health and quality of life of residents (Jones et al. 2017).

Therefore, sustainable retrofit can be defined as to improve the building fabric and system to extend the useful lifetime of existing buildings in order to improve energy efficiency, reduce carbon emissions, and improve the residents' quality of life.

Retrofit can be classified into 'shallow retrofit' (or 'elemental retrofit') and 'deep retrofit'. In recent years, a concept of 'whole-house retrofit' has come out in many journal articles, which is a type of deep retrofit. As Baeli points out (Baeli 2013), the phrase 'deep retrofit' often indicates that 'the combination of elements introduced will have a strong impact on the existing building's level of CO₂ emissions', while

'whole-house retrofit' is 'typically aiming for an 80% reduction in line with the Climate Change Act target figure'. 'Shallow retrofit' generally uses relatively limited or fundamental techniques, usually costing much less than deep retrofit and usually has a reduction of buildings' energy consumptions and CO₂ emissions in the range of 10–30% (Jones, Lannon & Patterson 2013).

2.2.2. Drivers and Reasons for Retrofit

In most areas in the UK, the expansion of the existing building stocks is taking place, with about 1% of new buildings being added to the total stock annually (Department of Energy and Climate Change 2015), which means up to 75% of the current building stocks will still exist in 2050 (Ravetz 2008). There are about 27 million existing dwellings in the UK, and only 120,000 new homes are built every year (Baeli 2013). Therefore, to achieve the target reduction of CO₂ emissions and energy consumptions in the built environment, attention should be given to the improvement of existing buildings (Clapham et al. 2012).

According to the National Bureau of Statistics in China (National Bureau of Statistics of the People's Republic of China 2011), the total floor area of the existing building stock had already exceeded 44 billion m² by 2011. More than 90% are high energy consumption buildings, of which residential buildings account for more than two-thirds of the total energy consumption. It is clear that many existing building stocks are in need of improvement to enhance their energy efficiency. Although some newly built low carbon city projects in China could improve the energy efficiency, the large number of existing buildings still accounts the significant part of CO₂ emissions, which is three times that in developed countries.

In addition, the air pollution in recent years in China is severe, especially in northern China at heating seasons, which poses a threat to Chinese public health. According to a report from China News, only 84 out of 338 cities met the national standard for air quality in China (Ecns.cn 2017). The Global Burden of Disease Study showed that there were approximately 1.2 million Chinese people died prematurely and 25 million

disability-adjusted life-years (DALY) were lost in 2010 as a result of air pollution (Yang et al. 2013).

One of the main objectives in achieving a more sustainable built environment is to retrofit existing building stock to improve energy efficiency and quality of life. As Phan pointed out, 'retrofitting offers many opportunities for the substantial improvement of the energy performance of residential buildings and the provision of sustainable alternatives to conventional heating and cooling'. (Schiano-Phan 2010)

However, most of the current retrofit projects of residential buildings in China fail to take into account of sustainability issues as well as the life quality of residents, which has led to multiple social and environmental problems, such as breaking up existing neighbourhood relationships, the loss of heritage and construction pollution (Plimmer al. 2008). A sustainable retrofitting must consider these aspects as well as reduce energy demand, and subsequently reduce energy consumption and greenhouse gas emissions. This is being considered as one of the leading approaches to achieve sustainability in the built environment at relatively lower costs and higher uptake rates.

2.2.3. What Kind of Buildings Should be Retrofitted?

One critical issue in the decision-making process is deciding what kinds of buildings should be retrofitted. It is essential to decide whether to retrofit an existing building or to build a new one, either by demolishing the existing one or choosing an empty place elsewhere. According to Appleby (Appleby 2013), there are many criteria when making this decision, such as location, plot size, structural conditions, budget, whether the buildings are residential or not, whether they are privately owned or public, etc.

As Appleby (2013) indicated, the primary challenge affecting this decision of whether to retrofit or build new is that most older buildings are not designed to be sustainable. The most sustainable part of an existing building is usually considered to be the components that can be re-used, including the site itself. He claims that the higher the volume of building materials that can be reserved, the lower the influence of the new materials need for retrofit. A key difference between retrofit and re-build is how much

solid waste material will be generated. Although much of the waste can be crushed and recycled, the impacts of environmental pollution, including noise and air pollution, are significant.

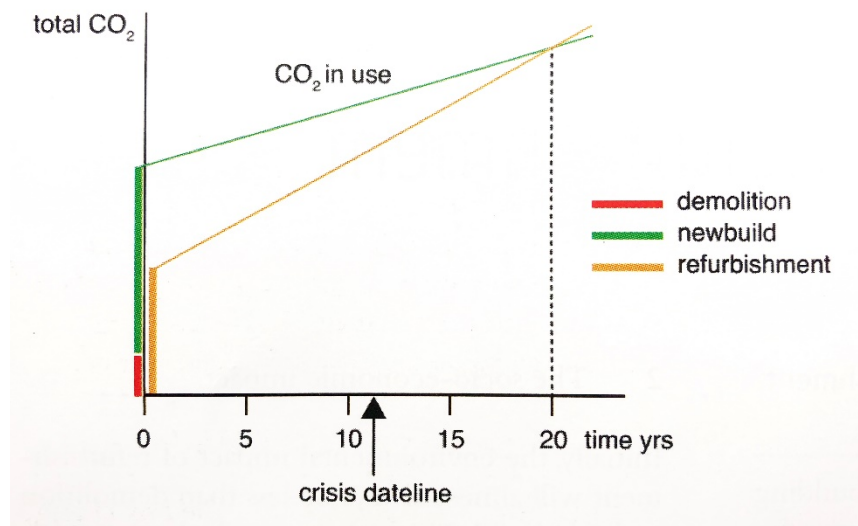


Figure 2.1 CO₂ emissions for new build and retrofit as a function of time (Baker 2009)

It is generally believed that the impact of the new building on the environment is less than that of the retrofitted one. Nevertheless, as shown in Figure 2.1, the CO₂ emissions for demolition and new build is only less than that of the retrofit after the break-even period, and this period can be extended through enhanced retrofit performance. If this critical period exceeds the CO₂ emission reduction target time, then the retrofit is obviously a better solution (Baker 2009).

Demolishing existing buildings which have not exceeded their use lifetime is a waste of resources and also increases pollution. However, retrofitting seems to be a more risky and expensive strategy than building new-build, particularly where the existing building or community is in poor condition (Plimmer al. 2008). If the building is not regularly maintained, so that the cost of the retrofit is close to the cost of demolishing and building new build, then it is necessary to weigh the advantages and disadvantages at this point. On the contrary, there are some trends of retrofitting the buildings built within a short period, which is also a resource waste.

A building should be treated as a complicated system. It may go through many times of the maintenance cycle. The components of the building envelope can usually be used for 30 to 40 years, so can the fixed parts, such as heat sinks and pipes in HVAC systems. The replacement cycle of moving parts, such as valves and motors, etc. in the HVAC system is about 20 years. If the necessary maintenance is done on a regular basis, then the life of the building in principle is permanent (Kerschberger 2010).

Consequently, it is essential to find out to what extent a building or a community should be retrofitted or rebuilt, and how to balance and combine sustainable urban development approaches to improve the existing communities and reduce energy consumption.

2.2.4.Key Elements Influencing Sustainable Retrofit

Retrofit projects can be achieved under certain situations, especially where the original buildings are in reasonable condition and have attractive features which are worthy of preservation (Plimmer al. 2008). Retrofitting can also be cost-effective where the buildings are relatively simple to be quickly converted, or on major projects that attract tax relief.

Ma, Z et al. (Ma et al. 2012) point out that the success of a building or community retrofitting depends on many issues. As shown in Figure 2.2, the essential elements that influence retrofitting include policies and regulations, client resources and expectations, retrofit technologies, building specific information, human factors and other uncertainty factors. These issues will be discussed respectively in detail later in this chapter.

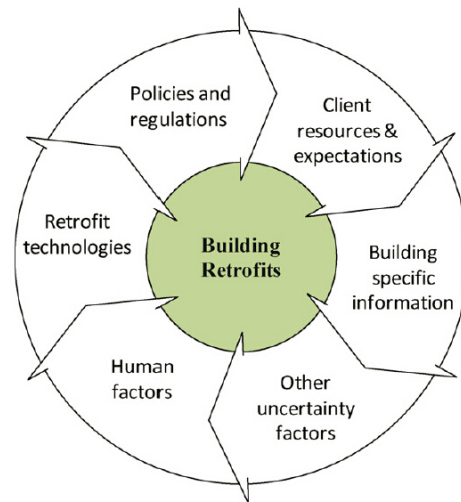


Figure 2.2 Key elements influencing building retrofits (Ma et al. 2012)

2.3.Sustainable Development and the Concept of ‘Sustainability’.

After understanding the issue of retrofitting, it is necessary to clarify the concept of ‘sustainability’ and its development history to understand better what ‘sustainable retrofit’ is.

2.3.1.Sustainable Development

Although the term ‘sustainable development’ was firstly used in the book named *Limits to Growth* in 1972, concerns about the rapid unsustainable development of industrial cities have existed since the early nineteenth century. In the middle and late nineteenth century, with the growth of factories and new technologies such as cars, electrical lights, railroads, modern plumbing, etc. in cities, increasing numbers of people moved from countryside to city, resulting in many problems such as pollution, health, sanitation, residential overcrowding, and insufficient infrastructure. Thus, the issue of how to keep the balance between humans and nature has begun to attract attention among researchers and observers. Since the late nineteenth and early twentieth centuries, the social reformers from Britain, continental Europe and the US started to draw attention to the deterioration of the urban environment and the demand for alternative living surroundings. So it can be seen that the central theme

of sustainability in the nineteenth century was focused on nature and cities (Wheeler & Beatley 2014).

As discussed in Wheeler and Beatley's book (2014), for more than a century, different individuals and organisations have a very different definition of 'sustainability' according to their different backgrounds, areas, roles, time scales and so on. Some stand for the 'eco-centric' view, by which nature and other species also have the right to grow, so humans should reduce their use of nature and limit the growth of cities to protect our shared living environment. Some may think of nature as a resource, which we should allocate and manage carefully for our future generations. Some from developing countries might focus more on human dimensions such as the inequality of resource allocation and global poverty, while some from developed countries may see the environmental aspect as the most crucial part. Others may prioritise the economic dimensions.

The most widely cited definition of sustainable development is 'development that meets the needs of present generations without compromising the ability of future generations to meet their needs and aspirations' (United Nations 2014). Despite the fact that this concept is considered vague to some extent and does not distinguish different aspects of sustainability, the critical concept of the future has become one of the leading aspects of the sustainable development literature.

2.3.2. Conceptualise 'Sustainability' in its Social, Environmental and Economic Aspects

2.3.2.1. Social Sustainability

Social sustainability is defined as a 'life-enhancing condition within communities, and a process within communities that can achieve that condition' (McKenzie 2004). It covers a range of issues. Firstly, equity is the main content, including the equity of access to basic services such as health, security, housing, education, and transport and the equity between generations, which means that the current generation will not harm the interests of later generations. Secondly, cultural diversity is an essential

aspect. The diversity and positive aspects of different cultures should be valued and well protected and the cultural integration should be supported and encouraged to meet people's desires. Thirdly, democracy and governance should be considered. Furthermore, the community also plays a significant role. It has a responsibility to maintain the system of transferring the social sustainability consciousness from one generation to the next. It should also maintain a good quality of life for all individuals and groups within it. Therefore, it is important to establish a mechanism for the community to determine its common strengths and needs. Also, social sustainability contains religion, shared values, relationships between families and friends, humans and nature. In short, social sustainability is often considered to be a 'moral capital', which requires maintenance by equality, cultural comprehensiveness, political participation, and community interaction (McKenzie 2004).

2.3.2.2.Environmental Sustainability

Regarding environmental sustainability, it is defined by Goodland (1995) as the 'maintenance of natural capital both as a provider of sources and as a sink for wastes'. This definition includes two fundamental aspects. On the one hand, waste emissions should be maintained within the absorptive capacity of the natural system without damaging its ability of absorption in the future. On the other hand, the input rates of renewable resources should be held below the regeneration rates of the environment and non-renewables should be reduced at the same rate as the generation of renewables. According to this definition, human activities and the economic subsystem should be kept at a level within the capacity of the environment to sustain, and new technologies for sustainable development and the exploitation of renewable resources should focus more on efficiency increasing rather than quantitative growth. Moreover, environmental sustainability also focuses on protecting the environment by reducing energy consumption, pollution and conserving biological diversity as well as efficiently using natural resources, etc., thereby supporting the long-term ecological balance. Therefore, humans should learn to live within the scope of the environment, using natural resources without exceeding their recovery capacity.

Environmental sustainability aims to improve human wellbeing by protecting the nature of human requirements and controlling waste emissions to stop harm to humans (Goodland 1995).

2.3.2.3. Economic Sustainability

Since the Middle Ages, the 'maintenance of capital' has been introduced by accountants to ensure businessmen to understand the value of their sales and how much they can spend without harming their capacity for future business. As indicated by Goodland (1995), over the past 20 years, economic sustainability has been more concerned with natural capital, because the human economy has grown at a scale that the ecosystem may not be able to support permanently, both as a provider of resources and as a sink for wastes. Thus, economic sustainability should focus more on maintaining steady economic growth without exceeding the capacity of the natural environment.

To sum up, sustainability is a changeable and complicated concept for which there is so far no commonly agreed definition. It is a precise concept that needs to be defined according to the specific context. However, no matter what definition of sustainability is applied, the consensus is that society, the environment and the economy are the three pillars of sustainable development. As shown in Figure 2.3, sustainability is an integrated concept of social, environmental and economic aspects which aims to achieve social well-being, environmental integrity and economic stability so that the general quality of life of present generations can potentially be shared by all future generations (Asheim al. 1994).

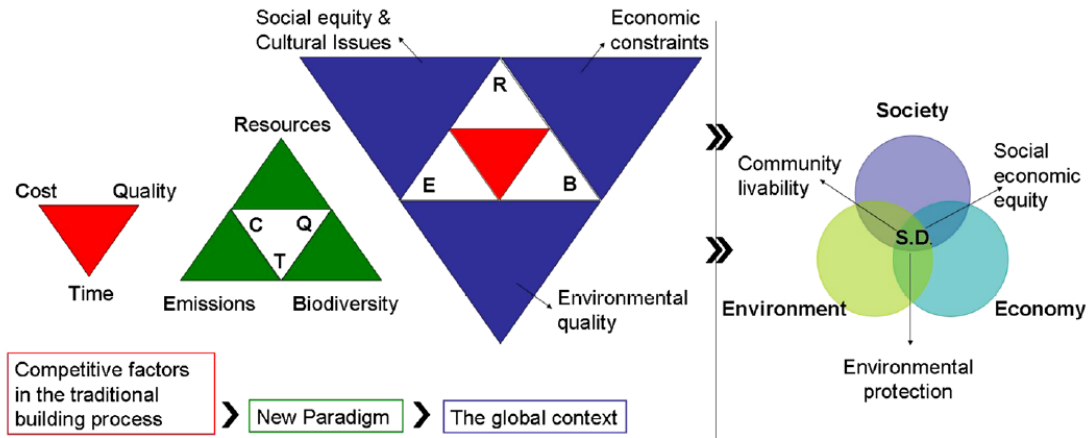


Figure 2.3 Requirements and pillars for sustainability, from the micro level to global level (Hassan & Lee 2014)

2.3.3. Sustainable Housing

The Oxford Dictionary defines the term ‘house’ simply as a ‘building for human habitation’. The term ‘housing’ means ‘houses and flats considered collectively’ (Soanes & Stevenson 2004). It is also a verb which applied a range of actions including planning, producing, financing, allocating and maintaining dwellings (Clapham et al. 2012).

The word ‘sustainable housing’ refers to a wide range of content. Firstly, the house should be sustainable in a physical condition, such as low energy, water and material use. Secondly, sustainable houses should be resilient and adaptable to changes of function or changes in the climate. Thirdly, it is supposed to support the ‘well-being’ and healthy lifestyle for people. Also, it ought to be part of a socially and economically vibrant community. It is not only about the quantifiable physical attributes but also about the design aspects of creating space and responding to the aesthetic and cultural identity of a community. It must encourage a sustainable lifestyle and environment for its occupants and the surrounding community (Jones 2012).

2.3.4.Sustainability at the Community Level

Communities to a city are like cells to a body. A community is an ideal place to start and implement change to help to achieve city sustainability. Communities can initiate and generate their solutions to their everyday economic problems and thereby build long-term community capacity (Roseland 2000).

A sustainable community is 'a community that uses its resources to meet current needs while ensuring that adequate resources are available for future generations. A sustainable community seeks a better quality of life for all its residents while maintaining nature's ability to function over time by minimising waste, preventing pollution, promoting efficiency and developing local resources to revitalise the local economy' (SEDEPTF 1995).

The community can be seen as the gateway to the city. Sustainability at the community level is a reflection of that at the urban level. Policy-making at a community level will highlight the role of all stakeholders, thus creating a demand for sustainability solutions. A crucial objective for communities to achieve sustainability is 'more efficient use of urban space, minimising consumption of natural capital, and multiplying social capital' (Roseland 2000).

2.3.5.Sustainable Cities

As mentioned by Wheeler and Beatley (2014), the social reformers from Britain, continental Europe and the US started to draw attention to the deterioration of the urban environment and the demand for alternative living surroundings in the late nineteenth and early twentieth centuries. Therefore, it is essential to review the development of different types of sustainable cities.

The idea of the 'garden city' was first proposed by Ebenezer Howard in 1898 (Howard 1898). It was aimed at solving the overcrowding problem in cities by encouraging the devolution of population from cities to the countryside. This idea has influenced many city planners and designers. It not only involved physical planning principles but also

referred to the social and economic aspects. It proposed to create a balance between city and country life, which was considered the main principle for establishing sustainable communities during the nineteenth century. Although the content of this balance has changed over time, the idea of ‘balance’ provided a roadmap for sustainable city development (Wheeler & Beatley 2014). Over the past forty years, there has been a general trend for city concepts to become more comprehensive, covering several aspects of sustainable development (Table 2-1).

Table 2-1 Features of different concepts

Features of different concepts.

Concept	Date of origin	Concept contents				
		Carbon efficient economy	Environmental protection	Energy efficiency	Economic growth	Social aspects
1 Green City	1970s		●			
	2000		●			
2 National Garden City	1990		●			●
3 National Environmental Protection Model City	1997		●			
4 Eco-demonstration Community	1995		●			
5 National Eco-garden City	2004		●			●
6 Eco-county, Eco-city and Eco-province	2003		●	●		●
7 Low-carbon City	2008	●		●		●
8 Low-carbon Eco-city	2010	●	●	●		●

Data sources: Sino-Singapore Tianjin Eco-city (2009); China Low-carbon Eco-city Development Report (2011); The Introduction of the National Environmental Protection Model City (MEP, 2009); National Standards for Developing a National Garden City (MOHURD, 2000).

Since the 1990s, China has made progress toward sustainable urban development in many ways. Different urban concepts such as Green City, Eco-city, Garden City, Low-carbon City, etc. have been used by the government in different periods in China. In the 1990s, city concepts were focused on environmental perspectives. The concept of ‘Green City’ has been explained in different ways over time. In the beginning, it was interpreted mainly as increasing green space in cities. Now the concept ‘Green City’ does not only refer to cities with green spaces but also ones with various environmental, economic and social aspects of development. The ‘Eco-city’ and ‘Low-carbon City’ are often recognised as approaches to achieve green cities in China. ‘Garden City’ focuses more on landscape and green space coverage in cities. In 1997, the Ministry of Environmental Protection of China issued the concept of the National Environmental Protection Model City and defined it as ‘a city with rapid economic growth, a clean and beautiful environment and healthy ecosystems’ (Ministry of Environmental Protection 2009). The ‘Low-carbon City’ is a newer concept than the ‘Eco-city’ and is more widely used at the international level. In 2007, the World

Wildlife Fund (WWF) started a 'Low Carbon City Initiative in China' project to explore approaches for low carbon development in China's urban areas. Shanghai and Baoding became the first pilot 'Low-carbon Cities' in China, and many other cities followed suit, creating a new layout of coordinated development between energy use and economic growth (WWF 2007).

2.4. Development of Sustainable Retrofit in China

2.4.1. Background Issues

As a pillar industry of the national economy, the construction industry in China has a long and convoluted history. In August of 1949, the same year as the establishment of the People's Republic of China, China's first national construction company opened. During the following eight years, construction sectors were set up throughout the country and the first architectural design institutes were established.

However, just as China's construction industry flourished, the 'Great Leap Forward' and the ten years of turmoil starting in 1958 caused tremendous damage to the development of the construction industry (Peng 1987). During the subsequent Cultural Revolution, the institutes of architectural design, research, and universities and colleges were discredited, and a set of well-developed architectural systems were mistakenly criticised. The entire construction industry was paralysed. At the same time, unrealistic economic goals led to extreme chaos in project management and implementation, and labour productivity dropped significantly. While construction costs nearly doubled, project quality declined generally, and the construction accident rate reached the highest level since the founding of the People's Republic of China.

China's Reform and Opening-Up Policy in 1978 was a historical turning point. At that time, the government shifted to focus on economic development. The construction industry also started restoring and developing. In 1983, the total output value of the construction industry in China was 105.3 billion yuan, an increased of 1.4 times since 1976. By 1998, the area of completed buildings reached more than 4.9 billion square meters, of which more than 2.3 billion were residential buildings, nearly four times

the total of 30 years before (National Bureau of Statistics of the People's Republic of China 1999).

At the same time, the process of rapid urbanisation closely accompanied China's economic growth and social development. At the beginning of the 1980s, a principle of restricting the size of large cities and promoting small cities and towns was adopted as the primary strategy for achieving urbanisation (Li 2010). A 'county to city' upgrade policy was adopted to grant city-level status to existing counties that met specific requirements. Through this policy, the total number of cities in China proliferated, from less than 250 in 1982 to more than 650 in 1997. In other words, urbanisation in China was characterised by a large number of new cities, which was different from the expansion of existing cities through migration from the countryside in most developed countries (Anderson & Ge 2005). The Chinese government stopped 'county to-city' upgrading in 1997, and since then, the total number of Chinese cities has changed little.

2.4.2. The Built Environment in Beijing, China

The built environment refers to 'the human-made space in which people live, work, and recreate on a day-to-day basis' (Roof & Oleru 2008). This includes 'the places and spaces created or modified by people including buildings, parks, and transportation systems'. Recently, the definition has been expanded by public health research to involve more aspects such as community gardens, and mental health (Assari et al. 2016).

Beijing, as the capital city of China, is the centre of politics, economy, culture and education. It is the second largest city by population in China after Shanghai (China Daily 2009). According to the latest census data from the National Bureau of Statistics of China, Beijing has a permanent population of 21.7 million, and the population density is 1324 people per square kilometre. There are 6.7 million households in the city of Beijing. The average household size is 2.45 people per household according to the latest census (Beijing Municipal Bureau of Statistics 2013).



Figure 2.4 The construction and completed areas of residential buildings in Beijing from 1978 to 2016 (Unit: km²)(Beijing Municipal Bureau of Statistics 2017b)

Since the Reform and Opening-Up Policy was launched in December 1978, China's economy has started to develop at a rapid rate, and the speed of housing construction has also accelerated significantly in Beijing, especially since the 1990s. According to the Beijing Municipal Bureau of Statistics (2017), the construction area of residential buildings in Beijing has grown from 4.6 km² in 1978 to 77.4 km² in 2016 and completed residential area has increased from 1.9 km² to 17.6 km² as shown in Figure 2.4.

2.4.2.1. Climate Zones in China

China has a vast territory with a total area of about 9.6 million square kilometres. The climate varies significantly from south to north and from east to west. China's Ministry of Construction has divided China into five climate zones as shown in Figure 2.5. They are the severe cold zone, the cold zone, the hot summer cold winter zone, the moderate zone, and the hot summer and warm winter zone (Sun 2013) Table 2-2 illustrates the average temperature of the five climate zones in China.

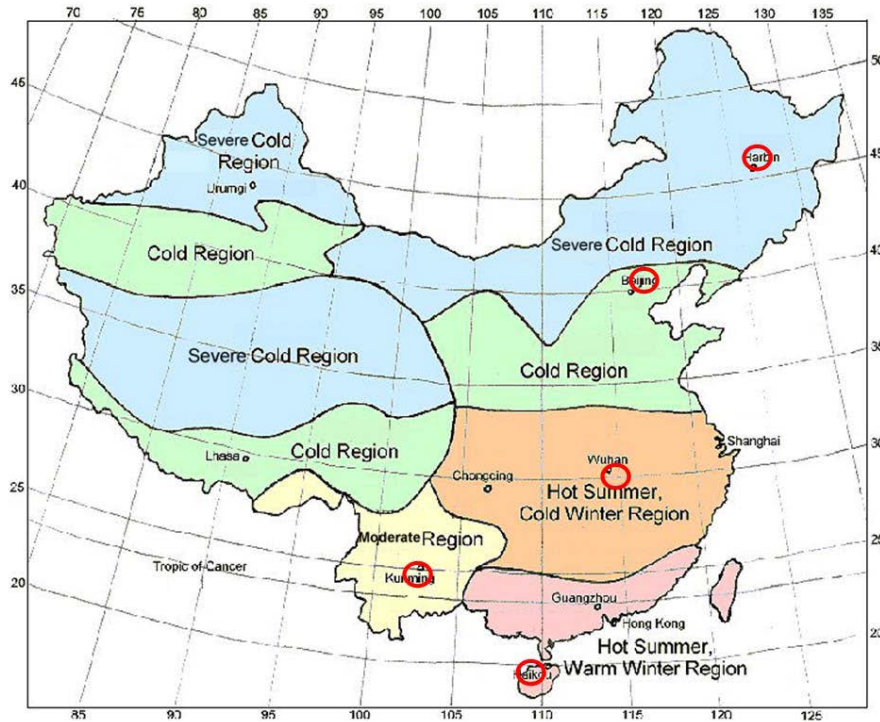


Figure 2.5. Five climate zones in China (Sun 2013)

Table 2-2 Average temperature of the five climate zones in China

Climate zone	Average temperature (°C)	
	January	July
severe cold	≤ -10	≤ 25
cold	-10 – 0	18 – 28
hot summer cold winter	0 – 10	25 – 30
hot summer warm winter	>10	25 – 29
moderate	0 – 13	18 – 25

2.4.2.2. Classification of the residential buildings in cold climate zone

China’s residential buildings can be divided into four types according to floor numbers. They are low-rise (1 to 3 floors), multi-storey (4 to 6 floors), mid-rise (7 to 9 floors), and high-rise (10 floors and above) (Ministry of Housing and Urban-Rural Development of the People’s Republic of China 2005). The low-rise buildings more exist in rural areas, which is not part of the scope of this study.

Although China formulated the first residential building standard in 1986 with a 30% energy saving target and raised the target to 50% in 1995, it was not until 2005 that the mandatory energy saving standard was adopted for the construction management system (Shui & Li 2012). Therefore, before 2005, most buildings did not adopt energy-saving measures by the design standards. Besides, the service life of residential buildings is fifty years in China and there were not a large number of residential buildings built before China's Reform and Opening Up Policy was launched in 1978 (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2001).

2.4.3. The Current Situation in China

China already has the highest number and largest size of cities in its history. According to recent statistics (December 2011), Chinese cities are now home to more than 50% of China's total population. If the current trend holds, it is predicted that by 2025 the urban population will be over 1 billion and there will be eight megacities, each with a population of over 10 million (Woetzel et al. 2009). Meanwhile, the environmental problems are severe. According to a recently released report by the Asian Development Bank, less than 1% of the 500 largest cities in China meet the air quality standards recommended by the World Health Organization, and seven of its cities are ranked among the ten most polluted cities in the world (Zhang & Crooks 2012).

In 1999, the Tenth Five-Year Plan on National Economic Growth and Social Development stated that China was 'actively and steady promoting Chinese urbanisation process'. The Twelfth Five-Year Plan in 2011 reported that 'the level of urbanization is not only regarded as an important indicator of industrialisation, but also an essential driving force for the country's future domestic market growth'. Therefore, urbanisation acceleration is still a vital policy for the Chinese government (Gu et al. 2012). As Liu (Liu et al. 2014) points out, through the guidance of government policy, cooperation with international partners and other approaches, China has now become one of the most active countries for sustainable urban development experiments in the world.

One of the most urgent issues for China to deal with is to improve resource use efficiency, including the use of energy and materials, and to reduce emissions. The complexity of the issue of sustainable development and the uncertainties regarding future development suggest that a critical factor is to build more robust and resilient cities (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012).

Meanwhile, due to rapid urbanisation and the rapid development of the construction industry, the quality of buildings built in the 1980s and 1990s was generally poor. According to the National Bureau of Statistics of China, the good quality rate of the construction project in China was about 30% in the 1990s (National Bureau of Statistics of the People's Republic of China 1999).

2.4.4.Challenges of Retrofitting Existing Residential Buildings in China

As shown in the report by China Academy of Building Research Shanghai Branch(China Academy of Building Research Shanghai Branch 2013) (CABR) in 2013, there are five challenges to the sustainable retrofitting of existing residential buildings in China.

- a) There is high energy consumption in buildings: residents pay more attention to the size, functions and decoration levels of the living space, yet ignore aspects of living quality such as thermal comfort, acoustic environment and air quality, resulting in high energy consumption in buildings. The heating and cooling loads in China are 3 to 4 times higher than in other developed countries with the same climate and the thermal insulation level in Chinese buildings is far behind. The external wall insulation is 4 to 5 times worse, the roof insulation is 2.5 to 5.5 times worse, and the airtightness is 3 to 6 times worse (Liu & Qin 2005).
- b) The capacity of the environment to absorb waste is overloaded: the productive process of concrete, clay bricks produces much pollution in the air and water. Also, due to insufficient attention to waste disposal, the recycling process is complicated to carry out.

- c) At present, China's housing construction system has not adapted to industrial production. The consultation, design, construction, management are relatively independent, which may limit the development of technology application, and also bring more economical and management problems such as proper external wall insulation with poor quality openings.
- d) Buildings have poor overall thermal performance: the average size of the flat has become larger, but the thermal performance of the envelope and the indoor thermal environment is poor. Besides, there is not a holistic evaluation system to assess the overall performance in China.
- e) The stakeholders lack awareness of sustainable retrofit. They do not have an in-depth understanding of a series of related issues such as upfront costs, savings and payback times of the retrofit projects, which limits the development of retrofitting works. (China Academy of Building Research Shanghai Branch 2013)

China has experienced more than 30 years of building and demolishing; many old residential buildings have been replaced by high-density, multi-storey buildings or high-rise buildings. China is now focusing on the residential buildings completed in the period from the 1980s to 2005. These buildings were mostly built at the national requirements of necessary living demand. Thus, their quality is relatively low. Besides this, these properties mostly are publicly owned. Hence the responsibility for maintenance and retrofitting is commonly shared by the property department of government agencies and the organisation. As a result, it is challenging to implement retrofitting projects without the government's participation.

2.5. Comparison of Sustainable Retrofit in the UK and China

With the rapid development of urbanisation, sustainable retrofit has become a hot topic in China in recent years. Many low carbon retrofit pilot projects have been built in different cities. Chinese local governments also have published some sustainable retrofit design and evaluation standards. However, as mentioned in the *Hundred Questions of Retrofitting Existing Residential Buildings* (Ministry of Housing and

Urban-Rural Development of the People's Republic of China 2012), there are still some problems of China's sustainable retrofit. For example, heat metering is a mostly unsolved problem in northern China, which makes it difficult to measure the actual energy-saving achievements. Also, most of the technologies used in China's retrofitting projects are merely elemental retrofit measures that still require optimisation and combination. Besides, the rough construction quality of retrofit projects in China will influence the further energy-saving effect. Therefore, sustainable retrofitting in China still needs much improvement in many aspects such as design, construction and supervision.

As retrofitting has been practiced in the UK for some time, it is significant to study the UK's experience on sustainable retrofit and make comparisons between different aspects of this in the UK and China to discover the gap and find out how and to what extent those technologies and processes can be transferred to China to optimise the sustainable retrofit solutions.

2.5.1. Energy Use and Retrofit Target

2.5.1.1. Energy Use and Retrofit Target in the UK

It is widely known that the UK government has committed to reduce CO₂ emissions by 80% compared with 1990 levels by 2050 (Climate Change Act 2008). In order to achieve this target, domestic CO₂ emissions have to be reduced by 17 MtCO₂ per year by 2050. Also, the government has an intermediate target of reducing the UK's CO₂ emissions to 34% below 1990 levels by 2020 (Bothwell et al. 2011). In Wales, since 2011, the government has agreed that action should be taken immediately to achieve its sustainability targets, which involves reducing CO₂ emissions by 3% each year from the average level of 2006–2010. Also, Wales has a higher target than the rest of the UK: it aims to reduce CO₂ emissions to 40% below 1990 levels by 2020 (Iorwerth et al. 2013).

In the UK, the CO₂ emissions associated with all energy use are 467.5 million tonnes in 2013 (Department of Energy & Climate Change 2015a). Around 50% of the energy

use in the UK and CO₂ emissions is related to energy use in buildings, where housing accounts for 28% (Palmer et al. 2011). About 27% of greenhouse gas emissions is attributed to around 6 million existing homes. (Bernier et al. 2010).

As analysed by DECC (2012), the UK's energy use for space heating (61% of household energy use (Figure 2.6) is more extensive than that of electrical power, commonly up to five times during the heating season, which shows the significant energy and CO₂ emission need to be reduced in this area. Therefore, for existing housing, reduction of energy use in space heating has to be a priority for achieving CO₂ emission reduction targets.

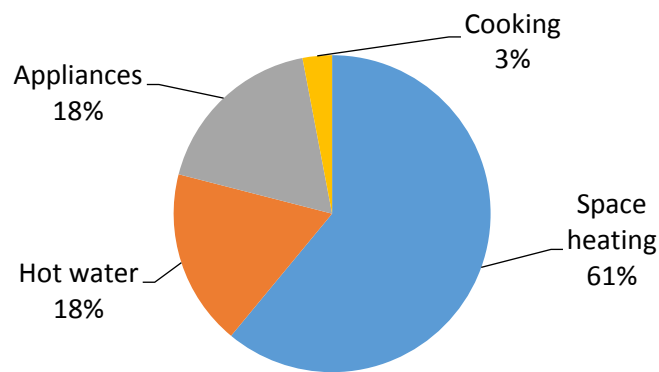


Figure 2.6 Percentage breakdown of household energy use. Source: Department of Energy and Climate Change (DECC 2012)

2.5.1.2. Energy Use and Retrofit Target in China

The Chinese government published the 'Design standard for energy efficiency of residential buildings in severe cold and cold zones' in 2010. In this standard, the target is to reduce CO₂ emissions by 65% compared with 1980 levels. Besides, the government also proposed a CO₂ emissions target of 40%–45% reduction by 2020 in comparison to 2005 levels (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012).

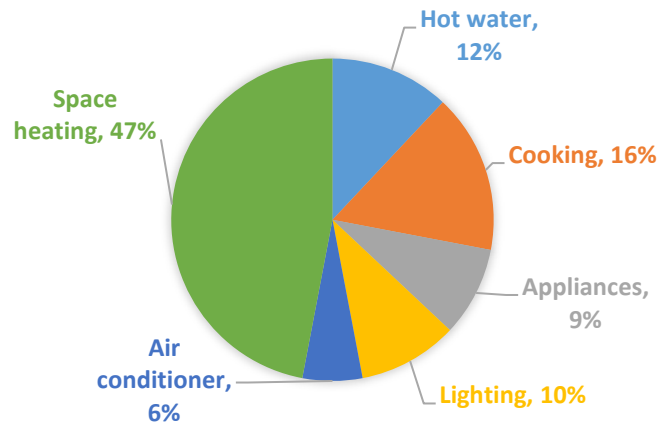


Figure 2.7 Percentage breakdown of household energy use (Shui & Li 2012).

As shown in Figure 2.7, the annual report on China's building energy efficiency indicated that China's urban residential energy consumption includes six major components, including space heating, air conditioning, lighting, cooking, domestic hot water, and home appliances (Shui & Li 2012). Among them, the energy use for space heating in China accounts for a relatively small proportion of 47% compared with the UK, whereas the proportion of cooking energy use in China is 13% more than that in the UK. The energy use of electrical appliances in China is half that of the UK. Even if considering the air conditioners, the energy use of the appliances in China is still less than in the UK. As pointed out by American Energy News (Hislop 2015), due to the increased incomes and modernisation, the energy use of buildings in China has grown by approximately 7.7% each year since 1998. Figure 2.8 shows the growth of the energy consumption of buildings in China from 1998 to 2012. It can be seen clearly that residential buildings account for more than two-thirds of the total energy consumption.

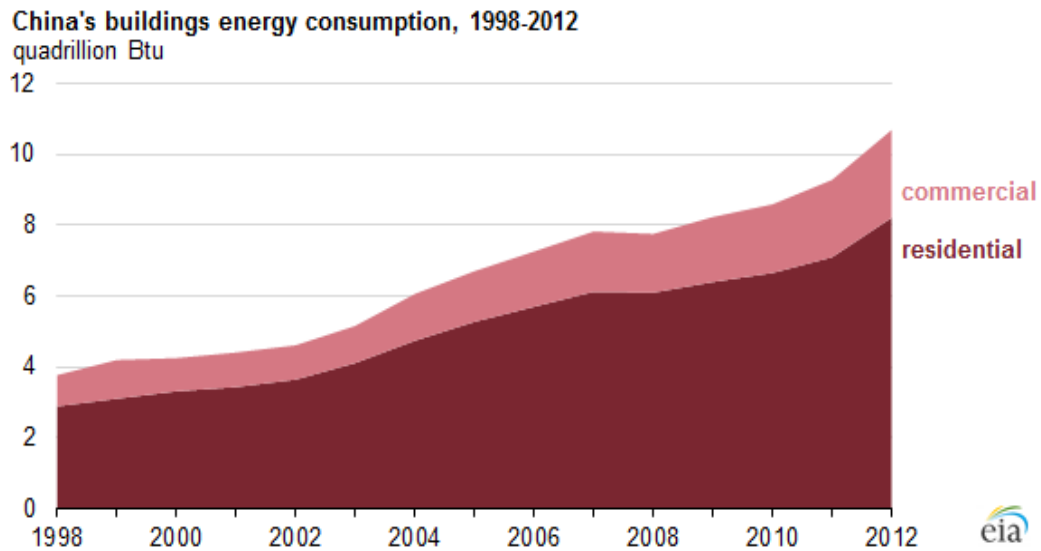


Figure 2.8 China's buildings energy consumption, 1998-2012 (Hislop 2015)

As shown in Figure 2.9, in China, space heating also accounts for more than 50% of household energy use and occupies approximately 65% of the total energy consumption, together with the energy use in air conditioning and ventilation. Also, it should be concerned that lighting also makes up a large proportion (Jiang 2014).

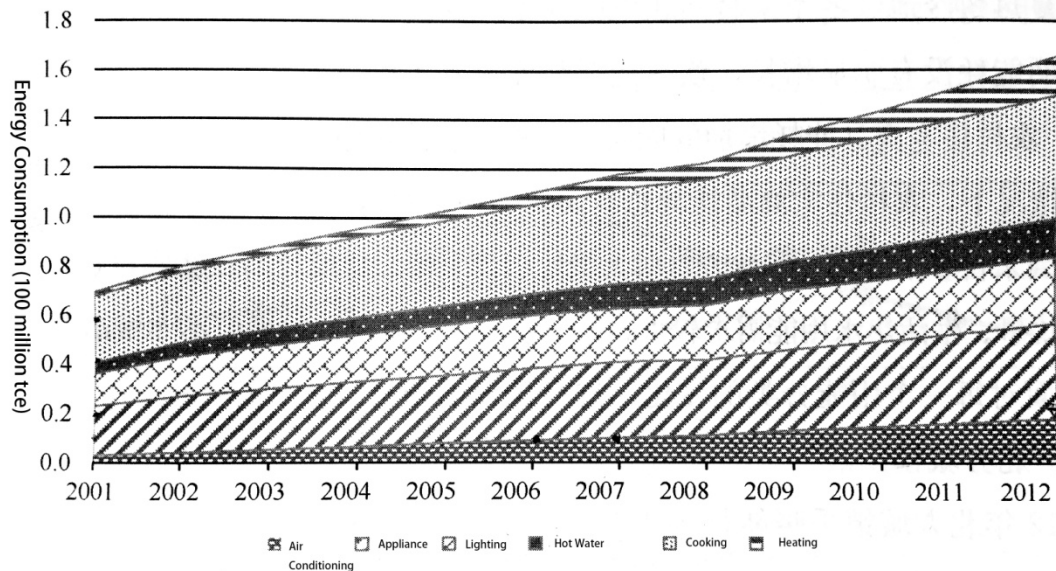


Figure 2.9 Annual changes in China's household energy consumption breakdown (Jiang 2014). (1kWh = 0.305 kg tce)

Building energy consumption is directly related to living standards. In the UK, due to

the relatively cold weather and high requirements for thermal comfort, the energy consumption for heating and hot water is relatively large, and the proportion of building energy consumption to the total national energy consumption is also higher than that of China (Liu & Qin 2005).

2.5.2. Policy, Legislation and Standards

2.5.2.1. Policy, Legislation and Standards in the UK

The UK government has created a series of regulations, standards and guidance to help homeowners, landlord, stakeholders and house associations to make existing buildings produce fewer carbon emissions.

The UK government's Carbon Act (Climate Change Act 2008) has a commitment to reduce 80% CO₂ emissions below 1990 levels by 2050, with interim targets of 26% by 2020. It was expected that residential buildings would achieve this reduction for the sake of counteracting transport growth (Gleeson et al. 2011).

The Energy Company Obligation (ECO) policy sets targets for the primary energy suppliers to deliver energy conservation measures to households. The delivery of the ECO is funded by the energy suppliers through levies on domestic energy bills. The targets are separated into two aspects: bill savings of low-income households and carbon savings by using cost-effective measures (The UK Green Building Council 2015).

The Minimum Energy Performance Standards (Private Rented Sector) are a set of standards that has been set for rental properties. The private rented sector (PRS) has the highest proportion of low energy efficiency building stocks. As a result of these new standards, it has been illegal to rent out the properties with the lowest energy efficient ratings since April 2018. Landlords have been required to improve properties with Energy Performance Certificate (EPC) bands of F and G to EPC band E. Besides this, landlords have also been required to accept reasonable requests from tenants to install energy efficiency measures since April 2016 (The UK Green Building Council 2015).

The UK Renewable Energy Feed-in-Tariff (FiT) is the main fiscal stimulus to incentivise the uptake of the UK's small-scale renewable electricity-generating technologies. Many household technologies qualify for the scheme, such as solar electricity (PV), wind turbines, hydroelectricity, anaerobic digesters, and micro combined heat and power (CHP) (The UK Green Building Council 2015). The scheme offers a guaranteed minimum payment per electricity unit (p/kWh) for renewable electricity generation and a further payment for each electricity unit which exports to the local network (Rhoads 2010). The FiT was cut for new installations from 1st January 2016. Since then, the return rates reduce every three months, which makes a longer payback time for solar PV investments (Which? 2018).

The Renewable Heat Incentive (RHI) is a proposed framework to encourage the uptake of renewable heat technologies for homes, businesses and public facilities. The scheme offers fixed payments for participants for over seven years for renewable energy generation and uses for homes heating. Heat will be supported from different sources including biomass boilers, heat pumps, solar thermal collectors, bio methane and biogas. The scheme aims to increase the UK renewable heat levels from 1% to 12% by 2020 (The UK Green Building Council 2015).

The Green Deal was the previous flagship energy efficiency policy. It was designed around a 'Pay as You Save' model: 'householders received up-front finance in the form of a loan to pay for energy-saving measures which were then paid back using the savings made on their energy bills' (The UK Green Building Council 2015). The fundamental principle of the Green Deal was payment by instalment for measures of energy saving, including that cost, labour and products should not go beyond the planned associated average cost savings on a bill during the period of the green finance arrangement (DECC 2011).

In July 2015, the Green Deal Finance Company (GDFC), which financed Green Deal loans, was no longer funded by the government. As a result, no new Green Deals have been offered since then, but this will not affect existing loans (The UK Green Building Council 2015).

The Existing Homes Alliance (ExHA) is a collaboration of organisations, to campaign and lobby for a national retrofitting programme to reduce carbon emissions in existing residential buildings in the UK. The ExHA published minimum standards of home energy efficiency by using an energy efficiency rating system, which is based on the current regulations requiring all new buildings to introduce minimum energy efficiency standards on all tenures through the targets of zero carbon homes for 2010, 2013 and 2016 (The Existing Homes Alliance 2010).

Energy Performance Certificates (EPC) require all new and existing buildings to have their energy performance assessment before being sold or rented, which results in increasing retrofitting through market pressures (Council 2013).

2.5.2.2. Policy, Legislation and Standards in China

In China, beginning with the Tenth Five-Year Plan on National Economic Growth and Social Development in 1999 and developed further in the Eleventh and Twelfth Five-Year Plans, the retrofitting of existing residential buildings has become a significant issue.

There are two main national policies to deal with the climate and energy issues in China: the 'The Twelfth Five-Year Plan' issued in March 2011 and the 'National Climate Change Programme' developed in 2007. The former has the objective of reducing energy consumption and CO₂ emissions per unit of GDP by 16% and 17%, respectively, by 2015. The outcomes will be in comparison to the levels of energy used in 2010. This plan also aims to increase the portion of renewable energy to 11.4%, along with the goal of covering approximately 21.7% of the nation's land with forest by 2015 (National Bureau of Statistics of the People's Republic of China 2011). The latter aims to treat the climate and energy issues and was the first policy plan directed towards climate change in China. This policy was developed over two years, with the engagement of 17 government ministries (National Development and Reform Commission of China 2007).

There is also a National Green Buildings Evaluation Standard (also called the ‘Three Star Standard’) (GB/T 50378–2006), which defines and describes the requirements of the criteria and the objectives of sustainable building in a clear and comprehensive way. It can be used as a ‘valuable design and quality assurance tool’ and a benchmarking tool to support clients and investors to understand sustainable buildings (Ebert et al. 2011).

Building energy codes. China’s first building energy code was issued in 1986 for residential buildings in north China, which required to reduce energy consumption in space heating to 30% below the 1980 levels (Hislop 2015). After that, the building energy codes have improved over time. Currently, there are three energy codes for housing in four climate zones, including severe cold climate and cold zones, hot summer and cold winter zones, and hot summer and warm winter zones. Besides, there is a building energy code for commercial buildings. These codes are mandatory for buildings in urban areas, and voluntary in the rural areas (Table 2-3).

Table 2-3 Development of Building Energy Codes in China (Yu et al. 2015)

Building Type	Climate Region			
	SC	C	HSCW	HSWW
Urban Residential	Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ 26); Years of Enactment: 1986, 1995, 2010 (Mandatory)		Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone (JGJ 134); Years of Enactment: 2001, 2010 (Mandatory)	Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zone (JGJ 95); Years of Enactment: 2003, 2012 (Mandatory)
Commercial	Design Standard for Energy Efficiency of Public Buildings (GB 50189); Years of Enactment: 1993, 2005 (Mandatory)			
Rural Residential	Design Standard for Energy Efficiency of Rural Residential Buildings (GB 50824); Year of Enactment: 2012 (Voluntary)			

Specific to the retrofitting of existing residential buildings, an energy efficiency retrofitting and the cost-sharing system was established by the State Council in 2008, formulating the targets, contents, procedures, technologies, standards, funding sources, cost sharing, operation and management for retrofitting through a legal point

of view. Hence, the sustainable retrofitting of existing residential building should be accorded with procedures prescribed by law (Bao et al. 2012).

The Green Building Action Plan released in 2013 indicates that by the end of 2015, more than 0.4 billion m² out of 3.5 billion m² of houses in northern China need to be retrofitted to achieve the level of current building energy code. By the end of 2020, all eligible buildings with retrofit values in the northern heating zones should be retrofitted (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2013a). Local governments also share these ambitious goals. For example, the government in Beijing set the goal to retrofit 150 million m² in the northern heating areas by 2015, which is equivalent of the total floor areas retrofitted in north China from 2006 to 2010 (Yu et al. 2015).

Besides, a national standard was released in 2015 entitled the 'Assessment Standard for Green Retrofitting of Existing Building', which takes into account the economic feasibility, technological improvement and geographical applicability of the sustainable building retrofit and aims to standardise the evaluation of sustainable retrofitting of existing buildings (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2015). It has seven evaluation categories including planning and architecture, structure and material, heating ventilation and air conditioning, water supply and drainage, electricity, construction management, and operation management, and one promotion and innovation part. The evaluation results are divided into three levels: one-star, two-star and three-star. Other existing retrofit strategies vary according to different cities and climates. For example, the government of Beijing published a strategy called 'Specific Implementation Plan of Sustainable Retrofit' in 2007.

In 2017, China's Ministry of Housing and Urban-Rural Development published the Building Energy Conservation and Green Building Development 'The Thirteenth Five-Year Plan'. It focuses on continually promoting the sustainable retrofitting of existing residential buildings, and also emphasises exploring holistic retrofit patterns that will improve existing buildings and the environment as a whole, as well as install suitable facilities for elderly people such as elevators for multi-storey buildings and expand the scale of renewable energy applications. To be specific, it aims to complete the existing

residential building retrofitting of more than 500 million square meters and increase the proportion of energy-saving buildings to more than 60% of the existing residential buildings in China, and replace the conventional energy sources with renewable energy ones by 2020 (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2017).

Although China has established a number of policies and regulations for the implementing housing retrofit, depending on local circumstances, there is still a lack of adaptability of economic management policies and procedures, the implementation of technology, and the evaluation system of standards. The overall perspective on the administrative examination and approval procedures, there is no difference between retrofit and new build projects in the steps of tendering, design, construction and other fundamental aspects. In addition, the procedures for retrofitting are relatively complex and have long implementation cycles. Also, the related organisations focus only on the statistics of the completion and there is a lack of regular assessments on the quality of the project. Thus, it is hard to achieve a potent inspection and supervision system.

From the British experience, establishing a thorough assessment system is the fundamental guarantee of carbon reduction. The UK is the first country to introduce a 'carbon budget' form with the regulations to cap national total CO₂ emissions. Combined with China's current situation, it should establish and improve energy saving as the main content of the legal system as soon as possible. It should establish an independent organisation similar to the British 'Climate Change Committee' to implement energy conservation monitoring and the inspection of illegal activities. Also, it should create an incentive system for householders to reduce their energy consumption. In conclusion, it requires the cooperation of all parties especially the actions of the government to achieve a sustainable retrofitting process and reduction of CO₂ emission in existing housing.

2.5.3.Retrofit Measures

In a retrofit project, solutions selection and design should be considered as the most critical part, as these have decisive impacts on the overall performance. A poor retrofit plan is difficult to improve through construction quality (Kerschberger 2010).

2.5.3.1.Retrofit Measures in the UK

In the UK, the retrofitting measures are designed to reduce energy demand, especially space heating. They cover a range of technologies (Figure 2.10), mainly including fabric insulation, air tightness improvement, windows and doors retrofit and heating system improvement. Other popular measures include lighting and control upgrading, energy-efficient equipment and appliances, and Mechanical Ventilation Heat Recovery (MVHR). These measures can be considered as 'easy targets' and natural substitutions. Cost-effective benefits can be seen gradually by occupants through these measures, not only in increased energy efficiency but also in improved thermal comfort (Jones, Lannon & Patterson 2013). In addition to typical retrofit technologies, the UK also focuses on renewable energy technologies such as solar photovoltaics (PV), wind turbines, biomass, etc. The implementation of low carbon technologies is often associated with added value 'multiple benefits', such as reducing fuel poverty, upgrading quality of life, improving health conditions, and promoting the local economy.

According to Ma et al. (Ma et al. 2012), the retrofit technologies can be categorised into four groups: heating and cooling demand reduction, energy-efficient equipment and low energy technologies, human factors, and renewable energy technologies and electrical system retrofits. Among them, the first two groups belong to energy demand-side management, renewable energy belongs to supply-side management, and human factors belongs to energy consumption patterns (Figure 2.10). To be specific, the following ranges of retrofit measures are generally considered.

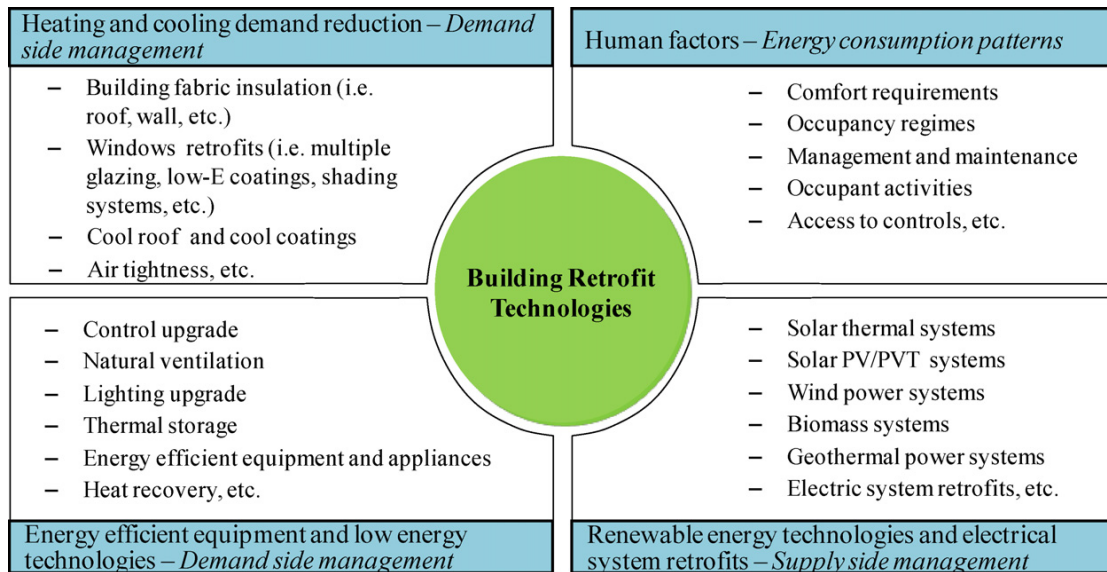


Figure 2.10 Main categories of building retrofit technologies (Ma et al. 2012)

Figure 2.11 illustrates three typical retrofit approaches applied in the UK: the technically led approach, the funding led approach and the whole-house approach. For the technically led approach, fabric improvement is normally the first approach to be considered in most retrofit projects because it has the possibility of being applied independently of the other measures. Thus, fabric improvement should be given priority in housing retrofitting. Besides, housing should be insulated to the best level in one go to achieve economically optimal levels (Route 2009).

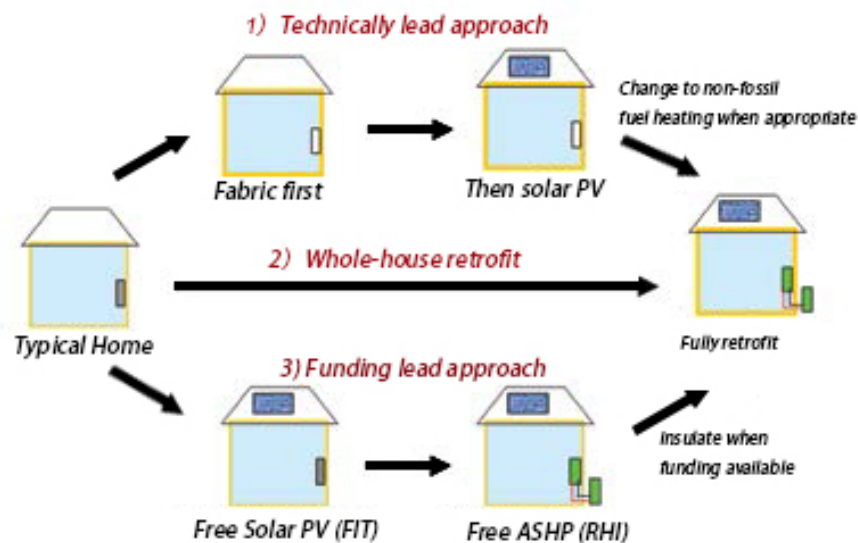


Figure 2.11 Different housing retrofit approach (Route 2009)

Fabric insulation is commonly considered the most effective strategy (Li et al. 2017). Figure 2.12 shows the different forms of the wall insulation. The most common retrofit measure in the fabric first approach in the UK is external wall insulation (EWI). In some of the UK's retrofit projects, internal wall insulation is needed because the average cost of it is low and it does not affect the exterior look of the building. For buildings with historical value, damage to the building look has to be strictly avoided. If the external insulation is only employed on a single terraced house or one of a pair of semi-detached houses, the whole row of houses can be visually obtrusive. However, in most non-historical cases, where the external appearance of the building is not a limiting factor, external wall insulation is highly recommended. It can be used on the flank walls or rear walls of some properties where the insulation work does not affect many external appearances. External insulation is best installed when repairs to walls are being done in order to save costs and reduce inconvenience. External wall insulation also has the potential to enhance wall conditions, facades, and damp penetration. It helps to reduce mould growth, which can impact householders' health. (Energy Solutions 2011)

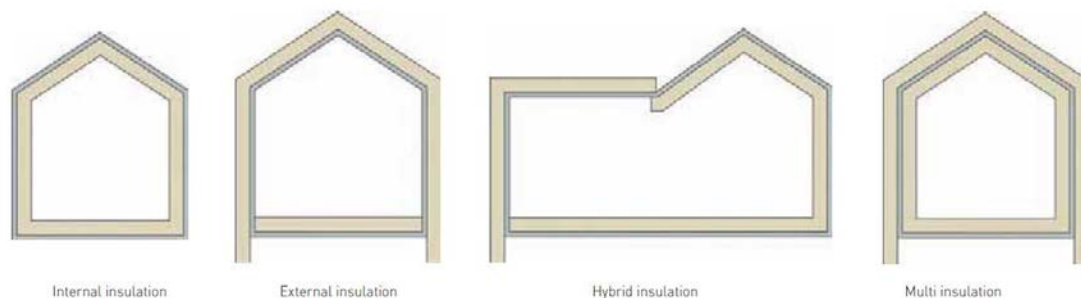


Figure 2.12 Wall insulation form

In the UK, many residential buildings were built with cavity walls, 60% of which did not have thermal insulation by 2004 (EHCS 2004). Cavity wall insulation can reduce up to 40% of heat loss through the walls (EST EEBPH, 2003). Older houses with solid walls require external or internal wall insulation to improve their performance. It is evaluated that improving an old house with poor insulation to post-1990 standards through the roof and wall insulation can reduce heat loss by 50%–80% (Roberts, 2008).

In addition, airtightness improvement can reduce heat loss from ventilation and can be an assistant benefit from the fabric improvement, which can significantly improve the thermal performance of the house (Everett 2007). Moreover, improving windows by replacing the single glazing to double glazing can reduce heat gains from outside. If replacing with low-E glazing, the heat gains and solar gains can be significantly reduced, thus decreasing the heating and cooling demands (Li et al. 2017).

Regarding system improvement, both large scale and small scale retrofit projects use the measures of updating to energy efficient boilers; some boilers with a hot water tank which can be combined with solar thermal for domestic hot water. Fuel switching is another measure to improve the system. Although 69% of the current fuel for domestic use in the UK is gas, which means the measure of fuel switching has a limited potential of only 22% in the UK, it is still considered as a relatively cheap retrofit measure with a significant effect (Patterson 2012).

Moreover, Mechanical Ventilation Heat Recovery (MVHR) system works well in the houses with good airtightness as it can reduce the heat loss by preheating the supply air and recover heat from the stale exhaust air. In doing so, it can not only improve the indoor air quality but also reduce the need for space heating energy. However, for the property with poor insulation or the system is not appropriately installed, the energy use may increase (White et al. 2016). Additionally, Electricity consumption can be reduced by installing LED lighting and energy-efficient appliances.

In terms of renewables, solar PV generally has up to 20% efficiency, which can offset the electricity required from the national grid. Over the past few years, solar PV has been drastically increasing in the UK, and the cost of purchase and installation has significantly reduced (Cherrington et al. 2013).

In addition, heat Pumps recover heat from a various sources and provide heat for buildings. The heat can then be used to provide domestic hot water and space heating and cooling (Xing et al. 2011). The air source heat pump (ASHP) and ground source heat pump (GSHP) are two main heat pump types. ASHPs are usually easier to install than GSHPs, as they do not need any trenches or drilling, but are often less efficient than GSHPs. Solar-assisted GSHP systems use solar thermal collectors as supplemental

heating components and to improve the thermal performance of the heat pumps (Reda et al. 2015). For building retrofit, the ASHP is considered a better option for retrofitting in the UK for its less space requirement, easiness of installation, and low operation and maintenance cost (Rad et al. 2013).

The funding led approach generally depends on the funding available and free measures provided by some non-profit scheme. This approach can improve some houses to a certain extent and householders can also benefit without paying large amounts of money. However, installing renewables without fabric retrofit is like heating a house with the windows open. The new measures cannot achieve a perfect retrofit result. Moreover, later on, when it is necessary to retrofit the fabric or add other retrofit measures, this will lead to rework, which will also cost more money, time and manpower.

The UK begins to look at the whole-house approach for retrofit the existing housing in recent year, which combines the fabric measures with system improvement and renewables, can reduce CO₂ emission by over 90% and cost saving by more than 200% (Li et al. 2015).

2.5.3.2. Retrofit Measures in China

Over the past few decades, the technology research and development of existing housing retrofitting in China has mainly focused on seismic reinforcement, engineering methods for equipment upgrades, energy-saving insulation construction, new materials, and solar heating systems, etc. It seems that many new technologies have been generated in China in recent years both for creating new low carbon projects and retrofitting old projects. However, some of the existing residential retrofit projects in China in the past few years have focused more on building fabric insulation than holistic improvement. As a result, although the thermal performance of the building has been enhanced, the overall living conditions of residents and the environment of the community have not improved significantly. (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012).

The retrofit measures for existing residential buildings in China mainly include the following content:

Building fabric retrofit includes wall insulation, waterproof roof insulation, floor insulation, balcony and other parts insulation, glazing improvement, and building entrance door replacement. Most of the existing residential buildings for retrofit in China have been in use for 20 to 30 years, and most of them have problems such as damage and lack of functionality etc. due to different structural design and seismic design standards at that time, as well as uneven construction quality. In the construction of the fabric retrofit, it may increase loads of the external walls and roofs. Therefore, it is essential to review and check the data of the original building structure. Reinforcement measures should be added when necessary to ensure structural safety (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2013b).

In China, it is preferable to use external wall insulation because of certain advantages. First, it has better energy saving performance. The building structure is entirely enclosed by external insulation layers, non-gap layers can help to prevent thermal bridges, so that the overall thermal insulation performance can be improved. External wall insulation could save 20% more heat loss than internal wall insulation and reduce energy demand for heating in winter and air-conditioning in summer. Second, it can improve the indoor thermal environment. External wall insulation helps to keep the building warm in the winter and cool in the summer because the thermal mass will absorb heat from the dwelling, leading to an even temperature and a more comfortable indoor environment. Thirdly, it can protect the exterior wall. External wall insulation will reduce the temperature difference of exterior walls and interior walls and reduce the structural damage by natural conditions. Besides, it does not reduce the size of the living area and does not require any moving of residents, which is especially essential for communities with a large population. It can also be combined with facade renovation for the purpose of improving appearances.

The flat-to-pitched roof retrofit refers to converting the flat roofs of multi-storey buildings into pitched ones to ensure the thermal insulation and waterproofing

function of the top floor, as well as increasing the renewable potential of the building (Beijing Municipal Commission of Housing and Urban-rural Development 2005).

Indoor heating system retrofit mainly includes installing household heat metres and adding thermostats to each room to achieve room temperature control, replacing old radiators and removing radiator covers, adding insulation to the heating pipes in public areas and replacing them if necessary.

Heat source and network retrofit consists of installing insulation or replacing heat networks, improving the heat supply efficiency of the pipe network, reducing heat loss and increasing safety, replacing low energy efficiency equipment in the boiler room and installing temperature adjustment devices to adjust the heat on different outdoor temperatures.

In addition, building airtightness will be improved after fabric retrofit. The installation of an organised fresh air system can reduce not only heat loss but also enable the combined effects of energy saving, dust prevention and noise reduction, and hence improve the indoor living quality as well as residents' health (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2013b).

Renewable energy technologies such as solar thermal systems and solar PV systems can also be installed. Solar thermal systems have been widely used in China for many years because of more mature technology development and relatively low costs. As an additional device, the collectors are mostly installed on the roof of the building, which to some extent affect the building appearance. Thus, before retrofit, it is necessary to consider the integration of solar equipment and construction design such as the location of the collector, pipe laying, and water tank, etc. (Song & Jiang 2007).

Generally speaking, the difference of retrofit measures between China and the UK is not great. The 'fabric first' approach is adopted in both countries as the main retrofit approach. However, UK has a more holistic approach involving a series of analysis before applying retrofit measures rather than rushing to start without paying enough attention to the design process in the early stages in China. As a result, most retrofit

projects in China have not achieved satisfying results. The retrofitting of existing residential buildings is a holistic process. It is essential to have a comprehensive survey to ensure that possible risk factors are appropriately evaluated when designing retrofit solutions in a particular construction element. The application of retrofit measures should focus on the consideration of appropriate technology combinations and energy efficiency rather than an uncontrolled bricolage of a large number of different technologies. Proper performance of retrofitting depends on an integrated approach with a proper preliminary design and a range of appropriate technologies.

2.5.4. Implementation Process

2.5.4.1. Implementation Process in the UK

In the UK, the process of retrofitting is very complex: in the pre-retrofitting phase, a large number of surveys and assessments will proceed on different aspects such as market, architectural design, energy use, retrofit technology, cost and stakeholders' perspectives, etc. Also, during and after the major retrofit activity, there will be a regular monitoring system and a persistent procedure of verification and assessment to ensure the retrofit performance (Zhou & Fan 2013).

In the UK, in addition to the government-led, top-down pattern for most large-scale retrofit projects, the 'bottom-up' approach related more to residents' daily decision-making has been given more and more attention. It is often locally driven at the neighbourhood scale, offering investment, jobs and profits to local stakeholders. According to this approach, stakeholders also play an essential role in the retrofit implementation process. In some cases, private sector stakeholders invest in and construct retrofit projects and they not only largely affect the landscape and urban space, but also impact the supply and design of home space, and consequently influence the living quality of residents (Kriese & Scholz 2011).

Figure 2.13 and 2.14 illustrate a systematic approach for the sustainable retrofitting of existing buildings to identify, determine and implement retrofit measures for the best result. The overall retrofit process includes two parts: first is strategic plan and

selection of tools and models; second is retrofit activities in the whole process. It should be noticed that regular monitoring systems and frequent reviews in the long period (i.e. post-retrofitting period) are necessary to ensure the efficiency of the operation system (Ma et al. 2012).

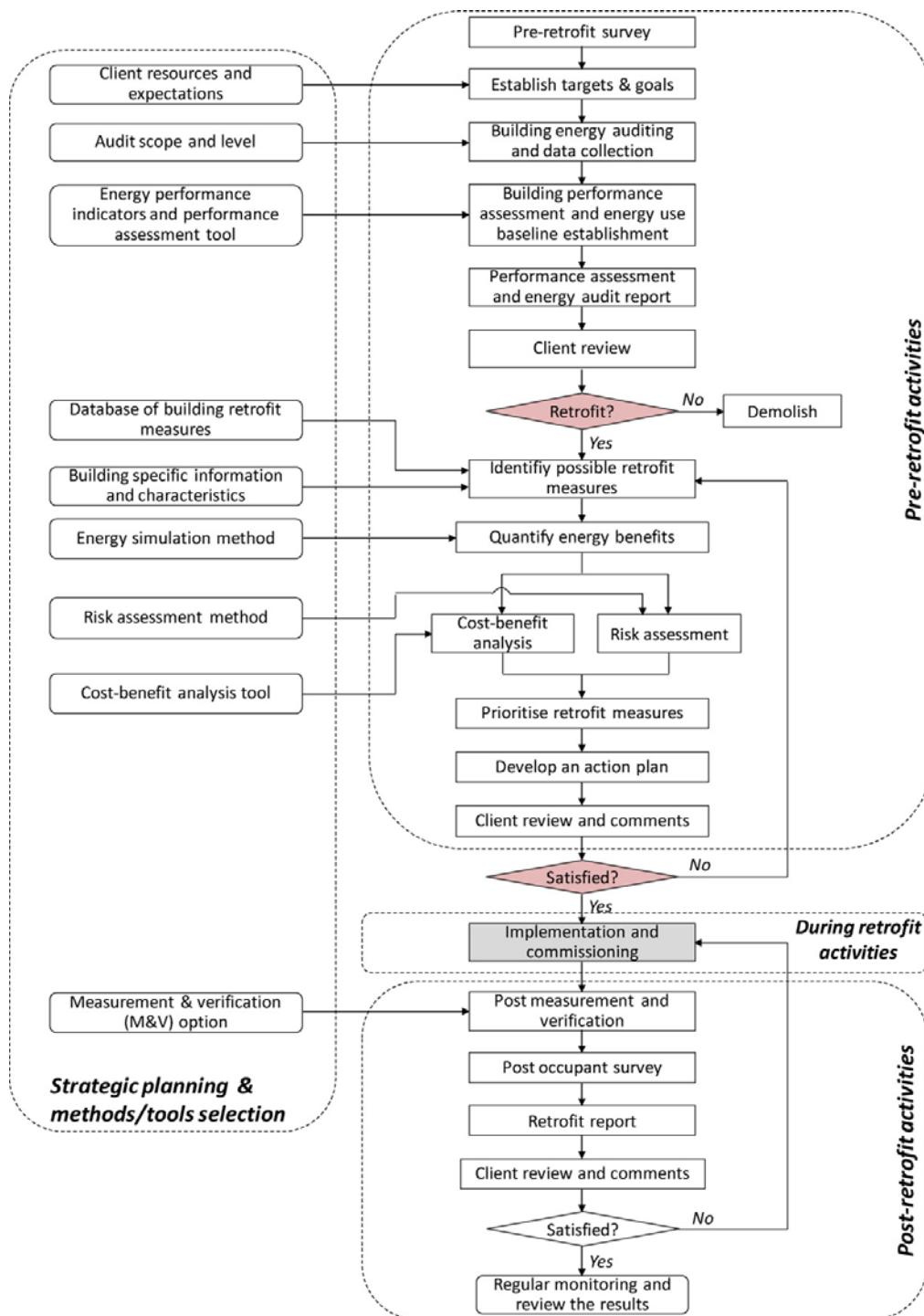


Figure 2.13 A systematic approach for sustainable building retrofits (Ma et al. 2012)

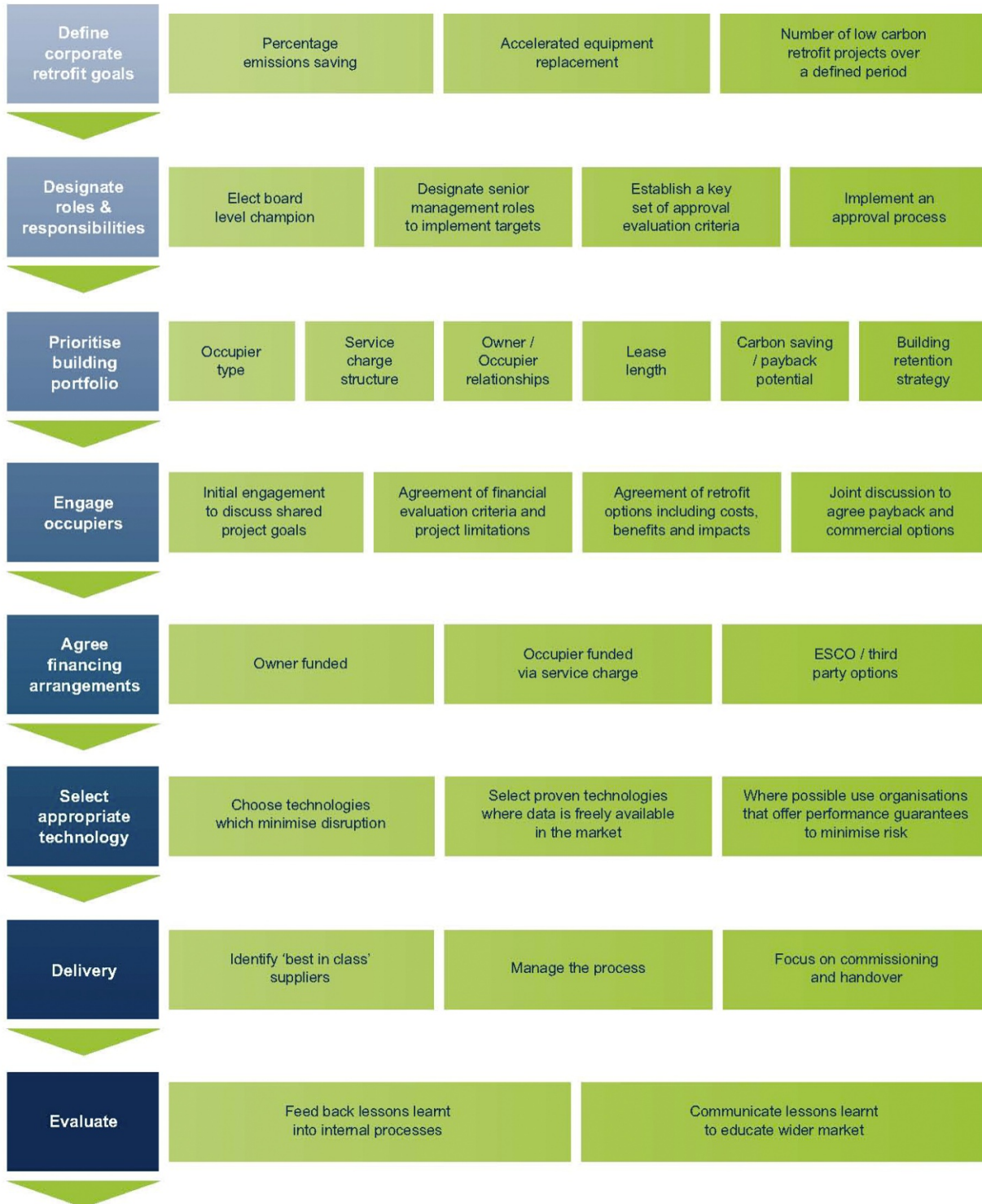


Figure 2.14 A roadmap of low carbon retrofit (Rhoads 2010)

2.5.4.2. Implementation Process in China

In China, most retrofit implementation is government-led, central, top-down, and supply-driven. As shown in Figure 2.15, it mainly controlled by government departments and authorities. The pre-retrofitting assessment is also led by the government. After the approval of different levels of the department, the retrofit will directly pass into the implementation phase. There are few monitoring processes after retrofitting, and the assessment and supervision are also inadequate.

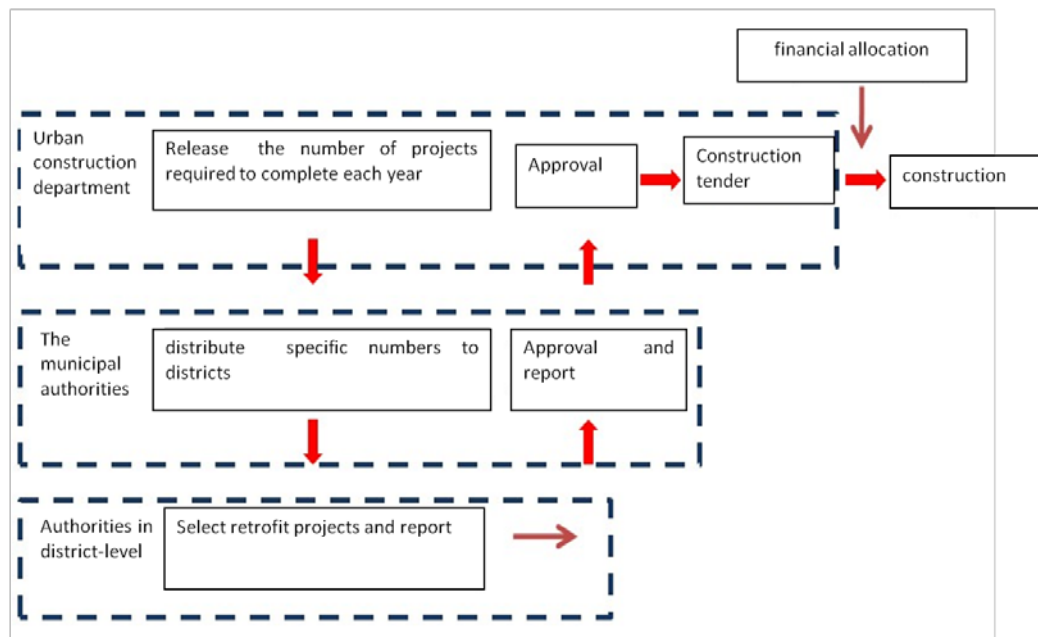


Figure 2.15 Implementation process of existing buildings retrofitting in China (Zhou & Fan 2013)

2.5.5. Financing of Retrofit

2.5.5.1. Financing of Retrofit in China

The cost of retrofitting existing housing in China is mostly funded by the government. The capacity of market financing is weak in most of north China, which leads to significant financing pressure.

Regarding the cost of retrofitting existing housing in China, energy-saving retrofit cost is in the range of 300 to 350 CNY/m² (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012). In 2017, Beijing introduced

technical and economic indicators for the retrofitting of the existing residential communities, which provide some detailed costs for different retrofit measures, as shown in Table 2-4 (Beijing Municipal Commission of Housing and Urban-rural Development 2017).

Table 2-4 Retrofit cost of different measures in China (Beijing Municipal Commission of Housing and Urban-rural Development 2017)

Retrofit measures		CNY/m ²
Wall retrofit	Insulation	196.35
	Painting	9.71
Roof retrofit	Roof insulation	111.93
	water proof	334.63
	Flat-to-pitched roof retrofit (including dismantle the original roof & build the new one)	1077.91
Window replacement	Multi-storey	103.62
	High-rise	110.15
Lighting retrofit	For a four-storey flat	74.7/floor
Heating system retrofit	Heating metering system retrofit	240
	Heating boiler coal-to-gas retrofit	7043.42
Renewables	Solar thermal	500-1500
	PV	1908.26
	GSHP	280-450

In recent years, the China central government has set an example, using the 'Award on Behalf' approach, offering financial award according to climate zones. The standard awards are 55 CNY/m² in the severe cold zone and 45 CNY/m² in cold zones. The award has been divided into two parts, the retrofitting content and process and the management and energy saving, which account for 70% and 30% of the funding, respectively.

Although the government has repeatedly emphasised that the government-led implementation pattern should be changed into a combination of government investment and social investment, this is still in the stage of exploration. China has not

established a mature financing model for this type of retrofit implementation (Fang 2009).

2.5.5.2. Financing of Retrofit in the UK

In the UK, the cost of retrofit existing housing to meet the targeted 80% CO₂ reductions is estimated to be between £200 billion and £400 billion (Sustainable Development Commission 2010). In contrast to China, the majority of retrofitting costs are paid by individual householders, though there is some financial support from the government.

The costs of retrofit measures that are commonly used in the UK, according to the report from the Department for Business, Energy & Industrial Strategy in 2017 (Palmer et al. 2017) are presented in Table 2-5 as below.

Table 2-5 Retrofit cost of measures commonly used in the UK (Palmer et al. 2017)

Retrofit measures		GBP (£)
Wall insulation	EWI	Fixed cost £6000+ variable cost of £111.49/m ² wall area
	IWI	Fixed cost £2400+ variable cost of £73.35/m ² wall area
	Cavity wall	Fixed cost £250-£2240+ variable cost of £4.76-£5.06/m ² wall area
	Solid wall	£55-£180/m ²
Loft/roof insulation		Fixed cost £157.97-£986.82 + variable cost of £22.79/m ² loft area
Floor insulation		£54-£272/m ²
Window replacement	Double glazing	£150-£585/m ²
	Triple glazing	£223-£1022/m ²
Heating (for a small semi-detached property)	gas boiler replacement	£1600-£4000
	oil boiler replacement	£2500-£5000
	cylinder jacket	£39.5-£90
LEDs	bulb only	£3.5-£10/bulb
	including installation	£50/bulb
Draught-proofing	DIY	£85-£290/home
	Professional	£200-£580/home

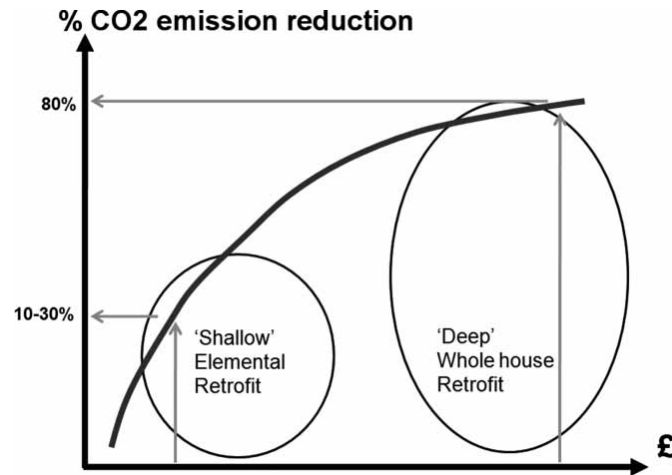


Figure 2.16 How the cost and complexity of refurbishment varies with percentage CO2 emission reductions (Jones, Lannon & Patterson 2013)

Figure 2.16 shows the potential trend in cost growth from ‘shallow retrofit’ measures to a ‘whole-house’ retrofit approach. It indicates that great improvements can be achieved at lower costs, while for savings above 30%–40%, the costs have a sharp increase, although major cost growths appear over 60% emission reductions. As a result, the majority of retrofit projects employ elemental ‘shallow’ retrofit because ‘whole-house’ retrofit normally costs too much, and can hardly be afforded by households (Jones, Lannon & Patterson 2013).

2.6. Fuel Poverty, Affordable Warmth and Human Health

Fuel poverty is ‘the situation where a household cannot heat their home to a comfortable level at a reasonable cost’ which may lead to households either inadequately heating their homes or to unaffordable heating costs (Grey et al. 2015). In the UK, this means that a household needs to spend more than 10% of their income on fuel consumption to maintain a sufficient standard of warmth (Department of Energy & Climate Change 2015b). The main reason of fuel poverty in the UK is identified as poor energy efficiency in homes and low incomes. Other causes are the

size of houses with regard to the number of people living in the properties and the fuel cost (Patterson 2012).

According to BBC News in 2011, 25% of UK homes, and around 41% of Wales homes suffer from fuel poverty and affordable warmth rather than energy saving is still their greatest concern. The paybacks of the large-scale application of energy-efficiency measures may be achieved not only by improving energy performance but also by increasing warmth (Jones, Lannon & Patterson 2013).

Fuel poverty is an important concept to understand the relationship between housing and health (Grey et al. 2015). Housing that does not meet building standards is often difficult to heat. It is estimated that health problems associated with poor building conditions cost the National Health Service (NHS) 2.5 billion pounds a year (Friedman 2010). Research shows that living in cold houses influences the physical health of all people, especially elderly, children, disabled or people with long-term illnesses. Indoor low temperature may result in plenty of health problems, such as cardiovascular disease, respiratory disease, arthritis, rheumatism, circulatory problems, etc. apart from a higher winter mortality. In addition, living in fuel poverty may also cause a series of mental health problems such as depression and anxiety and affect social well-being because of financial stress (Marmot & Bell 2012).

Jones, et al. (Jones, Lannon & Patterson 2013) point out that the built environment has an important influence on people's health and quality of life. Therefore, the reduction of energy consumption and CO₂ emissions can not only increase the energy efficiency of housing but also bring more benefit to residents' physical and mental health.

2.7. Summary

The aim of this chapter is to identify the definition, development, reason and importance of sustainable retrofit. It has reviewed a series issues of related to sustainable development and sustainable retrofit. It started by conceptualising 'retrofit' from a general definition to a concept within a specific context and discussed

the various depths of sustainable retrofit, following by clarifying the reasons, drivers and key elements of existing building retrofit. It then went over the existing literature on definition and development of 'sustainability' across social, environmental and economic aspects, and examined different concepts in the way of sustainable city development. After that, the sustainability at the community level was reviewed to illustrate the significance of community sustainability as a first step toward city sustainability.

As discussed in this chapter, the definition of sustainable retrofit is to improve the building fabric and system to extend the useful lifetime of existing buildings in order to improve energy efficiency, reduce carbon emissions, and improve the residents' quality of life.

To address the sustainability of the retrofitting of existing residential buildings in China, the issues of background, current situation, and challenges were discussed in the subsequent section. The drivers of sustainable retrofitting in China became clearer which can be summarised as follows: firstly, the existing buildings account for significant part of CO₂ emissions in China which is three times that in developed countries; Secondly, the energy consumption of buildings has been increasing more than 10% per year; Thirdly, the total floor area of existing buildings had exceeded 44 billion m² by 2011 and more than 90% are high energy consumption buildings. Moreover, severe air pollution in recent years in China poses a threat to Chinese public health. Also, the changes in building polices, regulations and standards require retrofit to improve energy efficiency and liveability.

In order to improve the energy efficiency and sustainability of cities in China, it is important to understand how and to what extent the retrofitting experiences can be transferred from the UK to China suitably and optimally. Several issues, including energy use, CO₂ reduction targets, policies and regulations, technology, implementation procedure and financial schemes were identified in the last section of this chapter to examine the gap between the UK and China. It found that the gap between the two countries is not great in terms of retrofit measures. However, China's construction methods, retrofit material standardisation and on-site detail handling still need to be improved. Comparing to China, the UK pays more attention to the

design processes and surveys at early stages and has a more holistic approach including a series of analysis before retrofit.

The best retrofit results can be achieved by applying an integrated approach with appropriate technology combinations. Therefore, a more detailed understanding of the retrofit measures, processes, costs and retrofit effects of the UK retrofit project, as well as current retrofit status and issues in reality in China, to further identify how to transfer the UK's advanced experience to China.

Chapter 3 Methodology

3.1.Introduction

This research investigates a series of questions about the retrofitting of existing residential buildings at community scale in China. A holistic method based on qualitative research and simulation research was developed, including a literature review, case studies, on-site surveys, interviews, and modelling for the Chinese case studies.

This chapter provides an overview of the research methods employed, the analytical framework developed and the case study selection in this research. It begins with a review of several traditional research methods for architecture research and is followed by descriptions of the research methods chosen. The next section introduces the building energy modelling development and the modelling software adopted in this research. Following this, the research framework and the simulation process flowchart are presented. Lastly, the method's limitations are discussed.

3.2.Research Method Review

As defined in the book of *Research Methods for Architecture*: 'A research methodology is a way of finding something out about a topic – a set of practical and pragmatic activities that allow you to ask the relevant questions and achieve some robust conclusions' (Ray 2016).

Architecture research does not contain only one research method, which is a big advantage of the discipline. It gives researchers the opportunity to access a wide range of issues related to the built environment (Ray 2016). Therefore, it is important to know the different methods available for architecture research and find out which is suitable to apply to this study.

3.2.1.Context-led Research, Methodology-led Research and Theory-led Research

Context-led research is doing research based on a typical or unique context to build the essential significance of the physical, social or historical setting. It allows the context to be the main part of the research process, and examine it according to other circumstances based on the same principle. The context can be in various forms such as a specific typology, a town, a period of time, or a particular career, etc.

Methodology-led research means applying a relatively developed methodology into a new context, which often leads to new possibilities arising. Knowledge plays a pivotal role during the research process. The context is a changeable setting. As a result, the results of the study may vary depending on the context, which may also modify the research method during the research process.

Theory-led research begins with an established form of understanding and applies this to a context through a method. As theory covers a wide range of category and does not have a direct difference with the method, many methods have a strong connection with theoretical content. Most of theory-led research is usually interdisciplinary and borrows theories from other fields like philosophy or the social sciences, etc. (Ray 2016)

This research is methodology-led and combines a range of established methods informed by previous social science researchers to produce a suitable and holistic approach and applies this approach to the context of the UK and China. The application of the methods is described in this chapter.

3.2.2.Qualitative Research

3.2.2.1.The Definition of Qualitative Research

The definition of qualitative research was given by Norman Denzin and Yvonna Lincoln:

'Qualitative research is multi-method in focus, involving an interpretive, naturalistic approach to its subject matter. This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret phenomena in terms of the meanings people bring to them. Qualitative research involves the studied use and collection of a variety of empirical materials' (Denzin & Lincoln 1994).

Qualitative research provides insights into the issue and helps to formulate ideas or theories for potential quantitative research. Qualitative research is often used to understand underlying opinions, reasons, thoughts, and motivations. The qualitative data collecting approach often uses unstructured or semi-structured techniques. Some common approaches contain development and practice, ethnography, research and service demonstrations, group discussions, individual interviews, case studies and participant observations. The sample size is often small and respondents are chosen to fulfil a given quota.

3.2.2.2.Key Elements of Qualitative Research

As indicated in the book *Architectural Research Methods*, qualitative research focuses on five key elements (Groat & Wang 2002).

The first element is a natural setting, which means the objects being studied commonly exist in the same context as part of daily life, the research will study its natural state rather than influence them.

The second element is interpretation and meaning. This means the researchers play an important role in explaining and making data clear during their work besides observations and interviews, etc.

The third element is whether the respondents understand their own circumstances. It is significant that researchers should explore and understand the respondents' perspectives about different aspects in detail to gain a holistic picture of the phenomenon.

The fourth element is the use of multiple approaches. This suggests that qualitative researchers should combine a series of approaches which are suitable for both research questions and the context being studied rather than focus on the single key question. This provides researchers with more comprehensive perspectives and data.

The final element is inductive logic. The research questions explored through a qualitative study are often developed and refined in a reduplicative process. This enables the researchers to examine the thinking and opinions identified from the ongoing observations.

3.2.2.3.Relation to this Research

Qualitative research emphasises a holistic exploration of complicated situations and context. This research has a comprehensive subject involving human factors as well as many aspects across the environment, society, economy, etc. It needs to compare multiple aspects, such as policy, retrofit measures, implementation processes, financial schemes, etc. through a variety of perspectives such as those of researchers, policymakers, technicians, project managers, and residents, etc. It also requires studying the literature and fieldwork to understand the whole process of the retrofit projects and collecting data. Therefore, this research employs a comprehensive qualitative approach to study the background, development, technology and current situations of the sustainable retrofitting of existing residential buildings in the UK and China.

3.2.3.Simulation Research

After data collection about the subjects through the survey approach, simulation can be considered as a measurable, relatively accurate approach to achieve the research main objective: to identify the most suitable, sustainable, cost-effective retrofit solution combinations for residential buildings in China to reduce energy consumptions and CO₂ emissions as well as to improve existing housing.

3.2.3.1. Definition of Simulation Research

According to Groat and Wang (2002), 'Simulation' is defined as 'the representation of the behaviour or characteristics of one system through the use of another system, especially a computer program designed for the purpose'. This definition contains the basic meaning of simulation and indicates the growing dominance of the computer in this area.

In terms of simulation of energy use in building sectors, it is necessary to create comprehensive models to assess the technical economic impacts of applying the energy efficiency and renewable energy technologies appropriate for residential applications, as the characteristics of energy consumption of the residential buildings are very complex (Swan & Ugursal 2009).

3.2.3.2. The Top-down and Bottom-up Approaches

Generally, there are two basic typical modelling methods applied for predicting and analysing different aspects of the energy consumption performance and CO₂ emissions of building stocks, which are the top-down and bottom-up approaches (Kavgic et al. 2010). The general content of these two approaches is outlined in Figure 3.1 and in the following.

The top-down approach regards residential building as an energy sink and does not differentiate between energy consumption for personal and other end-uses. Top-down models are often used to determine the supply demands and the impact on energy consumption from long-term changes within the residential building. Variables commonly used in top-down models are macroeconomic indicators such as gross domestic product (GDP), employment proportions, climatic conditions, building construction or demolition rates and numbers of units in residential buildings. The advantage of this modelling is that it is easy to obtain reliable, simple aggregate data. The disadvantage is the lack of detailed data of energy use from end-uses, so that it is

not able to find out the factors affecting the energy performance and improvements (Swan & Ugursal 2009).

The bottom-up approach is established from data on a hierarchical level of disaggregated components. The data can be combined and analysed to explain and estimate the impact of individual end-uses, individual houses, or groups of houses on energy consumption and CO₂ emissions (Kavgic et al. 2010). General input parameters include building attributes such as fabric, age, climate data, temperatures, occupancy and appliances, etc. The strength of bottom-up models is that they have a high level of detail, which allows the model to simulate technological options, so that it can predict the energy consumption of each individual end-use and explore improvement areas. The relevant drawbacks are that it requires the extensive of input data to support each component, which is difficult to obtain, and the calculation techniques are more complex than those in top-down models (Swan & Ugursal 2009).

A whole-house bottom-up approach have the potential to model buildings in detail to consider complicated interactions of residents, passive design and active systems, which is relatively easier to send the message of 'multiple benefits', while a top-down approach is more inclined to avoid problems. Sustainability should improve a better quality of living instead of avoiding problems (Jones & Jones 2017).

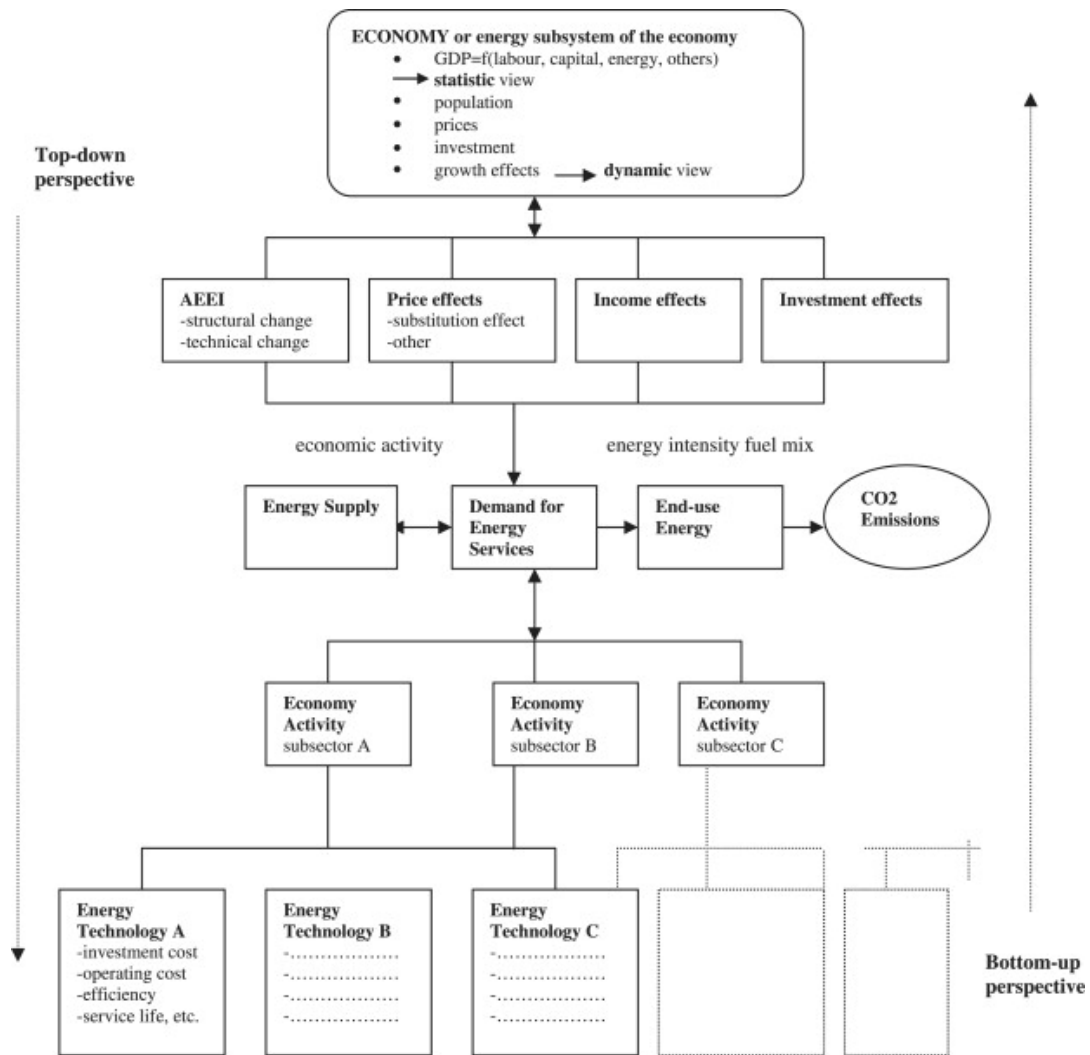


Figure 3.1 Top-down and bottom-up modelling approaches (de Sa al. 1999)

3.3. Details of Research Methods Used to Meet Thesis Objectives

This research adopts a holistic method based on qualitative research and simulation research, including a literature review, case studies, on-site surveys, interviews, and modelling for the Chinese case studies. The inductive approach is applied to analyse and summarise the research outcomes. The method employed in this research is outlined in Figure 3.2 as follows.

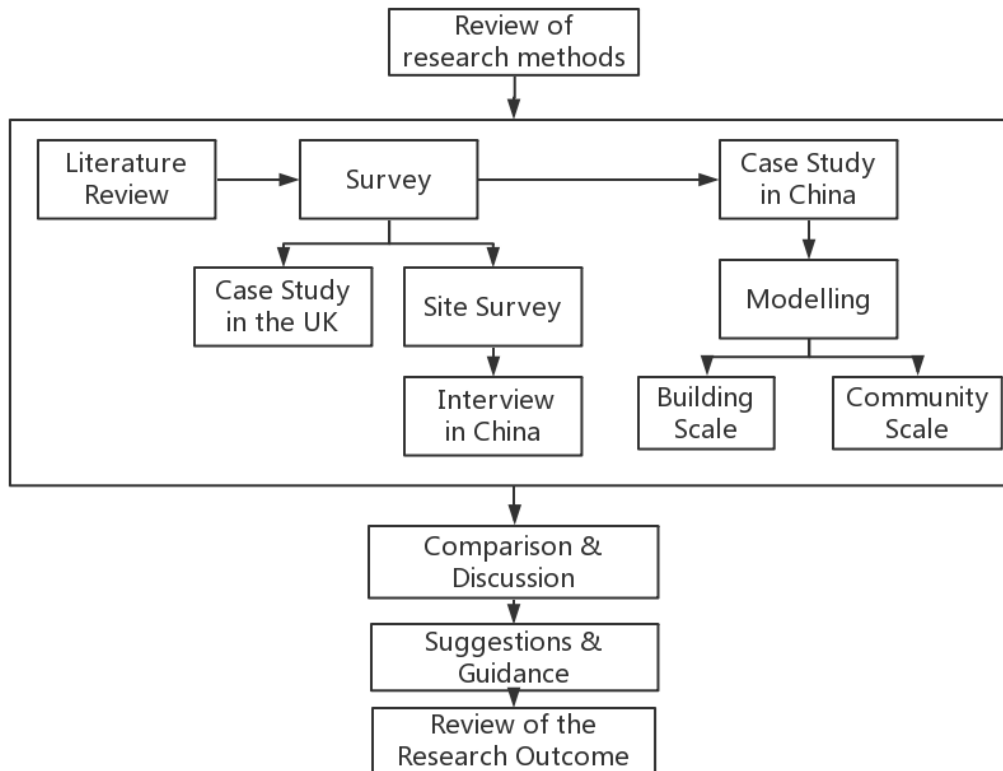


Figure 3.2 Research methods outline

Since the UK case studies in chapter 4 have already been modelled in the UK by others using the same software used in the China case studies in this thesis and compared with the actual monitoring data, the author did not repeat the simulation part for the UK cases, but carried out a comparative analysis and summary. The Chinese cases has been modelled, analysed and compared from different aspects at both building and community scale.

3.3.1. Literature Review

As presented in Chapter 2, a literature review was conducted at the beginning of this research in order to achieve Objective 1:

To identify the definition, development, reason and importance of sustainable retrofit.

This primarily involves the issues surrounding sustainable development and sustainable retrofitting in China and around the world, which can be summarised as follows:

- The concept of ‘retrofit’ from the general definition to concept within a specific context, and the reasons, drivers and key elements of existing building retrofitting;
- The definition and development of ‘sustainability’ across social, environmental and economic aspects and the different ways of sustainable city development;
- The concept of sustainability at the community level and the significance of community as a portal of cities toward sustainability.
- The issues of the background, current situation, challenges of the sustainability of retrofitting the existing residential buildings in China.
- The comparison of sustainable retrofitting between the UK and China in terms of energy use, CO₂ reduction targets, policies and regulations, technology, implementation procedures and financial schemes.
- The issues of fuel poverty, affordable warmth and their relationship with human health.

These issues are illustrated in Figure 3.3 as follows:

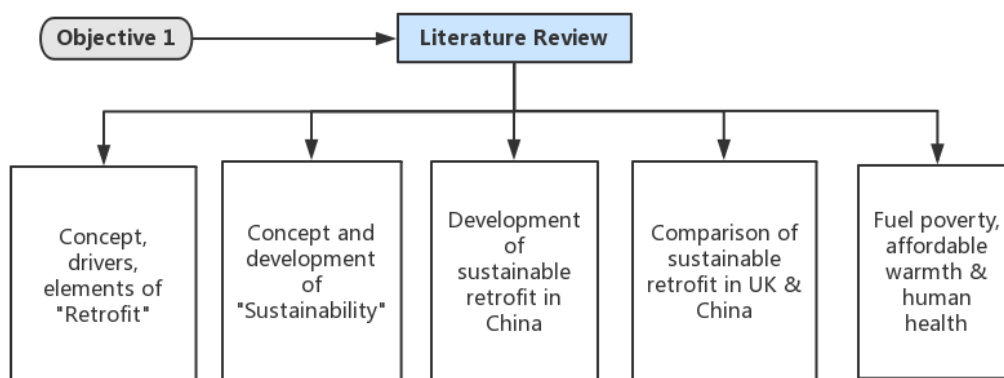


Figure 3.3 Outline of literature review

Throughout literature review, the definition, development, reasons and importance of sustainable retrofit have been identified.

3.3.2. Site Survey

Generally speaking, the survey research method is often used to collect information. As explained by Jackson, the essence of the survey method is ‘questioning individuals on a topic or topics and then describing their responses’ (Jackson 2015).

In this research, the survey is used for the investigation of the current situation, experience learning and data collection. It involves three main activities including case studies, site surveys and interviews for selected cases in Wales and China to find the answer to the second and third research questions, as shown below:

- How is the sustainable retrofit developed in the UK? What are the processes, implement methods, technologies and financial schemes of low carbon retrofitting in the UK in practice?
- What are the problems and challenges of current housing retrofit in China? To what extent can the UK’s experiences be transferred to China?



(a)



(b)



(c)



(d)

Figure 3.4 Photos of site survey at the retrofit project in Neath Port Talbot, Wales. (a) Construction site; (b) Insulation materials on site; (c) Insulation boards; (d) Time and temperature control on site

As mentioned by Ray (2016), site survey means gathering information directly from the site by going to and spending time there. This gives researchers opportunities to observe and record so that they can avoid second-hand observations and biases. Site survey requires a sufficient preparation, including collecting information about the social, political and historical context to obtain a better awareness to maximise the use of survey resources.



(a)



(b)



(c)



(d)

Figure 3.5 Photos of site survey at the retrofit project in Beijing, China. (a) Block of flats prior to retrofit; (b) Flats in the same community post retrofit; (c) Tail water recycling equipment; (d) Electricity data collection device

The purpose of site survey in this research is to investigate the housing retrofit technologies, material uses, implement processes, construction methods and the improvement effects in practice in order to learn from the experiences and analyse the effective strategies and areas for improvement.

The site survey in this research was carried out several times between 2014 and 2017 in the UK and in China. It contains three parts: first is the field research of selected retrofit project in Neath Port Talbot in Wales; second is the interviews conducted in Beijing, Tianjin and Xi'an in China; third is the field research of selected retrofit project in Beijing in China.

Before visiting, preparation works were carried out, including gathering information through the documental survey, figuring out the content being focused on in the field and contacting relevant people. During these visits, observations were made on a range of aspects including retrofit materials, construction technologies, and the implementation processes. Connections were made with the neighbourhood committee staff for the follow-up interviews in China. Figures 3.4 and 3.5 are the site survey photos taken by the author in Wales and China, respectively. It should be pointed out that for the case study in the UK, the main methods are literature review and data analysis from previous published papers and reports, and the site survey is used to better understand these cases.

3.3.3. Interviews

As mentioned by Ray (2016), interviews are an important method to obtain research information from many relevant people engaged in architectural projects, such as the architects, building users and project managers. It generally contains two basic types, which are structured questionnaire-based interviews and unstructured interviews and open-ended conversations.

In this research, interviews were used to accomplish Objective 3, which is: to discover the problems of current retrofitting of existing residential buildings in China to find out the gap between the UK and China.

Ten interviews were carried out between June 2015 and December 2017 in three cities in northern China in the form of unstructured face-to-face interviews and free-flowing conversations. The interviewees have been divided into four groups: researchers in universities, government staff from the Environmental Protection Bureau, residents living in a retrofitted community, and architects who participated in retrofitting projects. Initial questions about the sustainable retrofitting of existing residential buildings at a community scale were prepared for different groups of interviewees in order to start the conversation. Then, more open-ended talks were conducted to let the interviewees provide more extensive information from their perspective.

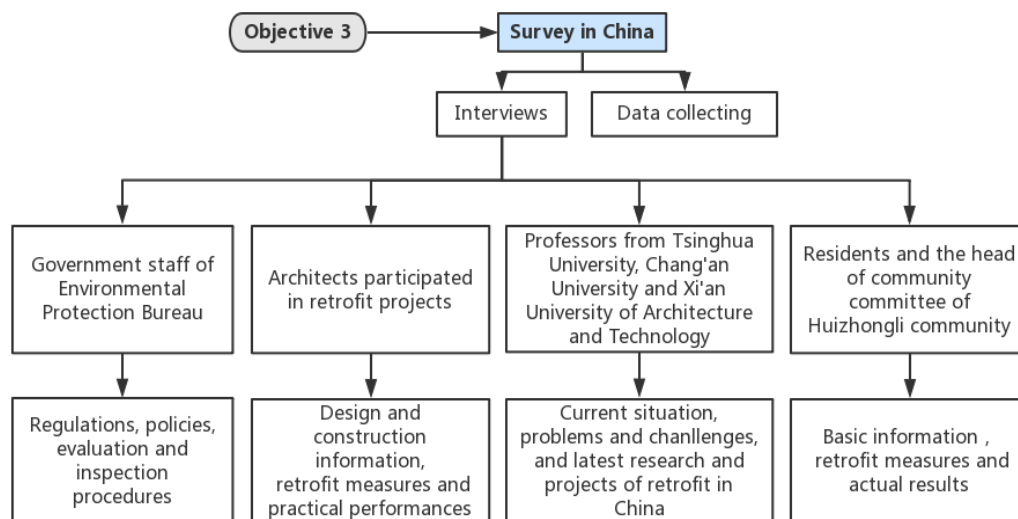


Figure 3.6 Four groups of interviewees

The purpose of the interviews is to understand the development of sustainable housing retrofitting in China from multiple points of view. First, this was done by interviewing university professors to know their perspectives on current research and to learn more about China's latest housing retrofit studies and projects. Second, interviews with government staff were conducted to find out the government point of view about sustainable housing retrofitting on policy formulation, retrofit supervision and management, etc. Thirdly, interviews were conducted with architects to learn more about the design and construction information for retrofitting existing communities. Lastly, interviews were conducted with residents of the local

communities to gain their opinions about the retrofitting performances and suggestions for improvement.

Through interviews, more insight and detailed data on sustainable housing retrofitting in China has been gained and collected, which is significant to evaluate the current sustainable retrofitting development in China and propose the case study framework.

3.3.4. Case Study

As defined by Robert Yin, 'A case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident' (Yin 2013). As for architectural research, case studies contain both contemporary and historical phenomenon and settings, so Groat and Wang (2002) modified this definition to be more applicable to architecture study, which is 'an empirical inquiry that investigates a phenomenon or setting'.

3.3.4.1. Case Study in the UK

The case study in the UK is used as a method to achieve Objective 2:

To explore the UK's retrofit methods, implement processes, technologies, financial schemes, and multiple benefits through practical projects.

This includes a desk-top research of project reports, government reports, news, local standards, architectural design documents and data analysis documents. These documents involve:

- The reports of seven exemplary housing retrofit projects in Wales.
- The clustering and modelling data of the housing retrofit projects in Wales.
- The documents of background, the census boundary data, and geographical data of the housing retrofit cases in Wales.

- The master plans, architectural designs and construction drawings of the selected cases in China.
- The latest local standards and regulations in cold and severe cold zones in China.
- Publications and basic information of the selected demonstration retrofit projects in Beijing.
- News and government reports from the internet and local media which give up-to-date information on the selected cases.

The purpose of the case study in the UK is to investigate the exemplary housing retrofit projects in Wales, explore the implementation of the reproducible and transferable low carbon technologies and strategies from the completed and ongoing housing retrofit projects. The outline of the case study is illustrated in Figure 3.7.

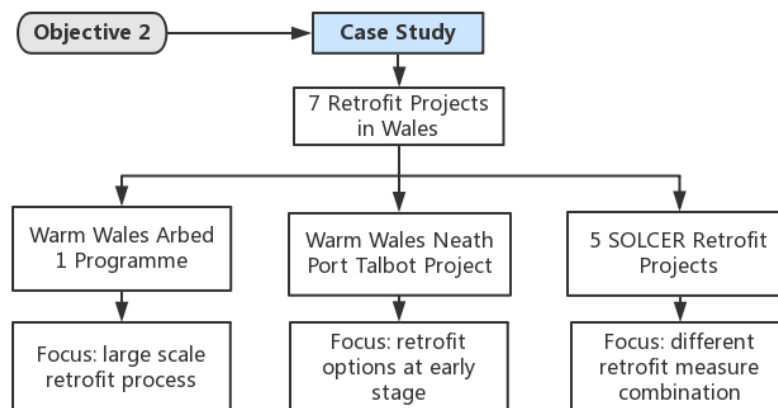


Figure 3.7 Outline of case studies in the UK

Through the case study, the UK’s low carbon housing retrofit processes, implementation methods, technologies and financial schemes have been investigated. The specific information and main outcomes of the selected projects in Wales are presented in Chapter 4.

3.3.4.2. Case Study in China

The aim of the case study in China in this research is to examine the effectiveness of different combinations of low carbon technologies and strategies in relation to reduction of energy consumption and CO₂ emissions in order to answer the fourth research question: ‘what strategies can be gathered to improve the existing housings and communities in China?’ Combined with the modelling simulation mentioned in next part, the aim is to achieve Objective 4: to identify the most suitable, sustainable, cost-effective approach in transferring the retrofit technologies and processes from the UK to China to improve existing residential buildings and communities.

In the case study, four typical residential buildings built between 1983 and 2001 in China were introduced. Two methods were applied to collect information including desktop data collection and interviews with staff involved in the projects’ design and implementation procedure. An energy performance prediction model was developed to simulate these dwellings within the local communities. The information of the selected cases in China will be introduced in detail in Chapter 6.

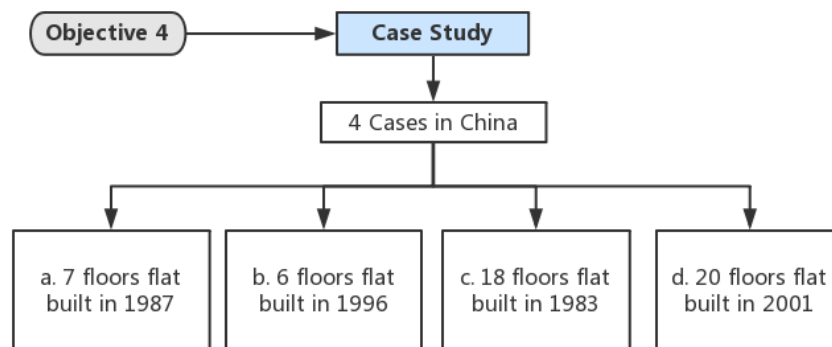


Figure 3.8 Selected cases in China in this research

3.3.5. Modelling

In retrofit design and planning, energy simulation modelling, as a very effective tool to examine a series of options quickly at an early stage, can be used to predict the

energy performance of the building in terms of energy reductions, CO₂ emission reductions and cost savings (Li et al. 2015).

This research adopts simulation method for predicting and evaluating the retrofitting of the existing residential buildings. This simulation is based on four cases at both the building and community scales and the input parameters include the information of location, weather data, layout, building dimensions, construction materials, and heating, cooling, ventilation, lighting, small power and occupancy data. The model can be modified along with the retrofitting work when more retrofitting measures are being checked, so more realistic conditions can be modelled. The information used was taken from national statistics, design principals, building standards, and site surveys.

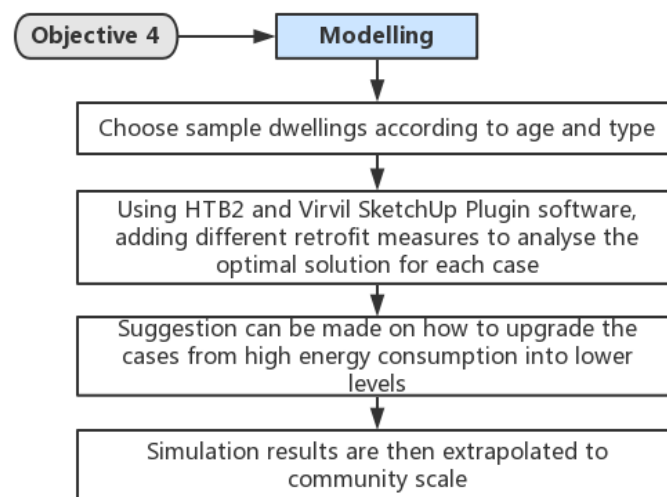


Figure 3.9 Basic modelling process

3.3.5.1. The Software Selected for this Research

The software employed in this research includes HTB2 and VirVil SketchUp Plug-in. Both of them are developed at the Welsh School of Architecture, Cardiff University (Li et al. 2015).

3.3.5.1.1.Introduction of HTB2

As defined by Alexander (Alexander 2008), 'HTB2 is a computer program designed for simulating the thermal performance of energy efficient occupied buildings'. It has been developed over 30 years and aims to provide a flexible tool to study the detailed operation of a building stock on a short timescale. HTB2 is built to calculate the energy demand to maintain particular indoor thermal performance, and involves indoor temperature prediction, solar gain, ventilation, etc. The fundamental building processes and interactions of HTB2 are presented in Figure 3.10.

The input data of HTB2 includes the hourly climate of the place, site location and layout, building dimensions, construction materials, service system and occupancy data, and ventilation characteristics, which have been illustrated in Figure 3.11. The method employed in HTB2 is to divide time into discontinuous slots and to assume that each heat flow process stays constant and independent of the others. The time slot is normally less than one minute so that the data can be output on a small timescale. Because of the flexibility and ease of modification, HTB2 is suitable for applying to the field of low carbon design of buildings and energy efficiency predictions.

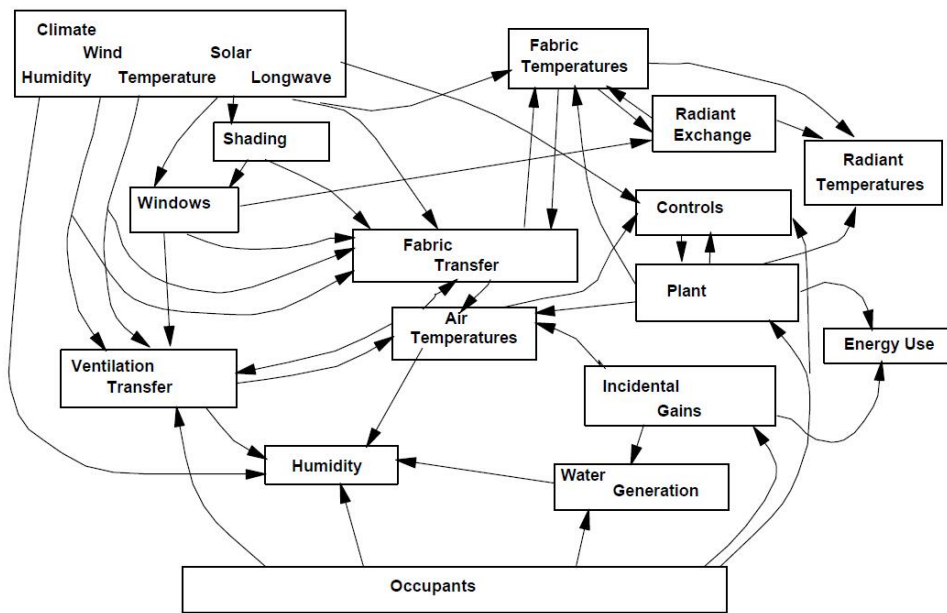


Figure 3.10 Fundamental Building Processes and Interactions (Alexander 1996)

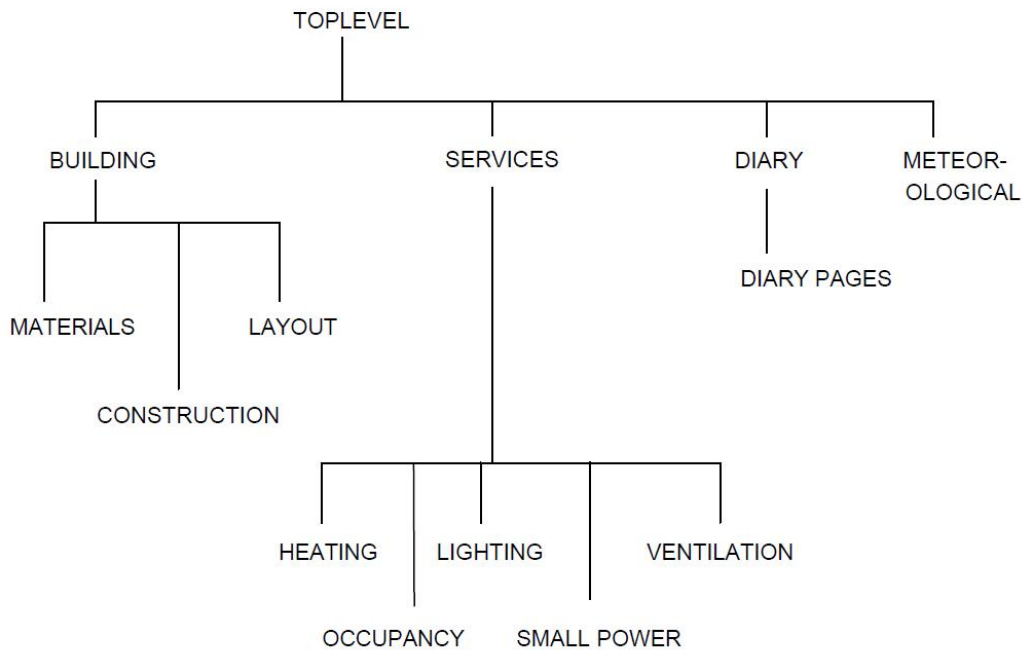


Figure 3.11 HTB2 hierarchical file structure (Woetzel et al. 2009)

3.3.5.1.2. Introduction of VirVil Plug-in

The VirVil SketchUp Plug-in is an extension development of HTB2, which links the 3D design tool to a dynamic simulation model and uses it to predict the energy consumption and evaluate the impact of sustainable technologies and measures in the built environment at community or urban scale at an early stage.

As mentioned by Smith et al. (2008), VirVil concerns the impact on the community or the city as a whole, as well as on single buildings, and combines current state-of-the-art simulation capabilities to provide the most comprehensive and reliable modelling possibilities. VirVil contains three groups of tools. The first is used for 3D model simplification; the second is designed for connection of the model and surrounding areas; the third is developed for building attributes setting up and calculation control. The interface and flow diagram of the VirVil are shown in Figures 3.12 and 3.13 respectively.

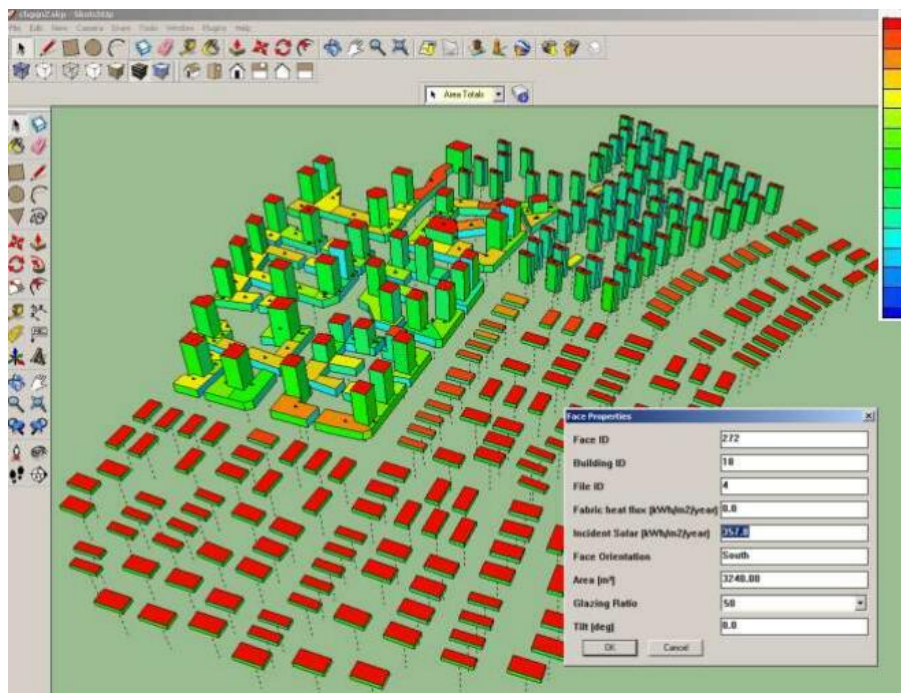


Figure 3.12 The interface of VirVil Plug-in (Bassett 2012)

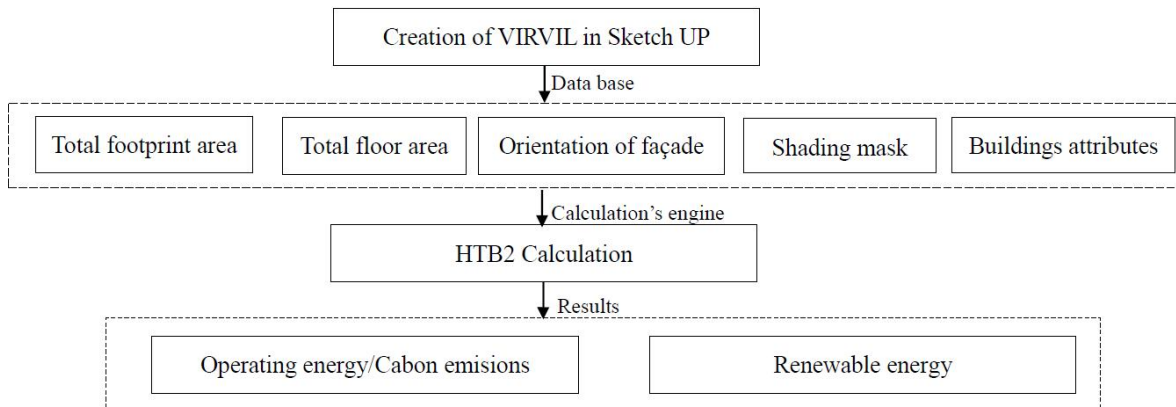


Figure 3.13 Flow diagram of the VirVil tools (Bassett 2012)

In short, HTB2 can predict the hourly energy data of the building and is easy to adjust, and VirVil can effectively simulate the energy flow and can be used for large scale modelling with consideration of the shading effects from adjacent buildings. Due to the comprehensive consideration of the potential of renewable energy and the implicit energy and CO₂ emissions of buildings and components, the simulation tools can provide a more accurate and holistic assessment of the overall energy performances of the residential buildings at different scales. By combining HTB2 with VirVil SketchUp, multiple buildings in a community or in a city can be simulated in terms of overshadowing impacts, landscape features and typography (Jones et al. 2013).

3.3.5.2. Research Model

Data was collected before doing the simulation work, including the weather data for Beijing, the site location, the building layout of selected buildings and communities and construction data such as the fabric materials, glazing ratios, thermal properties of the materials and service systems. Some information about indoor conditions such as heating, ventilation, internal gains from occupants and appliances have been adjusted and assumed by referring to benchmarks and typical scenarios. After refining and classifying the property data by age and typology, the four original cases, without any internal heat gains settings, were modelled in VirVil SketchUp and HTB2 as base

cases, following by the four cases with internal heat gains for comparison. After that, a range of retrofit measures were selected and modelled based on the previous survey. Then the modifications of heating, lighting and ventilation systems and renewable energy were made to explore the impact of each combination of retrofit measures on energy consumption, CO₂ emissions and cost savings. Lastly, an analysis of the simulation result was carried out, and the accuracy and limitations of the simulation were evaluated. Figure 3.14 shows the basic simulation process as follows.

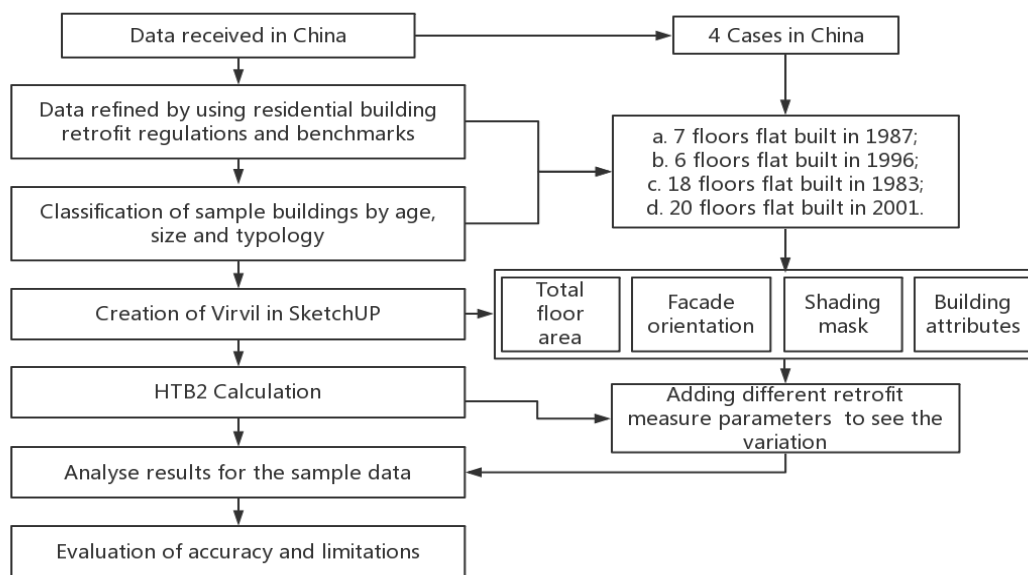


Figure 3.14 The simulation flow chart for case studies in China

3.3.6. Analysis

An overall analysis was conducted on three aspects, including the modelling results, suitable retrofitting solutions to be transferred, and the discussion of practical implications, combined with social, environmental and economic aspects in order to achieve the last objective: to discuss research outcomes with more social, economic aspects and multiple benefits to provide suggestions and guidance for retrofitting residential buildings in China to create a high quality living environment.

The following chart illustrates the analysis process in this research. The modelling results are analysed by combing with elevator installing, indoor living quality, costs,

potential savings, local culture, and multiple benefits, etc. to find out a more suitable, feasible, cost-effective solution for retrofit projects in practice.

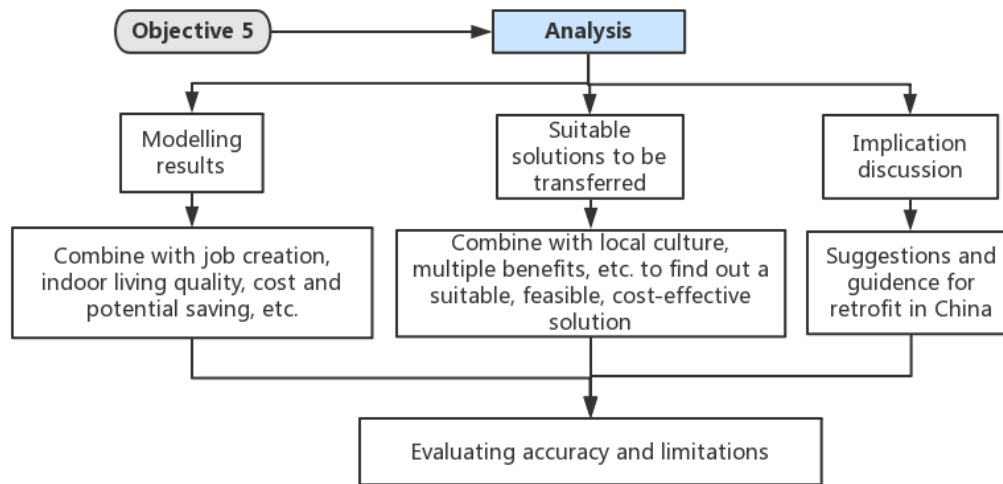


Figure 3.15 An overall analysis of modelling results, suitable transferred solutions and implications for practice.

3.4.Limitation of this Method

There are some limitations of this method:

Firstly, this research method focuses on the cold and severe cold climate zones in northern China, which may not be suitable for predicting the impact of sustainable housing retrofitting in other climate zones or in other contexts in the world.

Secondly, this research method focuses on existing residential buildings, so that it may not be used for evaluating the energy performance of other types of buildings.

Thirdly, this research method is for the community scale and might not be able to assess housing retrofitting effects on an urban scale.

In addition, the context, scale, typology and age, etc. of housing retrofitting projects between the UK and China are slightly different. As a result, there are some limitations in the comparison of the sustainable housing retrofitting between UK and China, and the delivery of sustainable retrofit measures combination may not be a perfect fit in

reality. Therefore, it is important to consider and choose each measure to combine with local conditions when applying the retrofitting.

Moreover, this research focuses on the operating energy consumptions and CO₂ emissions. The embodied energy has not been simulated, which may be considered a limitation as well.

Lastly, there are some assumptions in the simulation modelling. For example, the data of internal gains from occupants, lighting and other appliances are taken from benchmarks and typical scenarios.

3.5.Summary

This chapter systematically explains the methodology employed in this research, which is a holistic method based on qualitative research and simulation research, including a literature review, site surveys, interviews, case studies and modelling. The inductive approach is also applied to analyse and summarise the research outcomes at the end of this research.

Chapter 4 Case Study in the UK

4.1. Introduction

In order to understand more deeply about the current achievements in retrofitting existing residential buildings in the UK and answer the research question of ‘How is the sustainable retrofit developed in the UK? What are the retrofit methods, implement processes, technologies, financial schemes, and multiple benefits of low carbon retrofit in the UK in practice?’ it is necessary to analyse particular retrofit projects to obtain more detailed data for reference. Thus, based on the literature review, seven Welsh retrofit projects involving properties of different scales, ages and types were chosen for the case study in this chapter.

The reason for choosing these projects is that firstly there are over 20 million existing homes in the UK (Palmer et al. 2014)(Utley & Shorrocks 2012) where the housing replenishment rate is just 1% per year (Department of Energy and Climate Change 2015). Secondly, the residential buildings in the UK are some of the oldest in Europe (Baeli 2013). Many of them were built before 1919s with solid wall constructions, resulting in more difficulties in dealing with the implementation of energy efficient measures. Therefore, some effective solutions and practical experiences have been gradually explored and cumulated in treating problems and details in different situations. In addition, as the UK and Europe have been starting to focus on low-carbon retrofitting and CO₂ emission reductions for some time, they have more practical experience and a better understanding of building physics in existing residential buildings retrofit. Over the years, a series of relevant regulations, standards and procedures have been promulgated and modified, and they are gradually becoming more stringent on the efficiency of buildings. Therefore, it is significant to study the UK’s retrofitting of existing housing projects.

Table 4-1 lists a basic overview of the seven retrofit projects from scale, retrofit approach, number of property, dwelling age, type, and tenure.

Table 4-1 A basic information of seven Welsh retrofit projects

Basic Information	Retrofit 1	Retrofit 2	Retrofit 3	Retrofit 4	Retrofit 5	Retrofit 6	Retrofit 7
Project	Warm Wales Arbed 1	Warm Wales Neath Port Talbot	SOLCER retrofit project	SOLCER retrofit project	SOLCER retrofit project	SOLCER retrofit project	SOLCER retrofit project
Introduction	7 of 28 projects in wales funded by Welsh Government.	Housing stocks in Neath Port Talbot County Borough Council	67 m ² , 2-bedroom house with solid wall, gas boiler.	70 m ² , 3-bedroom house with cavity wall, gas combi-boiler.	86 m ² , 3-bedroom house with cavity wall, gas boiler.	74 m ² , 2-bedroom house with solid wall, gas combi-boiler	80 m ² , 3-bedroom house with cavity wall, gas combi-boiler
Scale	Regional	Regional	Building	Building	Building	Building	Building
retrofit approach	Elemental/ Shallow	Elemental/ Shallow	Whole-house/ Deep	Whole-house/ Deep	Whole-house/ Deep	Whole-house/ Deep	Whole-house/ Deep
Number of property	1147	46686	1	1	1	1	1
Age	Pre-1919: 40%; 1945-1964: 24%; 1965-1980: 18%; Post 1980: 18%	Pre-1919: 29%; 1919-1964: 43%; 1965-1980: 16%; Post 1980: 12%	Pre-1919	1960s	2000s	Pre-1919	1950s
Type	Semi-detached/ End-terrace: 49%; Mid-terrace: 29%; Flat: 21%; Bungalows: 1%	Houses: 82.7%; Bungalows: 8.4%; Flats: 8.7%; Maisonettes: 0.2%	End-terrace	Semi-detached	Semi-detached	Mid-terrace	Semi-detached
Tenure	Registered Social Landlords (RSLs): 57%; Local authority: 24%; Owner occupier: 19%	Owner occupied: 73%; Local authority rented: 20%; Private rented: 3%; Housing association: 4%	RSLs	RSLs	RSLs	RSLs	RSLs

The first two cases are elemental retrofit on a regional scale in Wales. The aim is to investigate the procedure of existing housing retrofitting in the UK at large scale and how to make the most effective and reasonable retrofitting in this scale in the case of limited funds. The reason for selecting these two projects is that currently, most of the existing residential building retrofit projects in China are done on a community scale. Thus, it is necessary to investigate and study retrofit projects on a similar scale. Besides, in-depth surveys and assessments have been carried out at the very beginning of these two projects and are crucial for any retrofit project. Moreover, the method for predicting the retrofit performance and CO₂ reduction is worth learning for reference. In addition, these two projects demonstrate good examples of the social, economic aspects of retrofitting. Therefore, it is significant to survey these two projects to see if any experiences can be transferred to the case studies in China.

After the first two cases, five Welsh retrofit projects in building scale were studied. A whole-house approach, which combines reduced energy demand, renewable energy supply and battery storage, were used in these retrofit projects. The purpose is to understand which combinations of retrofit measures can be used for retrofitting certain types of buildings in order to maximise the improvement result. The reason for choosing these five projects is that the whole-house approach is scarcely used in China's domestic retrofit due to high capital costs, but this approach has more advantages in terms of energy saving, CO₂ reduction as well as the social and economic aspects. Therefore, the whole-house approach will be more frequently used in future domestic retrofit projects for better retrofit results. Thus, it is important to identify how to import the deep or whole-house retrofit approach into China's domestic retrofit projects.

Each project begins with the description of the basic information, followed by a summary of the work. Then, the main outcomes of the environmental, social and economic aspects of the project are extracted. The retrofit measures, financial schemes, performances, CO₂ emission reductions, supply chains, potential savings and multiple benefits of each project are investigated and compared. After this, the main outcomes of the documental survey are discussed.

4.2.Survey of Project 1: The Warm Wales Arbed 1 Retrofit Programme

The word ‘arbed’ means ‘to save’ in Welsh. The Arbed programme was divided into two phases. The Arbed 1 retrofit programme was a regional scale “Strategic Energy Performance Investment Programme” established by the Welsh government in 2009. £60 million of funding was invested in Arbed 1 from a range of sources. More than 6000 properties were included in 28 separate projects. The scheme aimed to improve energy efficiency, reduce fuel poverty and carbon emissions, support the energy efficiency and renewable supply chain, and provide more local job and training opportunities (Patterson 2016).



Figure 4.1 Properties in the Warm Wales Arbed 1 Programme

The Warm Wales Arbed 1 retrofit programme was part of the Arbed 1 retrofit programme. It took place from 2010 to 2011 including 7 projects involving 1147 properties in total. Warm Wales as a community interest company was commissioned by five Registered Social Landlords (RSL) and two Local Authorities (LA) to design and manage the projects as well as work together with the contractors, RSL/LAs and energy suppliers to provide design advice (Patterson 2012).

4.2.1. Retrofit Measures

The Arbed 1 scheme planned to take a whole-house retrofit approach, while the Warm Wales Arbed 1 programme took an elemental approach to ensure more properties to be improved with limited funding.

The properties chosen to carry out retrofitting in this scheme included: a) properties with the type indicated by the Welsh Government that should be selected; b) low SAP rating homes; c) properties with solid walls which were suitable for applying EWI; d) off-gas households which were suitable for fuel switching; e) 'non-traditional' properties; f) zones distant to primary centres that sometimes got ignored; g) properties which were thought to be costly to retrofit; h) properties in a community that were alike to make the installation simple; i) properties involving a street-by-street principle to prevent neighbour envy.

The retrofit measures implemented consisted of wrapping the houses with external wall insulation (EWI) to improve the internal thermal conditions, installing solar PV, solar thermal and air source heat pumps (ASHP), and applying fuel switching to improve the efficiency of the energy supply system to reduce energy costs and CO₂ emissions. Window and boiler improvements were not covered in this programme because many properties already had double glazed windows and upgraded boilers

Table 4-2 Measures installed with the Warm Wales Programme (Patterson, 2016)

Summary of measures														
No. of measures	1	1	1	1	1	2	2	2	2	2	2	3	3	Total properties
RLS/Local authority	EWI	ASHP	Fuel switch	Solar PV	Solar thermal	EWI and fuel switch	EWI and Solar PV	EWI and Solar thermal	Fuel switch and solar PV	Fuel switch and solar thermal	Solar PV and solar thermal	EWI, solar thermal and solar PV	Fuel switch, solar PV and solar thermal	
1 Charter Housing (including Caerphilly CBC)	127	0	0	3	2	0	62	5	0	0	0	1	0	200
2 Melin Homes	36	42	0	93	0	0	18	0	0	0	0	0	0	189
3 Family	105	0	0	26	3	0	11	2	0	0	0	0	0	147
4 Coastal	115	0	0	108	0	0	0	7	0	0	0	0	0	230
5 City and County of Swansea	22	0	114	45	10	29	2	0	37	8	7	0	1	275
6 Tai Ceredigion	54	0	0	0	0	52	0	0	0	0	0	0	0	106
Total	459	42	114	275	15	81	93	14	37	8	7	1	1	1147

from other schemes. Table 4-2 illustrates the retrofit measures installed in the programme. Most of the houses (905) obtained one retrofit measure, 240 houses obtained two measures and 2 houses obtained three measures. EWI was the most common retrofit measure and was installed in 648 properties. 414 properties had solar PV installed, 46 had solar thermal, 241 switched fuels and 42 installed air source heat pumps. Fuel switching was mainly used in the age groups of 1945 to 1964 and 1965 to 1980. Solar PV installation was applied the most within the post-1980s properties. The measure of ASHP was used for properties constructed from 1965 to 1980 and post-1980.

To evaluate CO₂ savings and energy improvements, the Energy and Environmental Prediction (EEP) Model was introduced. The EEP model is based on Geographical Information System (GIS) techniques that can be used to assess the energy consumption and CO₂ emissions of building to urban scale. It calculated the SAP ratings for each cluster along with the CO₂ emissions and energy costs for each property. The properties were clustered into 100 groups according to age, type, heated ground floor area (m²), façade (m²), window-to-wall ratio and exposed end area (m²) as the above features were believed to have the greatest influence on energy use of housing stocks and CO₂ emissions (Patterson 2016).

4.2.2.Environmental Outcomes

In the Warm Wales Arbed 1 programme, the total CO₂ savings was 3,025 tonnes per year, with ranges from 90 to 10,000 kg per year per property. The highest percentage of CO₂ savings was achieved from the properties that switched fuels.

The UK government Standard Assessment Procedure (SAP) rating is an energy rating method on a scale of 1 to 100 to evaluate and compare the energy performance of residential buildings. A higher number represents better energy performance. Before retrofitting, the average SAP rating was 60, with a range from 43 to 66. After the works, the average increased to 69, ranging from 58 to 82.

EWI was identified to have the greatest improvement in reducing CO₂ emissions and enhancing thermal comfort in properties with solid walls.

In addition, the appearance of the communities was improved significantly, especially with the EWI installed properties.

Moreover, it changed the attitudes of the participating Registered Social Landlords (RSLs) on some low carbon retrofit measures from novel technologies to more commonly used measures (Laurentis & Hunt 2012).

4.2.1.Social Outcomes

Various training and job opportunities were provided in the Warm Wales Arbed 1 programme in order to help the locals find employment and to hire more appropriate staff. Training included building treatments, carpentry treatments, electrical and construction skills, plumbing and heating, etc. The training time varied from short-term to three to four years.

It is worth mentioning that there were 15 Community Energy Wardens recruited by Warm Wales as one of the pivotal training opportunities during the implementation process in this programme. They were trained to work together with Warm Wales and the main contractor to help with the engagement, retrofitting measures installation as well as assisting residents in better understanding the programme and making more proper use of the new equipment after retrofitting in order to obtain better retrofit performance.

4.2.2. Economic Outcomes

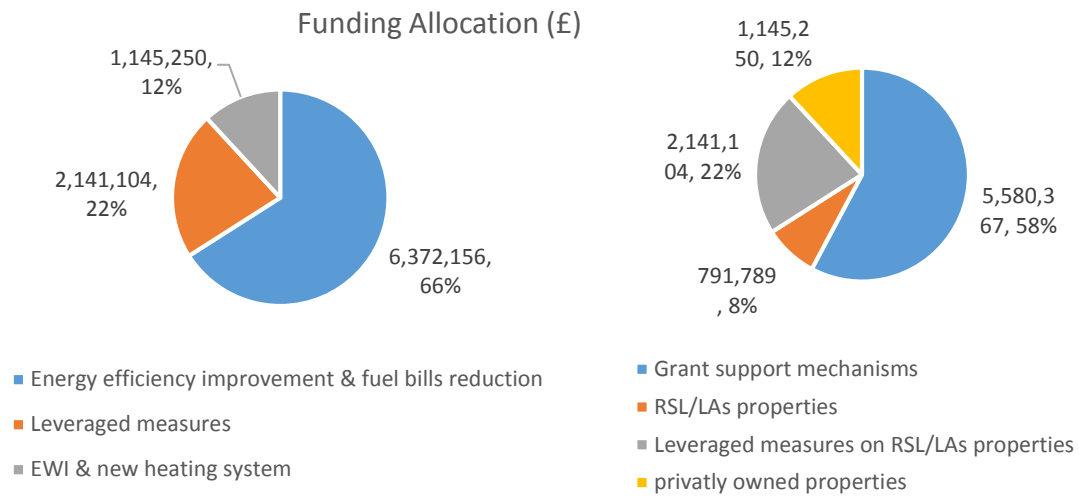


Figure 4.2 Funding allocation through Warm Wales Programme

A total cost of the Warm Wales Arbed 1 programme was £9,658,510, including £6,372,155 for implementation of the measures, using Arbed 1 scheme funding, £2,141,104 for leverage measures and £1,145,250 for installing EWI and heating systems. The grant support mechanisms contributed 58% of the funding and the rest was provided by RSL/LAs, as illustrated in Figure 4.2.

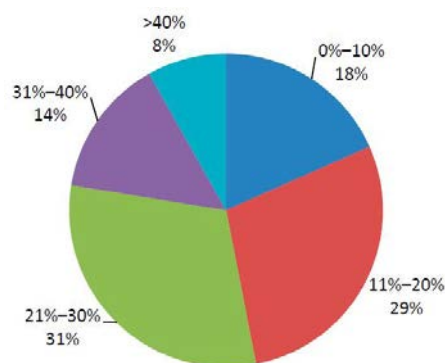


Figure 4.3 Percentage of potential financial savings on energy bills as a result of the Warm Wales Programme measures installed (Patterson, 2016)

The average costs per measure in actual use are shown in Table 4-3. The total savings in this programme was £285,000 per year. More than half of the homes could save more than 20% of the energy bills per year, as demonstrated in Figure 4.3.

Table 4-3 Average cost per measure installed & CO₂ savings for a semi/end terraced house in the Warm Wales projects (Patterson, 2016)

Measure	Average cost per Measure	CO ₂ Savings (kg/yr)	£ per kg CO ₂ per yr	% CO ₂ Saving (kg/yr)	No. of Measures Installed
EWI	£7,730	1,670	£4.63	25	648
Fuel Switching	£3,126	8,939	£0.35	57	241
Solar PV	£4,988	751	£6.64	11	414
Solar Thermal	£4,393	395	£11.12	6	46

As can be seen from Table 4-3 above that fuel switching provides the best CO₂ savings per £, followed by EWI, then solar PV. Therefore, for residential retrofit project at large scale where no fuel switching has been carried out, fuel switching can be considered as a more cost effective measure to reduce CO₂ emissions. In addition, EWI as the main retrofit measure has been installed in 648 houses, and it is the second cost effective measure to reduce CO₂ emissions.

4.2.3. Supply Chain

One of the aims of the Warm Wales Arbed 1 scheme was to enhance local employment. In this programme, four out of seven manufacturers were from Wales and 16 of 20 contractors were located in South Wales, which strongly supported the aims of this scheme.

4.2.4. Lessons Learned

Since the first case is a large-scale retrofit, its main focus is on exploring UK's large-scale retrofit method, implementation process and the financial scheme.

Regarding to the retrofit method, the lessons learned and experiences to be transferred from the UK to China are: for the retrofitting of existing residential buildings on a large scale, it is necessary to cluster the properties into several groups according to their age, type, tenure, size, etc. at the first stage and then apply different suitable retrofit measures for each group. In addition, for supply chain, it is good to create more employment for local people and employ local contractors and manufacturers. This is also good for retrofitting operation and maintenance phases, allowing for maintaining without going far, which can ensure work efficiency and saving resources. However, the problems caused by lacking experience and skills should also be noted.

In terms of implementation process, firstly, a detailed survey should be made as early as possible to obtain accurate data, which can then be modelled to decide the most appropriate energy efficient and cost effective retrofit solutions. Moreover, in order to achieve a high standard retrofitting work, it is important to establish thorough installation standards and provide sufficient training to local employees before the work begins. Supervision and evaluation should also be conducted during and after the implementation stage.

Regarding financial scheme, unlike most projects in China which are completely invested by the government, the funding of this project was mainly provided by the grant support mechanisms, and the rest was provided by the registered social landlords and local authorities, which should be transferred to China to establish a more mature residential retrofit financing mechanism.

4.3.Survey of Project 2: Warm Wales Neath Port Talbot Scheme

The Warm Wales Neath Port Talbot Scheme was a retrofitting of existing housing stock in Borough on a regional scale. It involved over £10 million worth of investment to install energy efficient measures to improve the energy efficiency in existing homes and reduce the number of households in fuel poverty across Neath Port Talbot. There were 49,831 properties involved in this scheme, accounting for 81% of the total housing stock of 61,698 properties.

The procedure of the scheme involved seven stages: firstly, two to eight weeks of marketing was carried out, including introduction letters, posters, advice booklet and marketing materials. This was followed by phone calls, published articles, local events and the creation of websites to make sure all householders received sufficient information. Second, surveys and assessment were made to find out whether the households were eligible for the free or discounted measures offer. Next, installation was followed up under the monitor of scheme operations manager to ensure that the performance level was achieved. After that, quality audits, including customer satisfaction audits, customer telephone audits, full technical audits and hearing and heating assessments were carried out. Further measures such as results review were carried out as the fifth stage. Then, a benefits advice service was provided to help residents to apply for further benefits. Additional works were offered, such as health professional training who could visit clients at home to identify people at risk of illness or death in relation to cold living conditions (Patterson 2008).

4.3.1. Retrofit Measures

The retrofit measures installed in the Neath Port Talbot Scheme consisted of: installing cavity wall insulation; installing loft insulation; installing hot water cylinder insulation jackets; installing central heating system involving new highly efficient gas boilers, radiators to all rooms, timers, room temperature controller and thermostatic radiator valves; installing external cladding for non-traditional constructions; and providing at least two compact fluorescent lamps (CFLs) to each householder (Patterson 2008).

4.3.2. Environmental Outcomes

In the Warm Wales Neath Port Talbot Scheme, the total CO₂ emissions were reduced from 196,824 tonnes per year to 178,641 tonnes per year, making for a savings of 18,183 tonnes per year, which accounted for 9.2% of emissions savings. The average SAP rating before retrofitting was 55, and after retrofitting, it increased to 60.

4.3.3.Social outcomes

The scheme created 54 new jobs and 127 training positions in Neath Port Talbot. In addition, 284 people were trained through the collaboration of Warm Wales and the Health through Warmth Scheme, including surveyors, social services staff, age concern, health visitors, physiotherapists, welfare rights units/benefits advice. 2305 families were removed from fuel poverty. Moreover, this project made some attempt to analyse the energy data together with a health programme called 'npower Health Through Warmth scheme' which provided training to the health professionals and encouraged them to find out the most in need house to be retrofitted.

In this scheme, the majority of households, 73%, were owner occupied. These properties resorted to npower funding, Warm Wales funding or the discount scheme depending upon their financial circumstances. 20% of the homes were owned by the local authority, which was involved in the scheme.

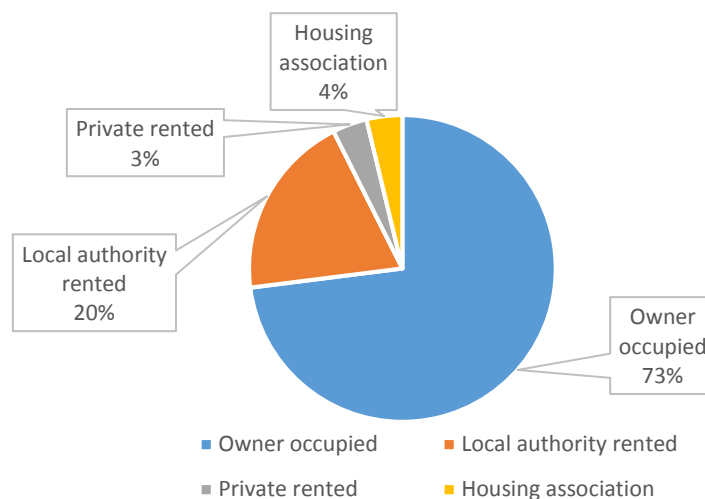


Figure 4.4 Tenure of households within the Warm Wales Neath Port Talbot Scheme (Patterson, 2008)

4.3.4. Economic Outcomes

The total investment in this scheme was £10,235,129. £732,734 was funded through the discount scheme. The further £290,050 was contributed by householders. The expenditure on different retrofit measures was shown in Table 4-4. On average, for each household, £543 was spent on substantial energy efficiency measures.

In addition, 3649 families received the offer of free benefits suggestion at the evaluation stage. 495 of which had made a wider range of benefits like Council Tax Benefit and Attendance Allowance, etc. and received an extra £4256 per year.

Table 4-4 Final expenditure on measures throughout the Scheme (Patterson, 2008)

Measure	Expenditure
Cavity wall insulation	£3,379,886
Loft insulation	£3,144,987
Hot water tank jackets	£29,318
Walkways - in loft space for safe access	£81,160
Scaffolding - for cavity wall insulation	£113,463
Central heating Local Authority, Health through warmth	£1,563,743
Mains gas extension projects	£1,430,000
Partner Benefit in kind	£500,000
Total	£10,235,129

4.3.5. Supply Chain

In this scheme, four home insulation installation contractors and one heating installation contractor were contracted; and one of three major insulation manufacturers in the UK was based in South Wales.

4.3.6. Lessons Learned

As Retrofit 2 is still a large-scale retrofit project, the main focus is its retrofit method, implementation process and multiple benefits.

In terms of retrofit process, this project has illustrated important aspects throughout existing housing retrofitting, which is the survey and assessment at the early stage, audits and communications with residents during the whole process, and the follow-up works and advice services after retrofitting. These aspects ensured that all the stakeholders understood the scheme from the very beginning and participated in every procedure of the retrofitting.

In regards to retrofit method, this project illustrated a great analysis method of identifying the most in need households for retrofitting. The energy data can be analysed together with health or some financial data like income to find out the households most in need or in fuel poverty so they can be targeted as a priority of a retrofitting project.

In addition, the retrofitting of existing housing is not just about improving energy efficiency, but more importantly, improving the living environment and comfort of residents as well as social and economic improvements. Moreover, the evaluation of housing retrofitting performance is not just a comparison of numbers of energy efficiency improvement and CO₂ emissions reductions. Evaluation should be made by the actual effect of retrofitting from a longer-term and broader perspective. For example, in this case, more job opportunities were created locally, more training opportunities were provided for local residents and combining a retrofitting survey with health issues is worth learning and studying.

4.4. Survey of Five Retrofit Projects at Building Scale:

In order to examine a series of retrofit solutions at the design stage and to better understand the improvement of different combinations of retrofit measures for a specific property, five SOLCER Retrofit projects on a building scale using the whole-house retrofit approach were chosen for case studies.

These five retrofit projects were part of the Low Carbon Research Institute (LCRI) SOLCER (Smart Operation for a Low Carbon Energy Region) Retrofit and LCBE (Low Carbon Built Environment) research projects based in South Wales. The SOLCER

Retrofit project was funded by the European Regional Development Fund (ERDF). It is a part of the LCRI WEFO Programme. SOLCER is led by the Welsh School of Architecture, Cardiff University which aims to ‘implement combinations of existing and emerging low carbon technologies through a systems-based approach in order to optimise the use of energy at the point of generation’ (ERDF n.d.). The SOLCER retrofit case study was aiming to ‘provide an affordable and replicable package of measures, applied to typical houses of different construction and age located across South Wales’ (LCBE n.d.).

4.4.1. Basic information

The five SOLCER retrofit projects represented a series of house types and ages as shown in Table 4-5. The houses were all owned by RSLs. The first and fourth houses were two-bedroom, pre-1919 houses with solid walls and with the type of end-terrace and mid-terrace. The other three were three-bedroom, semi-detached houses with cavity walls and were built in the 1960s, 2000s and 1950s, respectively. The first and fifth houses were not occupied. All five houses had gas boilers (Jones et al. 2017).

Table 4-5 The five SOLCER retrofit houses before and after retrofit (Jones, et al. 2017)



4.4.2. Retrofit Measures

All stakeholders including the project management team, contractors, house owners, modellers and residents were participated in the early stage of the project to make decisions. Surveys were conducted to decide suitable retrofit measures for a particular house.

The retrofit measures were on the basis of a fabric first approach, which consisted of external wall insulation, internal wall insulation, loft insulation, glazing improvement and air leakage measurements. The system improvement measures were then installed, such as energy efficient boilers, LED lighting, and MVHR, etc. After that, renewables like solar PV and energy storage battery were considered.

The retrofit measures were proposed and combined as different packages, ranging from fabric measures to a combination of solutions to demonstrate the possibilities in the retrofit process. These packages were then modelled for each house to evaluate their influence on energy performance, CO₂ reduction and cost effectiveness. After that, the most suitable and cost efficient package of measures was chosen for each house. The acceptable budgets and operational maintenance issues were discussed among the stakeholders. After the retrofitting, the five houses were monitored for more than two years.

4.4.3. Environmental Outcomes

After the retrofitting, the houses achieved a range of 37% to 84% savings in electricity, 6% to 56% savings of gas demand, and 49% to 74% reductions of CO₂ emissions. Retrofit 3 had the highest gas savings (56%) because it applied insulation to a pre-1919 house with a solid wall; whereas Retrofit 5 had little insulation enhancement. Table 4-6 summarised the energy performance improvement through retrofitting.

All of these five deep retrofit projects used energy batteries to store the electricity produced by the solar PV panels. The analysis compared the electricity import and cost

before retrofitting, post-retrofitting with battery and post-retrofitting without battery as shown in Table 4-7 (Jones et al. 2017).

Table 4-6 A summary of performance optimisation through retrofit (Jones, et al. 2017)

Savings	Retrofit 3	Retrofit 4	Retrofit 5	Retrofit 6	Retrofit 7
Electricity reduction	37%	41%	79%	72%	84%
Gas reduction	56%	23%	0%	35%	6%
CO ₂ reduction	64%	49%	54%	74%	61%
Cost savings	62%	52%	85%	81%	84%

Table 4-7 A summary of electricity import and cost before retrofit, after retrofit with 10 kWh Lithium-ion battery, and after retrofit without battery (Jones, et al. 2017)

Retrofit	Pre-retrofit		Post-retrofit with battery		Post-retrofit without battery	
	kWh/annum	£/annum	kWh/annum	£/annum	kWh/annum	£/annum
3	3227	426	793	105	2161	285
4	3227	426	859	113	2140	282
5	3227	426	515	68	2054	271
6	1614	213	153	20	958	126
7	3227	426	518	68	1992	263

It can be seen that the electricity savings were in a range of 1461 to 2712 kWh per year with battery compared to those of 656 to 1235 kWh per year without battery, which accounted for 73% to 91% savings with battery and 33% to 40% without battery, respectively.

4.4.4. Social Outcomes

After the retrofitting, the project outcomes were shown to the local stakeholders. According to the monitored indoor temperature, the thermal comfort of the occupants was improved, which would benefit their health condition and well-being, potentially reducing the stress on health care and social services. Due to the energy saving after retrofitting, local residents could escape fuel poverty and have more affordable warmth. The retrofit measures and control systems used in the retrofit projects were also presented to local residents to help them have a better understanding of the retrofit measures so that they could use and maintain their home in a 'smarter' way (LCBE n.d.).

4.4.5. Economic Outcomes

The retrofit costs of these five projects ranged from £23,852 to £30,510, which was half the costs of the earlier retrofit projects led by the UK government (Baeli 2013). If combined with some basic house improvements such as re-roofing, the total cost would be further reduced. The energy battery provided a cost-benefit in the range of £100 to £200 annually. The installation of solar PV and batteries could save 40% cost on energy operation, solar PV power generation and exportation. An extra 6% cost savings could be achieved by installing a hot water cylinder. The LED lighting installation could save a further 6% cost. The total cost savings were in the range of £402 to £621 per year (Jones et al. 2017).

The value of house selling and renting has increased. Take the first house for example, before the retrofitting, the house was hardly able to find a tenant, resulting in a basic rent loss of £450 per month according to the local average rent. After the retrofitting, the house was easily rented out, with an increased rent of £540 per month (Jones 2015).

4.4.6. Supply Chain

The retrofit measures applied in the five projects were all available in the local market. The five projects also used local building contractors and local suppliers. This not only increased local employment but also obtained a relatively low retrofit cost.

4.4.7. Lessons Learned

Since Retrofit 3 to 7 are building scale, the focus is mainly on their retrofit method and technology.

First of all, the whole-house approach combines energy efficiency retrofit measures with system upgrade, renewables and energy storage, which has the potential to

significantly reduce energy consumption, CO₂ emissions, and energy bills, etc. and has multiple benefits in terms of social and economic aspects.

In terms of technology, the energy battery can store the electricity generated from the solar PV panel, so the majority of the generated electricity can be directly used for the house than export to the grid, which can reduce the pressure on the electricity grid as well as save the power import cost. The rest of the electricity can be exported to the grid for more income. As new technology is developed, the costs of energy battery will be continuously reduced. Meanwhile, as the cost of grid energy continues to rise, energy batteries will be more widely used in the future.

In addition, the energy monitoring after retrofitting is essential in the retrofit process, which allows researchers to compare the modelling results with the actual performance to evaluate the improvement of a retrofit project. It is also important to know the post-retrofit performance when occupied by residents. The monitoring data and modelling results can be combined to estimate and select the most suitable package of retrofit measures. It can also be used to analyse the indoor living behaviours of residents and guide them to control their home energy in a more low-carbon way.

4.5. Comparison and Analysis of the Seven Projects

The seven Welsh retrofit projects are compared and summarised in Tables 4-8 and 4-9 in terms of retrofit measures, cost and potential savings. Analysis and discussion of the outcomes are made after this.

4.5.1. Retrofit Measures

The retrofit measures used in these seven projects are summarised in Table 4-8.

It can be seen from the table that the most common retrofitting measure in fabric first approach is external wall insulation (EWI), especially for the houses before 1919 with solid walls. Retrofit 6 used a hybrid approach which combined EWI and IWI together.

For system improvement, all of the seven retrofitting projects have updated to energy efficient boilers, two of the boilers have a hot water tank which can be combined with solar thermal for domestic hot water. Retrofit 1 applied the measure of fuel switching, which had a good result in improving the energy efficiency at a low price. There were six retrofit projects updated the lighting to LED. The MVHR system were installed in retrofit 3 and 4, which reduced the heating demand.

In terms of renewables, 30% of retrofit 1 and all of the retrofitting projects at building scale had roof replacement with integrated PV roof, and the five building retrofits had energy batteries installed for electricity storage. There were 3% of retrofit 1 adopted solar thermal and air source heat pump.

Table 4-8 The comparison of retrofit measures of the seven Welsh retrofit projects

		Retrofit 1	Retrofit 2	Retrofit 3	Retrofit 4	Retrofit 5	Retrofit 6	Retrofit 7
fabric	External wall insulation (EWI)	✓ (47%)	✓ (53%)	✓ (100 mm)	✓ (gable cavity wall insulation and front 1st floor EWI 50 mm)		✓ (rear 100 mm)	✓ (100 mm)
	internal wall insulation (IWI)						✓ (front)	
	loft insulation	✓	✓ (67%)	✓ (300 mm)	✓ (300 mm)	✓ (300 mm)	✓ (300 mm)	✓ (300 mm)
	floor insulation						✓ (rear extension)	
	draught proofing	✓	✓	✓	✓	✓	✓	✓
	double glazing			✓ (low-E)				
	external cladding for non-traditional constructions		✓					
system	fuel switching	✓ (17%)						
	new gas boiler with hot water tank		✓ (13%)	✓	✓	✓		
	hot water cylinder insulation jackets		✓ (13%)					
	MVHR			✓	✓			
	LED lighting		✓ (40%)	✓	✓	✓	✓	✓
renewable	solar PV	✓ (30%)		✓ (2.5 kWp)	✓ (2.7 kWp)	✓ (4.5 kWp)	✓ (2.6 kWp)	✓ (3.97 kWp)
	solar thermal	✓ (3%)						
	Air source heat pump (ASHP)	✓ (3%)						
	energy storage			✓ (lead acid battery: 4.8 kWh feed LEDs and hot water)	✓ (lead acid battery: 8.5 kWh feed LEDs and fridge)	✓ (lead acid battery: 18 kWh feed all electrical appliances)	✓ (Lithium battery: 2.0 kWh feed all electrical appliances)	✓ (Lithium battery: 10 kWh feed all electrical appliances)

4.5.2.CO₂ Reductions, Retrofit Costs and Potential Savings

Table 4-9 presents the CO₂ reductions, retrofit costs and potential savings of the five SOLCER whole house retrofit projects as follows.

It was estimated that in order to achieve the UK's target of 80% reduction in CO₂ emissions by 2050, one house should be retrofitted every minute for the next 40 years and the cost will be £85 billion approximately for homes alone (Dixon T 2012).

Large retrofit funding mainly comes from the following sources: government schemes, local authorities, social landlords and grant support mechanisms. From the perspective of government and local authorities, large-scale retrofit programmes could cover more households, so more achievements could be shown to the public. However, it can be seen from Table 4-9 that as the scale increases, the funding that can be spent on each house has been reduced. Lack of funding is identified as the main reason for large-scale retrofit adopting an elemental approach for most of the households.

As can be seen from Figure 4.5, the average cost of the five building-scale whole-house retrofit projects is much more than the two large-scale ones, which is around 3 to 4 times than that of the first retrofit project and is more than 100 times than that of the second project. From the perspective of CO₂ emission reduction, the second retrofit project has a minimum reduction due to the limited funds for each house. However, in the first project, 31% of houses have more than 3000 kg CO₂ reduction each year, which is better than that of Retrofits 4 to 7. Also, the most expensive retrofit that of Retrofit 1 has adopted four retrofit measures, with a total cost of £17,111, which is much lower than the price of the five building-scale deep retrofits. The cost of these five whole-house retrofits is already lower than that of the previous retrofits on the market. Therefore, it is therefore predictable that the cost of existing housing retrofit will gradually decline with the expansion of the retrofit scale and the maturity and popularity of new technologies. Large-scale in-depth retrofit will become a trend, making a greater contribution to the city's energy-saving, CO₂ emission reduction and sustainable development.

Table 4-9 The comparison of CO₂ reductions, costs and potential savings

		Retrofit 1	Retrofit 2	Retrofit 3	Retrofit 4	Retrofit 5	Retrofit 6	Retrofit 7
Energy savings (kWh/year)	Electricity	-	-	1195	1325	2560	1163	2709
	Gas	-	-	10163	2642	109	2828	496
CO ₂ reduction	CO ₂ saving/year	3025 tonnes in total; average 2637 kg/home <1000kg: 44%; 1001- 3000kg: 27%; 3001-5000kg: 8%; 5001- 7000kg: 6%; >7000kg: 15%	18183 tonnes in total; average 389 kg/home	3593 kg/home	2042 kg/home	1803 kg/home	1906 kg/home	2168 kg/home
	Saving in %	0-20%: 40%; 21%-40%: 29%; 41%-60%: 19%; >60%: 12%	9.20%	64%	49%	54%	74%	61%
Cost & potential saving	Cost	£9,658,510 (£8420/property, £100/m ²)	£10,235,129 (£219/property)	£30,452 (£455/m ²)	£27,438 (£392/m ²)	£30,446 (£354/m ²)	£23,852 (£322/m ²)	£30,510 (£381/m ²)
	Saving	£285,000/year; £216/year/property; 0-10%: 18%; 11%-20%: 29%; 21%-30%: 31%; 31%-40%: 14%; >40%: 8%	Euros 351,500 (= £309,320 with 0.88 exchange rate)	£661/ year (62%)	£430/ year (52%)	£594/ year (85%)	£402/ year (81%)	£613/ year (84%)
Supply chain		4 of 7 manufacturers were from Wales and 16 of 20 contractors were located in South Wales	1 of 3 major insulation manufacturers in the UK was base in south Wales;					

*The value is estimated at Euros 19/tonnes CO₂ (Jo 2008)

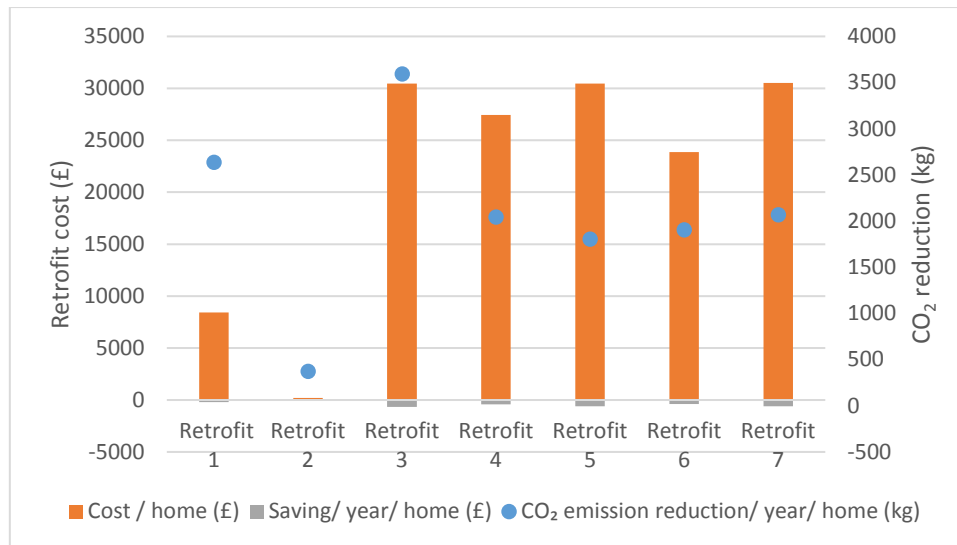


Figure 4.5 Comparison of retrofit costs and annual savings per home

In terms of cost saving evaluation, it is important to calculate the capital costs with long-term operational costs like maintenance and management as well as the potential benefits (Patterson 2016). For example, in the second large-scale retrofit project, although it is rarely seen from the cost savings of energy bill compared to the other six retrofit projects, 3,649 households received more than £2,100,000 of additional benefits, which should also be counted in the savings.

Thus, for the retrofitting of existing residential buildings, apart from comparing and analysing the before and after energy saving and CO₂ emissions reduction data from the environmental aspect, a comprehensive evaluation of the retrofit effect should be made in combination with multiple social and economic benefits of the projects.

4.5.3. Multiple Benefits

Retrofitting existing housing stocks can not only improve energy efficiency and reduce CO₂ emission but also bring multiple benefits in environmental, social and economic aspects. The benefits of whole-house retrofit especially on a large scale, could go beyond purely environmental achievements (Local Energy Assessment Fund 2012).

The 'Beyond Decent Homes' standard by Sustainable Housing Action Partnership suggested that in order to achieve the UK's 80% CO₂ reductions target, the whole-house approach should be considered the optimal option, and the cost, including renewables would range from £16,000 to £34,000 per house for at least 1000 houses (SHAP 2011). Although the Green Deal is no longer funded by the government, the assessment of the whole-house retrofit cost in this report is still a valuable piece of evidence to refer to. Based on the data above, the average cost of £25,000 can be calculated as a basis for quantifying some of the multiple benefits for large-scale whole-house retrofit.

It was suggested that the retrofit should be ideally carried out using the whole-house approach at one step (URBED 2015) to make it more cost effective and save time and resources, etc. (Route 2009). Therefore, retrofitting all the 291,000 Welsh houses in fuel poverty using the whole-house approach would cost £7,275 million in total.

It is difficult to measure the benefits of whole-house retrofit by simply calculating the annual energy cost savings. Take the five Welsh whole-house retrofit for example: the retrofit cost was in the range of £23,852 to £30,510, and the cost savings were from £402 to £621 per year. So it would take 50 to 60 years to pay this cost back in full, and this does not take into account the energy price rising or any rebound effect, etc. On the contrary, other social and economic aspects are considered, the benefits would be much greater than the retrofit investment (Jones et al. 2017).

4.5.3.1.Social Benefits:

4.5.3.1.1.Fuel Poverty Alleviation/ Affordability:

In general, there were 27.2 million households in the UK in 2017 (Knipe 2017). In Wales, there were 291,000 houses suffering from fuel poverty, which accounted for 23% of the total households in Wales (Welsh Government 2017b). These houses were considered as the most in need properties to be targeted for energy efficiency retrofit measures (International Energy Agency 2014) and the Welsh government published

the Fuel Poverty Strategy in 2010, which aimed to eradicate fuel poverty in all households by 2018 (Welsh Assembly Government 2010).

One of the most sustainable and cost-effective ways to deal with fuel poverty and prevent the negative impact of energy prices increase is to retrofit the existing houses to improve their energy efficiency (Jones, Lannon, Patterson, et al. 2013). As homes become more energy efficient, residents can have more and better energy services with lower energy bills. With the savings from energy efficient retrofit measures, they can also spend on other daily necessities (International Energy Agency 2014).

4.5.3.1.2. Job Creation:

Based on research by Janssen and Staniaszek, the Energy Efficiency Industrial Forum (2012) states that on average, investing €1 million energy efficiency for buildings will create 19 new local and non-transferable jobs in the construction sector. According to the current exchange rate, this means that for every £1 million investment spent on retrofitting, 23 new local jobs would be created in the construction sector in the UK (currency: 1 EUR=0.88 GBP) (XE 2018). On basis of this, £7,275 million investment on whole-house retrofit of the 291,000 Welsh houses in fuel poverty would create 160,050 person-years of employment in total for the local area.

The average weekly full-time salary in Wales was £498.4 in 2017 (Welsh Government 2017a), which was annually £25,916.8. So, 160,050 new jobs would increase the income of around £4,148 million per year for local residents.

In addition to the direct jobs created from retrofit projects, there are many indirect jobs generated from the supply chain, maintenance services and supporting industries.

Furthermore, the new jobs generated from retrofitting could also have a positive impact on society and the economy. For example, the Warm Wales programmes not only demonstrated that the large-scale retrofit can create more job opportunities for local residents, it also provide advice and trainings to help local people understand more about low carbon retrofit and how to use their home in a more sustainable way.

Some people benefited from the training programmes and started their own companies after that.

4.5.3.1.3. Health Improvement:

People living in cold, damp homes have a higher risk of illnesses such as respiratory and cardiovascular and arthritic diseases, especially for vulnerable groups like the disabled, elderly and children living in energy inefficient houses (International Energy Agency 2014). Evidence shows that excess winter deaths in the coldest quarter of the year are three times higher than that in the warmest quarter (Marmot Review Team 2011).

In addition to physical health, living in poor housing also has negative impacts on the mental health of the occupants due to chronic thermal discomfort, including anxiety, financial stress, depression and the stress of worrying about physical health (Marmot Review Team 2011). Besides, it can also have negative effects on people's social activities. For instance, the occupants may not want to invite friends to their homes due to the lack of heat (NICE guideline 2015).

The NHS has to spend £859 million each year to treat diseases related to cold homes. If the extra spending on social services or financial losses due to missed work were considered, the cost would be even more (Marmot Review Team 2011).

The retrofitting of existing housing, especially the households in fuel poverty, could significantly improve indoor air quality and provide warmer and more comfortable indoor environments for the occupants, which will improve their physical and mental health and well-being, and reduce the risk of illness, lowering healthcare expenditure (Washan et al. 2014).

According to recent research, for every £1 spent on fuel poverty alleviation, there would be 42 pence saved in annual NHS services (Department of Health 2010). Thus, as assumed above, an investment of £7,275 million in whole-house retrofit to remove fuel poverty in Wales would have an expected annual saving of £3,055.5 million on the NHS.

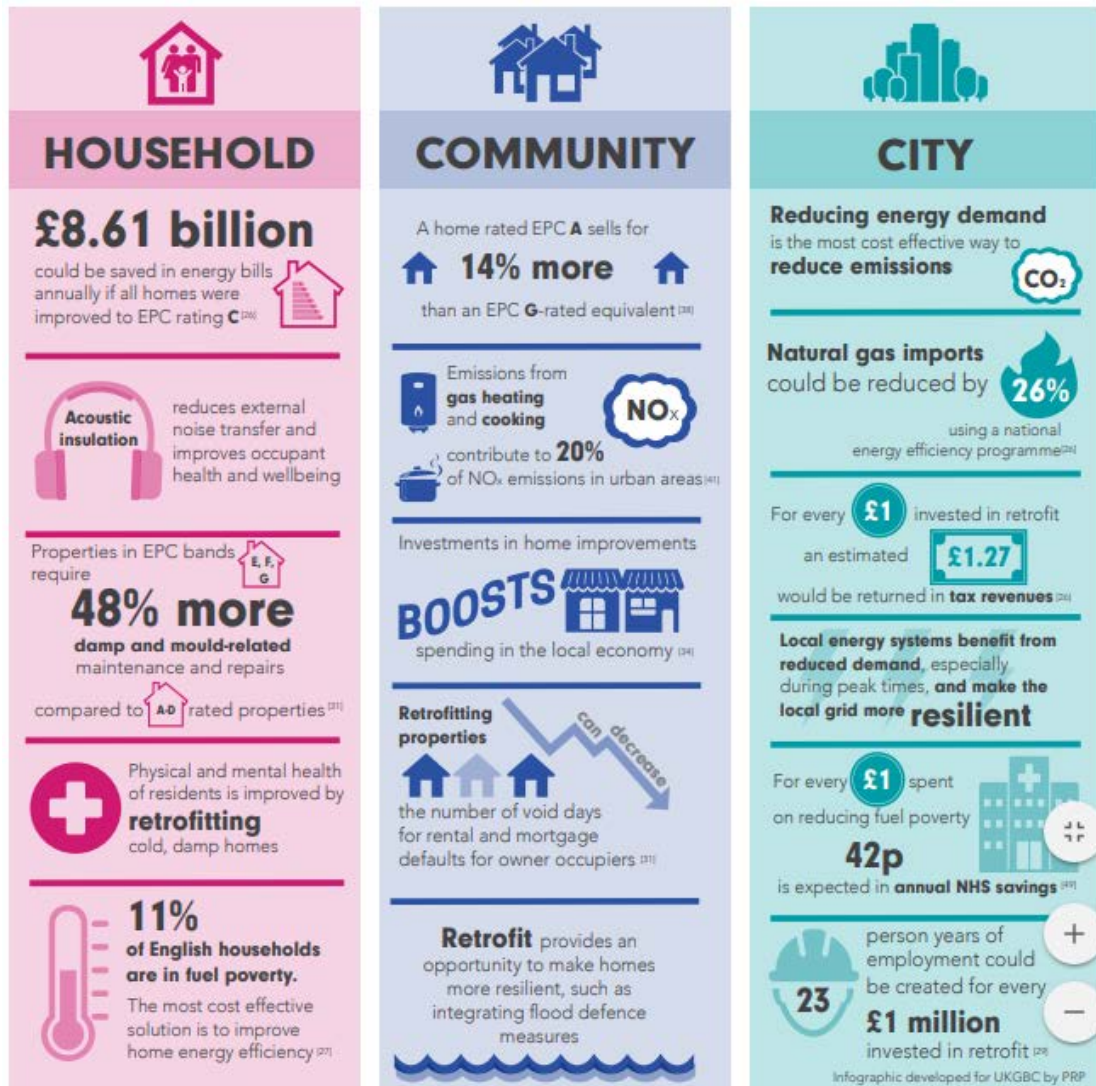


Figure 4.6 The multiple benefits of whole house retrofit (UK GBC, 2017)

4.5.3.1.4. Comfort Enhancement:

The recommend indoor temperatures by the World Health Organisation (WHO) is 21 degrees in living rooms and 18 degrees in bedrooms for at least nine hours a day (Marmot Review Team 2011). Retrofit can increase the internal temperature by 1°C or 2°C for existing housing, improving the thermal comfort of the occupants. Besides this, improving the air tightness would reduce draughts in the house. In this case, even if the internal temperatures are not increased, the occupants would still feel more

comfortable living in their houses (European Climate Foundation 2016). This could also significantly improve the health and well-being of vulnerable people (International Energy Agency 2014).

4.5.3.2.Economic Benefits:

4.5.3.2.1.Energy Bill Reduction:

According to the research by the Institute of Health Equity, the average energy bill for UK households was £605 per year in 2004 and increased to £1306 per year in 2013 (UCL Institute of Health Equity 2014). In the UK, for every £4 spent on heating homes with poor insulation, there was £1 being wasted (Friends of the Earth 2011).

The retrofitting of existing houses with energy efficient measures is an optimal way for the occupants to control their energy bills. It is estimated that in the UK, £8.61 billion spent on energy bills could be saved if the EPC ratings of all households were increased to Band C by 2035 through retrofitting (Washan et al. 2014).

In Wales, based on the five Welsh whole-house retrofit projects, the highest cost savings were £621 each year, with a CO₂ reduction of 75%, so the cost savings would be even more than when a CO₂ reduction of 80% is attained by using the whole-house retrofit approach. Therefore, retrofitting the 291,000 Welsh houses in fuel poverty could save more than £180 million on their annual energy bills.

4.5.3.2.2.GDP Growth:

In terms of GDP (Gross Domestic Product), it is estimated that every £1 invested in energy efficiency measures would have a payback of £3.20 to the government through increased GDP and £1.27 in tax revenues because of higher economic activity (Washan et al. 2014). Therefore, a £7,275 million investment in the 291,000 Welsh houses in fuel poverty would return of £23 billion to the government via increased GDP and £9 billion in tax revenues.

4.5.3.2.3.Asset Values Increasing:

After the retrofitting, the property value and rental level of existing buildings could be increased, which will benefit the owners to have more income through house reselling or renting. Evidence shows that individuals and businesses are willing to pay rent or sales for more energy efficient properties (Kok et al. 2011).

4.5.3.3.Environmental Benefits:

4.5.3.3.1.Energy Delivery Improvement:

The European Climate Foundation indicated that investing in energy efficiency in housing will reduce 26% of natural gas imports in 2030, which will save £2.7 billion in that year (European Climate Foundation 2016). Retrofitting the existing housing stocks can improve energy efficiency so that the energy providers can save costs on the operation and increase their profit margins as well as provide better services to their customers (International Energy Agency 2014).

4.5.3.3.2.Resource Savings:

Improving energy efficiency through retrofitting can save both energy and non-energy resources. For instance, energy efficient appliances such as LED lights reduce electricity use and low-flow shower heads reduce the energy used to provide hot water for showers. Energy-saving technologies used in industrial processes also reduce resource use and waste (European Climate Foundation 2016).

In addition, with local suppliers and contractors involving large-scale retrofit can save more costs, time and resources in transportation, installation, maintenance, and management process.

4.5.3.3. Air Quality Improvement:

Retrofitting existing housing with energy efficiency measures could improve air quality due to the air pollutions emissions being reduced at the energy generation stage as well as the direct fuel combustion stage in houses (European Climate Foundation 2016).

House retrofitting using the whole-house approach can have further benefits, such as enhancing the quality of the house in both energy efficiency and structure, thus extending the life of the building as well as improving the quality of life of the residents.

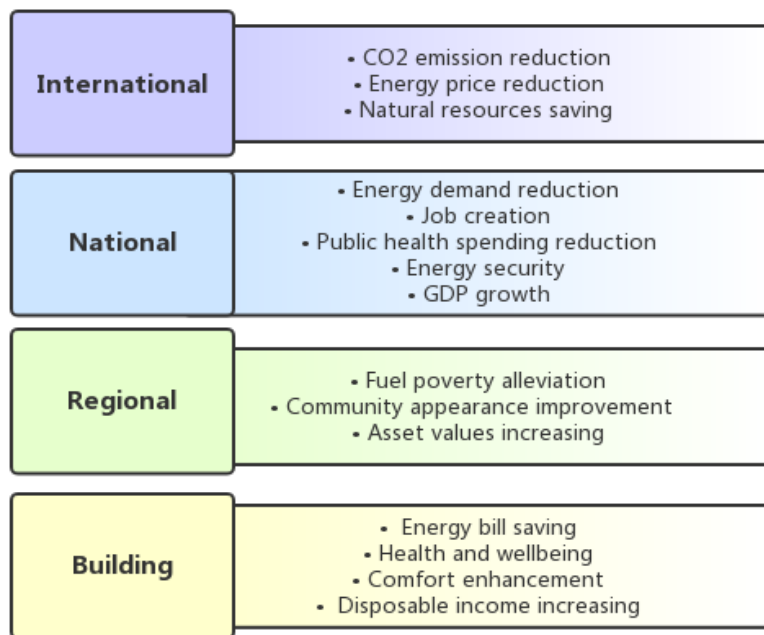


Figure 4.7 Multiple benefits of housing retrofit across different levels (Source: Ryan & Campbell 2012)

To sum up, as shown in Figure 4.7 above, multiple benefits from existing housing retrofit will be felt simultaneously from building to international scales. This illustrates how benefits, like improving health and wellbeing or reducing energy cost, can start at the building level and flow in the economy, which may affect the economy of a country and the world in terms of scale. This helps to provide a holistic view of the results, but it is important to evaluate the individual impact of each benefit and the

interactions among them to avoid double-counting the visible benefits of the whole retrofit project at different levels (Ryan & Campbell 2012).

4.5.3.4. The Rebound Effect

The rebound or take-back effect is often related to energy consumption. It is 'an increase in the level of efficiency in the use of energy decreases the marginal cost of supplying a certain energy service and hence may lead to an increase in the consumption of that service' (Orea et al. 2015).

There are three types of rebound effect. The first is the direct rebound effect. In some cases, due to energy efficiency improvement by retrofitting, occupants would like to access better services like increasing the indoor temperature to improve their comfort rather than saving energy bills, which would increase the actual energy demand, and this might result in potential energy bill rises. Direct rebound effects can be up to 65% (Hertwich 2005), but more estimates tend to be in the range of 10% to 30% (Jenkins et al. 2011).

The second is the indirect rebound effect. For instance, the residents choose to spend their energy savings on other energy consuming activities, such as buying cars (International Energy Agency 2014).

The third is called economy-wide rebound effect. The cost of products and services changes due to energy efficiency improvement, resulting in the structural changes to the economy (Orea et al. 2015).

The rebound effect is not always a drawback. For households in fuel poverty, the energy savings could be used to achieve their affordable warmth. This should be considered as an extra benefit of housing retrofitting (Jones, Lannon & Patterson 2013). From a wider perspective, this represents positive economic growth. In some cases, such as high growth rates in developing countries, their activities tend to be more energy-intensive, and a rebound is often desirable because it allows the economy to further use its energy resources and stimulate the development of other efficiencies (International Energy Agency 2014).

4.5.4. Scaling Up

The first two retrofit projects were regional scale projects using the elemental approach with one or two individual measures, whereas the other five were building scale, using the whole house approach, which combined fabric, system and renewable measures together. Therefore, it is necessary to discuss the relationship between scales and retrofit measures in the retrofit of existing residential buildings.

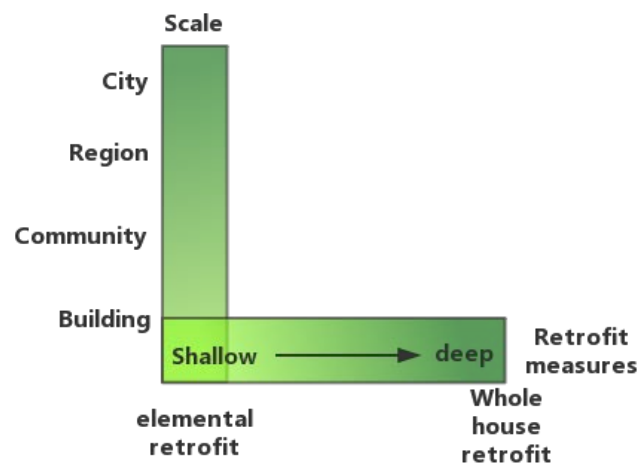


Figure 4.8 Retrofit scales VS retrofit measures (drawing by author)

Both large-scale retrofitting with 'small' measures and small-scale retrofitting with 'large' measures have their advantages and disadvantages. For large-scale projects with 'small' measures, the first two regional scale retrofit projects with the elemental approach had positive outcomes like improving energy efficiency, reducing CO₂ emissions and certain social achievements, and the retrofit cost was reduced due to economies of scale. For example, in the Arbed 1 retrofit programme, the retrofit cost was reduced by 20% to 50% in the installation process compared to individual retrofit (Burrell 2011). However, it also has some drawbacks. For example, in order to retrofit more properties with limited funding, each of the houses was given only one or two retrofit measures, resulting in limited retrofit performance in improving energy efficiency and reducing CO₂ emissions. Compared with the deep retrofit normally produces from 60% to 80% CO₂ reduction, elemental retrofit can achieve a result of

only around 10% to 30% (Jones, Lannon & Patterson 2013). In addition, the survey before retrofitting may not have been well-planned, because large-scale retrofit projects usually contain hundreds or thousands of properties of different ages, types, sizes, etc., but the time for surveys before retrofitting is limited. This may lead to some problems in later steps, such as inappropriate strategy design or poor retrofit quality in installation. Some of the poor work may have to be reversed after a few years, which may bring unnecessary trouble for the occupiers and waste more money, time and resources. Furthermore, because elemental retrofit uses individual measures, it does not consider much of the influence between different measures, which may affect the final effect of the retrofit.

For small scale retrofitting with 'large' measures, the five SOLCER retrofit projects in building scale applied the whole-house approach. The advantages of this have been identified as follows. First, all the retrofit measures can be integrated considered, so the most suitable combination of measures can be used for best results, and it will be more cost effective. Besides this, the retrofit performance has significantly increased both the energy efficiency and the liveability of the residences. All of the five whole-house retrofit projects achieved 50% to 70% CO₂ emission reduction (Jones et al. 2017). Moreover, some houses may need fabric refurbishment such as re-roofing, so the refurbishment and energy efficiency measures can be applied at the same time, which will save costs and time. Building scale retrofitting also has some drawbacks. For example, the retrofit cost is still relatively high. Also, the retrofitting on the building scale relies a lot on individual residents in installation and use, which may affect the retrofit result in reality. Furthermore, retrofitting single houses may fragment the original overall appearance of the community, as shown in Figure 4.9 (Route 2009), which may also raise some problems among neighbours.

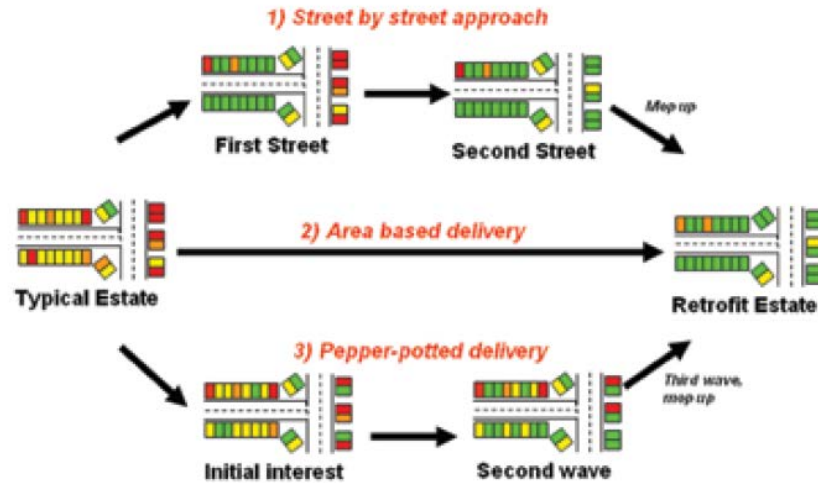


Figure 4.9 Delivery approach of housing retrofit in community scale (Route 2009)

Although the retrofitting of existing housing at the building scale can improve the energy efficiency of the house and enhance the indoor comfort and liveability to the occupiers, large-scale retrofitting has many additional benefits for the local area to create a sustainable, healthy environment for the whole community.

There are additional benefits to retrofit a whole community than individual building retrofitting. Scaling up could result in savings of about 10% due to labour efficiencies. Working teams can allocate time according to different construction content. For instance, the team could work on other parts of a site while some parts are drying or setting. Besides, with the reduction of labour costs, material costs and transportation costs, the cost of the retrofit will be further reduced due to economies of scale (Palmer et al. 2017).

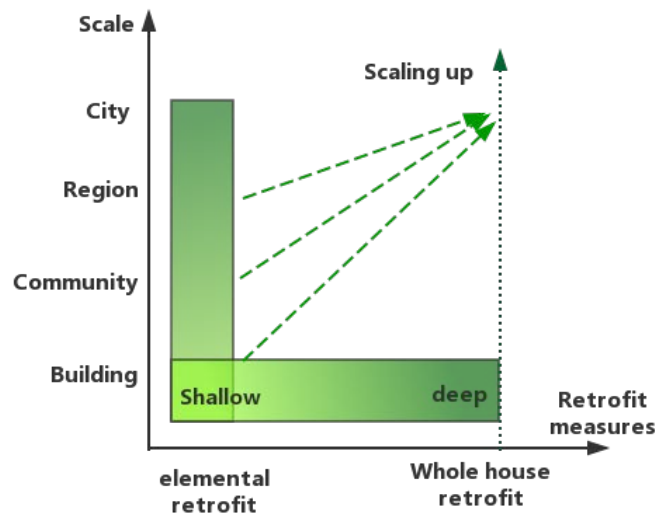


Figure 4.10 Scaling up of the housing retrofit (drawing by author)

In terms of renewables, the solar PV panels applied to a community will increase the total electricity generation and reduce cost, because the installation area can be increased in different orientations. For the houses with east-west orientations, the PV panels can be installed to the whole roof instead of the south-oriented side. In addition, the energy supply and storage systems can be shared in the community, which will benefit those houses that may not have an optimal orientation with regard to solar energy systems.

As shown in figure 4.10, the goal of the sustainable retrofitting of the existing housing stocks is to develop elemental retrofit to whole-house retrofit, from the building scale to larger scales. As retrofit technologies are developed, the cost of more deep retrofit measures will be reduced (Jones et al. 2016), which will make it more feasible and cost-effective to carry out large-scale whole-house retrofitting in the future.

4.6. Summary

This chapter investigated seven Welsh retrofit projects using elemental and whole-house retrofit approaches on different scales. It is found that elemental retrofit is

adopted in most of the large-scale retrofit projects in the UK, which mainly conducts one or two retrofit measures, such as the Warm Wales Arbed 1 and the Neath Port Talbot retrofitting programme. The retrofit costs are low, and the energy consumption reduction and CO₂ emissions reduction are relatively low as well.

There are examples of deep retrofit in the UK at small scales. The five SOLCER retrofit projects demonstrate that a whole-house, deep retrofit approach can provide much more improvements in environmental, social, financial, living quality, and carbon reduction aspects than elemental retrofit. The CO₂ emission reductions of the five retrofit projects are shown to be in the range of 50% to 70%, but the retrofit costs were still prohibitively high, so that large scale deep retrofit has not been considered to be financially available. The payback years of the five SOLCER retrofit projects are in the range of 46 to 63 years, so evaluating the energy retrofit simply by energy savings is difficult. There is a need to explore affordable solutions which can be replicable and rapidly applied to large-scale retrofit projects to improve the existing residential buildings, as well as reduce emissions significantly. (Patterson 2016).

In-depth surveys and studies are significant at the beginning of a retrofit project. They are a prerequisite for a good retrofit design. Inappropriate surveys may lead to an unreasonable design, which may not be adapted to the local climate, building age or specific architectural forms, and which may result in many construction detail problems during the installation process. In addition, dealing with the detail problems on site may also increase the difficulty and time of installation. Therefore, it is important to make an in-depth investigation and research at the early stage of the retrofit project, providing effective and appropriate solutions to ensure the rationality, accuracy and efficiency of the retrofitting implementation.

Energy simulation modelling plays an important role in planning and designing stage of the retrofit process, which can be used to predict the energy consumption and CO₂ emissions before and after retrofitting. It can also be used to estimate the operating energy bills by calculating with the current energy cost.

It is important to target the optimal combination of packages of energy-saving measures and renewable energy supply, for specific house types (Jones, Lannon & Patterson 2013).

The retrofit survey data can be used to combine with other statistical data such as health data or local income for more analysis to solve fuel poverty and other problems. The Warm Wales Neath Port Talbot project has made some attempt to combine energy with health data in order to identify the houses most in need of being retrofitting.

Chapter 5 Interviews in China

5.1. Introduction

This chapter presents the results obtained from ten interviews conducted in three cities in northern China in June 2015 and December 2017. It begins with the introduction of the interview procedure and the detailed information of the interviewees and continues with a discussion of multiple issues extracted from the interview results. Then, a summary is provided. These interviews are all in the form of unstructured face-to-face conversations, which generally start from some prepared questions for each group and followed by the free-flowing conversations.

The purpose of these interviews is to understand the current situation of the sustainable retrofitting of existing residential buildings at community scale in China from different perspectives and to accomplish **Objective 3: to discover the problems of current retrofitting of existing residential buildings in China to find out the gap between the UK and China.**

The interviewees have been therefore divided into four groups: researchers in universities, government staff from the Environmental Protection Bureau, residents living in a retrofitted community and architects with previous retrofitting experience. The details of the interviewees are listed in Table 5-1. First, university researchers were interviewed to know their perspectives on the retrofitting of existing residential buildings and China's latest retrofit projects. Second, a government staff was interviewed to find out the government point of view of sustainable housing retrofitting on implementation procedure, financial support, retrofit supervision and management, etc. Third, architects were interviewed to learn more about the design and construction information for retrofitting existing communities and the actual performance and problems in practice. Finally, residents were interviewed to gain their opinions about the retrofit results and their suggestions for improvement.

Table 5-1 List of interviewees

Group	No.	Interviewee	Position	Date	Site	City
Academic researcher	1	Mr. Yan	Professor	19/06/2015	Xi'an University of Architecture and Technology	Xi'an
	2	Mr. Han	Professor	20/12/2017	Chang'an University	Xi'an
	3	Mr. Tan	Professor	23/06/2015	Tsinghua University	Beijing
	4	Mr. Li	Professor	26/06/2015	Tsinghua University	Beijing
Government staff	5	Mr. Li	Specialist	25/06/2015	Tianjin Environmental Protection Bureau	Tianjin
Architect	6	Mr. Zhang	Senior architect	27/12/2017	Zhonglian Northwest Engineering Design & Research Institute	Xi'an
	7	Mr. Li	Project manager	15/12/2017	Beijing Architectural Design Institute	Beijing
Resident	8	Mrs. Luo	Head of neighbourhood committee	24/06/2015	Huizhongli Community	Beijing
	9	Mrs. Liu	Resident	24/06/2015		Beijing
	10	Mr. Zhang	Resident	28/12/2017	Chang'an University Community	Xi'an

5.2. Initial questions for the interviews

The initial questions prepared for the interviewees to start the conversations are as follows:

- **Why does China need to carry out the sustainable retrofitting of existing buildings?**
- **What are the current progress and problems of energy saving and existing community retrofit in China?**
- **What are the unique issues of residential building retrofit in China?**
- **What are the retrofit measures commonly used in current projects in China?**

- **How was the results and performances of the previous retrofit projects in China?**
- **How do residents participate in the retrofit?**
- **What are the financial issues of retrofit in China?**

After the interviews, all findings were organised and combined under five main themes, which are presented below.

5.3. Why Does China Need to Carry Out the Sustainable Retrofitting of Existing Buildings?

Regarding reasons for the retrofitting of existing communities, the interviewee from the government indicated that the energy consumption of buildings in northern China is relatively high, accounting for more than 40% of the energy consumption of buildings in cities in China. Besides this, the primary occupants of the existing communities are the low-income groups in the city. The indoor temperature is low in winter, and the living conditions are relatively poor, due to the lack of insulation measures. Therefore, the sustainable retrofitting of existing residential buildings in northern China is not only an essential part of building energy consumption reduction but would also be significant in improving the living quality for low-income and middle-income urban residents.

5.4. What are the Current Progress and Problems of Energy Saving and Existing Community Retrofit in China?

In the past 30 years, China has established and improved the building energy efficiency standard system. As pointed out by interviewees from universities, three stages of energy reduction targets in China have been established since 1986, which is also reflected in the China Building Energy Policy Progress Report (Shui & Li 2012). The first stage was carried out in 1988, which aimed to achieve 30% of the energy consumption compared with 1980 levels. The second stage was proposed in 1995 to reduce energy

use by 50% from 1980 levels. The third stage was implemented in 2010 to cut energy consumption by 65% from 1980 levels.

In terms of problems, the majority of interviewees maintained that the retrofitting of existing residential buildings in China has a number of problems, including:

- A lack of original design data and detailed information of the properties during the surveying phase, which results in a change in the retrofit approach;
- The lack of a holistic retrofit approach for existing residential buildings. Most of the previous projects only carried out a few individual measures such as external wall insulation or heating system improvements. These retrofit projects also required a large workforce, and a lot of materials, financial resources and time, but did not achieve satisfactory results.
- The content of energy efficiency retrofit standard updates is slow and is not mandatory.
- Poor workmanship and a lack of supervision and quality control. Many builders have not been professionally trained, resulting in many construction detail problems such as thermal bridging and poor finishing at casements and eaves, as well as unsatisfactory performance after the retrofitting.
- A low level of standardisation of building materials, which affects the construction efficiency and standardisation.
- Regarding project organisation, a complete organisation system for energy efficiency retrofitting of existing residential buildings has not been formed.
- A long-term investment and financing mechanism has not yet been established in energy-saving retrofit.
- Heating reform has not been put into practice in most of the existing communities. 70% of the buildings in northern China use central heating. The area-based heating billing still dominates in existing communities compared to consumption-based billing, which results in heat waste and high energy consumption in buildings.

- A lack of a systematic set of monitoring and verification criteria for existing residential building retrofitting. There are few follow-up measures, indoor condition monitoring and post-occupancy surveys or reviews of the retrofit in China.

5.5. What are the Unique Issues of Residential Building Retrofitting in China?

There are several unique issues of residential building retrofitting in China:

- The interviewees from architectural design institutes pointed out that the retrofitting of existing residential buildings is usually carried out with the occupants in residence. As there are a large number of residents in buildings in China and as their daily lives are affected during the retrofit process, the construction period must be kept as short as possible, which makes it a challenge to balance construction time and quality.
- Another specificity is the seasonality of construction. Summer is a crucial period for the construction of new buildings, but it brings many difficulties for the retrofitting of existing buildings, especially buildings that are inhabited. The installation of wall insulation requires the removal of outdoor pendants like air-conditioning, so windows and doors become the only means of ventilation in summer. Therefore, the impact on residents' lives can be reduced if the installation can be arranged in the spring or autumn.
- The interviewees also indicated that the conditions of existing residential buildings are complicated after long-term residence. The majority of residents living in the first to fourth floors often install safety grids on their windows, which have to be dismantled before retrofitting and reinstalled after the retrofitting.
- Also, during the 1990s, many residents used wood to cover the radiators when doing interior decoration, which may reduce heat dissipation up to 30%, but direct removal will affect the interior decoration. These situations may have impacts on the construction of the retrofit and delay the progress of the project. Therefore, before

carrying out the retrofit, it is necessary to conduct a more detailed and accurate survey of the site and indoor conditions.

5.6. What are the Retrofit Measures Commonly Used in Current Projects in China?

A common view amongst the interviewees is that the approaches of retrofitting the existing residential buildings should be comprehensively considered. In the case of limited funds, priority should be given to the retrofit measures with apparent improvements regarding energy efficiency and CO₂ emission reductions such as external wall insulation. The above view was reiterated by the interviewees from universities and architectural design institutions who suggested that the fabric improvement should be the first consideration, followed by system retrofit, and then renewables.

5.6.1. Fabric Improvement

One of the interviewees from universities indicated that 70% to 80% of heat losses occur through the fabric, including 20% to 30% from doors and windows, and around 25% from external walls. This is supported in detail in the *Hundred Questions of Retrofitting Existing Residential Buildings* (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012). 77% of heat loss is due to fabric (25% through external walls, 24% through external windows, 11% from walls between indoor and staircase without heating provision, 9% from roof, 3% from doors, and 5% from others). Therefore, by improving the thermal insulation performance of each part of the fabric structure, heat loss can be effectively reduced, thereby reducing the energy consumption.

The interviewees from architectural design institutes introduced the retrofit measures commonly used in China, including external wall insulation, roof insulation, enclosed balcony insulation, basement floor insulation, window replacement, building entrance

door replacement and necessary reinforcement measures. These measures are not much different from those in the UK. However, the interview results from universities indicated that the gaps in construction quality, on-site technical issues and other details (such as the rough handling of the insulation joints or using non-thermal break anchors) between China and Western developed countries cannot be ignored. Some projects directly add a layer of windows outside the original ones to save time and cost. Although the thermal performance is improved, this is inconvenient for the residents to use.

5.6.2. System Improvement

There are several retrofit measures regarding system improvement. The first is the heat metering retrofitting. The interviewees from universities indicated that the central heating system used in northern China started in the 1950s as a kind of residents' welfare. Now China has the world's largest central heating network, but it still has many problems, such as uneven heating, overheating, low-efficiency boilers, poor insulation of the pipe network, worn-out and leaking heating pipes, no heating metering devices and no thermostatic valves on radiators. The heating bills are charged on a floor area basis rather than consumption of the users. Therefore, the problem that needs to be solved most is to add a heat metering system so that the indoor temperature can be controlled by the occupants, thus enabling the heating bills to be charged by consumption.

The second retrofit measure is fuel switching. The interviewee from the government maintained that due to severe air pollution, especially during the heating season in winter, Beijing has implemented a coal-to-gas reform policy since 2009, and the use of coal for heating has been banned in many districts in Beijing since 2014. At present, most of the residential communities in the city of Beijing use natural gas for heating, which has significantly reduced air pollution in the city. Nevertheless, the interviewees from universities pointed out that rapidly promoting this policy caused severe shortages of natural gas. These views were shared by the residents, who stated that in the winter of 2017, there was a shortage of natural gas in some provinces such as

Shaanxi, and because of the prohibition of heating by coal, many people could not heat their homes in the winter.

In terms of MVHR, the interviewees from the architectural design institute explained that the MVHR is more pronounced when there is a vast temperature difference between indoors and outdoors, so it is more suitable for the severe cold zone than cold zone. Besides, compared with natural ventilation, the mechanical ventilation has higher energy consumption. Moreover, according to the feedback from residents, opening windows for ventilation is still a habit they have formed over years, despite the installation of a fresh air system. Therefore, the use of MVHR does not have many advantages in the cold zone and may even consume more energy. These views are also corroborated by the author's findings from the survey. Firstly, the MVHR system needs space for equipment and ducts to run, however, most of the retrofit projects of residential buildings in China are flats, which have very limited space for the MVHR to install. Secondly, most of the current retrofit projects using MVHR system are low-rise buildings, and the MVHR is also not commonly used in the UK's retrofit projects especially at large scales. Moreover, residents have to be entirely moved out to install the MVHR system, and the system needs to be regularly maintained such as changing filters, which is unrealistic for flats with large numbers of residents. Thus, the more sustainable and cost-effective way for the residential community is to increase the airtightness of the buildings and use natural ventilation system.

5.6.3. Renewables

Interviewees from universities said that, at present, many provinces and cities in China have issued policies and regulations to promote the application of renewable energy in buildings. Such policies and regulations mainly focused on the improvement and use of renewable energy technologies, including photovoltaic power generation, building integrated photovoltaic power generation, solar thermals and ground source heat pumps. At the same time, local financial departments also issued financial support plans and related policies. However, the interviewees also pointed out that

the scope of the application of renewables had been limited so far and that the development had been slow due to insufficient financial support.

Regarding heat pumps, the interviewees indicated that for severe cold and some cold zones in China, the air and soil temperatures are low in winter ($\leq -10^{\circ}\text{C}$ for severe cold zones and $-10\text{--}0^{\circ}\text{C}$ for cold zones in January), which means it is impossible to achieve high efficiency for the ASHPs and GSHPs, as heat pumps recover heat from air or soil source which require temperature variation. For those cities within the cold zones where winter is not too cold and where there is a need for summer cooling, the GSHP can be considered a better choice than the ASHP, but it still requires adequate attention to installation and operation issues. Also, they mentioned that in places with high plot ratios or high-rise buildings, the initial investments are often too high due to deep buried heat storage pipes, or that there is poor performance due to insufficient space for energy storage. Thus, the GSHP is more suitable for places with low plot ratios.

5.6.4. The Addition of Elevator

In recent years some multi-storey flats retrofit projects in China have included the addition of elevators. The main reason is that these multi-storey homes built in the 1980s and 1990s generally did not have elevators. With the ageing of community residents, the demand for elevators has become more and more urgent. Interviewees from the residents pointed out that due to the inconvenience of mobility, many elderly people in the community have not left the building for several years. Therefore, the addition of elevators will significantly improve the quality of life for the elderly in the community.



Figure 5.1 Elevator addition for existing residential building

5.7. What are the Results and Performance of Previous Retrofit Projects in China?

As an architect, the interviewee said that the evaluation of the retrofit improvement is based on the energy-saving calculation according to the benchmarks in the design standard for energy efficiency of residential buildings. If the calculation results are within certain ranges, the retrofit project can be considered as achieving the corresponding energy saving targets.

Similar findings were revealed by interviewing the residents. They mentioned that there was no actual monitoring of the energy consumption or inspection after the retrofitting, so it is impossible to know how much actual improvement has been achieved. The residents also claimed that the retrofit quality of the government pilot projects is better than the non-pilot ones in the same community. For example, the pilot flats used 100 mm EWI boards, whereas non-pilot flats used 50 mm ones. The quality of the windows was also different.

Regarding energy-saving targets, the interviewees from universities noted that the current energy-saving targets are for new constructions, which should be reduced to some extent for existing building retrofitting. So far, there is no energy-saving target for retrofitting existing residential buildings.

5.8. How do Residents Participate in the Retrofit?

One of the interviewees from the universities indicated that compared with the new build projects, the most significant difference in the retrofitting of existing residential buildings is in the simultaneous construction of the building and in the normal life of the occupants. The replacement of windows and heating system retrofits require workers access to residents' home for construction. As a result, obtaining the understanding and support of residents is the key to guaranteeing the smooth implementation of the retrofit work.

The interviewee from the community committee mentioned that it was not easy to mobilise residents' enthusiasm for retrofitting their community. For instance, the Huizhongli Community in Beijing was retrofitted in 2012. The residents were peasants who had been resettled due to the construction of venues for the Beijing Asian Games in early years. These residents are still low-income and middle-income people. Although many of them have strong desires to improve their living environments, they have doubts about the retrofit effect and are worried about the financial burden. Thus, the project team conducted a series of publicity projects in the early stages of the retrofit. For example, some residents were invited to visit the previous projects to see the retrofit results. Meanwhile, the office of the community committee was replaced with energy-saving windows and used as a demonstration room to show the effects of retrofit.

5.9. What are the Financial Issues of Retrofit in China?

The interviewees from universities indicated that the pilot projects were jointly funded by the municipal government and the residents according to the principle of 'whoever benefits, contributes'.

Regarding the retrofit cost, the project manager said that currently the cost of energy-efficiency retrofitting of the existing communities in China in practice is in the range of 1,500 to 2,000 CNY/m², and the limit is 3,000 CNY/m², which is generally consistent

with the data in the literature. For retrofit of energy-saving plus anti-seismic reinforcement, the cost usually is between 2,500 to 3,000 CNY/m² in practice.

The interviewee from government indicated that the government had issued an incentive scheme for the energy-efficiency retrofitting of existing residential buildings in northern China in 2007. It allotted 55 CNY/m² for the severe cold areas and 45 CNY/m² for cold areas. Beijing Municipality also provides a subsidy of 100 CNY/m² for the implementation of the retrofit projects. For solar thermal installation, Beijing Municipality provides a 200 CNY/m² incentive fund. The above point of view appears to contradict the concerns expressed by the residents living in a previously retrofitted community. The interviewees argued that the solar thermal incentive fund came with some conditions, one of which was that the installation area of the solar thermal collectors has to be over 100 m². In other words, residents cannot receive this fund if they install solar thermal collectors individually.

For elevator addition, the interviewee from universities mentioned that there is no uniform regulation for the installation, operation and maintenance costs in Beijing. The decision making was based on local conditions. Beijing University of Aeronautics and Astronautics subsidised 120,000 CNY for each elevator in their residential communities; the rest of the cost was funded by Beijing Haidian District government. Residents use elevators for rent and pay the rent on a monthly basis. The interviewee from the architectural design institute said another way is that the residents raise their funds based on the floor they live. High-level households pay more. The government subsidise the rest, and residents pay for the maintenance cost and use the elevator by swiping a pre-paid card.

However, as a project manager, the interviewee said that the residents' financial contribution is very low in the retrofit projects. The employers (privately-owned flats) or the housing association (rental flats) paid for the residents' financial contribution. The retrofit projects he had been involved in were all funded by the government.

5.10. Summary

Through interviews, more insight and detailed data on sustainable residential building retrofitting in China was gained and collected.

5.10.1. Comparison of retrofit measures between China and the UK

In order to better explore the most suitable, sustainable, and cost-effective retrofit measures of existing residential buildings in China, it is necessary to make a comparison of retrofit measures between China and UK to discover the problems of current retrofit in China and find out the gap between the two countries.

5.10.1.1. Wall Insulation Materials Comparison

As summarised by Forman (2015), in the UK, the following traditional insulation materials have been used for many decades:

- Polyurethane foam (PUR), board or sprayed;
- Polyisocyanurate (PIR), board or sprayed;
- Mineral wool;
- Glass fibre;
- Expanded polystyrene (EPS);
- Extruded polystyrene (XPS);
- Phenolic foam;
- Polyethylene foam;
- Cementitious foam.

According to the *Hundred Questions of Retrofitting Existing Residential Buildings* (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012), there are five recommended types of external insulation system in the Chinese market:

- Thin plastering of the external wall insulation

- On-site sprayed rigid polyurethane foam insulation
- Polystyrene particle jelly coating technology for cladding exterior insulation
- Polystyrene particle jelly coating on polystyrene board
- Decorative insulation board

Most of the retrofit projects in the UK employ EPS or mineral wool boards. Others also use phenolic and PIR foam boards (Forman 2015). In China, by contrast, some retrofit projects employed XPS, which is not appropriate for external wall insulation as the closed-cell structure of the board may cause shrinkage so that the mesh and finish cannot resist cracking due to the high modulus of elasticity caused by XPS (Kerschberger 2010). In consideration of different factors such as economic efficiency, insulation performance, constructability, environmental performance, fire resistance and durability, the using of the thin plastering method should be given priority in retrofitting in cold and severe cold zones in China (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2012).

5.10.1.2. Glazing Improvement

From what has been mentioned above, many buildings built before 2000 in China are still using single glazed sliding windows, which are poorly sealed. The double-glazed inswing casement cavity window used in UK retrofit projects is a good improvement upon this. A triple-glazed window with double sealing and a thermal insulation frame in the future could perform even better than double-glazed windows. Low-E glazing is recommended in retrofitting because the heat transfer coefficient of the current double-glazing plastic steel frame window is 2.5–2.8 W/m²K, while it could be easily lowered to 1.8–2.0 W/m²K by using Low-E glazing and better frames without extra technological effort.

In addition, the residential buildings in China are in favour of using large-sized windows for more natural light, while in the UK, the housing windows are relatively smaller. When the window occupies 30 percent of the area of the external wall, it will

become a thermal vent to the building. Energy saving efficiency can be improved by reducing the window area (Kerschberger 2010).

5.10.1.3. Heating System Comparison

In the UK, most of the residences have individual heating systems, while in China, due to the large numbers of the population, most of the communities have heat networks, which makes it much easier to supply heating and reduces the maintenance cost for the community. However, the heating network in China's residential buildings built before 2000 has low heating efficiency, which needs to be retrofitted.

In the UK, most of the residential buildings have thermostat in each room, whereas in China, most of the new buildings still do not have individual thermostats. The individual thermostat can control the temperature of every single room, as well as the whole property. The energy savings can be significant when individual thermostats are installed in buildings with large numbers of residents.

To sum up, through the investigation of the seven retrofitting projects, it is found that the retrofit measures of the existing residential buildings in the UK are basically carried out according to the following route: first is the fabric retrofit. The retrofit measures include external wall insulation, loft insulation, floor insulation, draught proofing, and window replacement. Followed by system improvement, including fuel switching, replacement of more efficient boilers, LED lighting, and MVHR. Then, the renewables such as solar PV, solar thermal, and ASHP/ GSHP are integrated.

5.10.2. Comparison of residential building retrofit between China and the UK across technical, social and economic aspects

The difference between China and the UK in the retrofitting of existing residential buildings has gradually become clear by combining this information with a literature review and case studies in the UK, which are summarised in Table 5-2 below.

Table 5-2 Difference between China and the UK on retrofitting of existing residential buildings

		China	The UK	
Technical issues	Retrofit measures	Wall insulation	<ul style="list-style-type: none"> • Most of the retrofits use EWI in order not to affect the occupants' interior decoration 	<ul style="list-style-type: none"> • EWI is mainly used. For some houses with historical values, IWI/ hybrid and multi insulation are also used
		Roof insulation	<ul style="list-style-type: none"> • The thickness of roof insulation normally from 50 mm to 100 mm in order not to increase the roof load 	<ul style="list-style-type: none"> • The thickness of roof insulation normally from 120 mm to 300 mm
		Window replacement	<ul style="list-style-type: none"> • Some projects directly added a layer of windows outside the original ones instead of replacement 	<ul style="list-style-type: none"> • Replaced with double or low-E glazing windows
		Heating system retrofit	<ul style="list-style-type: none"> • Central heating system • Most heating systems do not have thermostats • Heating bills are charged by floor area 	<ul style="list-style-type: none"> • Individual heating system • Each room has thermostatic valves on radiators • Heating bills are charged by consumption
		Renewables	<ul style="list-style-type: none"> • GSHP is more suitable for places where winter is not too cold and there is a need for cooling in summer 	<ul style="list-style-type: none"> • ASHP is used more widely than GSHP due to suitable temperature and no need for pipeline space
	Quality control	On-site technical issues	<ul style="list-style-type: none"> • Many builders have not been professionally trained • The old building materials are not standardised, resulting in more time consumed and many on-site technical problems 	<ul style="list-style-type: none"> • Some large-scale projects have trainings for workers • The sequence of work had been inadequately planned in some houses, resulting delayed works and extra costs
		Detailing	<ul style="list-style-type: none"> • Thermal bridging, rough handling of the insulation joints, using non-thermal break anchors, poor finishing at casement 	<ul style="list-style-type: none"> • In many older properties, detailing was complex • Quality compromised by tight deadlines and cost issues
Social issues	Energy-saving target		<ul style="list-style-type: none"> • 65% CO₂ emission reduction from 1980 levels 	<ul style="list-style-type: none"> • 80% CO₂ emission reduction from 1990 levels by 2050
	Implementation		<ul style="list-style-type: none"> • Completely government led (Top-down) • Inadequate surveys before and after retrofit 	<ul style="list-style-type: none"> • The bottom-up approach has been paid more attention • surveys and assessments proceed before, during and after the major retrofit activity.
	Supervision & Evaluation		<ul style="list-style-type: none"> • Lacks of supervision and post evaluation in practice 	<ul style="list-style-type: none"> • A more systematic supervision and evaluation system
Economic issues	Retrofit cost		<ul style="list-style-type: none"> • 1,500-2,000 CNY/m² for energy-saving retrofit • 2,500-3,000 CNY/m² for energy-saving plus anti-seismic reinforcement 	<ul style="list-style-type: none"> • £100/m² for elemental retrofit (Arbed Project) • £322 - £455/m² for whole house retrofit
	Funding		<ul style="list-style-type: none"> • Mostly funded by the government 	<ul style="list-style-type: none"> • Funding is from different sources including government schemes, local authorities, social landlords, grant support mechanisms, and residents

To sum up, five main points have emerged from interviews in China. They are:

- China's existing residential building retrofit has just recently started. There are still many problems and some particularities. It needs to learn from countries like the UK that have some retrofit experience and combine with China's situation to identify a set of appropriate retrofit approaches.
- Regarding retrofit measures, the gap between China and the UK is not large, but China's construction methods, retrofit material standardisation and on-site detail handling need to be improved.
- China lacks a comprehensive set of standards and adequate supervision and management mechanisms for the retrofitting of existing residential buildings.
- Residents' participation and understanding is not only a guarantee of smooth construction work but also an essential part of the retrofit of existing residential communities.
- China needs to explore a set of fund-raising mechanisms for sustainable retrofitting of existing residential buildings.

After this chapter, the lessons learned and the retrofit measures can be transferred from the UK have become explicit, and are significant for evaluating the current sustainable retrofit development in China and propose the case study of China and the simulation frameworks.

Chapter 6 Case Study in China

6.1.Introduction

This chapter focuses on the energy simulation of four existing housing retrofit cases in China to answer the research questions: ‘What strategies can be gathered from this research to improve the existing housings and communities in China?’ and ‘To what extent can the UK’s experiences be transferred to China?’, which are the two central research questions of this study.

This chapter begins with the introduction of the climate and built environment in Beijing. Following this, the interior conditions and simulation parameters are presented. Next, each case is introduced in detail from the location, architectural layout, simulation settings and construction details. Then, several individual and combined retrofit measures are examined, and the modelling results of each case are outlined and analysed. After that, the results of the four cases are compared and discussed. Finally, the outcomes of this chapter are summarised.

6.2.The Basic Information for Beijing, China

6.2.1.The Climate in Beijing, China

Beijing is located at the northern end of the North China Plain in northeast China, with an average elevation of 43.5 metres (China Daily 2009). It belongs to the cold climate zone, with a monsoon-influenced humid continental climate. Beijing has four distinct seasons: windy springs, hot, humid summers, cool autumns and cold, windy, dry winters. The average annual temperature in Beijing is about 13.2 °C. The coldest month (January) has an average temperature of -2.9 °C, and the hottest month (July) has an average temperature of 27.9 °C (Beijing Municipal Bureau of Statistics 2012). Figure 6.1 to 6.3 use the weather data file from the Energy Plus web site. Figure 6.1

shows the daily dry bulb temperature in Beijing. It can be seen that the daily highest temperature reaches nearly 37 °C in June, and the daily lowest temperature is about -14 °C in January.

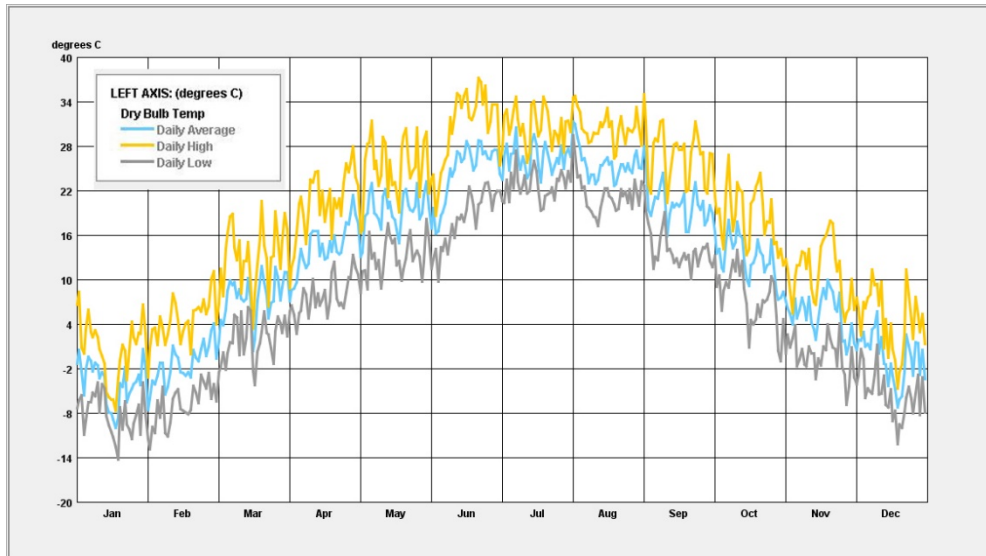


Figure 6.1 The statistics of daily dry bulb temperature in Beijing (the weather data is from Energy Plus website)

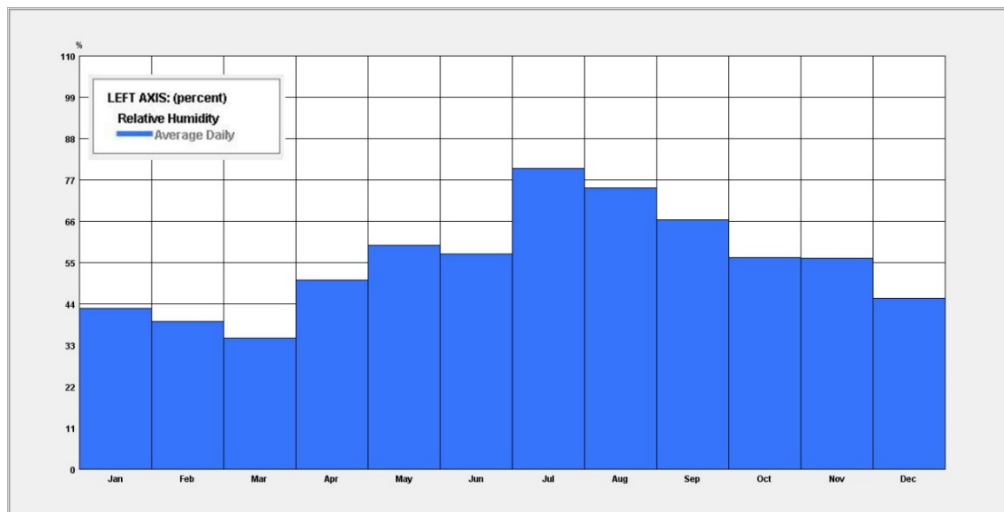


Figure 6.2 The statistics of relative humidity in Beijing (the weather data is from Energy Plus website)

It can be seen from Figure 6.2 that the monthly relative humidity in Beijing ranges from 30% to 80%. The most humid month is July, with an average humidity of 78%.

60% of the precipitation in the whole year is concentrated in July and August in summer, while other seasons are relatively dry (Beijing Municipal Bureau of Statistics 2012).

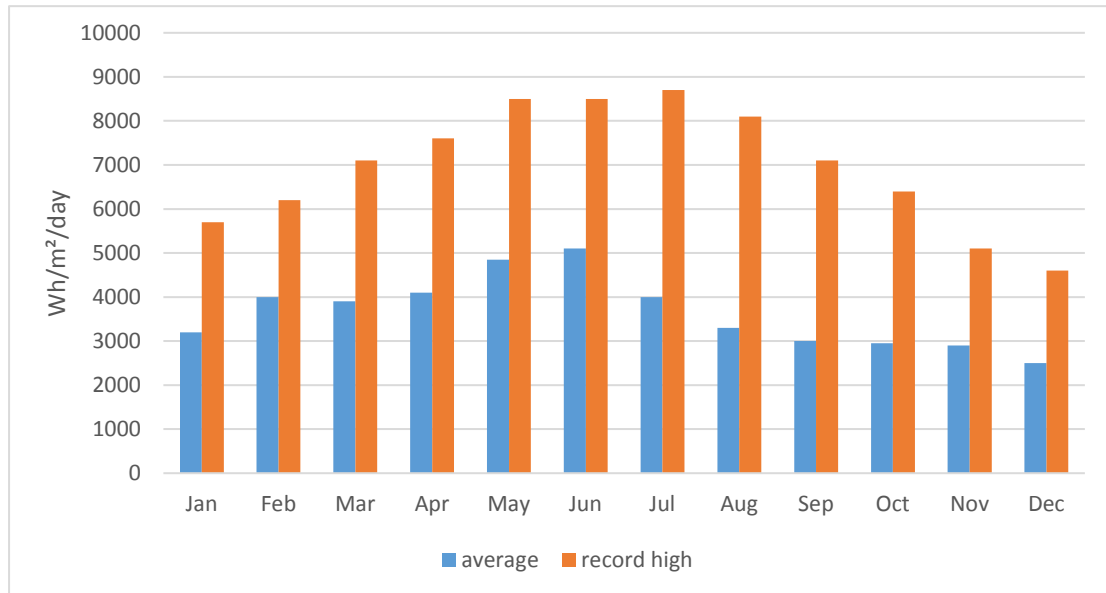


Figure 6.3 The statistics of direct normal solar radiation in Beijing (the weather data is from Energy Plus website)

Figure 6.3 illustrates the monthly direct solar radiation in Beijing. The average daily direct solar radiation is about 3600 Wh/m², and the peak value is in June with around 5000 Wh/m² per day. The record high of the daily direct solar radiation is shown in the orange bars, and the peak value is about 8700 Wh/m² in July. The average annual sunshine hours in Beijing is in the range of 2000 to 2800 hours (Zhao 2013).

Figure 6.4 shows the predominant wind direction and the wind speed in Beijing in four seasons from 2011 to 2015. It shows that the wind is most often from the southwest in spring and summer, northeast in fall and north in winter. The wind speed is in the range of 1 m/s to 9 m/s, and there are more windy days in spring and winter.

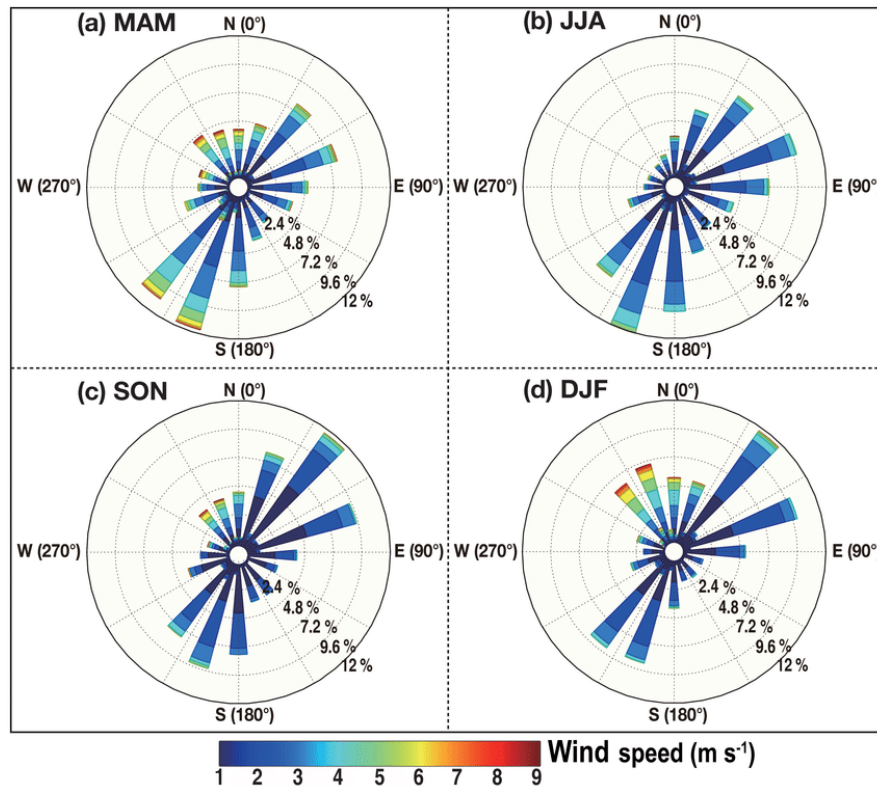


Figure 6.4 Wind rose of Beijing in four seasons from 2011 to 2015 (Zheng et al. 2017)

6.3. Interior Conditions and Input Parameters for the Simulation

6.3.1. Internal Heat Gain (IHG)

The definition of the internal heat gain (IHG) is ‘the sensible and latent heat emitted within an internal space from any source that is to be removed by air conditioning or ventilation, and/or results in an increase in the temperature and humidity within the space’. It comes from occupants, lighting, and small powers including electric motors, cooking equipment and other domestic appliances such as computers and televisions. The total internal heat gains are proportional to the density of occupants. Table 6-1 is an example of the relationship of the internal heat gains and the occupant density of office buildings in the UK (Guide A CIBSE 2006).

Table 6-1 Benchmark values for internal heat gains for offices

Building type	Use	Density of occupation / person·m ⁻²	Sensible heat gain / W·m ⁻²			Latent heat gain / W·m ⁻²	
			People	Lighting	Equip't	People	Other
Office	General	4	20	12	25	15	—
		8	10	12	20	7.5	—
		12	6.7	12	15	5	—
		16	5	12	12	4	—
		20	4	12	10	3	—

As can be seen in Figure 6.5, IHG is also related to the total floor area of the building because the actual electricity consumption depends on the size of the living areas (Passive House Institute 2015).

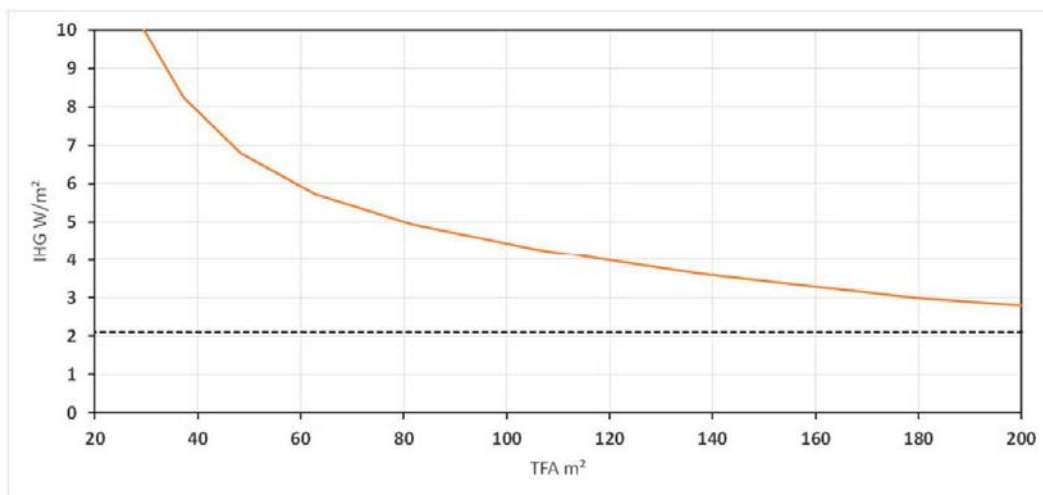


Figure 6.5 Internal heat gains depending on the living area (Passive House Institute 2015)

It is essential to consider the IHGs together with solar gains, fabric gains, ventilation gains, as well as heater and cooler gains to decide the overall heating and cooling demand. Currently, most of the published surveys of IHGs are for office buildings, and there are few publications of measured IHGs for residential buildings in China. Besides, although there is an official benchmark of 3.8 W/m² for the IHGs for the cold zone in China (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2010a); this is not suitable as a basis for dynamic simulation due to lack of information on indoor hourly changes over time. Therefore, the CIBSE Guide A (2006)

and the Intertek Report of Household Electricity Survey (Zimmermann et al. 2012) are used for evaluating the IHGs in this research. Meanwhile, as China's typical residential buildings are multi-storey and high-rise flats with large total floor areas and a high density of occupants, which are different from most houses in the UK, and the annual energy consumptions in the UK and China are different. Thus, it is necessary to adjust the IHGs from the UK to China, combining with the household average total floor area, the average density of the urban residents of the two countries instead of directly using the UK's benchmark value for Chinese scenario.

6.3.1.1. Occupants

Table 6-2 Typical rates at which heat is given off by human beings in different states of activity (Guide A CIBSE 2006)

Degree of activity	Typical building	Total rate of heat emission for adult male / W	Rate of heat emission for mixture of males and females / W			Percentage of sensible heat that is radiant heat for stated air movement / %	
			Total	Sensible	Latent	High	Low
Seated at theatre	Theatre, cinema (matinee)	115	95	65	30	—	—
Seated at theatre, night	Theatre, cinema (night)	115	105	70	35	60	27
Seated, very light work	Offices, hotels, apartments	130	115	70	45	—	—
Moderate office work	Offices, hotels, apartments	140	130	75	55	—	—
Standing, light work; walking	Department store, retail store	160	130	75	55	58	38
Walking; standing	Bank	160	145	75	70	—	—
Sedentary work	Restaurant	145	160	80	80	—	—

Table 6-2 lists the typical heat emission rates by human beings in different activities. According to CIBSE Guide A, there are two heat emission rates related to apartments. The rates of sensible heat emission for a mixture of males and females are 70W for activities like seated, very light work, and 75W for activity degrees similar to moderate office work (Guide A CIBSE 2006). According to the National Bureau of Statistics of China, the average household size is 2.45 people per household (Beijing Municipal Bureau of Statistics 2013). Therefore, the heat emissions per household for the two activities above are 172 and 184, respectively. Since people's activities are changing throughout the day, so an occupancy schedule is developed for Simulation. Also, as in workdays, some people are not at home, therefore assuming there is 1 person staying at home doing activity similar to moderate office work on average during working

hours. The diary of occupancy for workdays and weekends is listed in Table 6-3 and the profile of the internal heat gains from occupants is presented in Figure 6.6.

Table 6-3 Schedule of occupancy for case studies in China

IHG from occupancy	Number of occupant	Degree of Activity	Weekdays	Weekend
			Mon-Fri	Sat-Sun
172 W	2.45	Seated, very light work	00:00-06:00 & 20:00-23:00	00:00-08:00 & 22:00-23:00
184W	2.45	Moderate office work	07:00-08:00 & 18:00-19:00	09:00-21:00
75 W	1	Moderate office work	09:00-17:00	-

* For IHG from occupancy, the average household size is 2.45 people per household in Beijing (ref: Beijing Municipal Bureau of Statistics 2013);

* Assume there is 1 person staying at home on average during working hours.

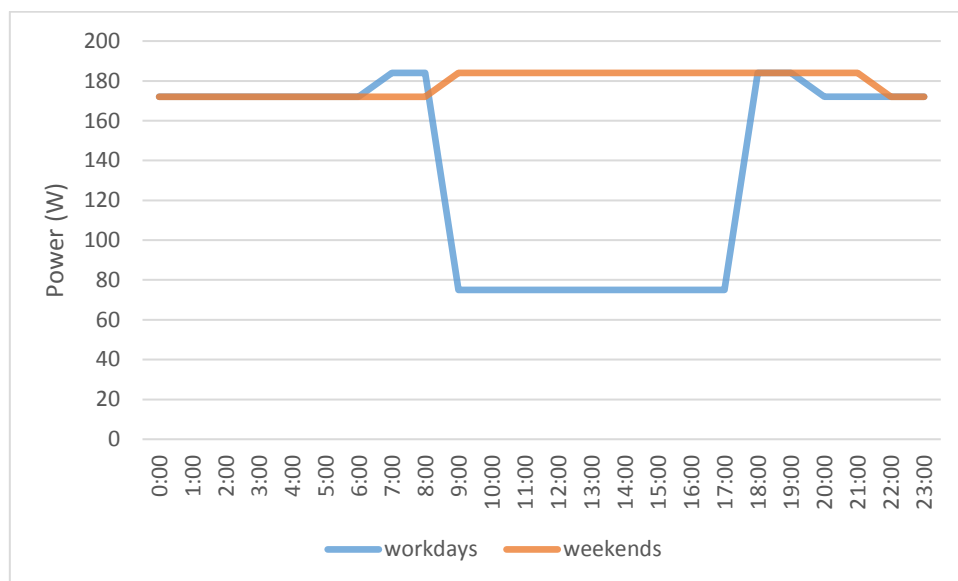


Figure 6.6 Hourly internal heat gains from occupants for case studies in China

6.3.1.2. Lighting and Small Power

The evaluation of the IHGs from the perspective of lighting and small power is based on the hourly IHG loads in the Intertek Report of Household Electricity Survey (Zimmermann et al. 2012). This report has the results of energy consumption from

251 households in England monitored from May 2010 to July 2011. It is a more detailed energy data of the IHGs for residential buildings. Figure 6.7 and 6.8 illustrate the hourly IHG curve from lighting and different electrical appliances between workdays and weekends.

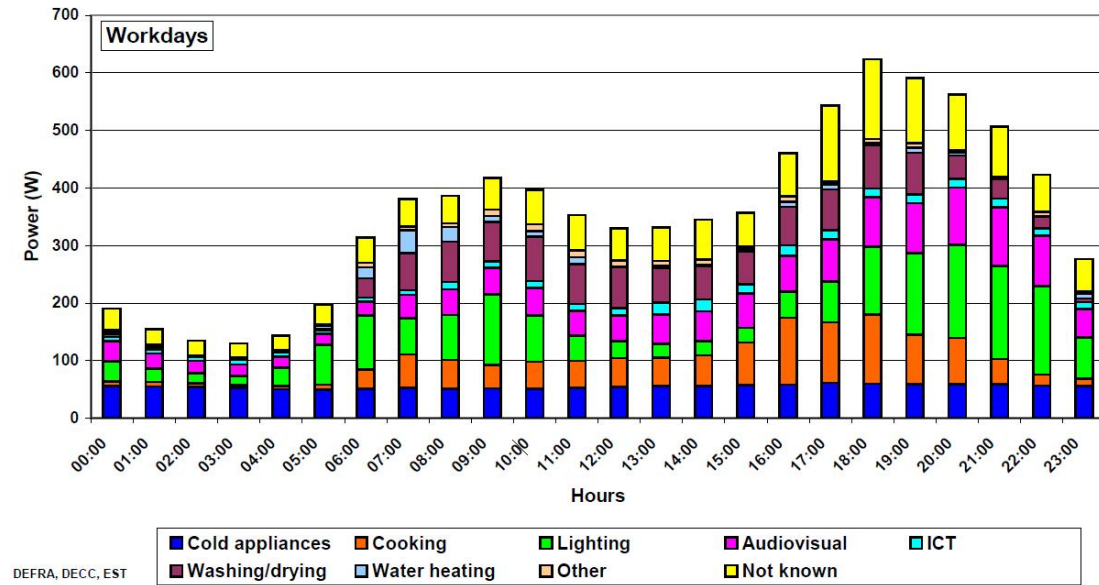


Figure 6.7 Workdays hourly internal heat gain curve from small power and lighting in UK housing (Zimmermann et al. 2012)

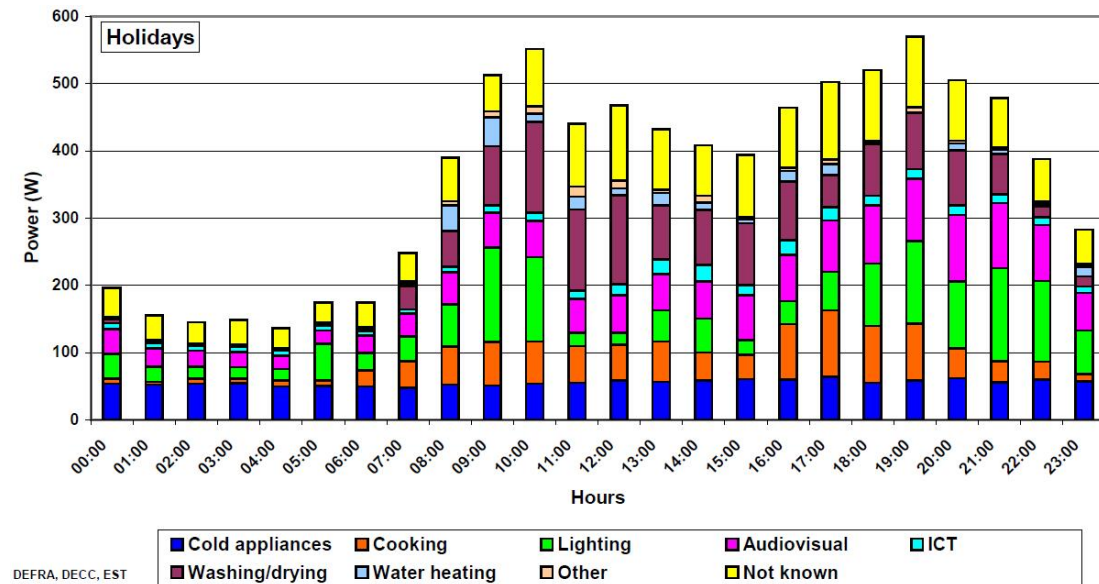


Figure 6.8 Weekends hourly internal heat gain curve from small power and lighting in UK housing (Zimmermann et al. 2012)

In this research, all the electrical appliances are considered to be small power. Plus the IHG from occupancy mentioned above, the UK's hourly IHGs including lighting, small power and occupancy can be made out from the yellow lines shown in Figure 6.9 and 6.10. This report has also provided the annual electricity consumption of 65 kWh/m² on average in the UK (Zimmermann et al. 2012), which can be used to adjust the hourly IHG loads in China.

According to the Beijing Bureau of Statistics in 2016, the urban residential electricity consumption in Beijing is 16,645.39 GWh (Beijing Municipal Bureau of Statistics 2017a), and the urban population is 18.796 million with an average living area of 32.38 m² per person (Beijing Municipal Bureau of Statistics 2017). Thus, the annual average electricity consumption of urban housing in Beijing can be calculated as 27.35 kWh/m².

The UK's hourly IHGs per square metre can be calculated by dividing the total hourly IHGs, including occupancy, lighting and small power by the average property area in the UK of 85 m² (Roberts-Hughes 2011). Therefore, the hourly IHG loads per square metre in China can be adjusted by using the promotional value of the annual electricity consumption in the two countries. Figure 6.9 and 6.10 illustrate the hourly IHG curves for workdays and weekends, respectively. The blue lines are the adjusted profile for the Chinese scenario.

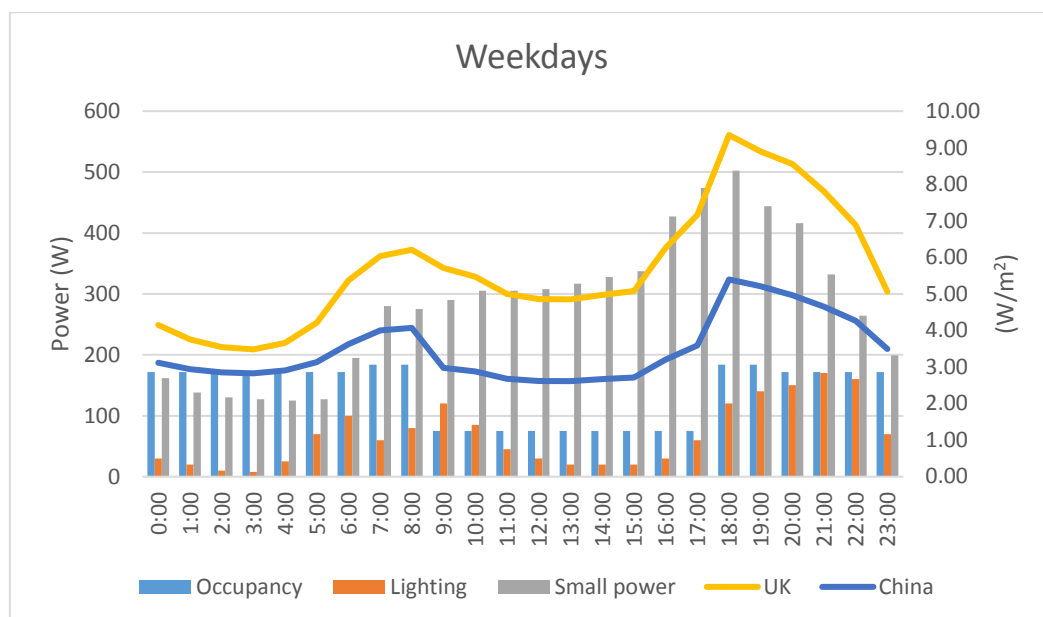


Figure 6.9 Weekdays average hourly IHG load curve in the UK and China (drawing by author)

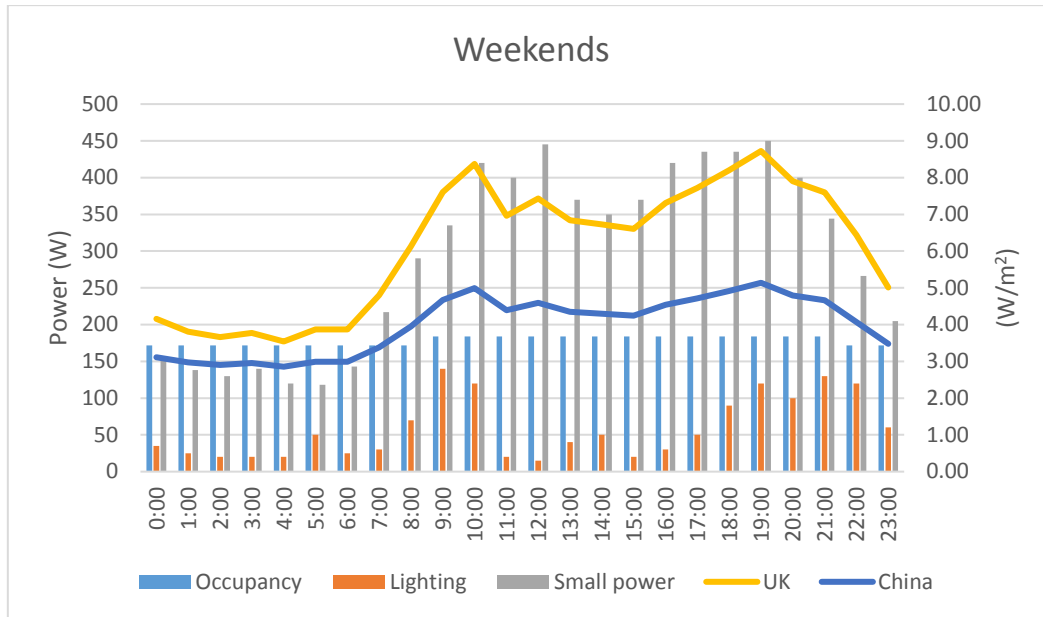


Figure 6.10 Weekends average hourly IHG load curve in the UK and China (drawing by author)

6.3.2. Diary and Input Parameter Settings for Simulation

The diary refers to the time setting of the heating and cooling systems, occupants' activities, lighting, small powers and ventilation in the simulation. For occupancy, this research assumes that one person is staying at home for each household and doing activity similar to moderate office work during working hours (from 09:00 to 17:00 on workdays). For lighting and small powers, as the operation hours of different appliances are various and since some appliances, such as fridges, do not stop for a long time, the diary is set to hourly and the loads are taken from the adjusted results of the UK survey. The diary of heating, cooling, IHG from occupants and ventilation as well as other input parameters is listed in Table 6-4.

Table 6-4 Diary and input parameter settings for simulation

		Input parameter	Weekdays	Weekend
			Mon-Fri	Sat-Sun
Heating		18 °C (Nov.15-Mar.15)	00:00-24:00	00:00-24:00
Cooling		26 °C (Jun.1-Aug.31)	00:00-08:00 & 18:00-24:00	
IHG from occupancy		172 W	00:00-06:00 & 20:00-23:00	00:00-08:00 & 22:00-23:00
		184W	07:00-08:00 & 18:00-19:00	09:00-21:00
		75 W	09:00-17:00	-
Ventilation	1.0/h	Winter (Nov.15-Mar.15)	06:00-08:00 & 18:00-20:00	06:00-20:00
		Other seasons	00:00-08:00 & 18:00-24:00	00:00-24:00

6.4. Introduction of the Four Base Cases

The purpose of selecting these four buildings as case studies in China is to compare the performance of different types of residential buildings built in the same period and the same types of buildings built at different times in terms of energy consumption, carbon emissions, renewables, as well as retrofit measures, costs, potential savings and multi-benefits.

6.4.1. The Basic Information of the Four Cases in Beijing

The simulation in this study focuses on the residential buildings built after 1978 and before 2005. The categories of the four selected cases are shown in Table 6-5.

Table 6-5 Categories of the four selected cases

	Low-rise	Multi-storey	Mid-rise	High-rise
Storey	1 to 3	4 to 6	7 to 9	> 10
Pre-1978	x	x	x	x
1978-1990	x		√	√
1991-2005	x	√		√
Post 2005	x	x	x	x

The locations and basic information of the four cases in Beijing are shown in Figure 6.11 and Table 6-6 as below.

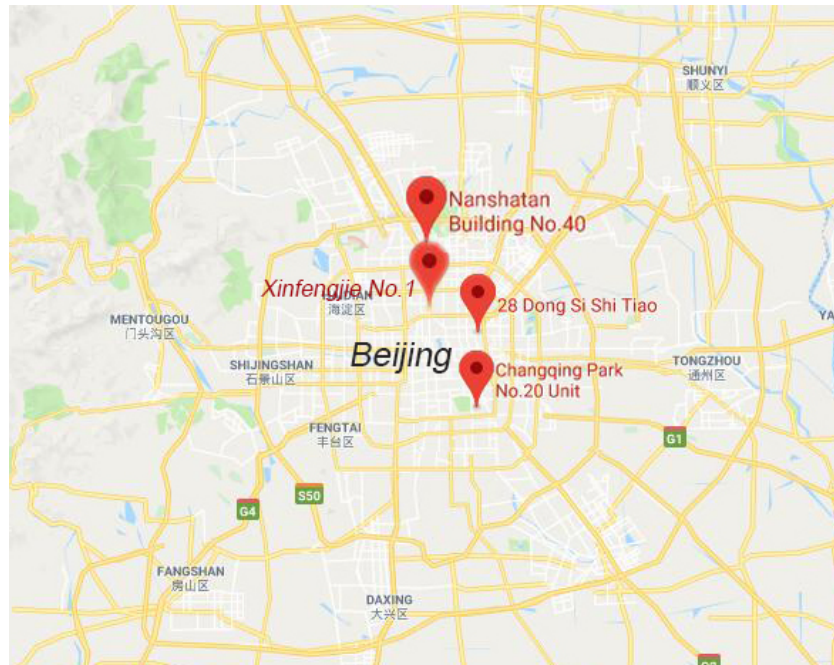


Figure 6.11 Location of the four cases in Beijing

Table 6-6 Basic information of the four base cases in Beijing

Case	Address	Built year	Type	Storey	Total floor area (m ²)	Household number	Floor height (m)
1	Changqingyuan No.20	1987	Mid-rise	7	8255	84	2.7
2	Nanshatan No.40	1996	multi-storey	6	4015.56	66	2.7
3	Dongsishitiao No.28	1983	high-rise	18	8165.97	121	2.9
4	Xinfengjie No.1	2001	high-rise	20	17533.85	160	2.7

The layouts, construction methods and materials of the four cases are determined according to the data collected from the survey in Beijing and the construction atlas during the period of 1980 to 2001. These data reflect the typical characteristics and

development of residential buildings in the cold zone of China in the 1980s and 1990s. The construction materials are summarised and transformed as the base case settings of the simulation models.

Regarding the heating system, as the four chosen communities have all experienced coal-to-gas reforms carried out in Beijing around 2005, the four communities were all gas-fired before retrofit. However, due to the lack of system maintenance, after more than a decade of use, the boilers and gas pipelines have different degrees of ageing and damage, which affects the efficiency of the heating system. Also, there is no heat metering system in any of the four communities, and the gas bills are charged based on the floor areas.

6.4.2. The Retrofitting Measures for Simulation

Table 6-7 Retrofit measures for simulation in building scale

Retrofit Measure	Strategy Package				
a. 50mm EWI	Retrofit approach	Measure	Symbol	50mm (EWI/Roof Insulation)	100mm (EWI/Roof Insulation)
b. 100mm EWI					
c. 50mm Roof Insulation					
d. 100mm Roof Insulation	Fabric	Wall	W	1. a.	2. b.
e. Draught Proofing		Roof	R	1. a.c.	2. b.d.
f. Double Glazing		Draught Proofing	DP	1. a.c.e.	2. b.d.e.
g. Low-E Glazing		window	G	1. a.c.e.f.	2. b.d.e.g.
h. LED Lighting	System	Lighting	L	b.d.e.g.h.	
i. Boiler Efficiency Improvement		Heating	H	b.d.e.g.h.i.	
j. Solar thermal + PV Roof	Renewable	PV roof	PV	b.d.e.g.h.i.j.	
k. Solar PV façade		PV roof + façade	PVf	b.d.e.g.h.i.j.k.	
l. Ground Source Heat Pump 1		GSHP1 (COP 3.8)	GSHP1	b.d.e.g.h.i.j.k.l.	
m. Ground Source Heat Pump 2		GSHP2 (COP 4.6)	GSHP2	b.d.e.g.h.i.j.k.m.	

Through the literature review, the case study in the UK and the interviews in China, the above retrofit measures are simulated in this chapter to evaluate the performance of different combinations and to explore the energy demand and supply needs in

relation to fabric and system improvement as well as the availability of renewable energy. The simulation followed the fabric first approach, and the retrofit measures are listed in Table 6-7. As the comparison of the 50mm (a,c) and 100mm insulations (b,d) and the comparison of double and Low E glazing (f,g) only exist in the fabric retrofit packages, and the subsequent comparisons on system improvement and renewables are the same, so the measures of system improvement and renewables are only applied to the 100mm ones.

6.4.3. Simulation Stages of the Case Studies in China at the Building Scale

There are three stages of the simulation of the retrofit measures at the building scale:

The first stage is to simulate the building with and without the IHGs to identify the impact of occupancy, lighting and appliance on heat gains and the thermal performance of the building.

The second stage is to simulate the individual retrofit measures separately to explore the retrofit effect that each measure can achieve. The retrofit measures include EWI (100mm), roof insulation (100mm), draught proofing (the infiltration rate is reduced from 1.0 to 0.5, and the occupied ventilation rate is reduced from 2.0 to 1.0), window replacement (using Low-E glazing to replace single glazing), LED lighting, heating system efficiency improvement (90%), solar thermal (50% efficiency), and solar PV (15% efficiency) to the roof and the south facade above the third floor. Each retrofit measure is applied to the building individually to compare the improvement of energy demand, electricity supply, gas supply and CO₂ emissions.

The third stage is to simulate different retrofit packages of measures ranging from simple to more comprehensive and complex actions to see the combined effects. It adopted the fabric first approach, followed by system retrofit and renewables.

For fabric retrofit, the measures used are EWI, roof insulation, draught proofing and the replacement of exterior windows. Among them, the EWI simulated the expanded polystyrene (EPS) boards with two thicknesses, 50 mm and 100 mm, and the roof insulation simulated the 50 mm and 100 mm composite polyurethane boards. As

excessive insulation will increase the load of the old building structure, the thickness of the insulation board is based on the design standard for energy efficiency of residential buildings in cold and severe cold zones and the up-to-date architectural design atlas in China (Ministry of Housing and Urban-Rural Development of the People's Republic of China 2010b). There are two types of replacement windows to be simulated: double glazing and low-E glazing.

For system improvement, the measures include the installation of LED lighting and the improvement of the heating system efficiency by applying the energy efficient system boiler (90% efficiency) and insulating the pipes of the heating network.

Regarding renewables, the retrofit measures consist of adding solar thermal (50% efficiency) and solar PV (15% efficiency). Since the efficiency of solar thermal is higher than that of solar PV, in order to minimise CO₂ emissions and increase energy self-sufficiency rate, in this simulation, solar thermal is installed to minimise the gas use for hot water, and solar PV is installed on the remaining roof area and the south facade above the third floor.

As natural gas reserves in China are not abundant, with the continuous increase in gas costs and the increasing requirement of environmental protection, many northern cities in China have begun to explore the ground source heat pump (GSHP) as a clean energy source in recent years. In the previous discussion of the literature review and the interview in China, it was concluded that the GSHP is more suitable for buildings with lower plot ratios as the initial investments are often too high due to deep buried heat storage pipes in places with high plot ratios or high-rise buildings, or that there is poor performance due to insufficient space for energy storage. Thus, in this research, the GSHP has been simulated for mid-rise of Case 1 and multi-storey building of Case 2 to explore the energy saving potential.

6.4.4. Introduction of simulation results presentation

The simulation results of the four cases in China at the building scale are presented in accordance with the three simulation stages: firstly, the results of buildings with and

without the IHGs are presented to identify the impact of occupancy, lighting and appliance on heat gains and the thermal performance of the building. Secondly, the results of individual measures are presented to show the retrofit effect that each measure can achieve. Thirdly, the results of retrofit packages of measures are presented in terms of energy demand, energy supply, CO₂ emission reduction, operating cost, and percentage of improvement to see the combined retrofit effects. In addition, for Cases 1 and 2 with GSHPs which only consumes electricity, it can more intuitively reflect the relationship of electricity consumption of the whole flat and the electricity generated by solar PV during a certain period of time. Thus, the hourly electricity use including the GSHP and the solar PV generation are presented at the end of Case 1 and Case 2 to show the possible improvements of adding these renewables in retrofit of residential buildings.

6.5. Modelling of Case 1: Flat 20 of Changqingyuan Community

6.5.1. Introduction of Case 1

Case 1 is a seven-storey flat in Changqingyuan Community located in the southeast of Beijing. The building was built in 1987 with a solid wall. The total floor area is 8255 m² and the floor height is 2.7m. 84 households live in this building. There was no insulation on the roof and external walls before retrofit. The painted surface of the external wall had been weathered due to years of use and lack of maintenance. The gutter and drainpipes had some damages, and most of the windows were single glazed with poor sealing.

The location, the building facade before retrofit and the standard floor plan are displayed in Figures 6.12, 6.13 and 6.14.



Figure 6.12 The location of Case 1



Figure 6.13 The building facade of Case 1 before the retrofitting

It can be seen from Figure 6.13 that the overhead cables in the community were quite messy, which may affect the residents' safety. The 3D model of Case 1 with colour faced for solar radiation and the shading mask of the south roof are demonstrated in Figure 6.15. As shown in the picture, the model is slightly simplified for the simulation. The construction materials of the building components including external walls, internal walls, roof, floors and ceilings, ground, and external windows before and after retrofit are listed in Tables 6-8 and 6-9.

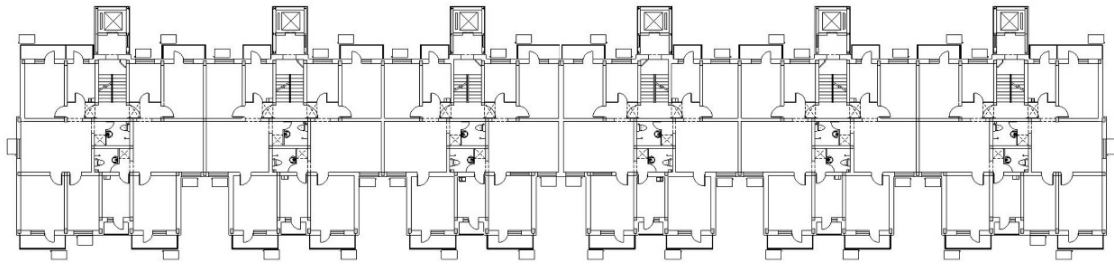


Figure 6.14 The standard floor plan of Case 1

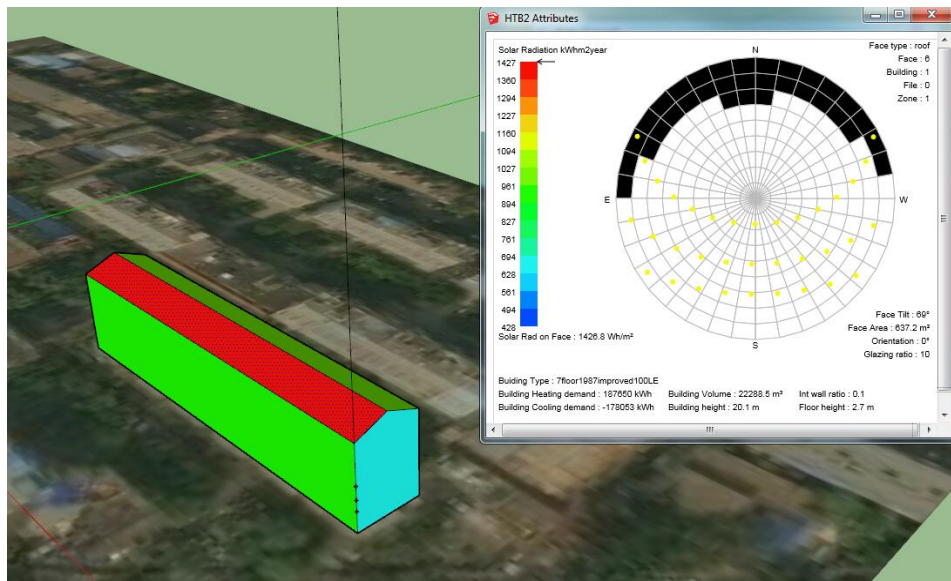


Figure 6.15 The 3D model of Case 1

Table 6-8 The construction details of Case 1 before the insulation retrofit

Construction	U-Value (W/m ² /°C)	Building Materials	Thickness (mm)	Conductivity (w/m·C)	Density (kg/m ³)	Specific heat capacity (J/kg/C)
Exterior Wall (From Outside to Inside)	1.06	cement mortar	20	0.93	1800	1050
		red brick	360	0.5	1700	1240
		cement mortar	20	0.93	1800	1050
Interior Wall (From Outside to Inside)	1.42	cement mortar	20	0.93	1800	1050
		red brick	240	0.5	1700	1240
		cement mortar	20	0.93	1800	1050
	2.67	cement mortar	20	0.93	1800	1050

Roof (From Top to Bottom)		SBS modified asphalt waterproof membrane	6	0.23	900	1620
		slag cement	30	0.76	1500	1050
		cement mortar	20	0.93	1800	1050
		precast reinforced concrete slab	150	1.74	2500	920
Floor-Ceiling (From Top to Bottom)	2.58	cement mortar	20	0.93	1800	1050
		slag cement	60	0.76	1500	1050
		reinforced concrete	150	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Ground (From Top to Bottom)	1.14	cement mortar	30	0.93	1800	1050
		C15 concrete	80	1.51	2300	920
		gravel	150	2.04	2400	920
		rammed earth	500	0.93	1800	1010
Exterior Window	5.32	plate glass	6	0.76	2500	840

Table 6-9 The construction details of Case 1 after the insulation retrofit

Construction	U-Value (W/m ² /°C)	Building Materials	Thickness (mm)	Conductivity (w/m·C)	Density (kg/m ³)	Specific heat capacity (J/kg/C)
Exterior Wall (From Outside to Inside)	0.39 / 0.26	insulating mortar	25	0.06	250	1049.6
		Expanded polystyrene (EPS)	50 / 100	0.041	18	2414.8
		red brick	360	0.5	1700	1240
		cement mortar	20	0.93	1800	1050
Interior Wall (From Outside to Inside)	1.42	cement mortar	20	0.93	1800	1050
		red brick	240	0.5	1700	1240
		cement mortar	20	0.93	1800	1050
	0.4 / 0.22	insulating mortar	5	0.06	250	1049.6

Roof (From Top to Bottom)		composite polyurethane board	50 / 100	0.024	30	2475.2
		SBS modified asphalt waterproof membrane	6	0.23	900	1620
		slag cement	30	0.76	1500	1050
		cement mortar	20	0.93	1800	1050
		precast reinforced concrete slab	150	1.74	2500	920
Floor-Ceiling (From Top to Bottom)	2.58	cement mortar	20	0.93	1800	1050
		slag cement	60	0.76	1500	1050
		reinforced concrete	150	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Ground (From Top to Bottom)	1.14	cement mortar	30	0.93	1800	1050
		C15 concrete	80	1.51	2300	920
		gravel	150	2.04	2400	920
		rammed earth	500	0.93	1800	1010
Exterior Window	3.27 / 2.66	plate glass	6	0.76	2500	840
		cavity	3 normal / 3 low-E	n/a	n/a	n/a
		plate glass	6	0.76	2500	840

6.5.2. Results of Case 1 With and Without IHGs before the Retrofitting

The modelling results present the average monthly values of Case 1 without IHGs (Figures 6.16 & 6.18) and with IHGs (Figures 6.17 & 6.19) in different gains including heater gain, cooler gain, internal gain, solar gain, ventilation gain and fabric gain. To be specific, firstly, the solar gain is stable throughout the year. Secondly, it can be seen that the IHG occupies a part that cannot be ignored, which is half of the solar gain. When adding the IHG, the heater gain decreases by a small amount, but the cooler

gain increases remarkably, to almost twice of that without IHG. This is due to the effects of the heat generated by occupants, lighting and appliances in the building. Thirdly, the ventilation gain and fabric gain slightly increase with IHG. Therefore, for energy performance simulation and analysis, it is pivotal to take the IHG into account. Besides, for the dynamic energy analysis, the accurate hourly data for IHG is also one of the key factors to ensure the accuracy of the simulation results. Moreover, no matter with or without IHG, the heater gain dominates in winter, which is the most significant energy saving potential in retrofit.

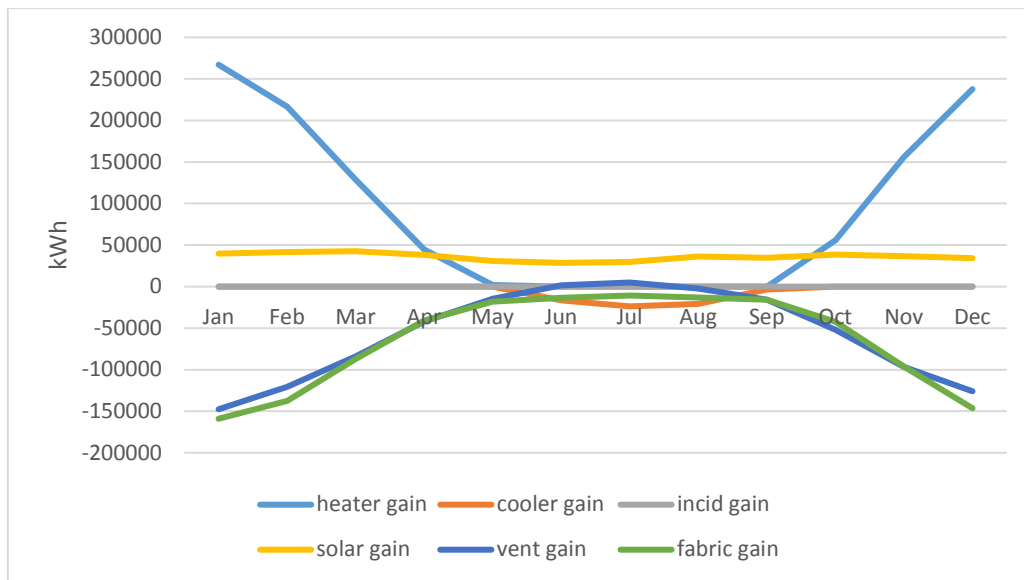


Figure 6.16 Monthly gains of Case 1 without IHGs

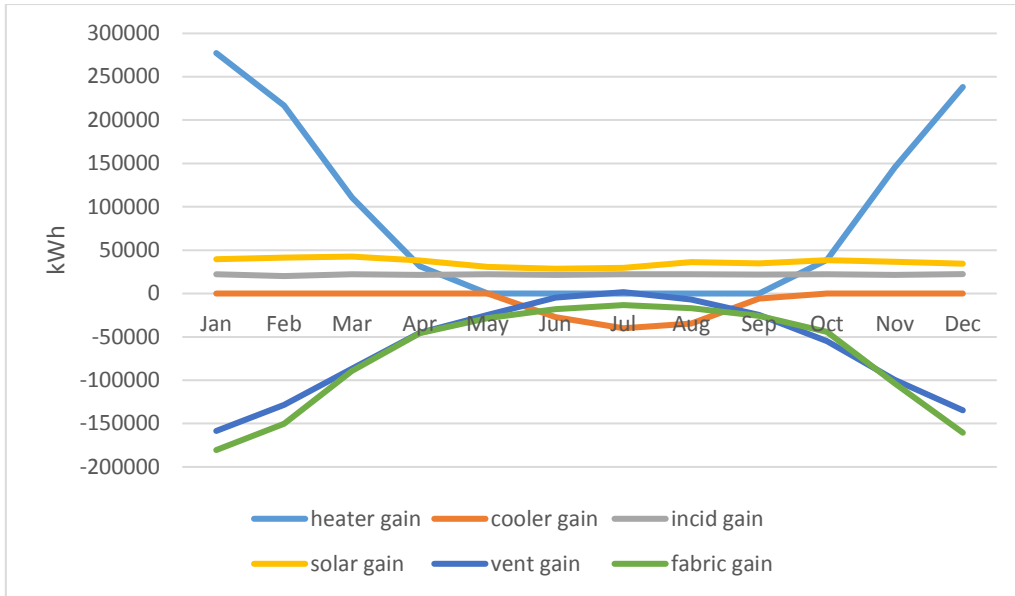


Figure 6.17 Monthly gains of Case 1 with IHGs

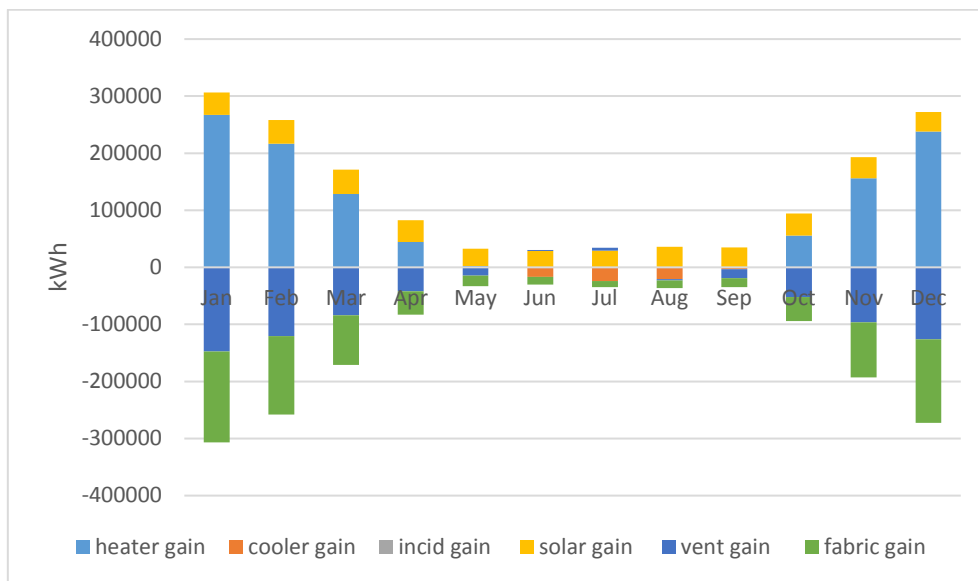


Figure 6.18 The proportion of monthly gains of Case 1 without IHGs

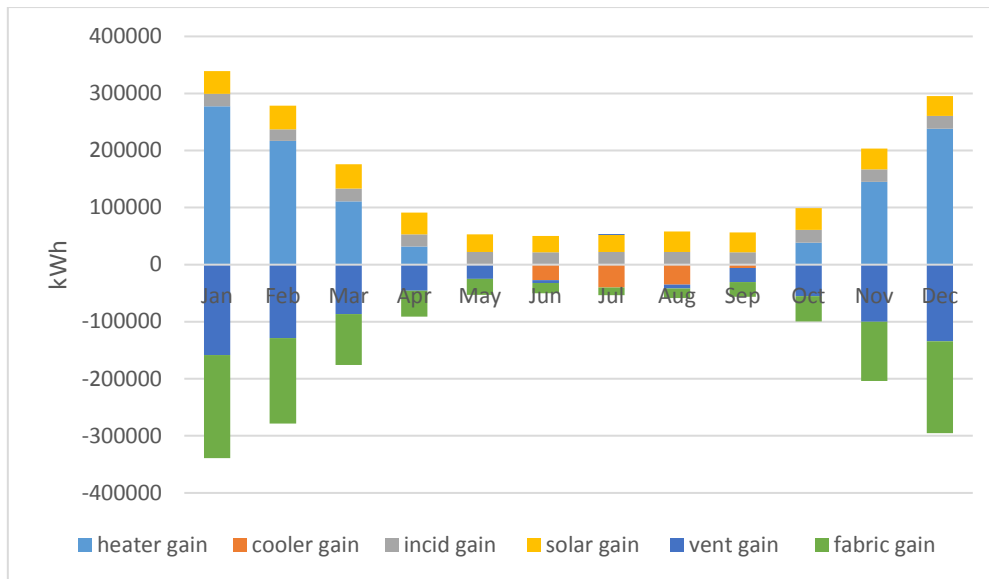


Figure 6.19 The proportion of monthly gains of Case 1 with IHGs

6.5.3. Results of Case 1 after Retrofitting

6.5.3.1. Improvement of Individual Retrofit Measures

Figures 6.20 and 6.21 show the percentage of improvement in energy demand, electricity supply, gas supply and CO₂ emission for each retrofit measure. From the two radar charts, it can be seen that first, for energy demand reduction, the measure of draught proofing contributes the most, at 23.4% improvement. Roof insulation also has a relatively large impact of 11%, whereas the heating system improvement, solar thermal and solar PV have no improvement in reducing energy demand. Second, the draught proofing and heating system improvement have the most substantial impact on energy supply, with reduction of 26.1% and 30.8%, respectively, mainly in reducing gas consumption. Lighting and PV only have an impact on the reduction of electricity consumption, of which PV reduces electricity use by 147%. Third, heating system improvement and solar thermal only affect gas reduction. Moreover, the LED lighting reduces electricity supply by 10.8%, but also increase the gas consumption by 1% due to less heat gain from the LED lamps compared with the incandescent lamps. Additionally, regarding CO₂ emissions, PV has the most reduction, with a proportion of 37.9%, while draught proofing and heating also improve a lot, accounting for 20.7% and 24.7% respectively.

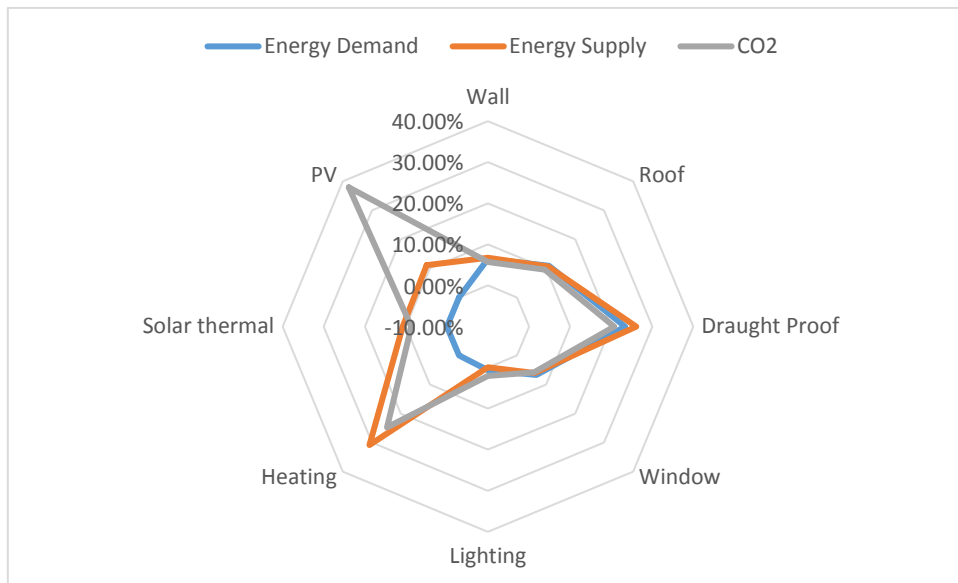


Figure 6.20 The percentage of improvement in energy demand, energy supply and CO₂ for each retrofit measure of Case 1

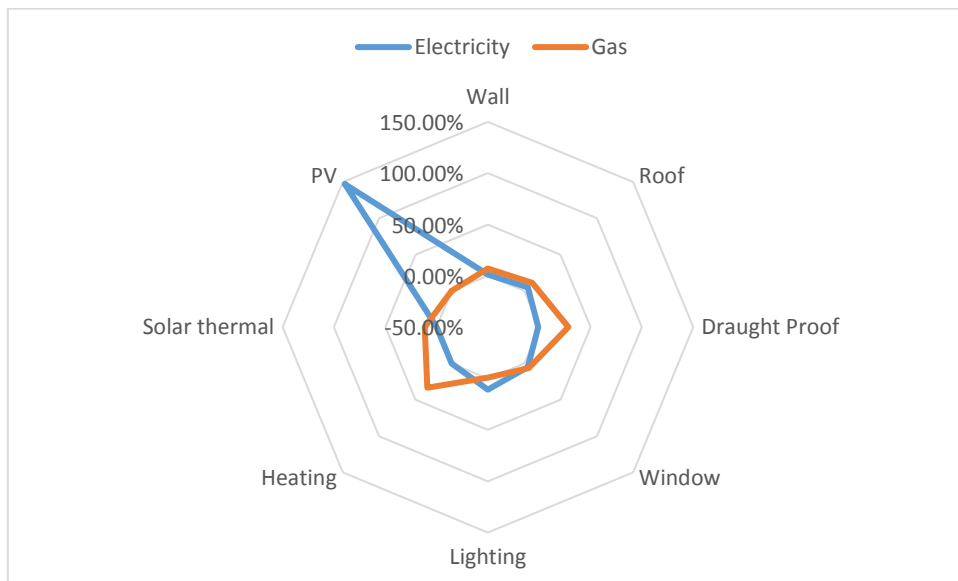


Figure 6.21 The percentage of improvement in electricity and gas for each retrofit measure of Case 1

6.5.3.2. Improvement of the Retrofit Packages

6.5.3.2.1. Energy Demand

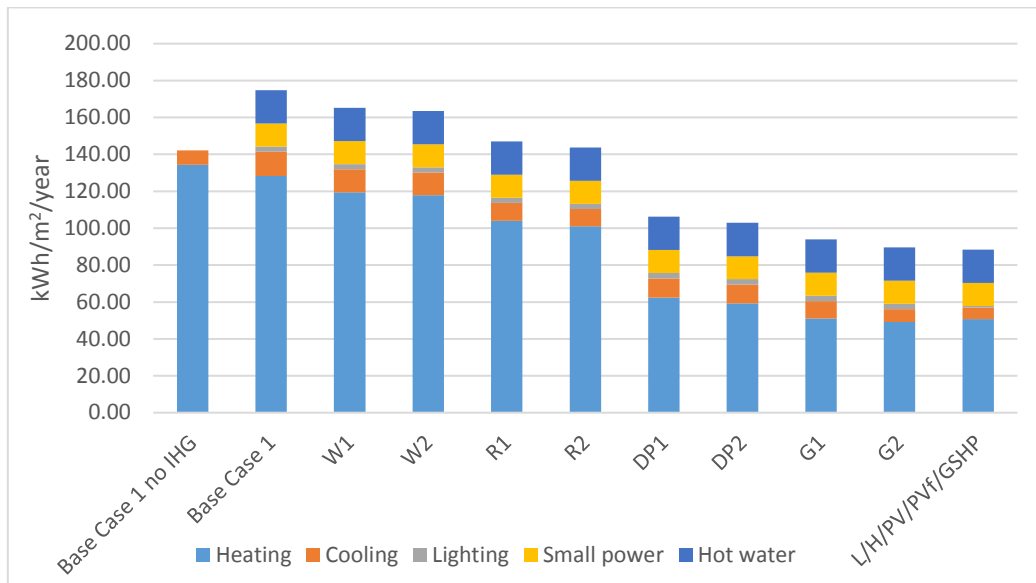


Figure 6.22 Annual energy demand of Case 1 for a range of retrofit measures (ref: Table 6-7)

Figure 6.22 illustrates the energy demand breakdown of Case 1. The base case with and without IHG are also presented for comparison. To begin with, as can be seen from the chart, the energy demand decreases with the successive addition of the retrofit measure packages. Second, the package of draught proofing (including EWI, roof insulation and draught proofing) has the most significant effect on reducing energy demand, with reductions of 40.9 kWh/m² and 49.9 kWh/m² for the 50 mm and 100 mm insulation packages, respectively. Third, the roof insulation plays an essential part in reducing both heater and cooler gains. Fourth, the window replacement can also reduce heater and cooler gains, where the low-E glazing has a better performance than the double glazing, especially for reducing the cooling demand. Also, the impact of 50 mm and 100 mm of the insulation boards on energy demand is not that obvious. The difference is about 2 to 4 kWh/m². In addition, the packages of heating system improvement and renewables do not affect energy demand. Therefore, it can be seen that the fabric retrofit could be the most effective strategy for existing residential buildings, as the heating demand can be significantly reduced as a result of less heat loss through the fabric and infiltration. Moreover, it is notable that the draught

proofing increases the cooling demand due to improved airtightness so that the heat is more difficult to be removed in summer by natural ventilation and infiltration. Besides this, the LED lighting reduces the cooling demand but increases the heating demand due to less heat gain from the LED lamps than the incandescent lamps.

Further information on heating and cooling gains, ventilation gains, fabric gains and solar gains can be found in Appendix 1.

6.5.3.2.2. Energy Supply

Figure 6.23 demonstrates the annual electricity supply of Case 1. Firstly, except in the last two scenarios, which use GSHP, heating and hot water are provided by natural gas. Electricity is mainly used for cooling, lighting, and small power. Secondly, small power accounts for the most considerable proportion of electricity use. Thirdly, we can see the package of lighting contributes the most in reducing electricity supply, whereas other packages do not have much impact. Moreover, the retrofit packages of GSHP increase the electricity consumption significantly, as GSHP system only uses electricity, so the electricity is used for heating and hot water as well.

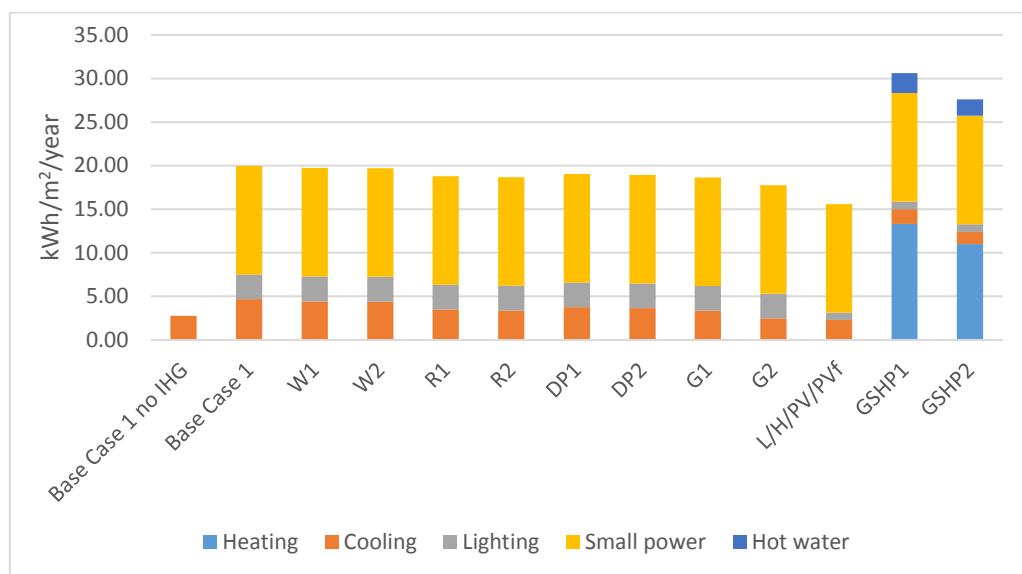


Figure 6.23 The annual electricity supply of Case 1 for a range of retrofit measures (ref: Table 6-7)

For annual gas supply, as displayed in Figure 6.24, first, the most significant improvement lies in the package of draught proofing, with the annual reduction of more than 69.4 kWh/m². This is due to better airtightness lessening the building's heating demand, thereby reducing the consumption of gas on space heating. Second, the package of EWI and roof insulation have good performance in gas reduction. Additionally, the gas supply also decreases apparently through the packages of heating system improvement and solar thermal, where the former mainly reduce the gas consumption for space heating, and the later reduces the gas used for hot water. Besides, there is no gas consumption in the GSHP packages.

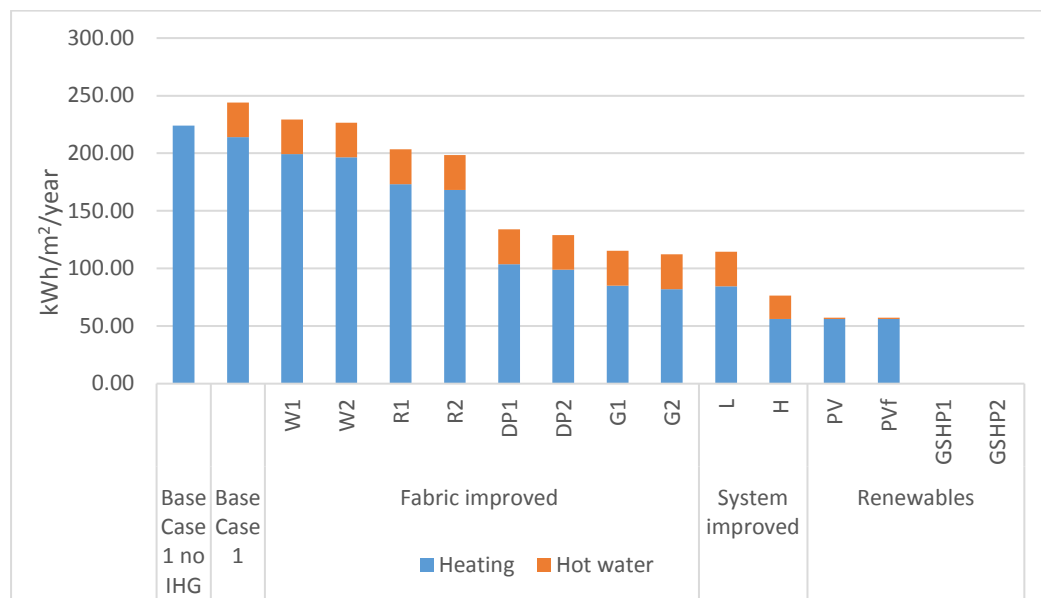


Figure 6.24 The annual gas supply of Case 1 for a range of retrofit measures (ref: Table 6-7)

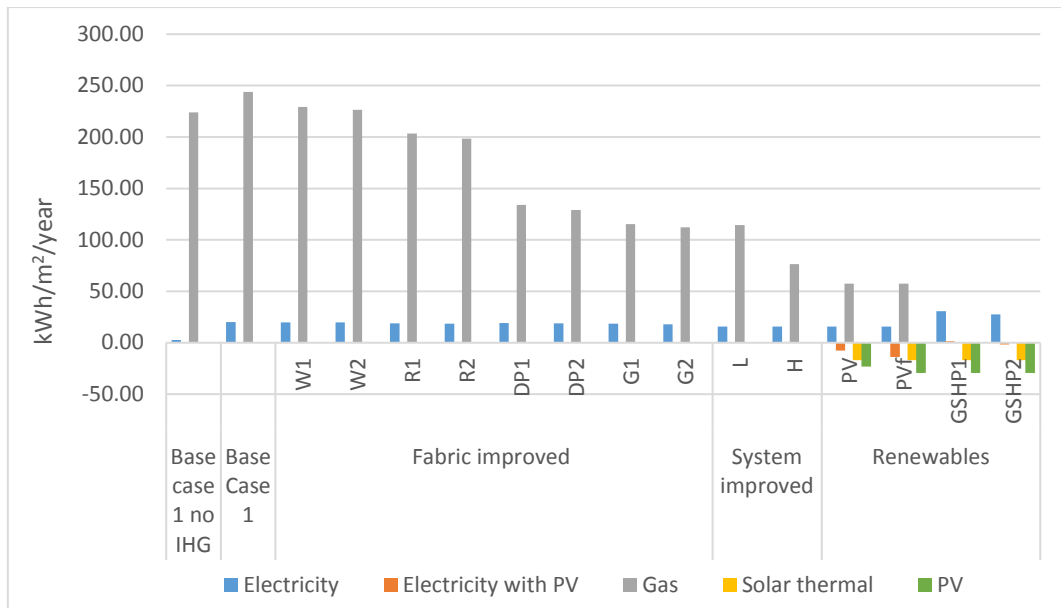


Figure 6.25 The summary of annual electricity and gas supply and renewable energy of Case 1 for a range of retrofit measures (ref: Table 6-7)

Figure 6.25 illustrates the summary of annual energy supply, the electricity generated by solar PV and the gas reduced by solar thermal. First of all, the gas consumption decreases significantly compared with the electricity use. This is due to the reduction of space heating through the fabric and system improvement. Second, the electricity use can be reduced dramatically by installing the solar PV panels. Third, in terms of the GSHP packages, the energy supply drops from 73 kWh/m² with the PV roof and facade package to 30.6 kWh/m² and 27.6 kWh/m² with the GSHP packages with COP of 3.8 and 4.6, respectively. This is because GSHP does not need to use gas for space heating and hot water, which greatly reduces the energy supply. Although the GSHP packages have higher electricity use than other packages, they do not consume gas so that have the best overall performance in reducing energy consumption.

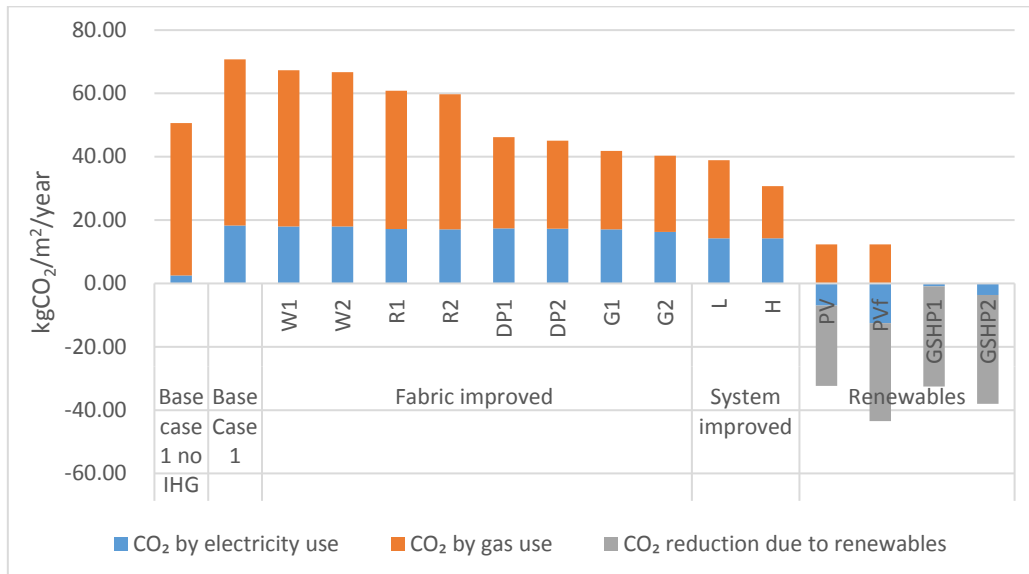
6.5.3.2.3. CO₂ Emission Reduction

Figure 6.26 Summary of the CO₂ emissions of Case 1 for a range of retrofit measures (ref: Table 6-7)

Figure 6.26 illustrates the CO₂ emissions reductions by different retrofit measures. The negative CO₂ figures mean that the electricity generated by solar PV directly exported to the national grid and the gas consumption reduced by solar thermal can offset the energy consumption and act as energy sources. As shown in Figure 6.26, the annual CO₂ emissions gradually decrease with the successive application of the fabric and system retrofit packages, mainly in the reduction of gas use due to the decreased heating demand. Also, the CO₂ emissions drop significantly when adding the renewables. The electricity generated by the PVs offsets a large part of the electricity use so that the CO₂ emissions caused by electricity use are greatly reduced. Also, for the CO₂ by electricity use, the GSHP produces slightly more than using the PV roof and facade packages, but less than the PV roof packages, and as the GSHP does not have CO₂ emission by gas use, the total amount is much smaller than the two PV packages. Besides, it can be seen from the grey bars that the GSHPs provide more CO₂ reduction than the two PV packages.

6.5.3.2.4. Operating Cost

The electricity and gas tariffs and the government subsidies for solar PV in Beijing are listed in Table 6-10. According to this, the operating cost of electricity and gas use, the savings, and the earnings from solar power can be calculated as shown in Figure 6.27.

Table 6-10 Electricity and gas tariffs in Beijing

Category	Level	Usage / Household/ month		Tariff (CNY/kWh)	
Electricity	1	1–240 kWh		0.4883	
	2	241–400 kWh		0.5383	
	3	> 400 kWh		0.7883	
Gas		Hot water usage/ household/ annual	Heating usage/ household/ annual		
	1	0–3360 kWh (0–350 m ³)	0–14400 kWh (0–1500 m ³)	0.24 (2.28 CNY/m ³)	
	2	3360–4800 kWh (350–500 m ³)	14400–24000 kWh (1500–2500 m ³)	0.26 (2.5 CNY/m ³)	
	3	> 4800 kWh (500 m ³)	> 24000 kWh (> 2500 m ³)	0.41 (3.9 CNY/m ³)	
Generation tariff for solar PV	government subsidies	National		0.42	1.12
		Beijing		0.3	
		District		0.4	
Export tariff for solar PV				0.36	

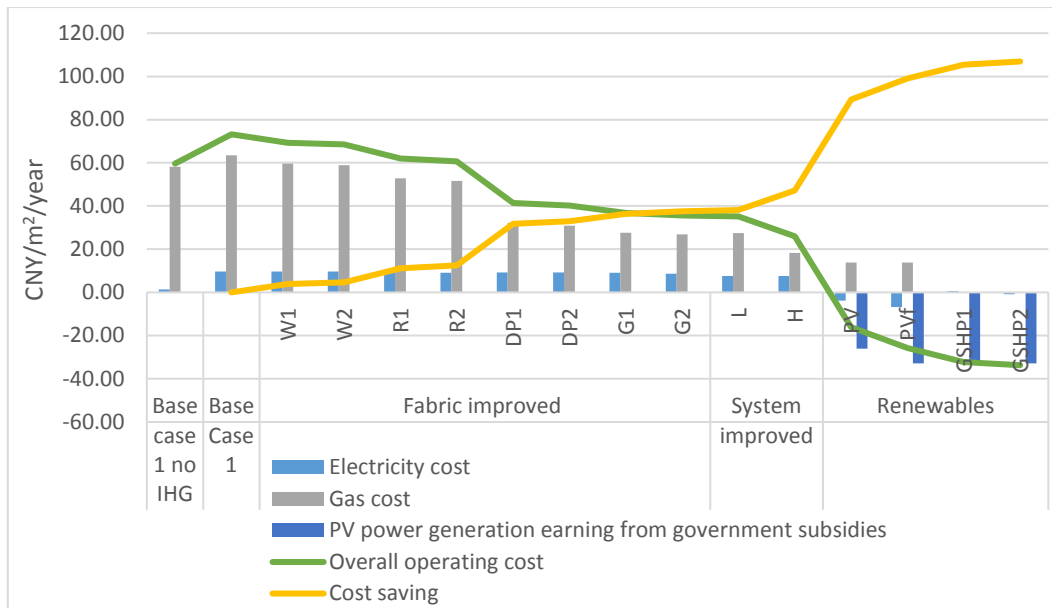


Figure 6.27 The summary of the operating cost and saving of Case 1 for a range of retrofit measures (ref: Table 6-7)

Figure 6.27 illustrates the operating cost and savings of Case 1. The negative costs represent the earnings of PV electricity generation from government subsidies. As can be seen from the chart, first, for the annual cost of electricity and gas, the tendency is consistent with the CO₂ emission reduction chart (Figure 6.26). Second, the gas cost decreases along with the increasing retrofit measures, while the electricity cost has not changed much until adding the renewables. Third, the greatest reductions in the overall operating cost, as well as the biggest savings, appear when the PV packages are installed. The overall operating cost decreased from 26 CNY/m² after system retrofit to -16.1 CNY/m² after the first renewable package is adopted. Moreover, for the renewables, the GSHPs have slightly less operating costs and more savings than the PV packages. Lastly, the total annual savings of the operating cost are 106.9 CNY/m², which reduced from 73.2 CNY/m² before the retrofitting to -33.7 CNY/m² after the retrofitting.

6.5.3.2.5. Percentage of Improvement

Figures 6.28 and 6.29 summarise the percentage of the retrofit improvement of Case 1 with 50mm and 100mm insulation, respectively. In general, improvements in electricity, gas, CO₂, and operating costs have risen as the retrofit packages are installed. The overall improvement of the packages with 100mm insulations is slightly better than that with the 50mm ones. The measures of system improvement and renewables are only applied to the 100mm ones.

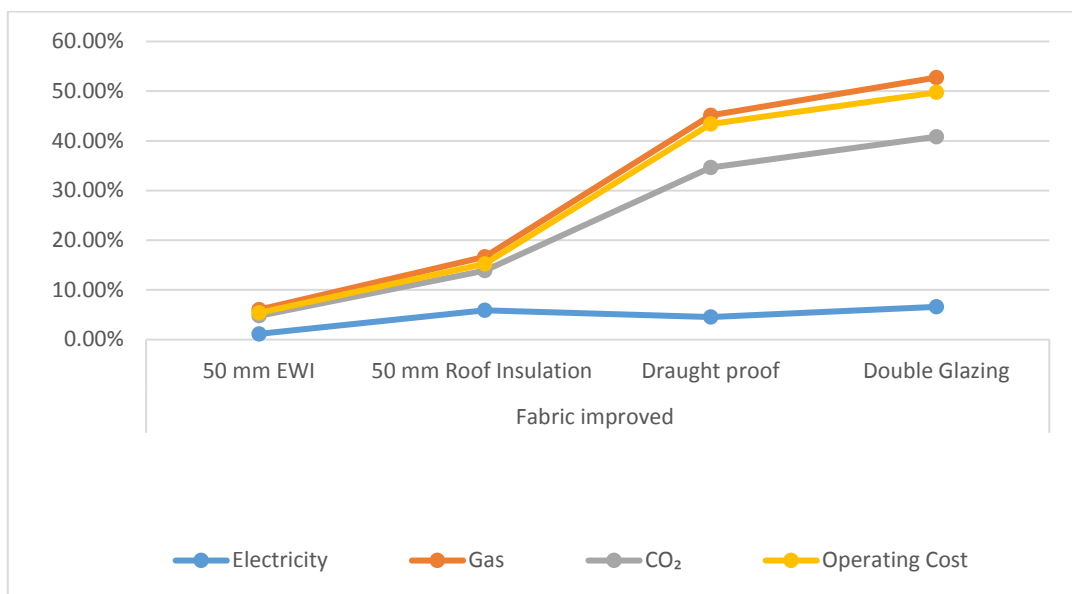


Figure 6.28 The percentage of improvement of Case 1 with 50 mm insulation (ref: Table 6-7)

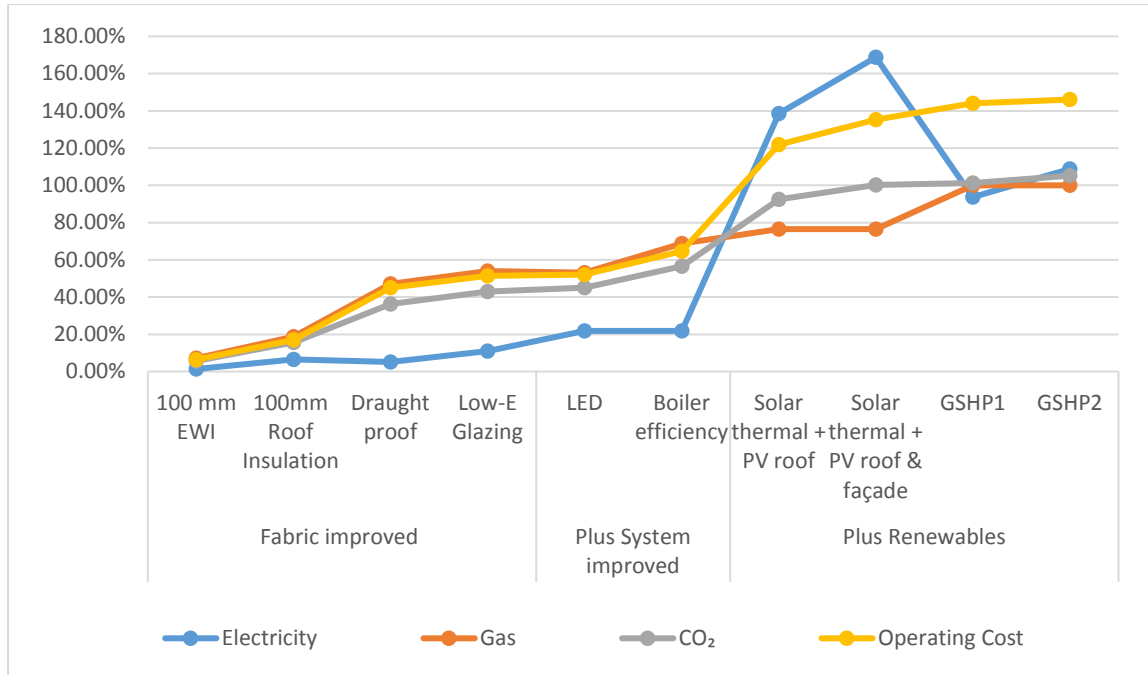


Figure 6.29 The percentage of improvement of Case 1 with 100mm insulation (ref: Table 6-7)

To be specific, first of all, the LED packages can save 21.8% of the electricity use. Second, after PVs are installed on the roof, the improvement is 138.5%. After PV added on the south facade above the third floor, the percentage increases to 168.8%. Third, PV packages contribute the most in reducing electricity and operating cost, with the operating cost reductions of 122% and 135.2%, respectively. In addition, the retrofitting of fabric and system provides the most significant improvement in gas, where the most exists in the measure of draught proofing, with more than 45% of the total gas reduction. Moreover, renewables have the greatest improvement in operating costs, all exceeding 100%. Besides, after installing the GSHPs, although the improvements of electricity use have no advantage over the PV packages, the improvements of other three elements have all increased, with the most improvement of 146.1% in operating cost.

6.5.3.3. Profiles of Hourly Electricity Supply and Generation by PV

In order to reflect the relationship of electricity use of the whole flat and the electricity generated by solar PV during a certain period of time, and to show the possible

improvements of adding these renewables in retrofit of residential buildings, Figures 6.30 to 6.34 illustrate the hourly data of the electricity supply using the GSHP system and the electricity generated by solar PV of Case 1 during two winter and summer weeks, in January and July, and within the whole year.

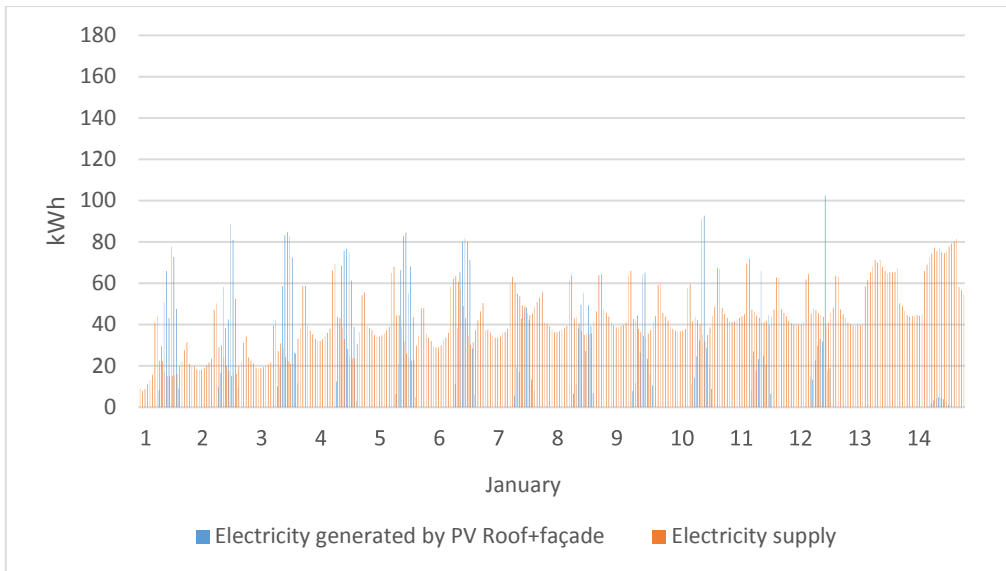


Figure 6.30 Hourly electricity supply and PV generation of Case 1 in two weeks in January

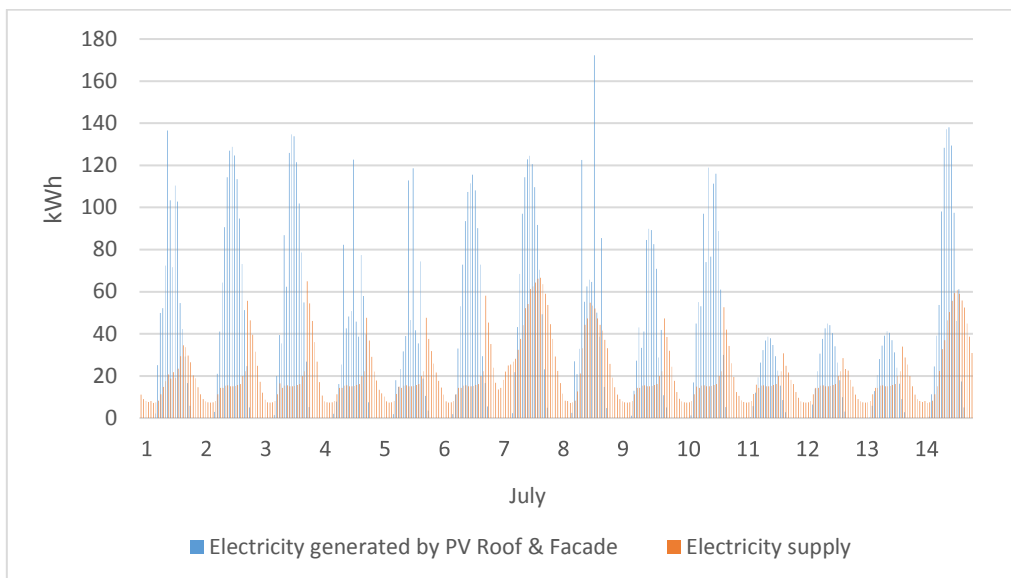


Figure 6.31 Hourly electricity supply and PV generation of Case 1 in two weeks in July

It can be seen from Figures 6.30 and 6.31 that the profiles of the electricity supply and generation fluctuate along with the time of day and the schedule of the occupancy during the week. There is more electricity usage in winter than in summer, there is more on weekends than during weekdays, and there is more in the evenings, with the peak at around 7:00 pm. The PVs generate electricity in the daytime, with the peak at around 12:00 o'clock. Also, the electricity production of PV is about 1.5 times higher in summer than in winter. Besides, the electricity generated by PV varies with the weather conditions and other unpredictable factors. For example, the amount of the electricity production on 13th to 14th in January and on 11th to 13th in July are relatively small.

Figures 6.32 and 6.33 show the hourly electricity consumption and generation by PV in January and July. Firstly, the electricity usage and production are more in January than in July due to high heating demand. Secondly, it can be seen from the chart in July that the electricity use on weekends is around two times more than on average weekdays. Thirdly, it is noticed that from January 13th to 15th, PV produces little or no electricity, since it is very likely to be affected by bad weather. At this time, the electricity consumption increases dramatically.

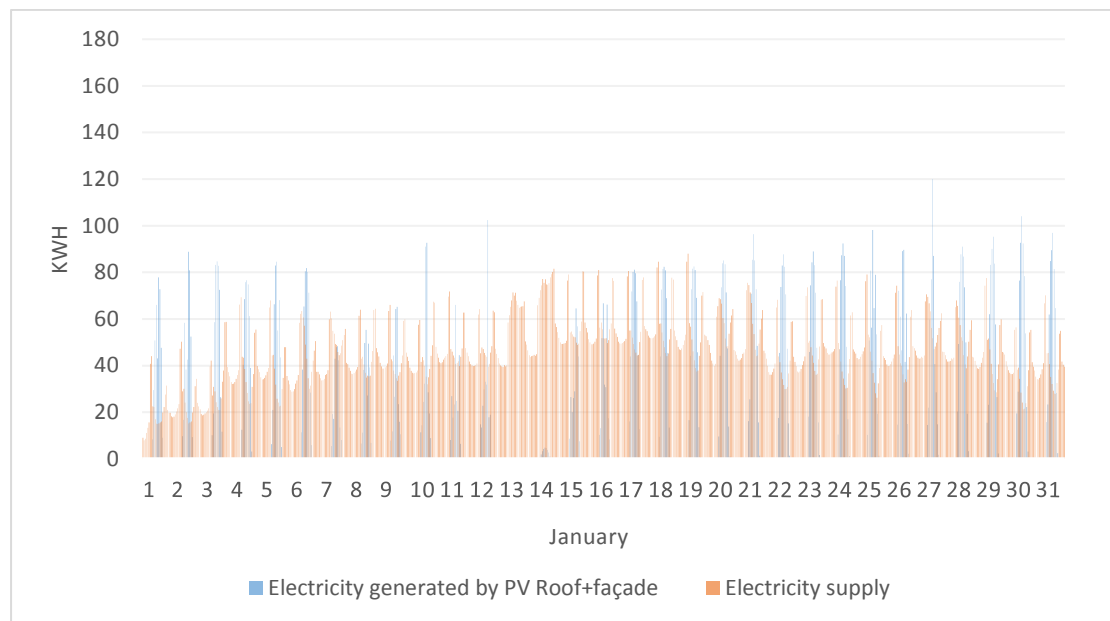


Figure 6.32 Hourly electricity supply and PV generation of Case 1 in January

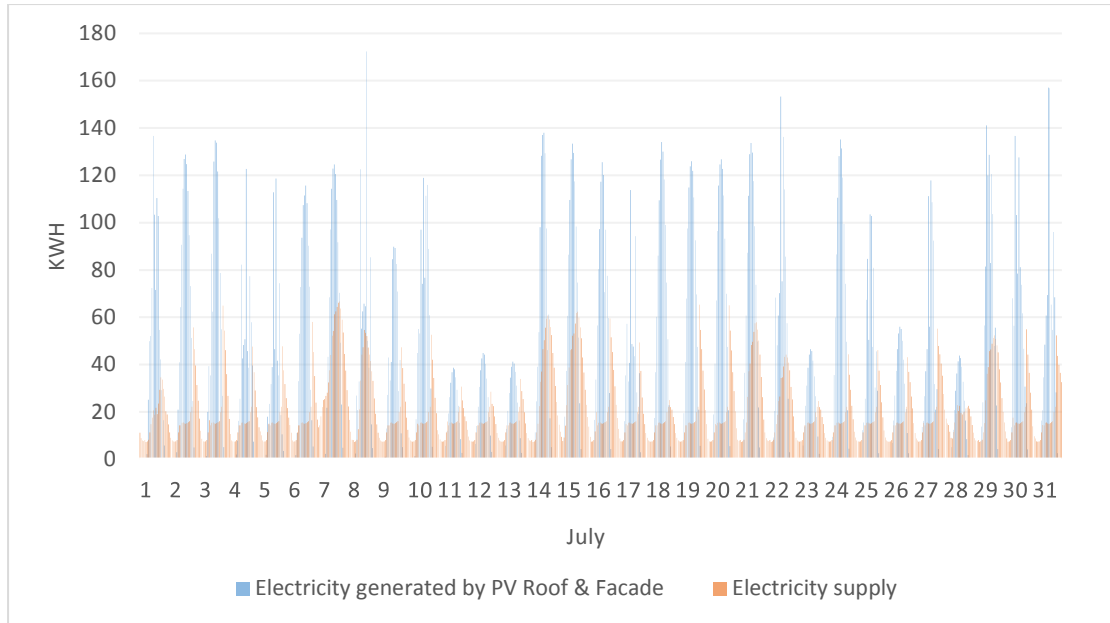


Figure 6.33 Hourly electricity supply and PV generation of Case 1 in July

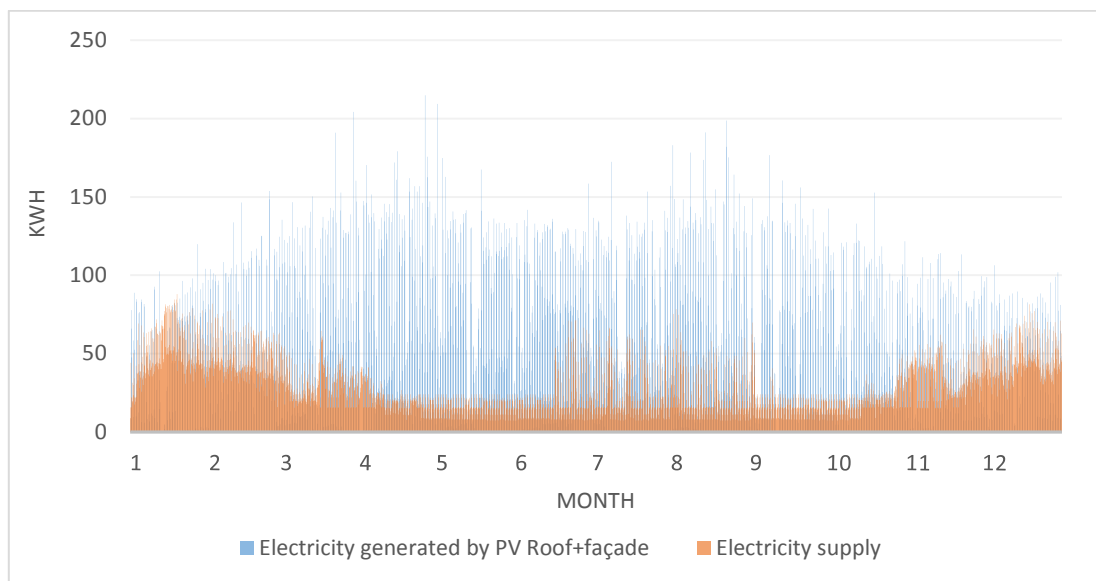


Figure 6.34 Hourly profile of the electricity supply and PV generation for the whole year of Case 1

The hourly profile of the electricity supply and generation by PV for the whole year is presented in Figure 6.34. As can be seen, the main two peaks of electricity use are in winter and summer, and there is more consumption in winter. Besides, the electricity produced by PV can cover almost all of the electricity consumption. In addition, the

peaks of the electricity production by PV are in May and August, of which the most massive amount that can be exported to the grid is in May.

Consequently, the overlapping parts of the two colours in the graphs are represent the electricity consumption that can be fully covered by the PV productions. The blue parts that are not blocked by the orange colour represent the amount of electricity that can be exported to the grid, and the non-overlapping orange parts represent the amount of electricity that needs to be imported from the grid. Therefore, it can be seen that, Case 1 as a mid-rise building, has high self-sufficiency rate. Installing solar PV to the roof and south facade above the third floor can not only cover the electricity consumption, but also produce much more electricity to be exported to the grid for extra income.

6.6. Modelling of Case 2: Building 40 of Nanshatan Community

6.6.1. Introduction of Case 2

Case 2 is a six-storey flat located in Nanshatan Community of Chaoyang district in north Beijing. The building was built in 1996 with solid wall. The total floor area is 4015.56 m² and the floor height is 2.7m. There are 66 households living in this building. Before retrofitting, there was no insulation on the roof and external walls. Similar to Case 1, the windows were single glazed with bad sealing.

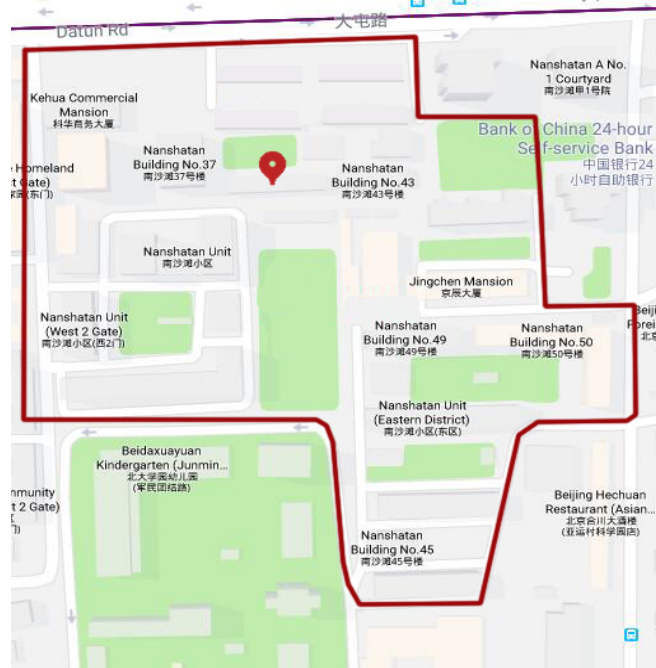


Figure 6.35 The location of Case 2



Figure 6.36 the building facade of Case 2 before retrofitting

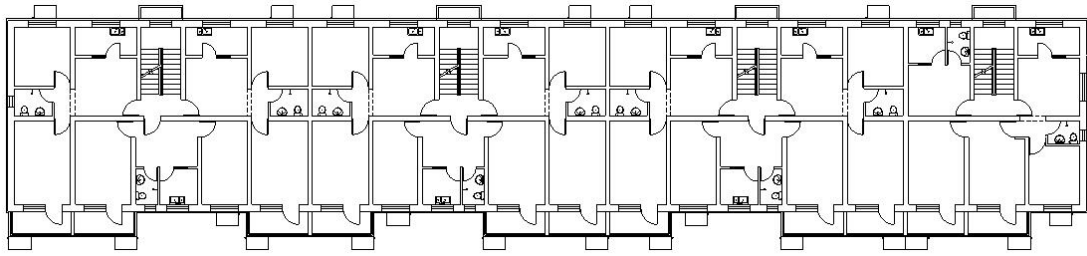


Figure 6.37 the standard floor plan of Case 2

The location, the building before retrofitting and the standard floor plan are demonstrated in Figures 6.35, 6.36 and 6.37. As shown in Figure 6.36, most of the windows have safety grids and the outside air-conditioning units were placed randomly. The 3D model of Case 2 with colour faced for solar radiation and the shading mask of the south facade are presented in Figure 6.38. The construction materials of the building components before and after insulation retrofit are listed in Tables 6-11 and 6-12.

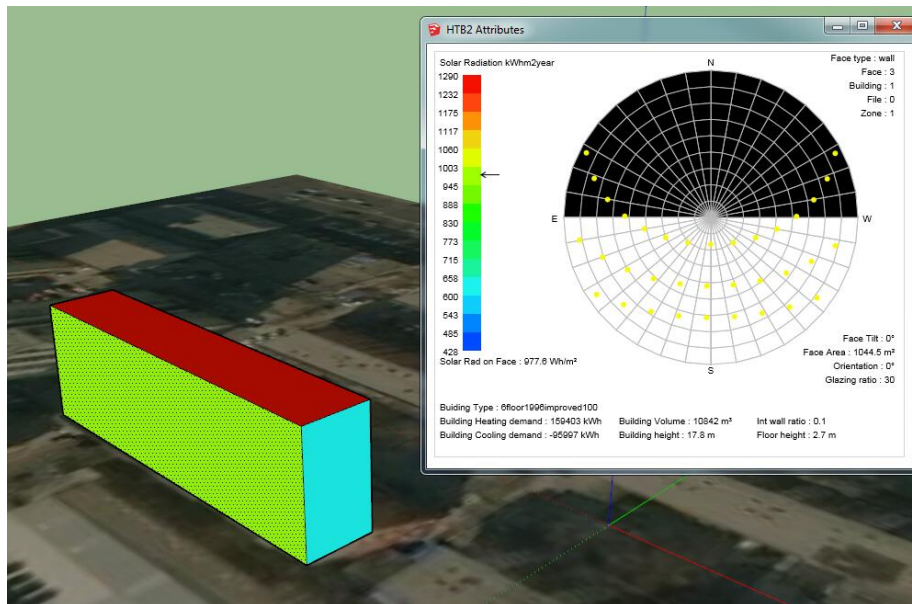


Figure 6.38 The shading mask of the south facade of Case 2

Table 6-11 The construction materials of Case 2 before the insulation retrofit

Construction	U-Value (W/m ² /°C)	Building Materials	Thickness (mm)	Conductivity (w/m·C)	Density (kg/m ³)	Specific heat capacity (J/kg/C)
Exterior Wall (From Outside to Inside)	1.04	cement mortar	20	0.93	1800	1050
		red brick	370	0.5	1700	1240
		cement mortar	20	0.93	1800	1050
Interior Wall (From Outside to Inside)	1.42	cement mortar	20	0.93	1800	1050
		red brick	240	0.5	1700	1240
		cement mortar	20	0.93	1800	1050
Roof (From Top to Bottom)	3.06	linoleum	2	0.17	600	1460
		cement mortar	25	0.93	1800	1050
		slag cement	30	0.76	1500	1050
		reinforced concrete	120	1.74	2500	920
Floor-Ceiling (From Top to Bottom)	3.42	cement mortar	20	0.93	1800	1050
		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Ground (From Top to Bottom)	1.33	cement mortar	30	0.93	1800	1050
		C15 fine aggregate concrete	80	1.51	2300	920
		gravel	120	2.04	2400	920
		rammed earth	400	0.93	1800	1010
Exterior Window	5.32	plate glass	6	0.76	2500	840

Table 6-12 The construction materials of Case 2 after the insulation retrofit

Construction	U-Value (W/m ² / °C)	Building Materials	Thickness (mm)	Conductivity (w/m·C)	Density (kg/m ³)	Specific heat capacity (J/kg/C)
Exterior Wall (From Outside to Inside)	0.39 / 0.26	insulating mortar	25	0.06	250	1049.6
		Expanded polystyrene (EPS)	50 / 100	0.041	18	2414.8
		red brick	370	0.5	1700	1240
		cement mortar	20	0.93	1800	1050
Interior Wall (From Outside to Inside)	1.42	cement mortar	20	0.93	1800	1050
		red brick	240	0.5	1700	1240
		cement mortar	20	0.93	1800	1050
Roof (From Top to Bottom)	0.38 / 0.21	insulating mortar	5	0.06	250	1049.6
		composite polyuretha ne board	50 / 100	0.024	30	2475.2
		roofing felt	6	0.19	960	837
		cement mortar	25	0.93	1800	1050
		slag cement	30	0.76	1500	1050
		reinforced concrete	120	1.74	2500	920
Floor-Ceiling (From Top to Bottom)	3.42	cement mortar	20	0.93	1800	1050
		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Ground (From Top to Bottom)	1.33	cement mortar	30	0.93	1800	1050
		C15 fine aggregate concrete	80	1.51	2300	920
		gravel	120	2.04	2400	920
		rammed earth	400	0.93	1800	1010
		plate glass	6	0.76	2500	840

Exterior Window	3.27 / 2.66	cavity	3 normal / 3 low-E	n/a	n/a	n/a
		plate glass	6	0.76	2500	840

6.6.2. Results of Base Case 2 With and Without IHGs before the Retrofitting

Figures 6.39 and 6.40 show the average monthly value of Case 2 without and with IHGs in different gains, including heater gain, cooler gain, internal gain, solar gain, ventilation gain and fabric gain. Figures 6.41 and 6.42 illustrate the proportion of the different gains without and with IHGs, respectively.

Specifically, first, the solar gain is the most stable part during the year. Second, the IHG occupies a large proportion, approximately 1.5 times more than the solar gain. In addition, after taking the IHG into account, the heating demand has slightly dropped, but the cooling demand has risen drastically, and is more than twice that without IHG. Furthermore, the ventilation gain and fabric gain have slightly grown with IHG. Thus, the IHG plays a significant part in energy thermal performance that cannot be ignored. More importantly, no matter with or without IHG, the heater gain dominates in winter, which represents the largest energy saving potential in retrofit.

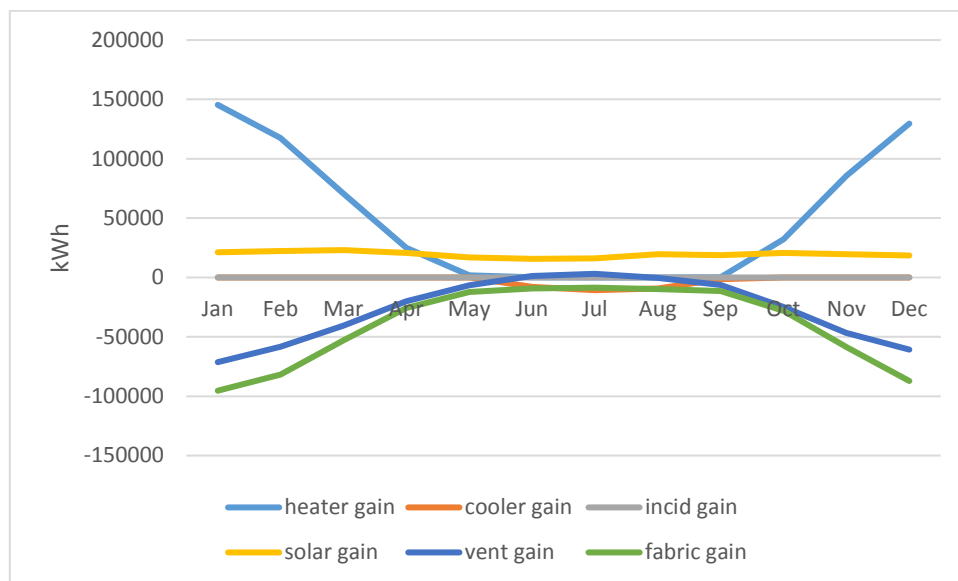


Figure 6.39 monthly gains of Case 2 without IHG

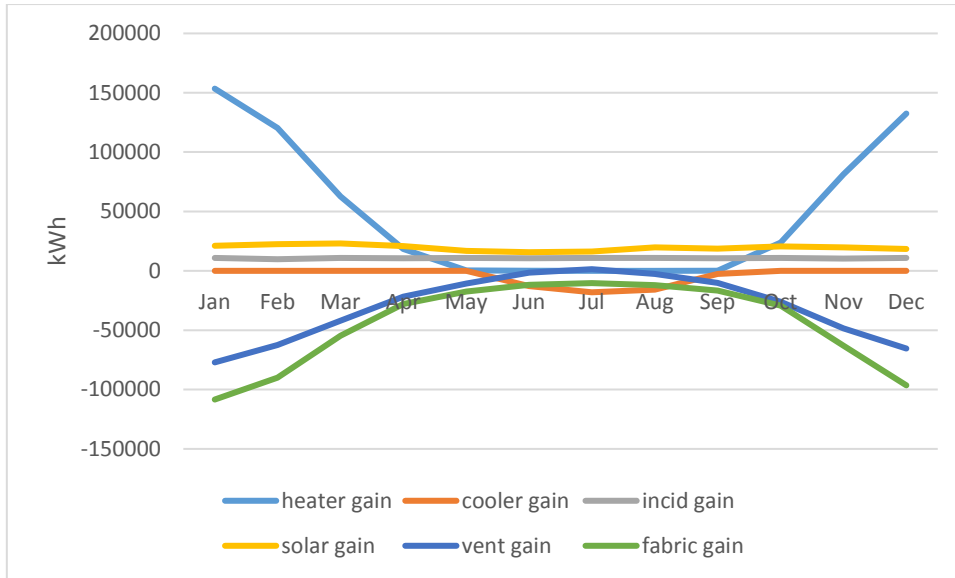


Figure 6.40 monthly gains of Case 2 with IHG

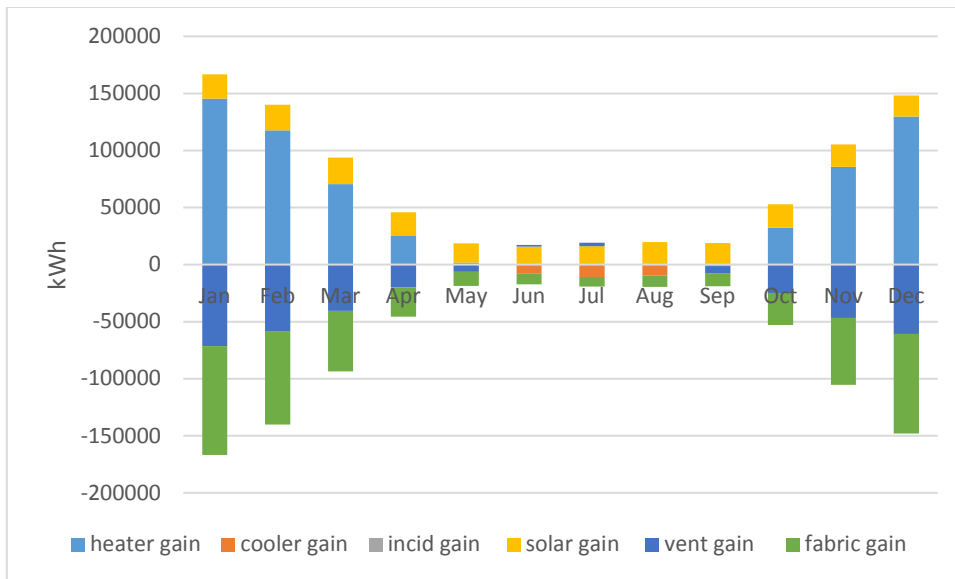


Figure 6.41 Proportion of monthly gains of Case 2 without IHG

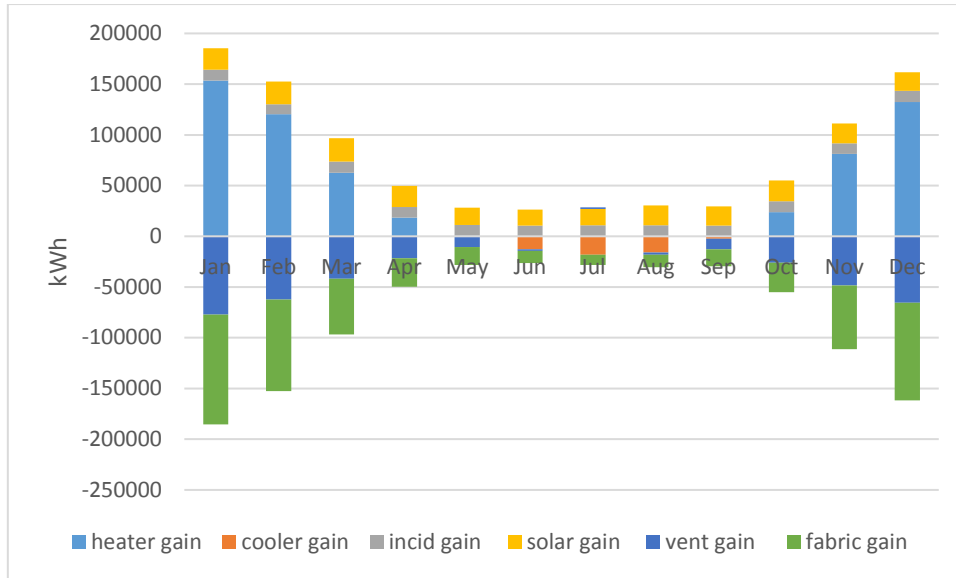


Figure 6.42 Proportion of monthly gains of Case 2 with IHG

6.6.3. Results of Case 2 after Retrofitting

6.6.3.1. Improvement of Individual Retrofit Measures

Figures 6.43 and 6.44 describe the percentage of improvement in energy demand, electricity supply, gas supply and CO₂ emission for each retrofit measure.

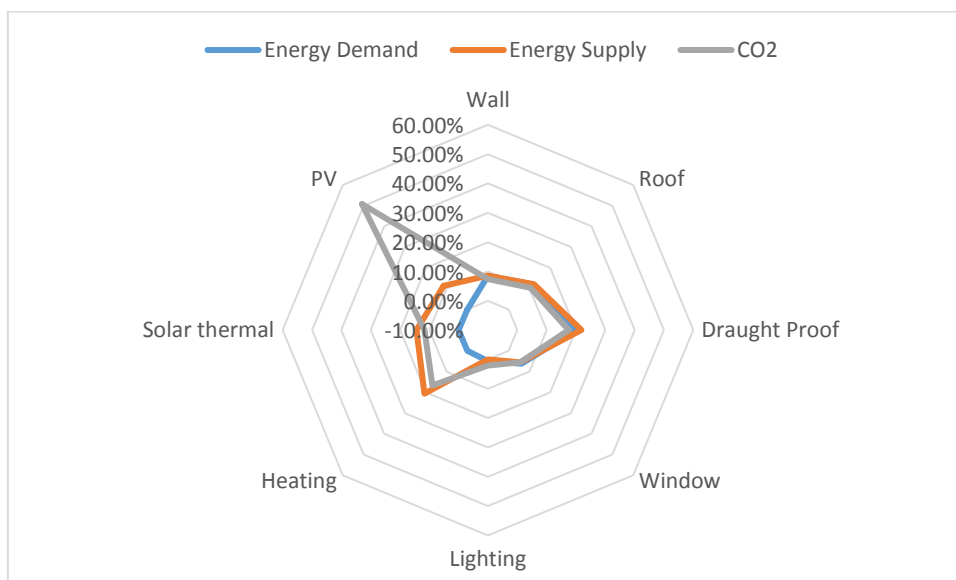


Figure 6.43 The percentage of improvement in energy demand, energy supply and CO₂ for each retrofit measure of Case 2

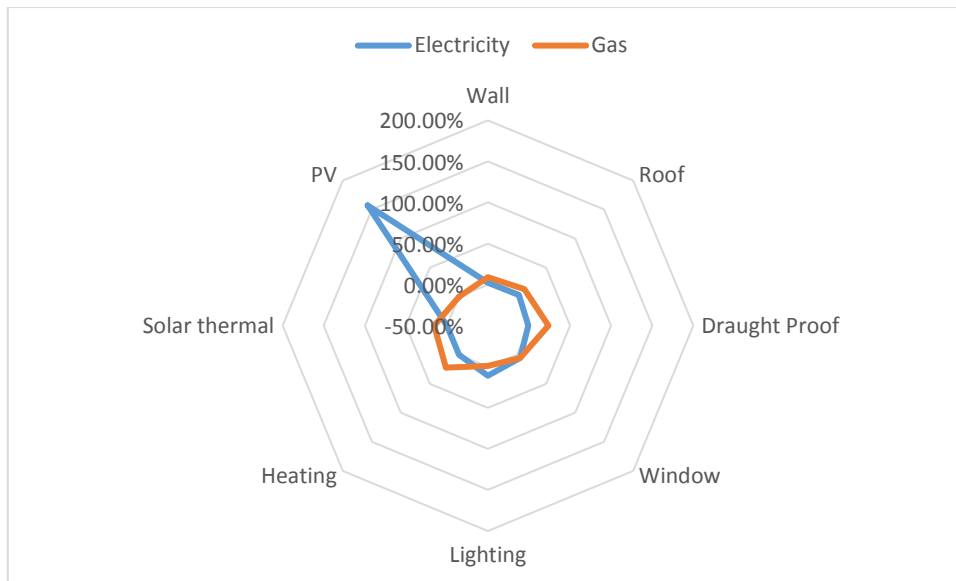


Figure 6.44 The percentage of improvement on electricity and gas for each retrofit measure of Case 2

For energy demand reduction, firstly, the measure of draught proofing has the most substantial improvement in reducing energy demand, by 20.2%. Secondly, roof insulation and EWI also have relatively large effects, with proportions of 11.9% and 8.4%, respectively. Thirdly, heating system improvement, solar thermal and solar PV have no improvement in energy demand reduction.

Regarding energy supply, the measure of draught proofing contributes the most, which has 21.9% improvement with a major reduction in gas consumption. The heating system improvement and solar PV also have large influences on energy supply, the former in reducing gas consumption and the latter in electricity reduction.

Regarding CO₂ emissions, solar PV reduces them the most, with a proportion of 50.7%, while draught proofing and heating system improvement also have an influence of 17.5% and 16.7%, respectively.

6.6.3.2.Improvement of the Retrofit Packages

6.6.3.2.1. Energy Demand

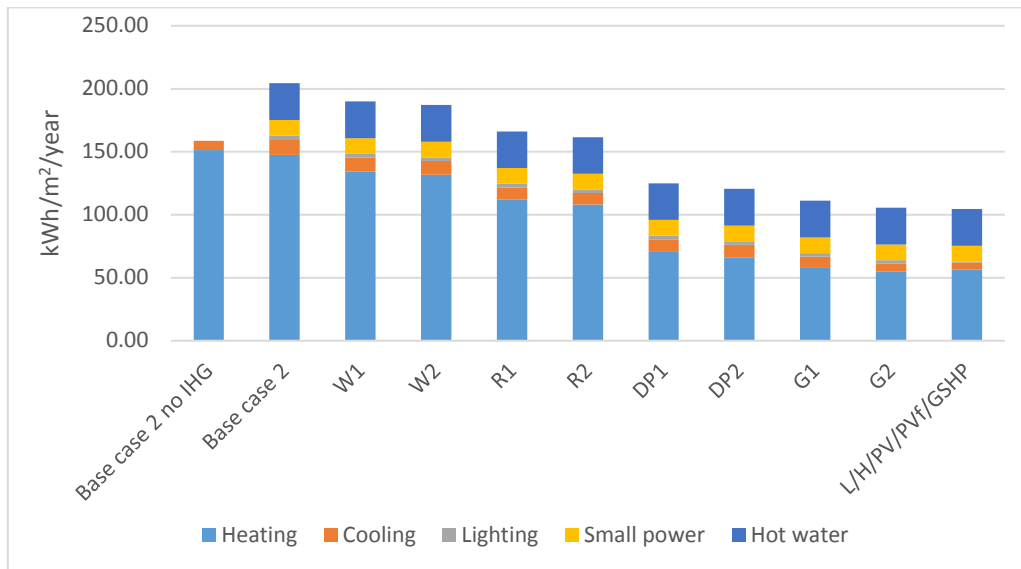


Figure 6.45 Annual energy demand of Case 2 for a range of retrofit measures (ref: Table 6-7)

Figure 6.45 demonstrates the results of the annual heating and cooling demands of Case 2 before retrofitting with and without IHGs and after retrofitting by different measure packages. As shown in the bar chart, the energy demand drops with the increasing of the retrofit measure packages. First, the package of draught proofing has the maximal impact on energy demand reduction, with values of 41.2 kWh/m² and 41.1 kWh/m² for the 50mm and 100 mm insulation packages, respectively. Second, EWI and roof insulation also play essential parts in reducing heating and cooling demands. Third, the effect of different thicknesses of the insulation boards is not that obvious. Also, the low-E glazing has a better performance in energy demand reduction than the double glazing. Furthermore, the cooling demand is relatively stable, which slightly goes up after upgrading the airtightness. Because it is more difficult to remove heat in summer by natural ventilation and infiltration with higher airtightness. Moreover, the heating system improvement and renewables have no improvement in energy demand. Besides, the LED lighting reduces the cooling demand, but slightly increases the heating demand, as LED lamps produce lower heat than incandescent lamps.

Further information on heating and cooling gains, ventilation gains, fabric gains and solar gains can be found in Appendix 1.

6.6.3.2.2. Energy Supply

The annual electricity supply of Case 2 is displayed in Figure 6.46. From the graph, we can see that firstly, electricity is mainly used for cooling, lighting, and small power. Secondly, the internal gains occupy a major part of electricity consumption, which cannot be ignored. Thirdly, the heating and hot water do not consume electricity except the GSHP packages. In addition, lighting improvement reduces the most electricity use of 2.2 kWh/m², whereas other packages do not have many contributions.

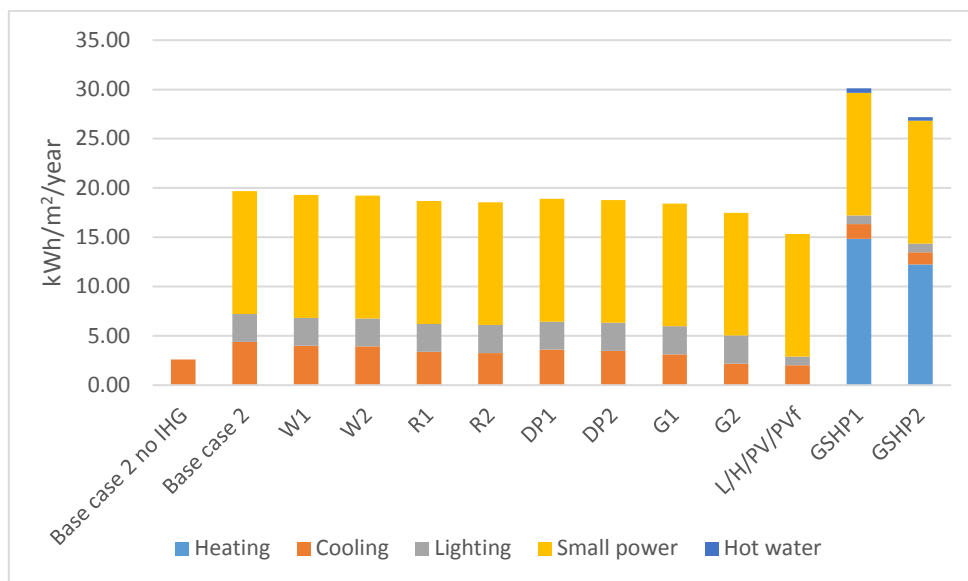


Figure 6.46 The annual electricity supply of Case 2 for a range of retrofit measures (ref: Table 6-7)

In terms of gas supply, as shown in Figure 6.47, firstly, the most significant improvement is through the package of draught proofing, with annual reduction of 59.7 kWh/m². Because the heating demand is lower with improved airtightness, the gas use on space heating is reduced. Secondly, EWI and roof insulation also reduce the

relatively large amount of gas consumption. In addition, improving the heating system also contributes to the reduction of gas use for space heating. Moreover, the use of solar thermal offsets a large part of the gas consumed by hot water. Lastly, the GSHPs do not use gas at all, so the gas consumption of both packages is zero.

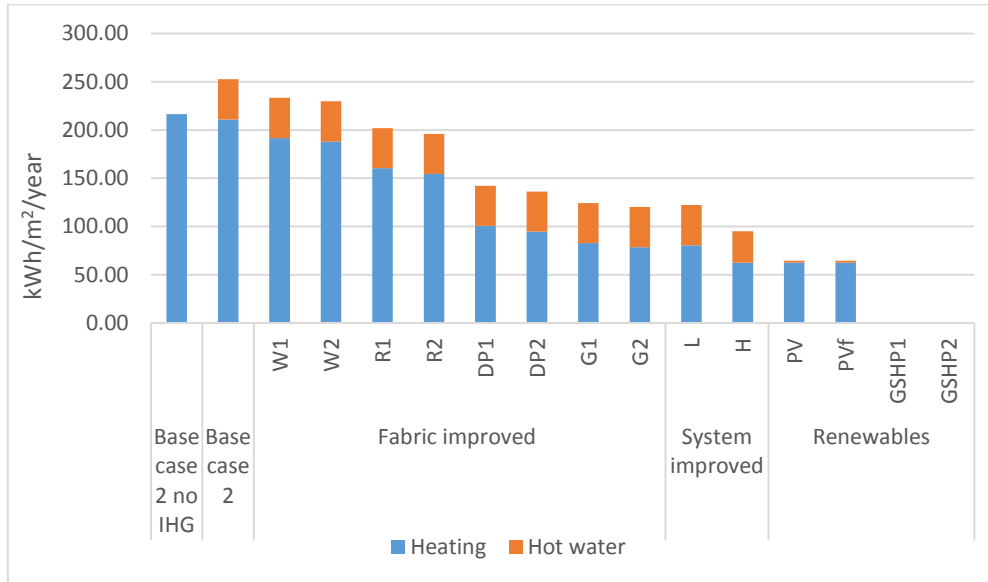


Figure 6.47 The annual gas supply of Case 2 for a range of retrofit measures (ref: Table 6-7)

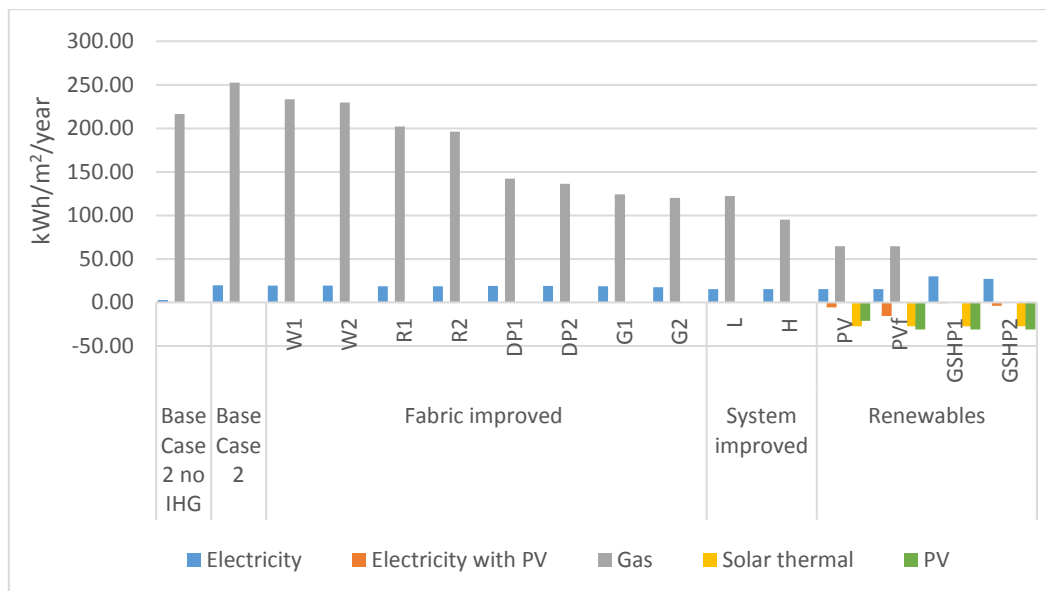


Figure 6.48 The summary of annual electricity and gas supply and renewable energy of Case 2 for a range of retrofit measures (ref: Table 6-7)

Figure 6.48 presents the annual energy supply, the electricity generated by solar PV and the gas reduced by using solar thermal. According to the chart, firstly, the gas consumption has drastically reduced compared with that of the electricity. This is because the fabric and system retrofit decrease the heating demand. Secondly, there is a substantial electricity reduction after installing solar PVs. Thirdly, when adding the GSHPs to the PV roof and facade package, the energy supply drops from 49.1 kWh/m² to -0.8 kWh/m² and -3.7 kWh/m² with COP of 3.8 and 4.6, respectively.

6.6.3.2.3. CO₂ Emission Reduction

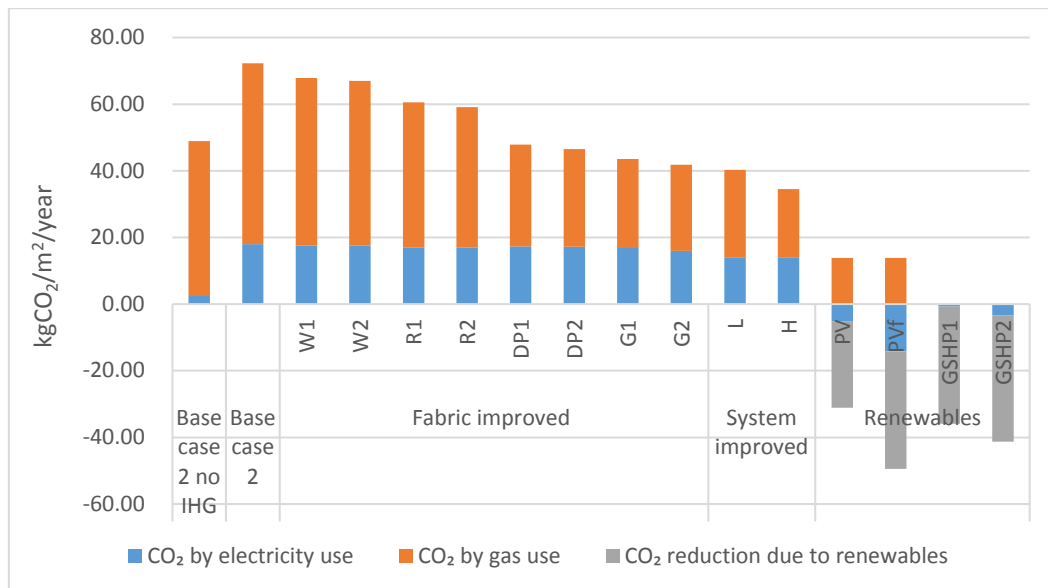


Figure 6.49 Summary of the CO₂ emissions of Case 2 for a range of retrofit measures (ref: Table 6-7)

As shown in Figure 6.49, the annual CO₂ emissions steadily reduce with the sequential adoption of the fabric and system retrofit packages, principally in the reduction of gas consumption. Also, the CO₂ emissions drop considerably when including the renewables. Since the electricity created by the PVs balances a large proportion of the electricity use, so the CO₂ emissions caused by electricity use are significantly reduced. In addition, the GSHPs have more CO₂ emissions from electricity but have less overall CO₂ emissions than the PV roof and facade packages. Moreover, the overall CO₂

emissions are reduced from 72.3 kg/m² to -3.4 kg/m² (combined with negative carbon due to power exportation).

6.6.3.2.4. Operating Cost

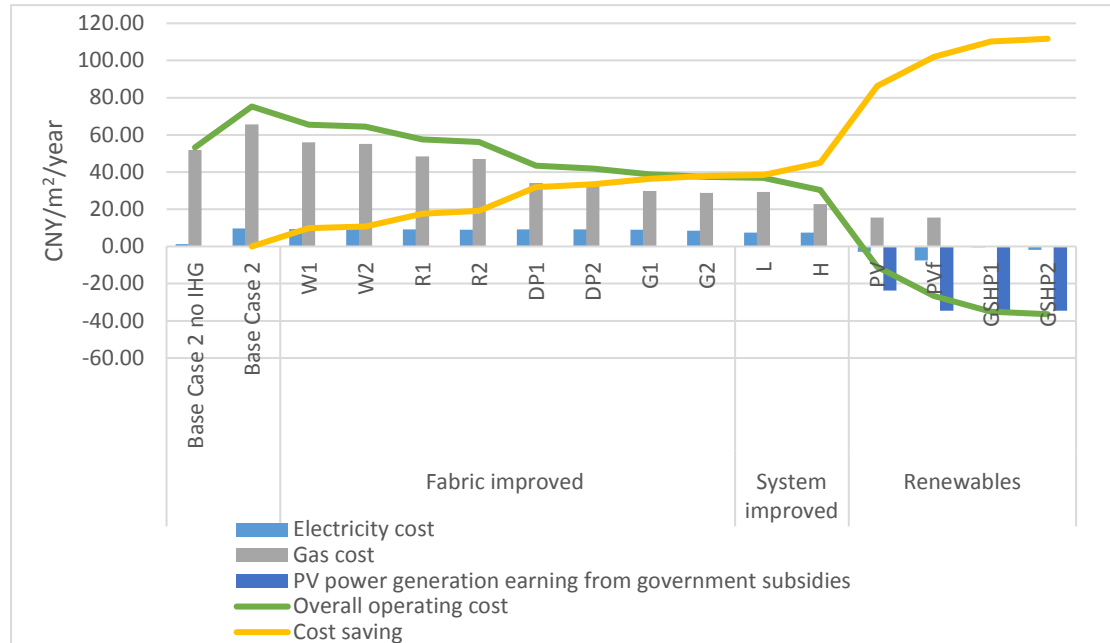


Figure 6.50 The summary of the operating cost and saving of Case 2 for a range of retrofit measures (ref: Table 6-7)

Figure 6.50 shows the summary of the operating costs and savings of Case 2. From the graph, firstly, the overall operating cost decreases along with the increasing retrofit measures, with the biggest decline in the renewable packages, while the saving ascends accordingly. Secondly, the reduction trend of gas cost is consistent with the overall operating cost, but the electricity cost has not changed much by the fabric and system retrofit until renewables are added. In addition, the packages of PV roof reduce the most of the overall cost, with the reduction of over 41.3 CNY/m². Moreover, the overall operating cost are decreased from 75.3 CNY/m² to -36.4 CNY/m². Besides, the GSHPs have lower overall operating cost and provide more savings than the PV roof and facade package.

6.6.3.2.5. Percentage of Improvement

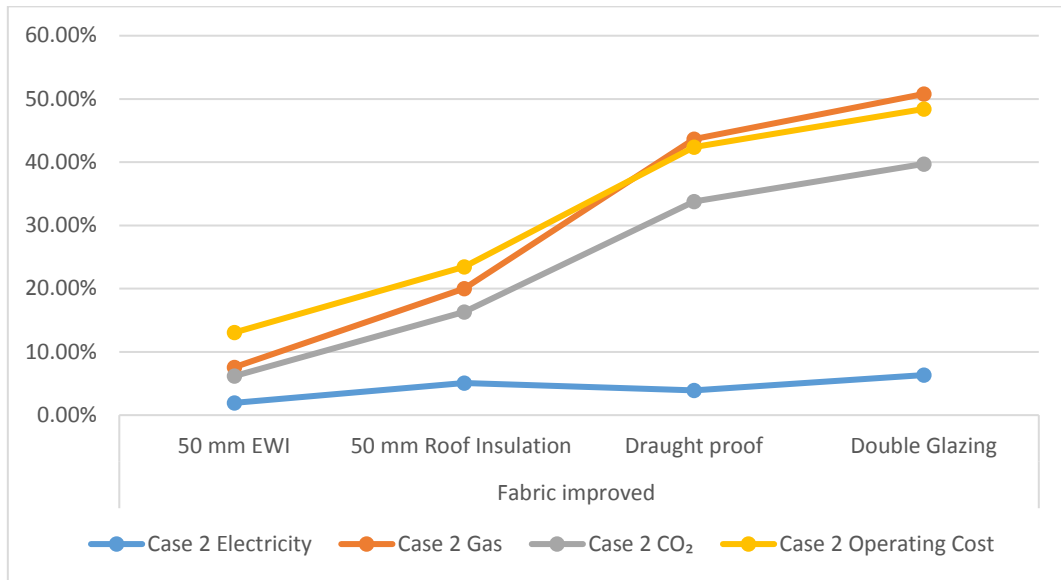


Figure 6.51 The percentage of improvement of Case 2 with 50 mm insulation

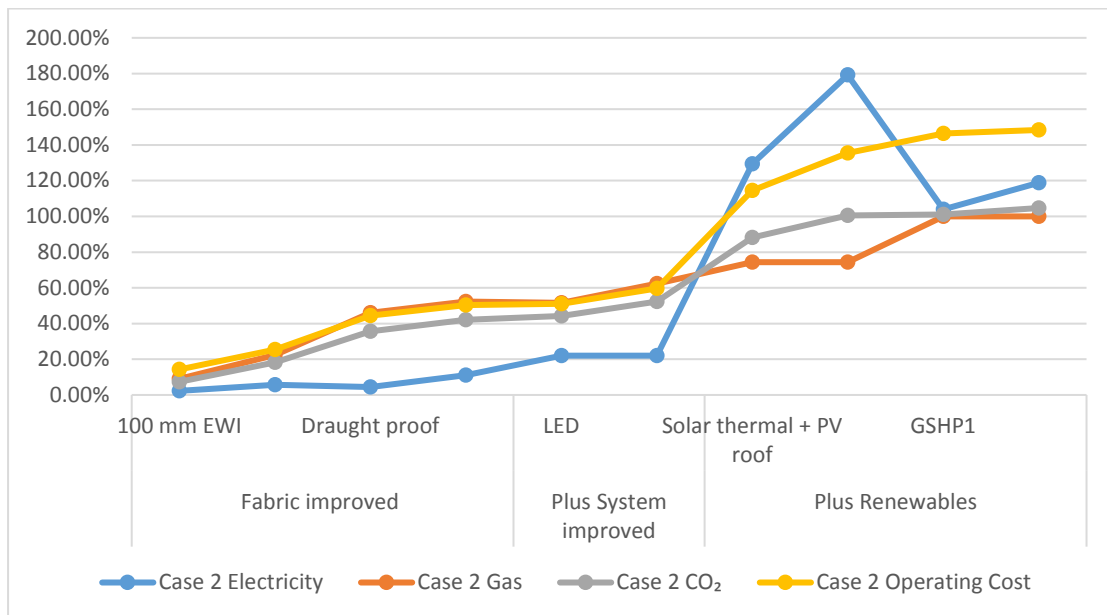


Figure 6.52 The percentage of improvement of Case 2 with 100 mm insulation

Figures 6.51 and 6.52 demonstrate the percentage of the retrofit improvement of Case 2 with 50 mm and 100 mm insulation, respectively. All trends go up as the retrofit

packages are applied. The 100mm insulations show marginally higher improvement than that of the 50mm insulations.

As far as electricity use is concerned, the LEDs reduce it by 22% and the PVs reduce it by 179.2%. Also, the PVs have the most noticeable improvement in electricity and the operating cost reductions. In addition, fabric retrofit has the largest gas reduction, where the draught proofing package contributes the most, with more than 43.7% of the total gas reduction. Furthermore, renewable packages have the most considerable improvement in operating costs, with the largest improvement (148.4%) in GSHP2.

6.6.3.3.Flat-to-pitched Roof Retrofit

In order to repair residential buildings and improve the urban landscape, Beijing has carried out a flat-to-pitched roof retrofit project from 2004 to 2006. As Case 2 is a multi-storey building with a flat roof, it is used to examine the flat-to-pitched roof retrofit performance and the results of energy demand, energy supply and solar potential between the flat and pitched roof are compared and presented below.

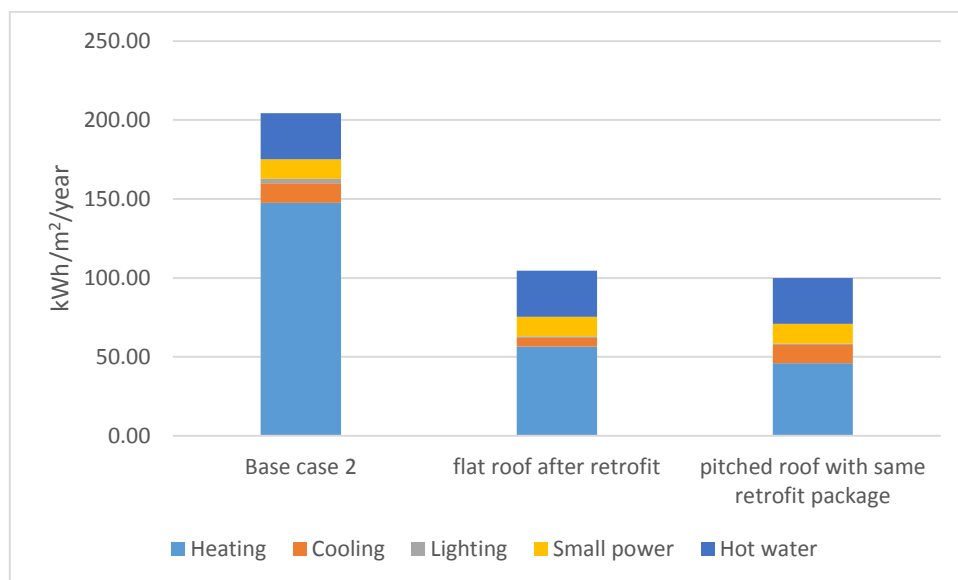


Figure 6.53 Comparison of flat roof with pitched roof on energy demand

Figure 6.53 depicts the energy demands of the flat and pitched roof cases after retrofitting together with the base case for comparison. From the chart, we can see that the heating demand of the pitched roof is lower than that of the flat roof, whereas the cooling demand is higher. This is because the added roof space acts as a loft, which makes the heat more difficult to lose through the roof. The cooling load can be reduced by ventilation through adding windows on the pitched roof. It also can be seen that the heating demand of the pitched roof case has more reduction than cooling demand.

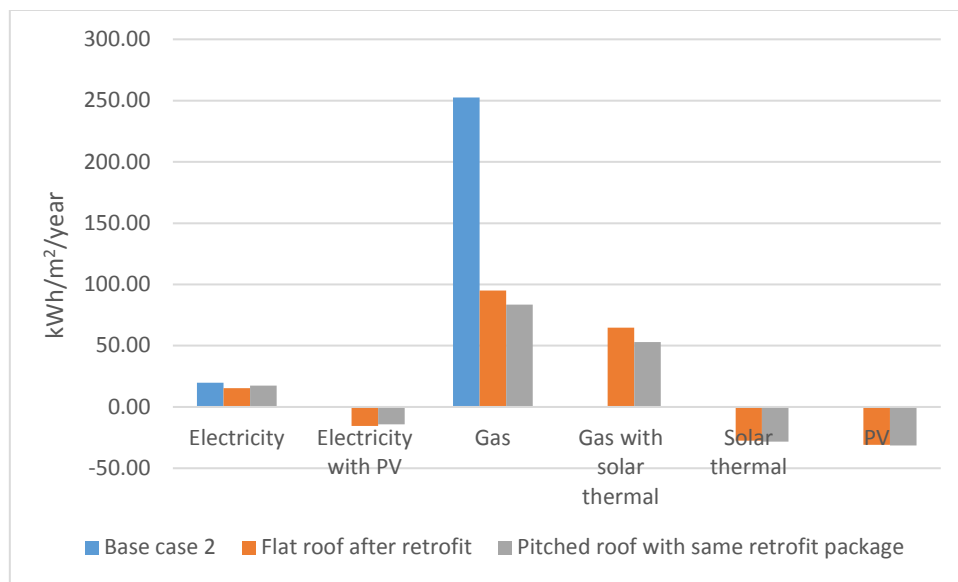


Figure 6.54 Comparison of flat roof with pitched roof on energy supply and solar potential

Figure 6.54 shows the energy supply and solar potential of the flat and pitched roofs. According to the graph, the pitched roof has better performance in electricity and gas consumptions as well as solar potential than the flat roof, where the greater difference lies in gas use. This is consistent with the result of heating and cooling demand.

Figure 6.55 illustrates the comparison of the flat and pitched roof on gas reduction for hot water use by solar thermal and electricity production by solar PV. It can be seen that the pitched roof has slightly higher reduction on gas use by solar thermal than the flat roof, with values of 28.2 kWh/m² and 27.4 kWh/m², respectively. For solar PV generation, the pitched roof has 21.7 kWh/m² for roof-only packages and 30.9

kWh/m² for roof and facade packages, which is 0.6 kWh/m² higher than that of the flat roof.

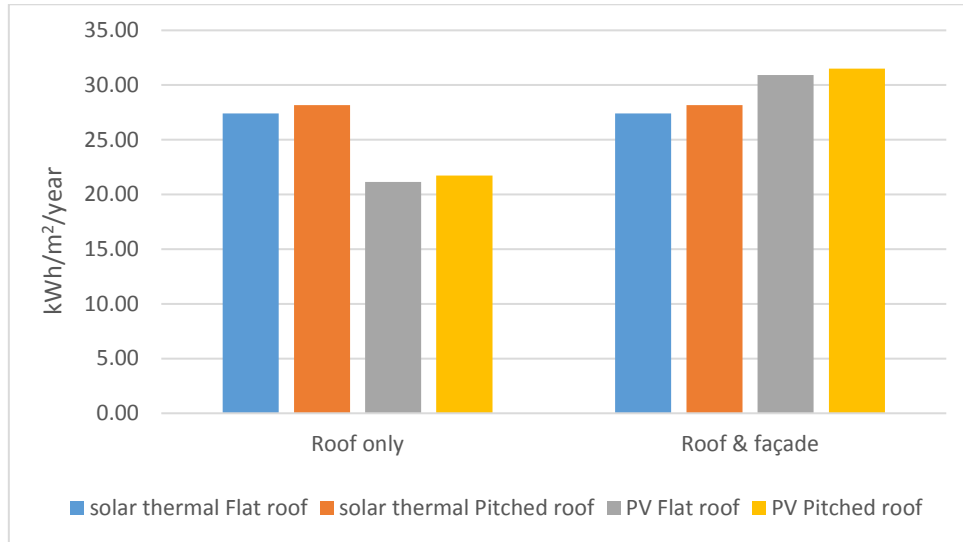


Figure 6.55 Comparison of flat and pitched roof on solar potential

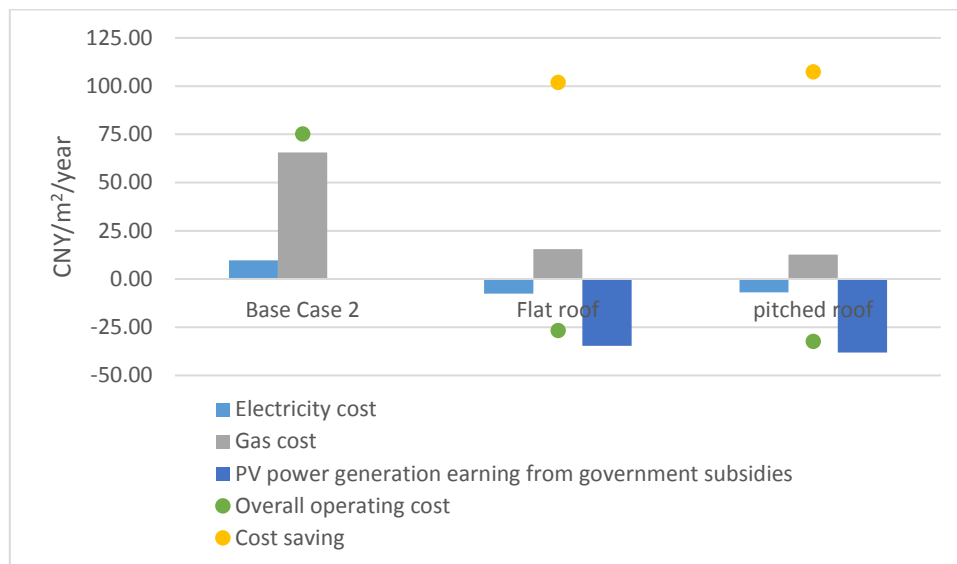


Figure 6.56 Operating cost and saving comparison of the flat and pitched roof

Figure 6.56 compares the operating costs and savings of the flat and pitched roof after the retrofiting. From the chart it can be seen that in general, the pitched roof has the

lower overall operating cost of -32.3 CNY/m² per year, compared with the flat one of -26.7 CNY/m² per year. Specifically, the electricity cost of the pitched roof is 0.74 CNY/m² higher and the gas cost is 2.78 CNY/m² lower than that of the flat one. Also, the PV power generation earning for the pitched roof is 3.5 CNY/m² higher than that of the flat roof. Moreover, the total savings of the pitched roof is 107.5 CNY/m² per year, which is 5.5 CNY/m² more than that of the flat roof.

6.6.3.4. Profiles of Hourly Electricity Supply and Generation by PV

Figures 6.57 to 6.61 describe the hourly profile of the electricity supply by the GSHP system and generation by PV for Case 2 during two typical weeks in winter and summer, in January and July, and throughout the whole year.

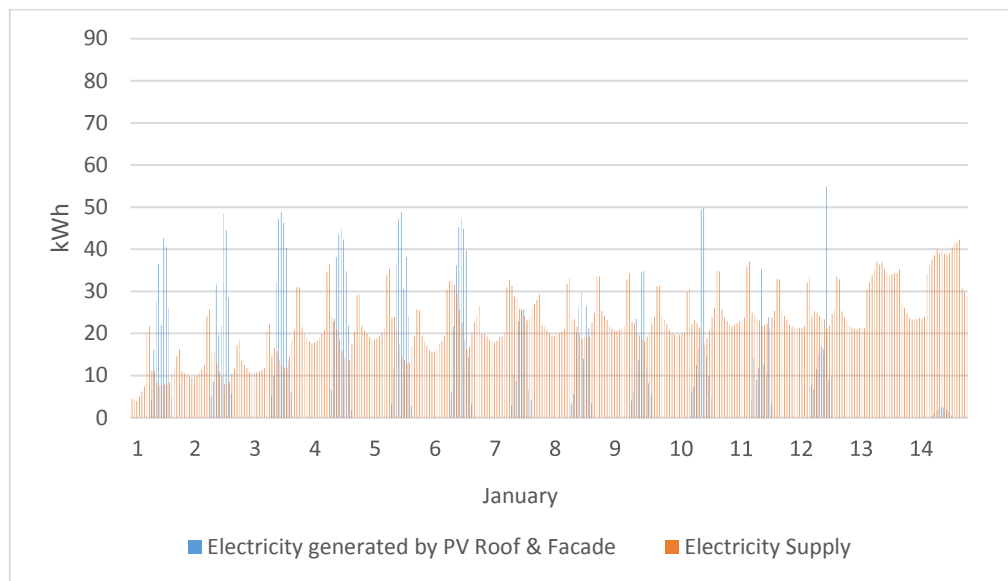


Figure 6.57 Hourly electricity supply and PV generation of Case 2 in two weeks in January

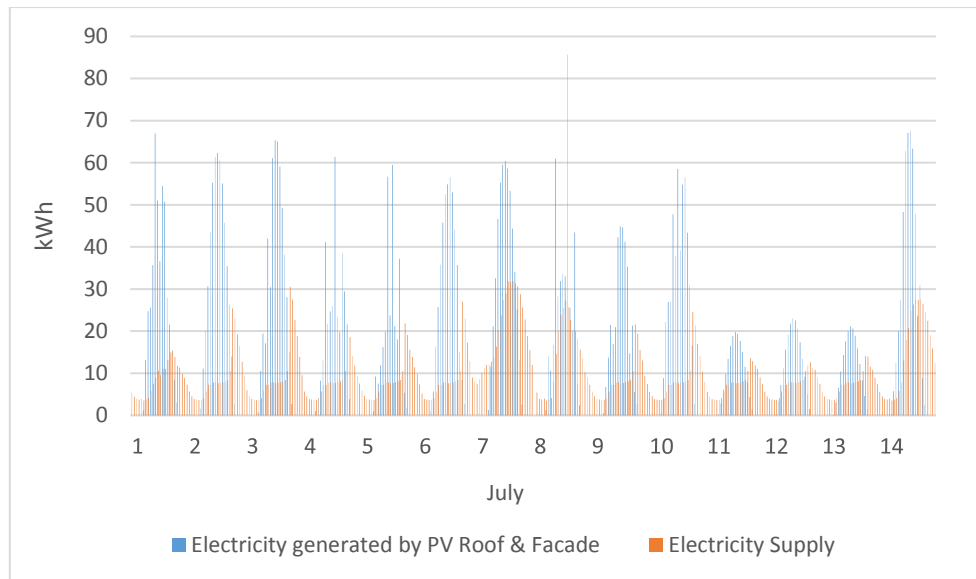


Figure 6.58 Hourly electricity supply and PV generation of Case 2 in two weeks in July

As shown in Figures 6.57 and 6.58, the data of the electricity supply and generation fluctuate with the time of day and the occupancy timetable during the week. First of all, electricity consumption is higher on weekends than on weekdays, and more in winter than in summer. For each day, more electricity is used in the evenings, reaching the highest point at about 7:00 pm. In comparison, the PVs generate electricity in the daytime, with the peak at around 12:00 o'clock. Additionally, the electricity produced by PV changes with factors such as weather conditions. For instance, the electricity generated on the 13th to 14th in January and on the 11th to 13th in July is relatively lower than on regular days.

The hourly electricity supply and generation by PV in January and July are demonstrated in Figures 6.59 and 6.60. To begin with, the electricity consumption and generation are more in January than in July. Also, the electricity use on weekends in July is approximately two times more than that of the average weekdays. In addition, similar to Case 1, the solar PV generates little or no electricity from January 13th to 15th, which may be due to the weather conditions or other unpredictable factors. Meanwhile, the electricity supply surges drastically in those days.

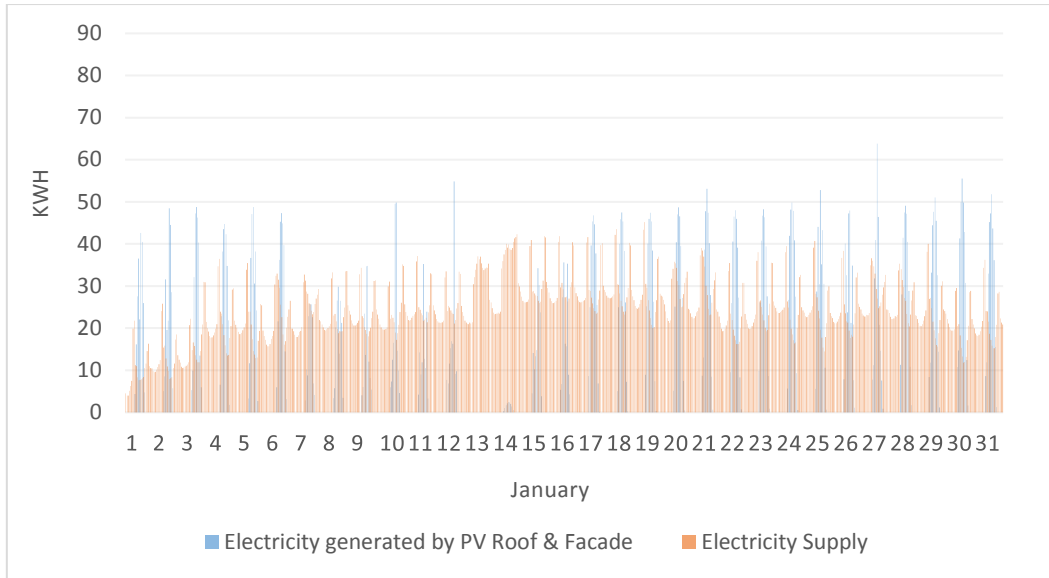


Figure 6.59 Hourly electricity supply and PV generation of Case 2 in January

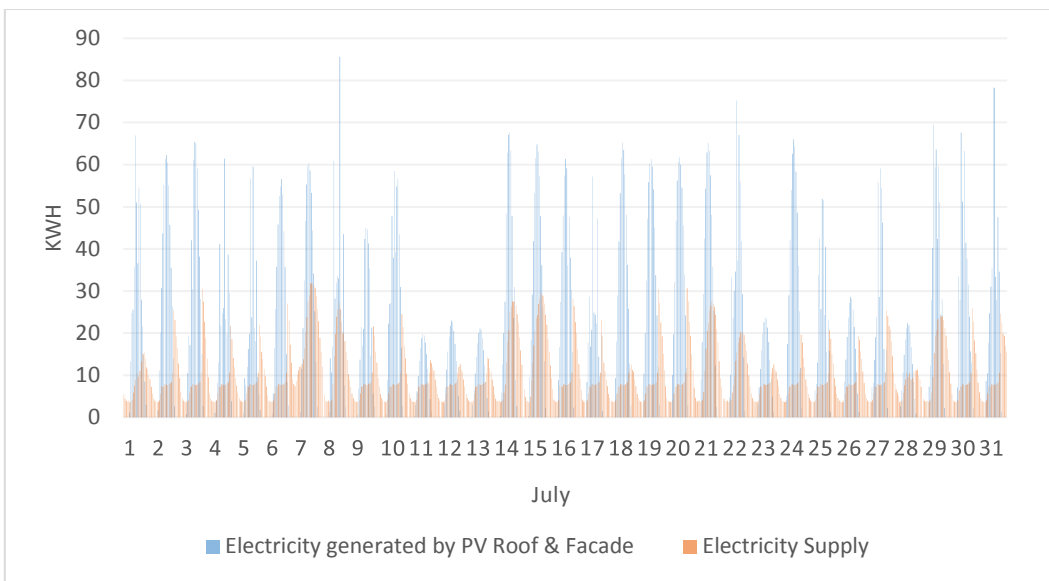


Figure 6.60 Hourly electricity supply and PV generation of Case 2 in July

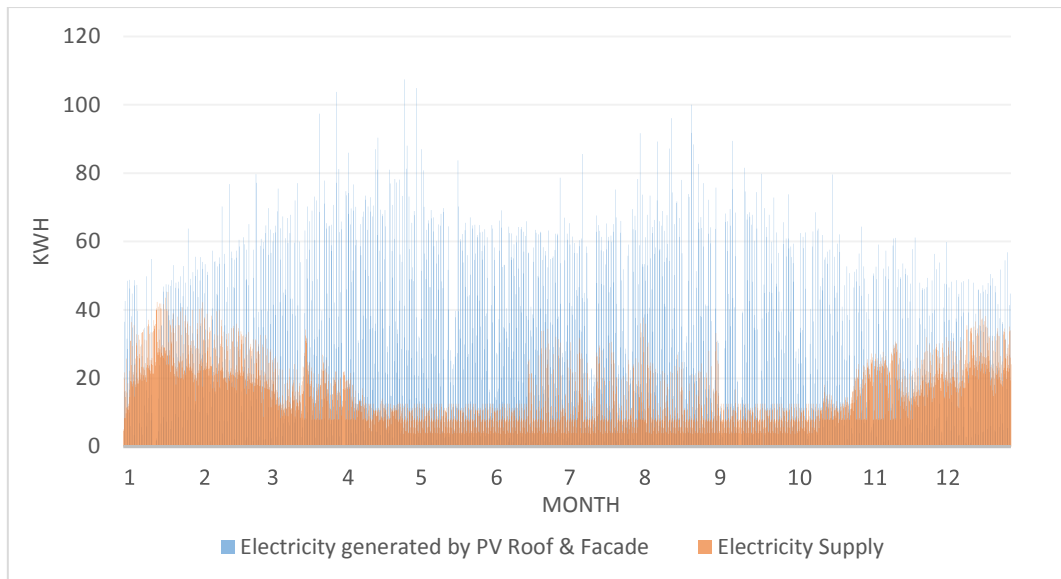


Figure 6.61 Hourly profile of the electricity supply and PV generation for the whole year of Case 2

Figure 6.61 indicates the hourly data of the electricity consumption and generation by solar PV during the year. It is manifest that the electricity supply has two peaks, in winter and summer, and in other two seasons it remains stable. Also, the electricity generated by PV can almost offset all of the electricity use. In addition, the peaks of the solar PV generation are in May and August, and the most power can be exported to the national grid in May.

Therefore, the electricity consumption that can be covered by the solar PV lies in the overlapping area of the two colours in the figures. The blue colours that are not covered by the orange area represent the electricity to be exported to the grid, while the electricity that need to be imported from the grid is the orange part that does not overlap in the graph.

6.7. Modelling of Case 3: Building 28 of Dongsishitiao Community

6.7.1. Introduction of Case 3

Case 3 is a high-rise flat with 18 floors in Dongsishitiao Community located in the northeast of Beijing. The building was built in 1983 with a cast-in-place structure of

reinforced concrete. The total floor area of this building is 8165.97 m², and the floor height is 2.9m. There are 121 households in this building. As the building was built in the early 1980s, there was no insulation on the roof and external walls before the retrofitting.

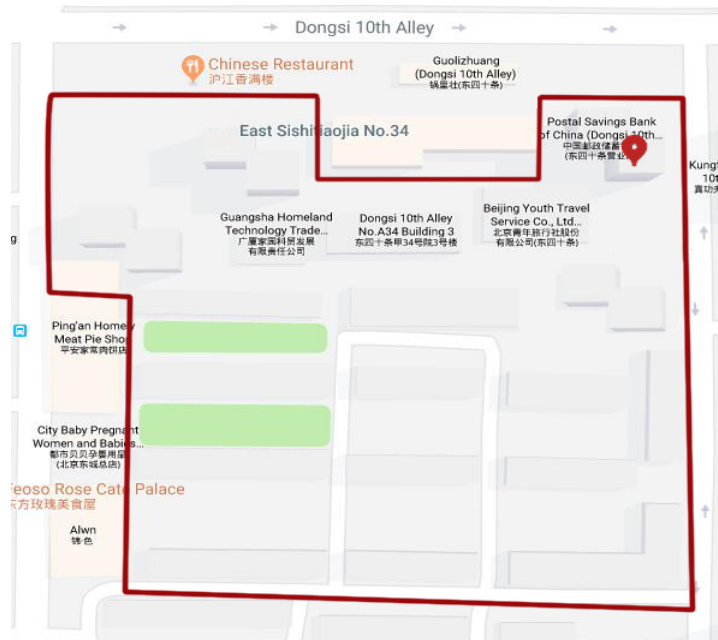


Figure 6.62 The location of Case 3



Figure 6.63 The building facade of Case 3 before the retrofitting

The location, the building facade before retrofit and the standard floor plan are shown in Figures 6.62, 6.63 and 6.64. It can be seen from Figure 6.63 that the overhead cables were messy, a common problem in many existing Chinese communities, which may affect the residents' safety. Some windows were replaced with double-glazed windows by occupants, but most of the windows were single glazed with poor sealing before the retrofitting.

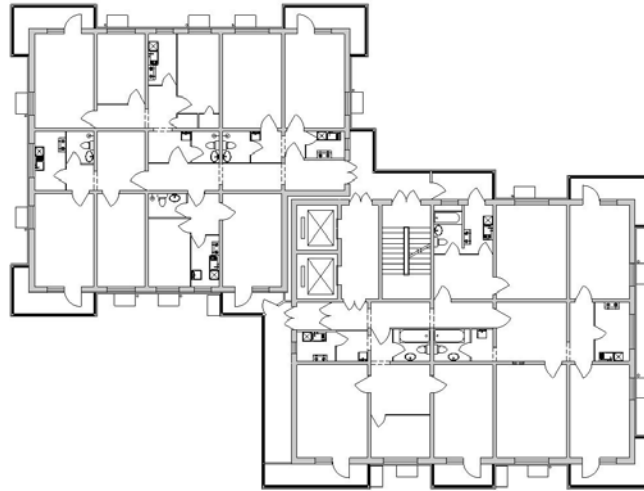


Figure 6.64 The standard floor of Case 3

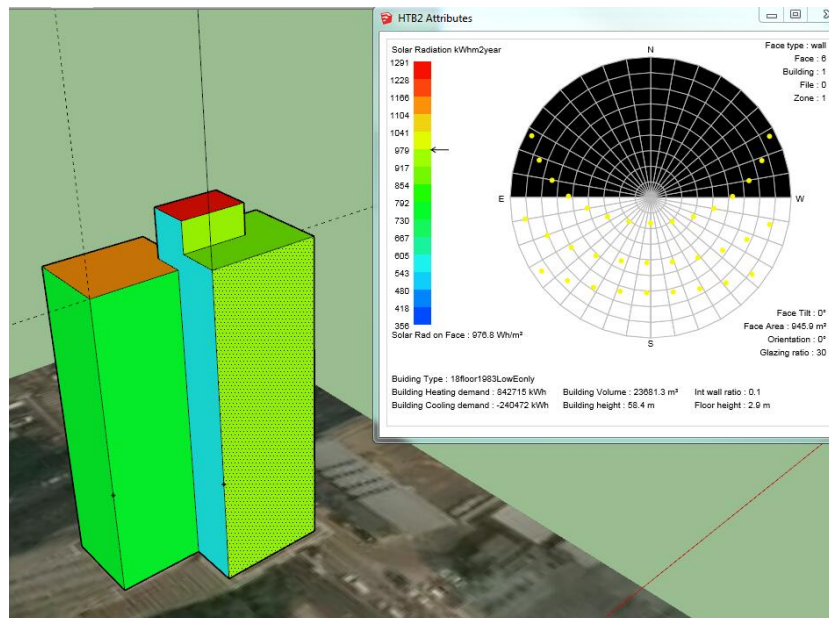


Figure 6.65 The 3D model of Case 3

The 3D model of Case 3 with colour faced for solar radiation and the shading mask of the south facade are illustrated in Figure 6.65. The construction materials of the building components, including external walls, internal walls, roof, floors and ceilings, ground, and external windows before and after insulation retrofit are outlined in Tables 6-13 and 6-14.

Table 6-13 The construction details of base Case 3 before the insulation retrofit

Construction	U-Value (W/m ² /°C)	Building Materials	Thickness (mm)	Conductivity (w/m·C)	Density (kg/m ³)	Specific heat capacity (J/kg/C)
Exterior Wall (From Outside to Inside)	2.53	cement mortar	20	0.93	1800	1050
		reinforced concrete	300	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Interior Wall (From Outside to Inside)	3.06	cement mortar	20	0.93	1800	1050
		Aerated concrete block	180	0.24	750	1000
		cement mortar	20	0.93	1800	1050
Roof (From Top to Bottom)	2.86	linoleum	3	0.17	600	1460
		cement mortar	20	0.93	1800	1050
		slag cement	30	0.76	1500	1050
		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Floor-Ceiling (From Top to Bottom)	3.42	cement mortar	20	0.93	1800	1050
		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Ground (From Top to Bottom)	1.16	cement mortar	30	0.93	1800	1050

		C15 fine aggregate concrete	80	1.51	2300	920
		gravel	120	2.04	2400	920
		rammed earth	500	0.93	1800	1010
Exterior Window	5.32	plate glass	6	0.76	2500	840

Table 6-14 The construction details of Case 3 after the insulation retrofit

Construction	U-Value (W/m ² /°C)	Building Materials	Thickness (mm)	Conductivity (w/m·C)	Density (kg/m ³)	Specific heat capacity (J/kg/C)
Exterior Wall (From Outside to Inside)	0.5 / 0.31	insulating mortar	25	0.06	250	1049.6
		Expanded polystyrene (EPS)	50 / 100	0.041	18	2414.8
		reinforced concrete	300	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Interior Wall (From Outside to Inside)	3.06	cement mortar	20	0.93	1800	1050
		Aerated concrete block	180	0.24	750	1000
		cement mortar	20	0.93	1800	1050
Roof (From Top to Bottom)	0.36 / 0.21	insulating mortar	20	0.06	250	1049.6
		composite polyurethane board	50 / 100	0.024	30	2475.2
		roofing felt	6	0.19	960	837
		cement mortar	20	0.93	1800	1050
		slag cement	30	0.76	1500	1050
		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
	3.42	cement mortar	20	0.93	1800	1050

Floor-Ceiling (From Top to Bottom)		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Ground (From Top to Bottom)	1.16	cement mortar	30	0.93	1800	1050
		C15 fine aggregate concrete	80	1.51	2300	920
		gravel	120	2.04	2400	920
		rammed earth	500	0.93	1800	1010
Exterior Window	3.27 / 2.66	plate glass	6	0.76	2500	840
		cavity	3 normal / 3 low-E	n/a	n/a	n/a
		plate glass	6	0.76	2500	840

6.7.2. Results of Case 3 With and Without IHGs before the Retrofitting

The average monthly gains including heater gain, cooler gain, internal gain, solar gain, ventilation gain and fabric gain of Case 3 without IHGs and with IHGs are shown in Figures 6.66 to 6.69. First of all, the heater gain is the primary heat source in winter. Second, solar gain stays stable throughout the year. Third, the IHG occupies a part that cannot be ignored, which is about half of the solar gain. After including the IHG, the heater gain slightly drops and the cooler gain increases. This is because the occupants, lighting and appliances increase the heat of the building. Additionally, the ventilation gain and fabric gain are the two major heat loss factors in winter, which have increased after considering the IHGs. Therefore, to reduce the heater gain and fabric gain can be the most effective way to improve the building.

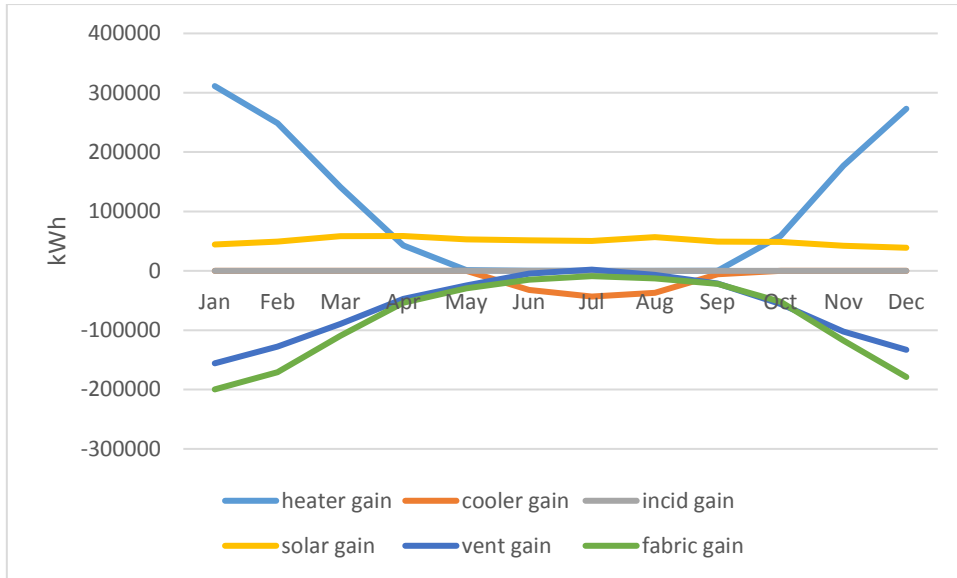


Figure 6.66 Monthly gains of Case 3 without IHGs

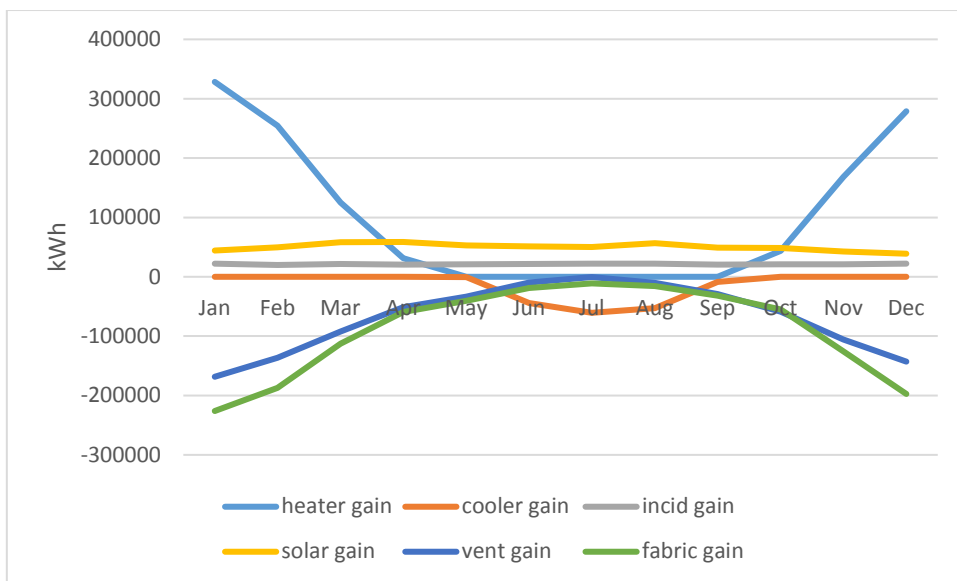


Figure 6.67 Monthly gains of Case 3 with IHGs

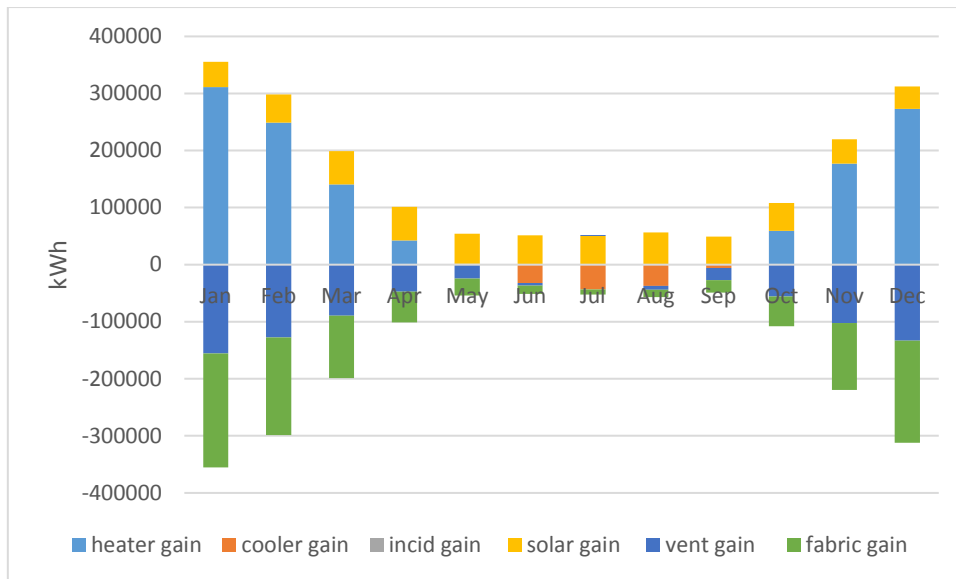


Figure 6.68 The proportion of monthly gains of Case 3 without IHGs

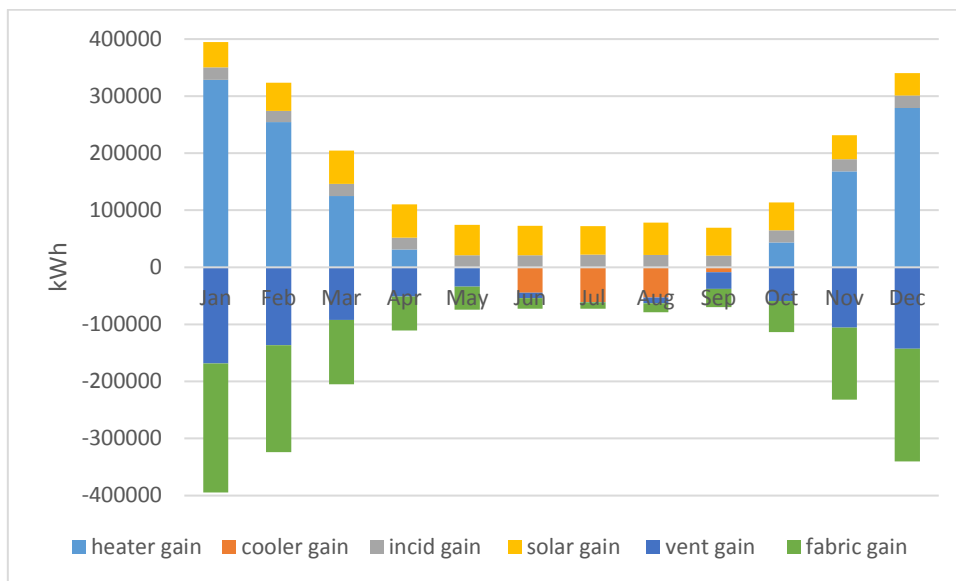


Figure 6.69 The proportion of monthly gains of Case 3 with IHGs

6.7.3. Results of Case 3 after Retrofitting

6.7.3.1. Improvement of Individual Retrofit Measures

Figures 6.70 and 6.71 indicate the percentage of improvement in energy demand, electricity supply, gas supply and CO₂ emissions for each retrofit measure. According to the two radar graphs, firstly, for energy demand reduction, the measure of draught

proofing has the most substantial improvement, with proportions of 20.5%. EWI and window replacement also have good performance, with the reductions of 10.7% and 10.5%, respectively, while the roof insulation only provides a 3.9% reduction. This is because the proportion of roofing in high-rise buildings is small, so the contribution of the roof insulation in reducing energy demand is relatively limited. Secondly, the improvement of the heating system, solar thermal and solar PV has no reduction of energy demand. Thirdly, for the energy supply, the draught proofing and the heating system improvement have the greatest effect, with major reductions in gas consumption. Also, lighting, window replacement and PV decrease most of the electricity use; PV has the most significant electricity reduction, of 72.6%. Moreover, the heating system improvement and solar thermal only affect gas reduction. Besides this, regarding CO₂ emissions, the measure of heating system improvement, draught proofing and solar PV all provide a relatively substantial reduction.

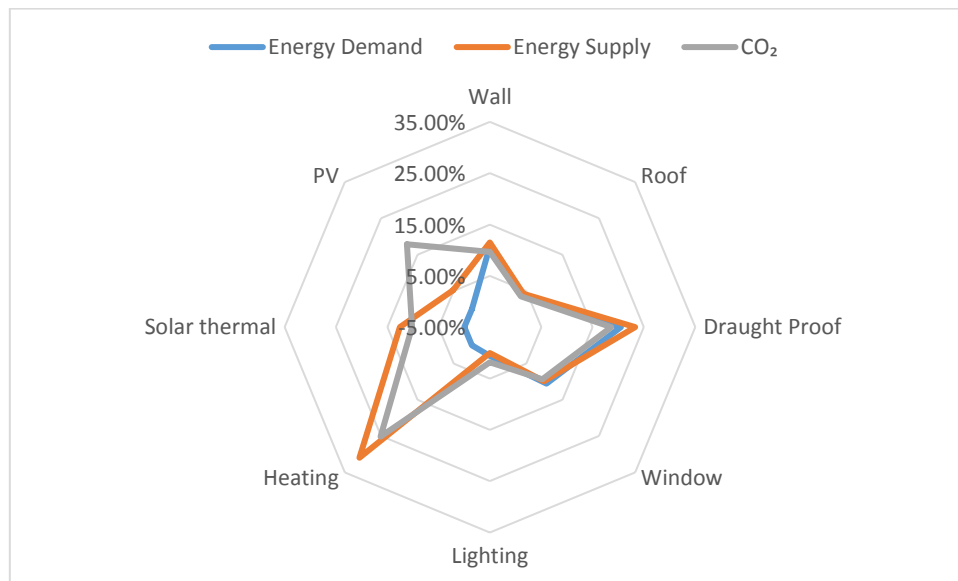


Figure 6.70 The percentage of improvement in energy demand, energy supply and CO₂ for each retrofit measure of Case 3

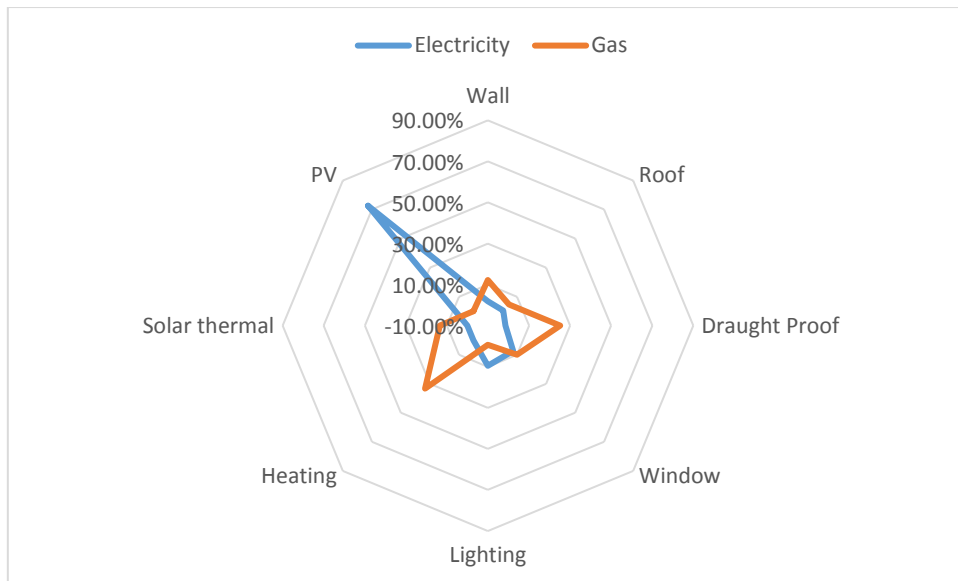


Figure 6.71 The percentage of improvement on electricity and gas for each retrofit measure of Case 3

6.7.3.2.Improvement of the Retrofit Packages

6.7.3.2.1. Energy Demand

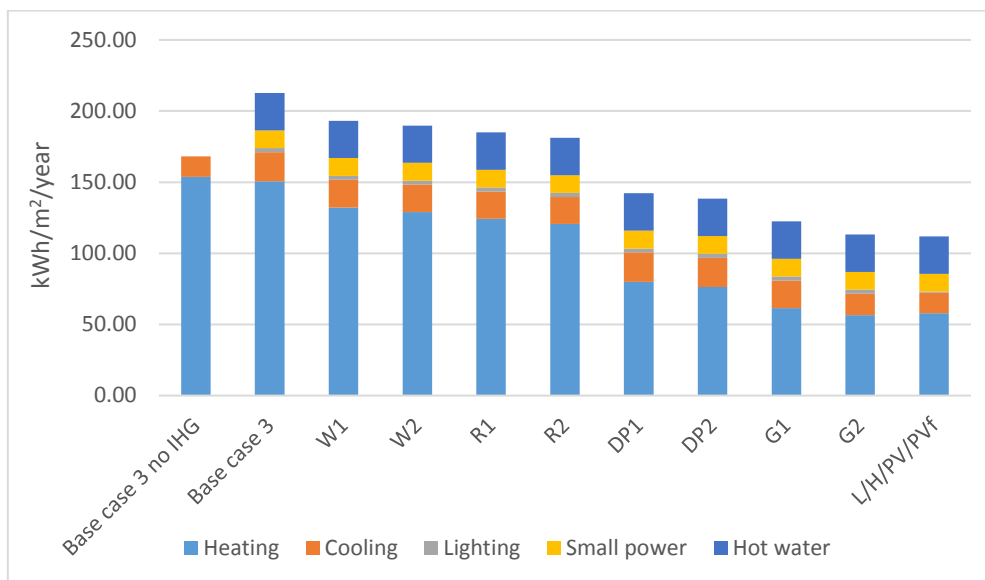


Figure 6.72 Annual energy demand of Case 3 for a range of retrofit measures (ref: Table 6-7)

Figure 6.72 presents the energy demand breakdown of Case 3. According to the graph, first of all, the energy demand declines with the addition of the retrofit packages. Second, the draught proofing package has the most enormous impact on energy

demand reduction, with values of 42.9 kWh/m² and 42.8 kWh/m² for the 50mm and 100 mm insulation packages, respectively. Third, the cooling demand drops apparently when installing the low-E glazing. In addition, the LED lighting package slightly reduces the cooling demand, but also moderately increases the heating demand due to less heat gain from the LED lamps compared with the incandescent lamps. Furthermore, the difference between the 50mm and 100mm insulations on energy demand is not obvious. Besides this, the heating system improvement and renewables have no impact on energy demand reduction. Moreover, it is notable that the draught proofing increases the cooler gain as enhanced airtightness makes it more difficult to lose heat through natural ventilation and infiltration.

Further information on heating and cooling gains, ventilation gains, fabric gains and solar gains can be found in Appendix 1.

6.7.3.2.2. Energy Supply

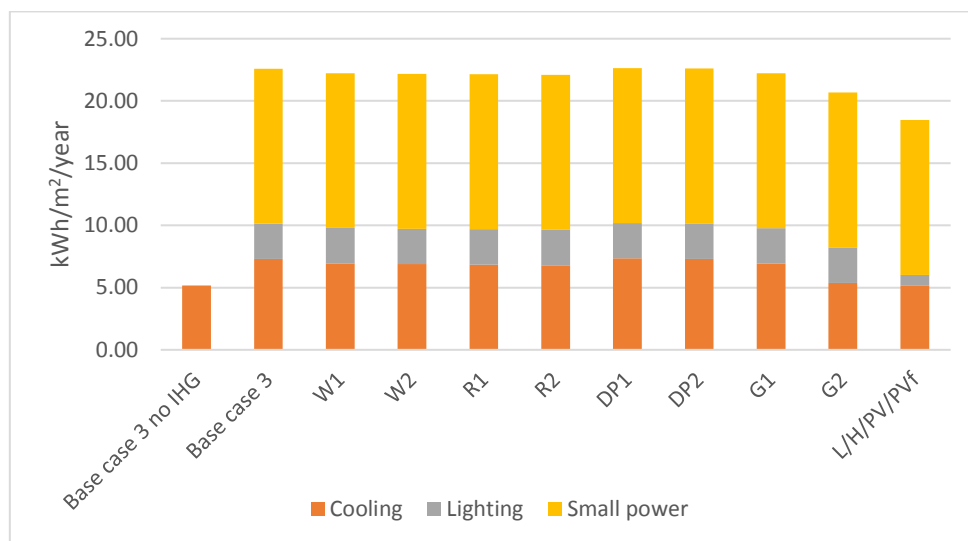


Figure 6.73 The annual electricity supply of Case 3 for a range of retrofit measures (ref: Table 6-7)

Figure 6.73 demonstrates the annual electricity supply of Case 3. To begin with, the electricity is generally stable for cooling and small power. Secondly, lighting contributes the most to improving the electricity supply, with a decrease of 2.2 kWh/m². Thirdly, small power makes up the major part of electricity consumption.

Besides this, draught proofing increases the cooling load, so that the electricity supply slightly rises.

Figure 6.74 outlines a decline of the annual gas supply of Case 3 through different retrofit packages. First of all, draught proofing appears to be the most significant improvement, with annual reductions of more than 73.7 kWh/m². Second, the package of EWI and window replacement have good performance on gas reduction. Additionally, the gas use has also decreased rapidly by adopting the heating system improvement and solar thermal packages, where the former mainly decreases the gas supply for space heating and the later reduces the gas consumption for hot water.

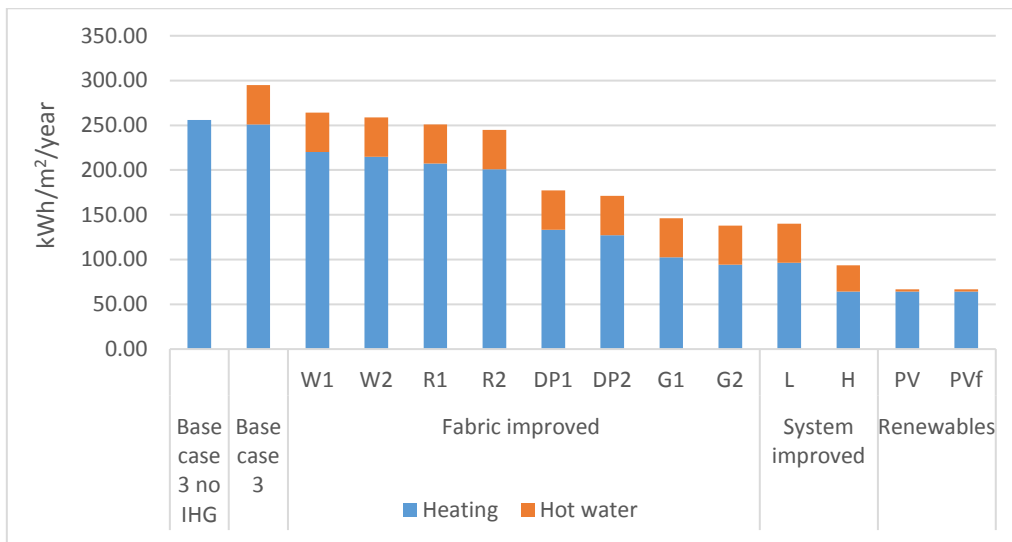


Figure 6.74 The annual gas supply of Case 3 for a range of retrofit measures (ref: Table 6-7)

Figure 6.75 summarises the annual energy supply, the electricity generated by solar PV and the gas reduced by solar thermal. Firstly, the gas consumption consistently declines due to the heating loads for space heating decrease through fabric and system improvement. Secondly, the electricity supply stays stable through fabric and system retrofit, with only a little visible reduction in the lighting improvement. Thirdly, the electricity consumption declines when applying the solar PVs, with the drop of 1.8 kWh/m² for PV roof and 16.4 kWh/m² for PV roof and facade.

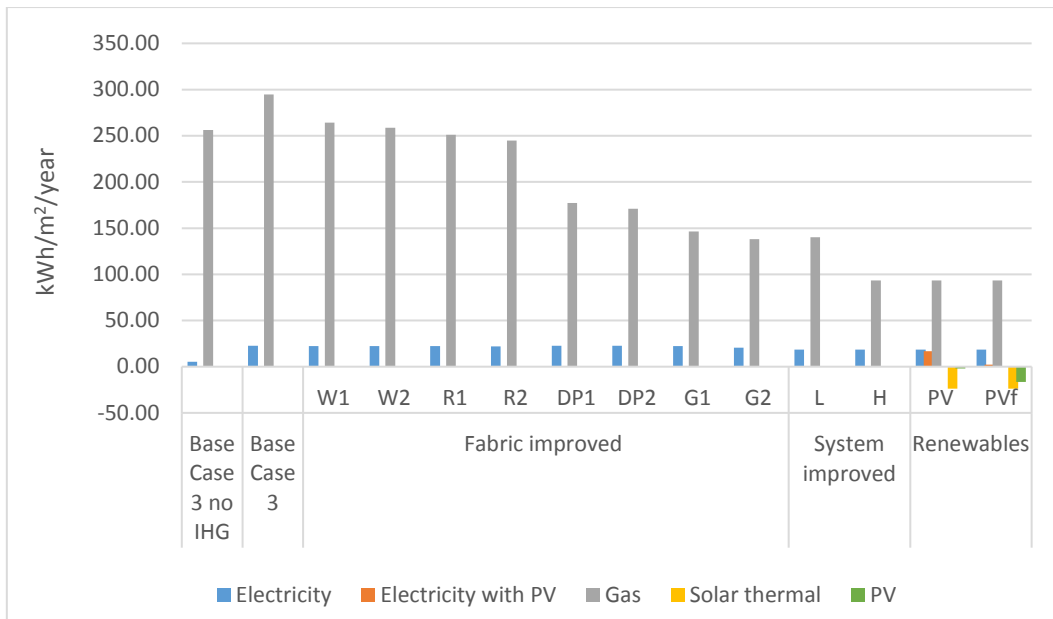


Figure 6.75 The summary of annual electricity and gas supply and renewable energy of Case 3 for a range of retrofit measures (ref: Table 6-7)

6.7.3.2.3. CO₂ Emission Reduction

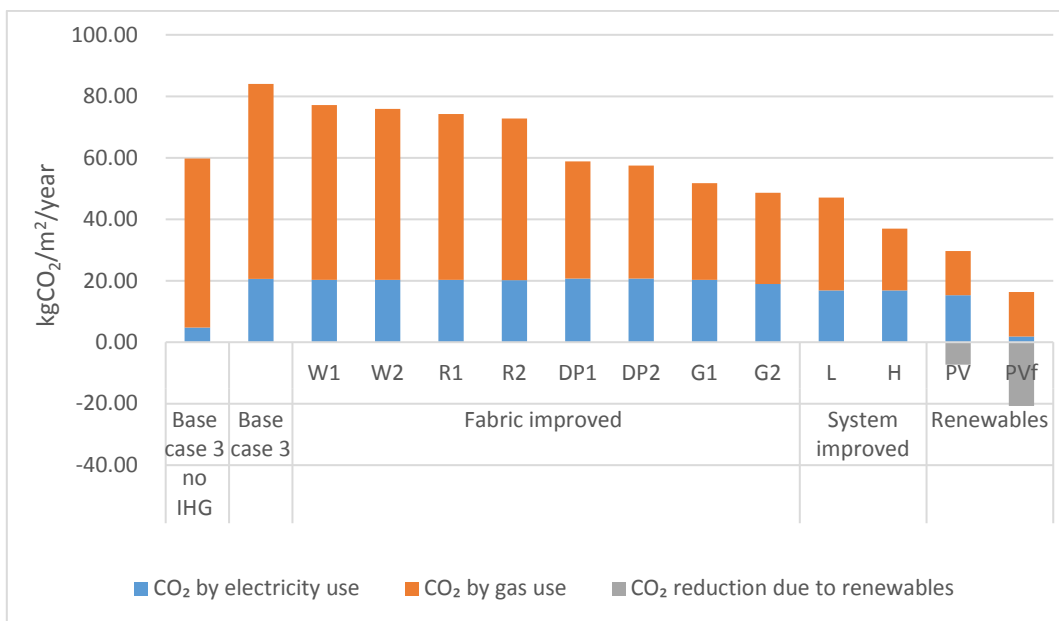


Figure 6.76 Summary of the CO₂ emissions of Case 3 for a range of retrofit measures (ref: Table 6-7)

As can be seen in figure 6.76, the annual CO₂ emissions gradually decrease with the successive application of the fabric and system retrofit packages, mainly in reducing the CO₂ by gas use. In addition, the CO₂ by electricity use levels off at around 20 kg/m²

and has a visible decline with lighting improvement. Moreover, the most significant reduction in CO₂ emissions comes after installing the solar PV panels to the roof and the south facade above the third floor, with the reductions of 7.3kg/m² and 20.7 kg/m².

6.7.3.2.4. Operating Cost

The summary of the annual operating costs, savings and earnings from solar PVs is presented in Figure 6.77. Firstly, for the annual electricity and gas cost, the trend is consistent with the CO₂ emissions reductions. Secondly, the draught proofing package has greatest reductions of more than 22.3 CNY/m² in gas cost. Thirdly, the electricity cost generally stabilises at 10 CNY/m² with fabric and system retrofit and decreases to 8.2 CNY/m² when including a solar PV roof, and to 1 CNY/m² when including a PV facade. In addition, the overall operating cost reduces from 69.1 CNY/m² to -1.3 CNY/m². Moreover, the overall cost saving is 89 CNY/m² per year.

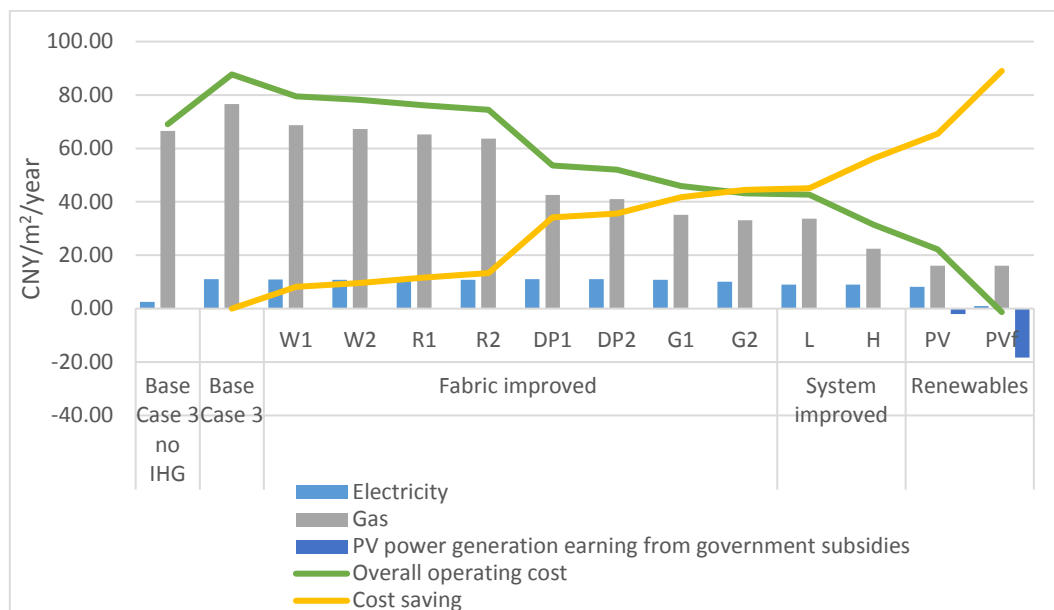


Figure 6.77 The summary of the operating cost and saving of Case 3 for a range of retrofit measures (ref: Table 6-7)

6.7.3.2.5. Percentage of Improvement

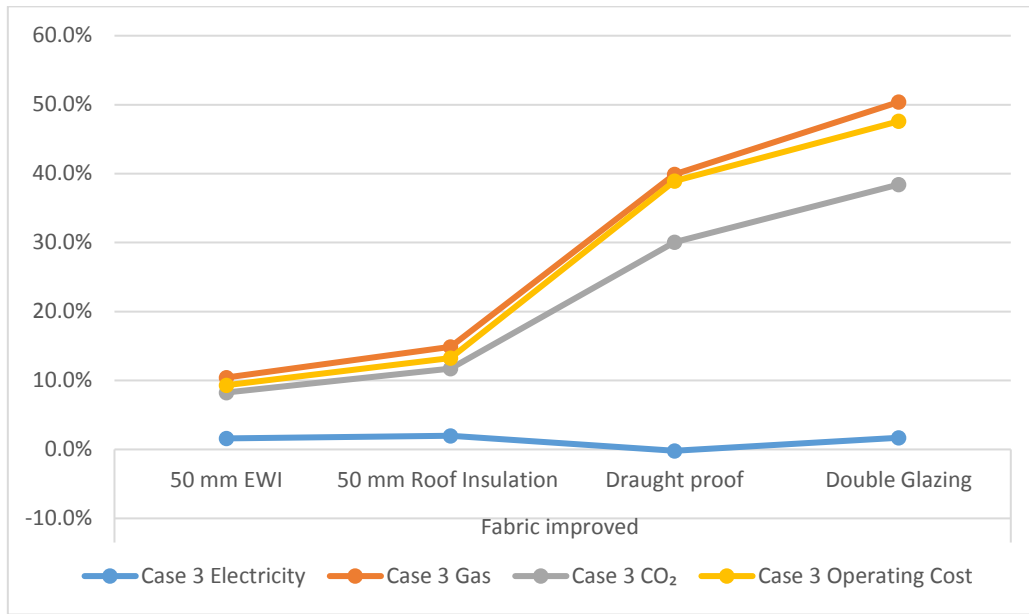


Figure 6.78 The percentage of improvement of Case 3 with 50 mm insulation

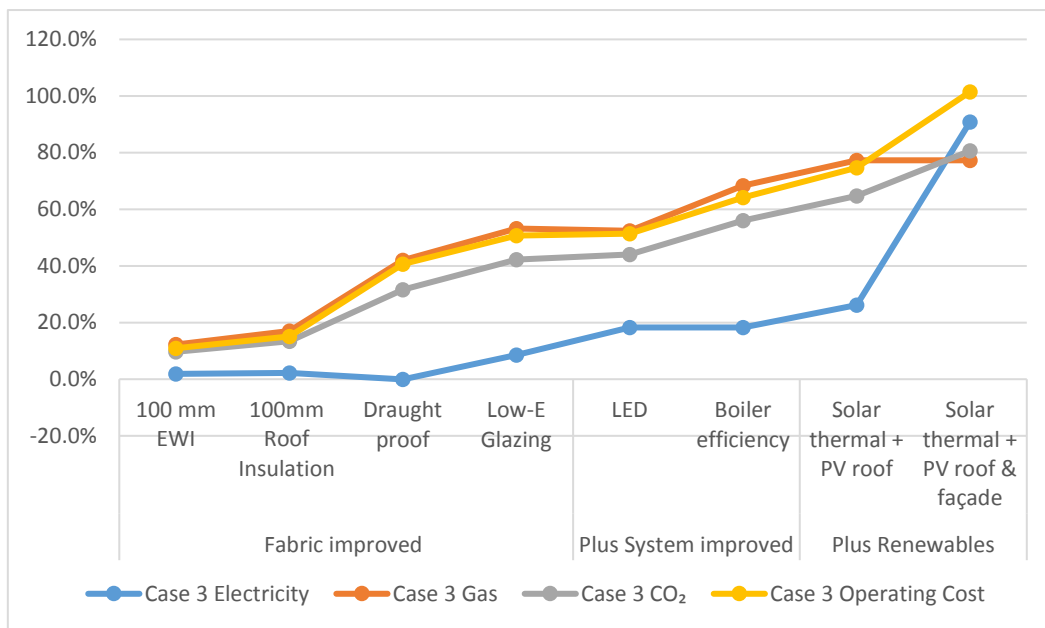


Figure 6.79 The percentage of improvement of Case 3 with 100mm insulation

Figures 6.78 and 6.79 outline the percentage of the retrofit improvement of Case 3 with 50mm and 100mm insulation, respectively. Firstly, all the improvements grow as the retrofit packages are applied. Secondly, the overall improvement of the packages

with 100mm insulations is slightly better than those with the 50mm ones. Thirdly, in the domain of electricity improvement, the LEDs can save 18.2% of electricity use. After PV is applied to the roof, the improvements is 26.1% and the numbers rise to 90.9% after PV is installed on the south facade above the third floor. In addition, PV packages have the most massive reduction in electricity and operating cost. Moreover, the fabric and system retrofit have the most significant improvements in gas, where the most reductions lie in the draught proofing packages, with 40% and 42% of the gas reduction. Besides, renewables provide the maximum improvements in operating cost, with the percentages of 74.7% and 101.5% for solar PV roof package and PV roof and facade package, respectively.

6.8. Modelling of Case 4: Building 1 of Xinfengjie Community

6.8.1. Introduction of Case 4

Case 4 is a 20-floor high-rise flat in Xinfengjie Community located in the north of Beijing. It was built in 2001 with a cast-in-place structure of reinforced concrete. The total floor area is 17533.85 m², and the floor height is 2.7 m. 160 households were living in this building. Before retrofitting, there was 20 mm external wall insulation and no insulation on the roof. Some of the windows were replaced with double-glazed windows by residents, but still had problems such as thermal bridges and bad sealing, and there were still many single-glazed windows.

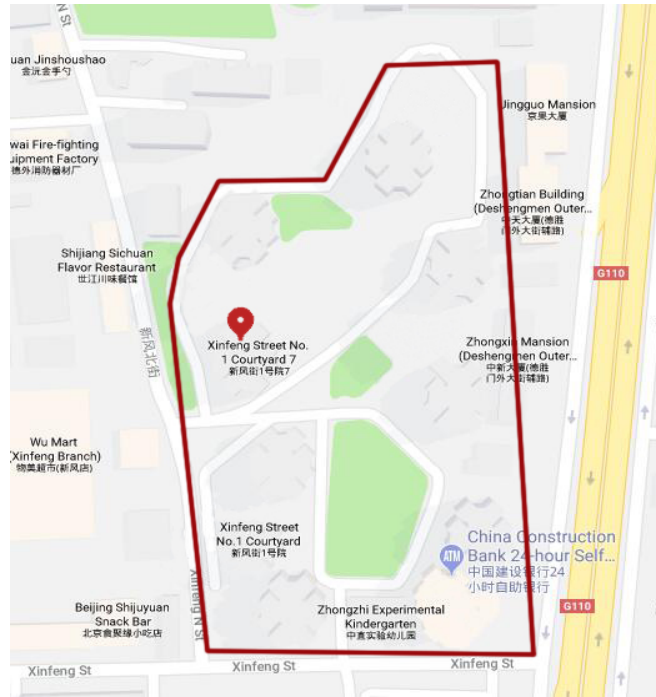


Figure 6.80 The location of Case 4



Figure 6.81 The building facade of Case 4 before the retrofit

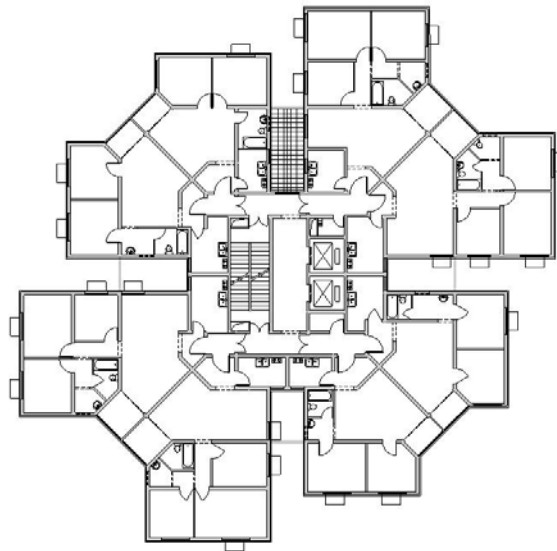


Figure 6.82 The standard floor plan of Case 4

The location, the building facade before retrofitting and the standard floor plan are displayed in Figures 6.80, 6.81 and 6.82. It can be seen from Figure 6.81 that most of the air-conditioning outside units and cables were placed randomly, which affected the appearance of the wall. The 3D model of Case 4 with colour faced for solar radiation and the shading mask of the south facade are demonstrated in Figure 6.83. The construction materials of the building components are shown in Tables 6-15 and 6-16.

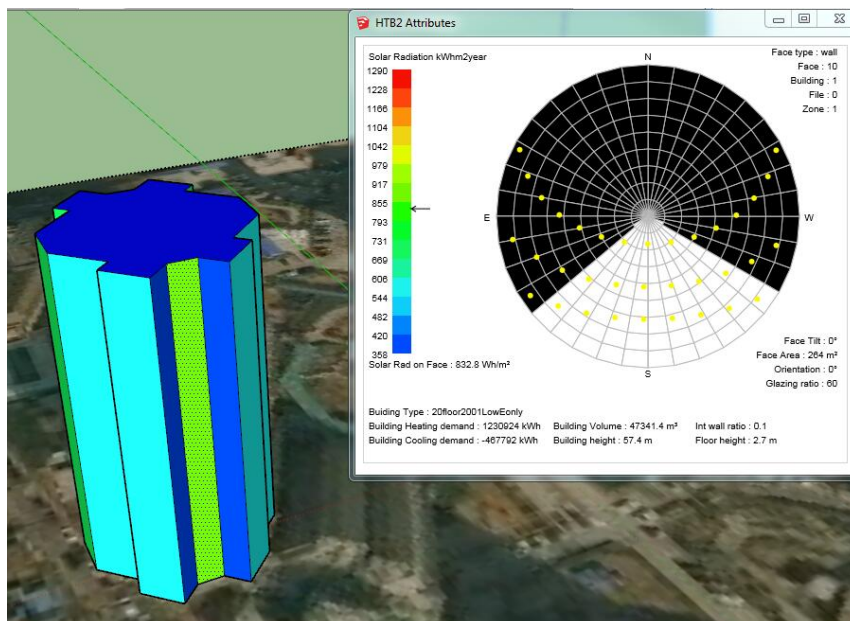


Figure 6.83 The 3D model of Case 4

Table 6-15 The construction details of Case 4 before the insulation retrofit

Construction	U-Value (W/m ² /°C)	Building Materials	Thickness (mm)	Conductivity (w/m·C)	Density (kg/m ³)	Specific heat capacity (J/kg/C)
Exterior Wall (From Outside to Inside)	1.22	granite	6	2.9	2650	900
		cement mortar	10	0.93	1800	1050
		Expanded polystyrene (EPS)	20	0.041	18	2414.8
		reinforced concrete	200	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Interior Wall (From Outside to Inside)	0.95	cement mortar	20	0.93	1800	1050
		Aerated concrete block	200	0.24	750	1000
		cement mortar	20	0.93	1800	1050
Roof (From Top to Bottom)	2.8	cement mortar	20	0.93	1800	1050
		SBS modified asphalt waterproof membrane	6	0.23	900	1620
		slag cement	30	0.76	1500	1050
		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Floor-Ceiling (From Top to Bottom)	2.7	cement mortar	20	0.93	1800	1050
		slag cement	60	0.76	1500	1050
		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
	1	cement mortar	30	0.93	1800	1050

Ground (From Top to Bottom)		C15 fine aggregate concrete	100	1.51	2300	920
		gravel	150	2.04	2400	920
		rammed earth	600	0.93	1800	1010
Exterior Window	5.32	plate glass	6	0.76	2500	840

Table 6-16 The construction details of Case 4 after the insulation retrofit

Construction	U-Value (W/m ² /°C)	Building Materials	Thickness (mm)	Conductivity (w/m·C)	Density (kg/m ³)	Specific heat capacity (J/kg/C)
Exterior Wall (From Outside to Inside)	0.51 / 0.32	granite	6	2.9	2650	900
		insulating mortar	25	0.06	250	1049.6
		Expanded polystyrene (EPS)	50 / 100	0.041	18	2414.8
		reinforced concrete	200	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Interior Wall (From Outside to Inside)	0.95	cement mortar	20	0.93	1800	1050
		Aerated concrete block	200	0.24	750	1000
		cement mortar	20	0.93	1800	1050
Roof (From Top to Bottom)	0.36 / 0.21	insulating mortar	20	0.06	250	1049.6
		composite polyurethane board	50 / 100	0.024	30	2475.2
		SBS modified asphalt waterproof membrane	6	0.23	900	1620
		slag cement	30	0.76	1500	1050

		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Floor-Ceiling (From Top to Bottom)	2.7	cement mortar	20	0.93	1800	1050
		slag cement	60	0.76	1500	1050
		reinforced concrete	120	1.74	2500	920
		cement mortar	20	0.93	1800	1050
Ground (From Top to Bottom)	1	cement mortar	30	0.93	1800	1050
		C15 fine aggregate concrete	100	1.51	2300	920
		gravel	150	2.04	2400	920
		rammed earth	600	0.93	1800	1010
Exterior Window	3.27 / 2.66	plate glass	6	0.76	2500	840
		cavity	3 normal / 3 low-E	n/a	n/a	n/a
		plate glass	6	0.76	2500	840

6.8.2. Results of Base Case 4 With and Without IHGs before the Retrofitting

Figures 6.84 to 6.87 show the average monthly gains of Case 4 before retrofitting without IHGs (Figures 6.84 & 6.86) and with IHGs (Figures 6.85 & 6.87). First of all, it can be seen that the heater gain dominates in winter no matter with or without IHGs; this is the main heat source and represents the primary energy saving potential. Second, the solar gain is stable throughout the year. Third, the IHG makes up a considerable part of the heat gains: almost the same with the solar gain. Fourth, after adding the IHG, the heater gain declines moderately, whereas the cooler gain grows significantly by approximately twice as much as without IHG. This is due to the heat generated by the occupants, lighting and appliances in the building. Additionally, the ventilation gain and fabric gain slightly increase with IHG. In short, from the diagram, reducing the heating, fabric and ventilation losses in winter, and cooling gains in

summer might provide opportunities to improve the building and save energy. Besides this, it is necessary to take the IHGs into account in the base case to get more accurate and realistic results.

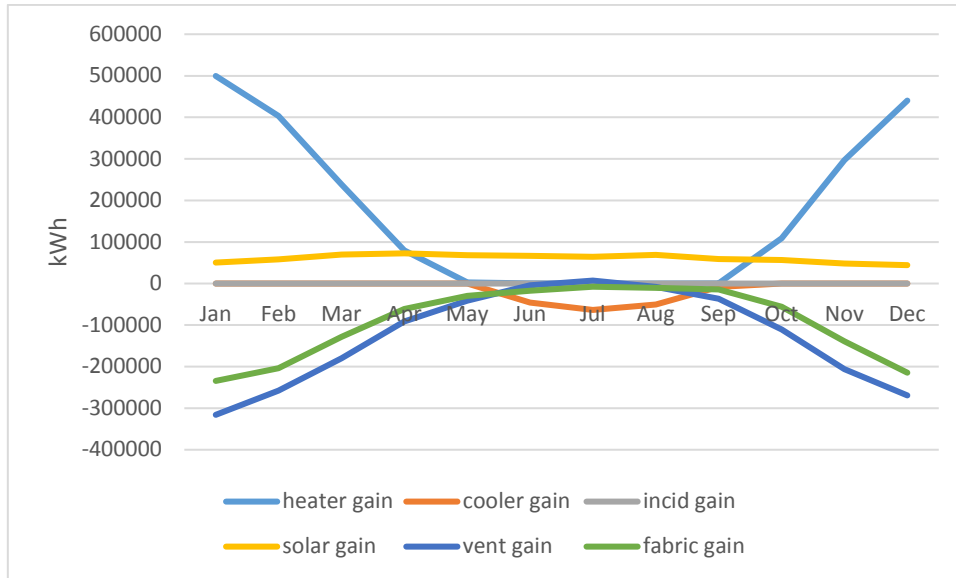


Figure 6.84 Monthly gains of Case 4 without IHGs

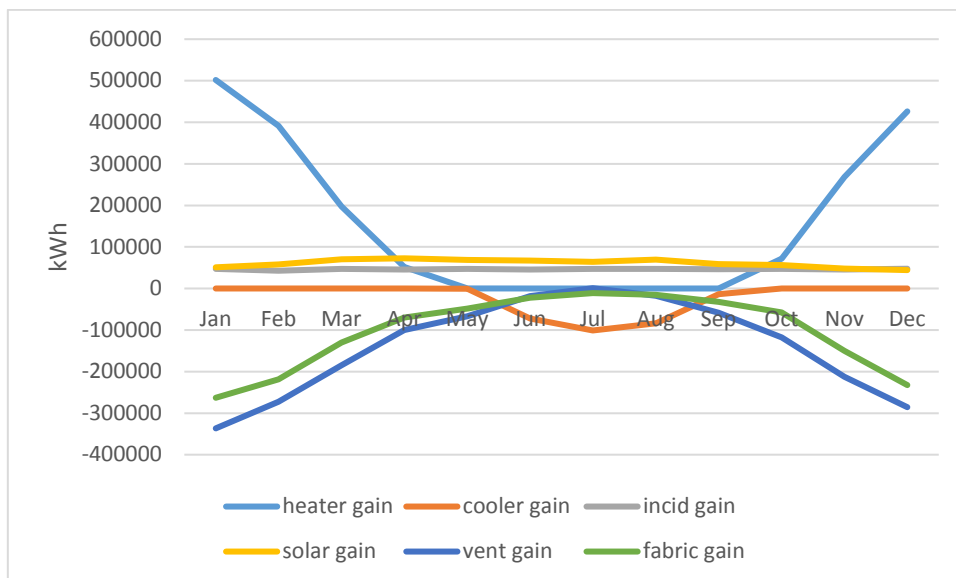


Figure 6.85 Monthly gains of Case 4 with IHGs

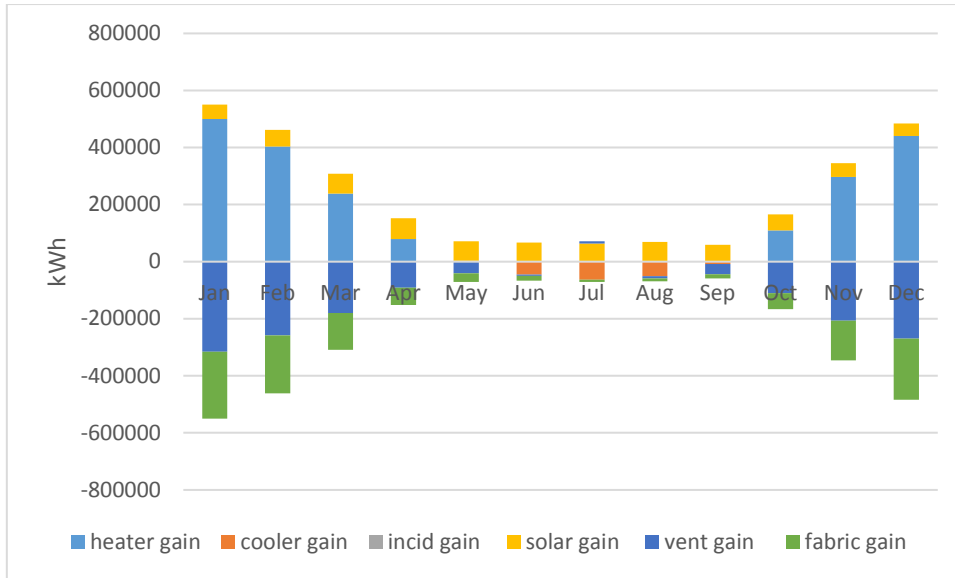


Figure 6.86 The proportion of monthly gains of Case 4 without IHGs

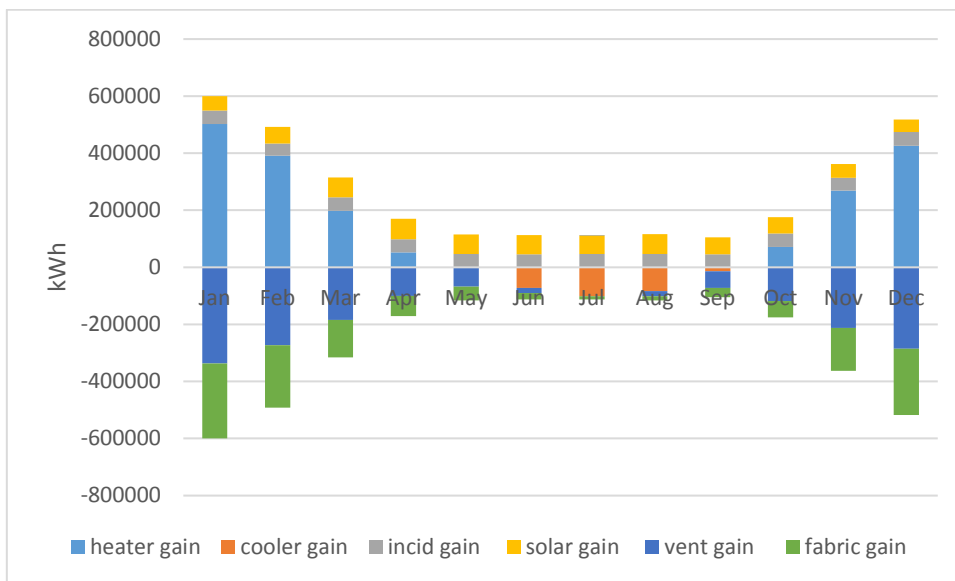


Figure 6.87 The proportion of monthly gains of Case 4 with IHGs

6.8.3. Results of Case 4 after Retrofitting

6.8.3.1. Improvement of Individual Retrofit Measures

Figures 6.88 and 6.89 present the percentage of improvement in energy demand, electricity supply, gas supply and CO₂ emission for each retrofit measure. As shown in the two charts, first, the measure of draught proofing provides the most significant

contribution in reducing energy demand, at 25.9% improvement. Second, the EWI and window replacements also decrease the energy demand, while the heating system improvement, solar thermal and solar PV provide no reduction in energy demand. Third, draught proofing and heating system improvement have the most impact on energy supply decreases, especially in gas consumption. Fourth, lighting and PV only reduce electricity consumption, of which PV reduces the electricity use most considerably, by 65.8%. Moreover, PV has the best performance in reducing CO₂ emissions, representing 21.8%.

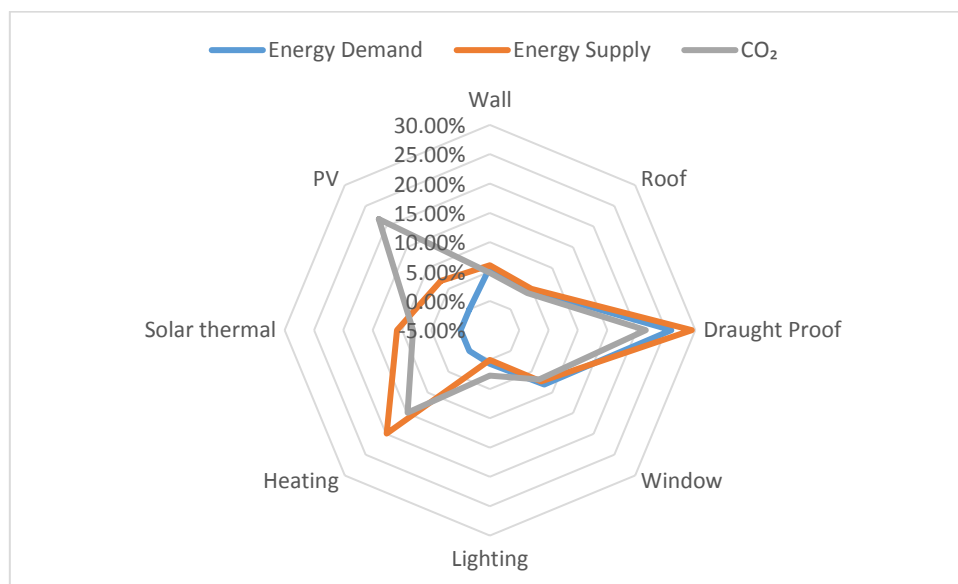


Figure 6.88 The percentage of improvement in energy demand, energy supply and CO₂ for each retrofit measure of Case 4

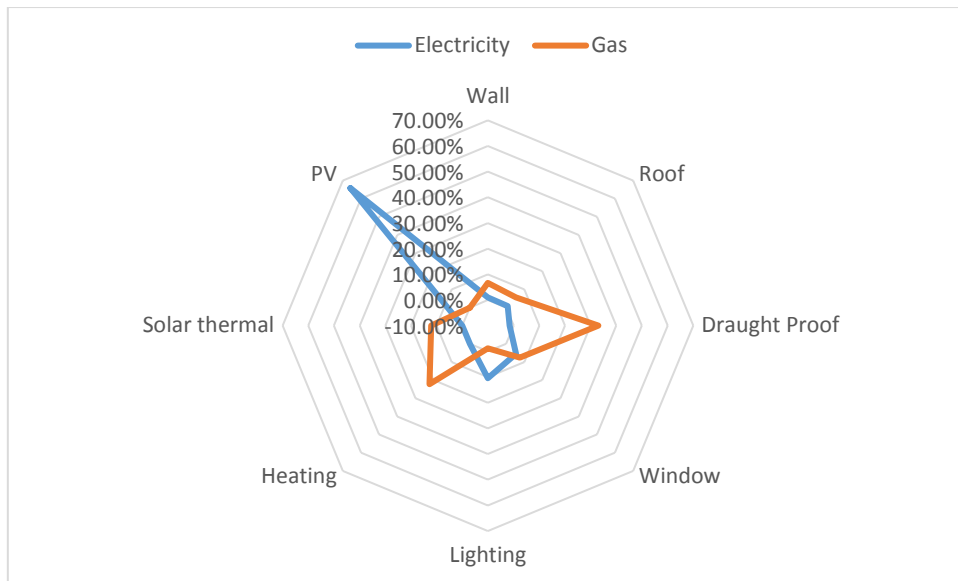


Figure 6.89 The percentage of improvement on electricity and gas for each retrofit measure of Case 4

6.8.3.2.Improvement of the Retrofit Packages

6.8.3.2.1. Energy Demand

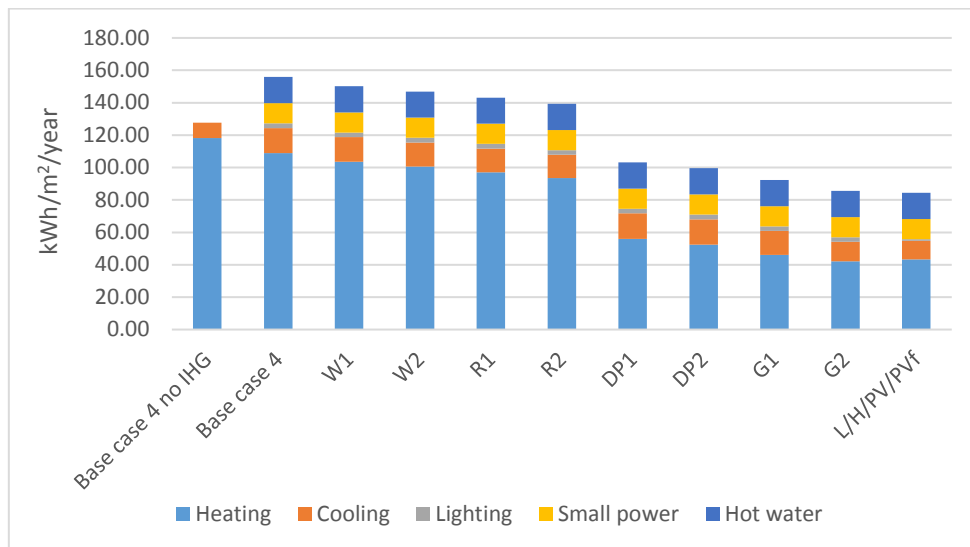


Figure 6.90 Annual energy demand of Case 4 for a range of retrofit measures (ref: Table 6-7)

Figure 6.90 demonstrates that the energy demand of Case 4 descends with the successive addition of the retrofit packages. As can be seen from the graph, to begin with, the draught proofing package has the most significant improvement in reducing

energy demand, with the reductions of 40 kWh/m² and 39.8 kWh/m² for the 50mm and 100 mm insulations, respectively, but it also increases the cooling demand, as the improved airtightness makes the heat more difficult to be removed by natural ventilation and infiltration. In addition, the cooling demand levels off at approximately 15 kWh/m² until adding the low-E glazing and the LED lighting, which reduce the cooling demand to 12.1kWh/m² and 11.4kWh/m². Also, the LED lighting reduces the cooling demand but increases the heating demand due to less heat gain from the LED lamps than the incandescent lamps. Moreover, the impact of 50 mm and 100 mm insulations on energy demand is not apparent, with a difference of 4–5 kWh/m². Additionally, the packages of heating system improvement and renewables provide no reduction in energy demand.

Further information on heating and cooling gains, ventilation gains, fabric gains and solar gains can be found in Appendix 1.

6.8.3.2.2. Energy Supply

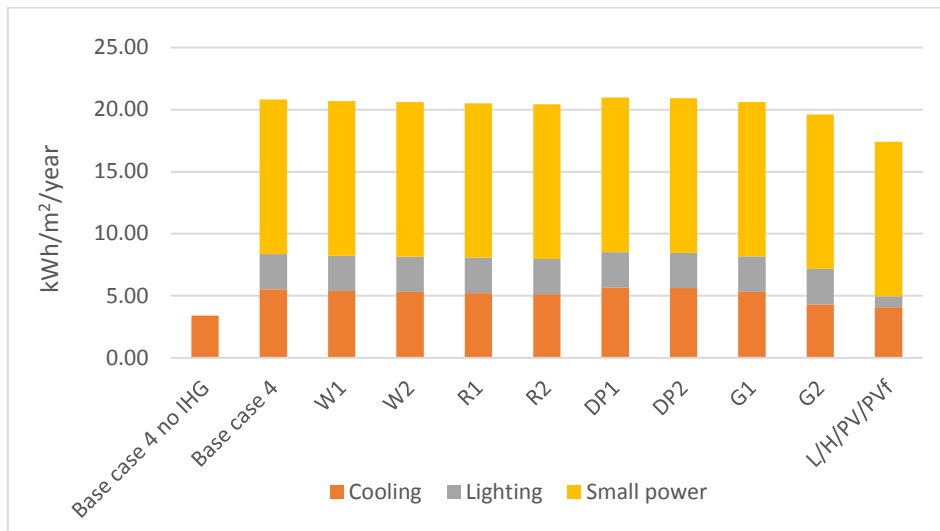


Figure 6.91 The annual electricity supply of Case 4 for a range of retrofit measures (ref: Table 6-7)

Figure 6.91 describes the annual electricity supply of Case 4. As shown in the graph, first, electricity is used for space cooling, lighting, and small power. Second, small power occupies the major proportion of electricity consumption. Besides, the lighting improvement reduces the maximum electricity use, while other retrofit packages do not contribute much.

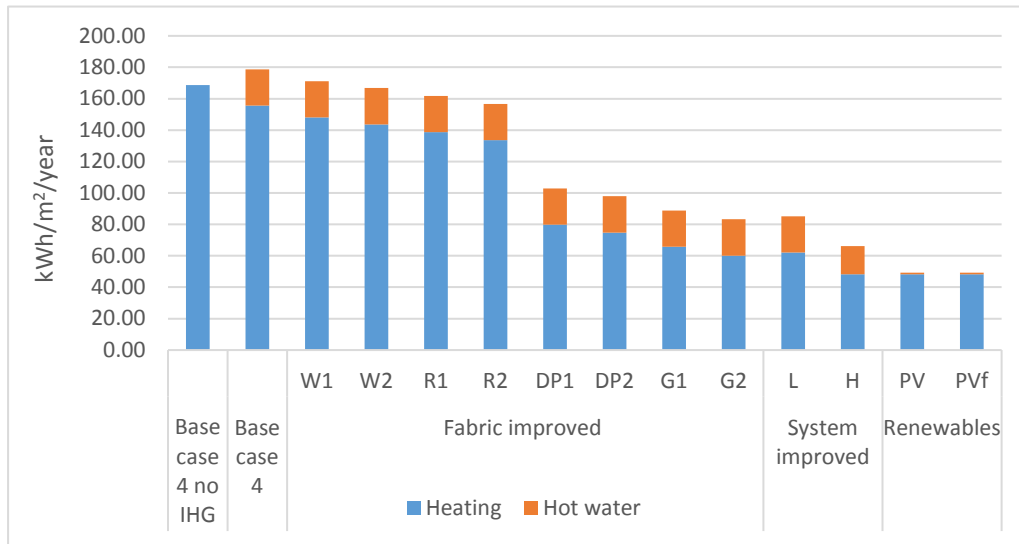


Figure 6.92 The annual gas supply of Case 4 for a range of retrofit measures (ref: Table 6-7)

The annual gas supply is demonstrated in figure 6.92. From the chart, firstly, it can be seen that the most significant improvement is through draught proofing package, and the gas use is reduced by of 58.9 kWh/m² and 58.8 kWh/m² for the 50 mm and 100 mm insulation packages, respectively. This is due to the fact that better airtightness lessens the building’s heating demand, thereby decreasing the gas used for space heating. Secondly, the package of window replacement also has a good performance on gas reduction, where the low-E glazing has a better result than double glazing. Thirdly, the gas supply is reduced considerably through heating system improvement and solar thermal; the former mainly cuts down the gas used for space heating and the latter decreases the gas consumption for hot water.

Figure 6.93 summaries the annual energy supply, the electricity generation by solar PV and the gas reduction by solar thermal. First, the gas supply declines gradually with the retrofit packages applied, while the electricity supply mainly remains stable until renewables are added. Second, after applying the solar PV, the electricity

consumption has reductions of 4.6 kWh/m² for PV roof packages and 13.7 kWh/m² for PV roof and facade packages. Third, the gas consumption has a decline of 15.2 kWh/m² when installing the solar thermal.

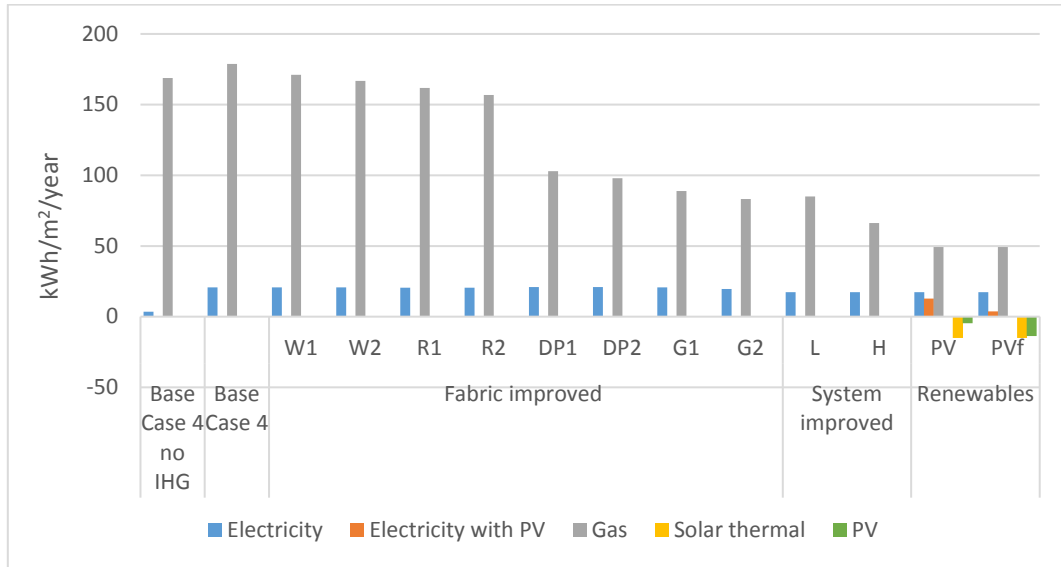


Figure 6.93 The summary of annual electricity and gas supply and renewable energy of Case 4 for a range of retrofit measures (ref: Table 6-7)

6.8.3.2.3. CO₂ Emission Reduction

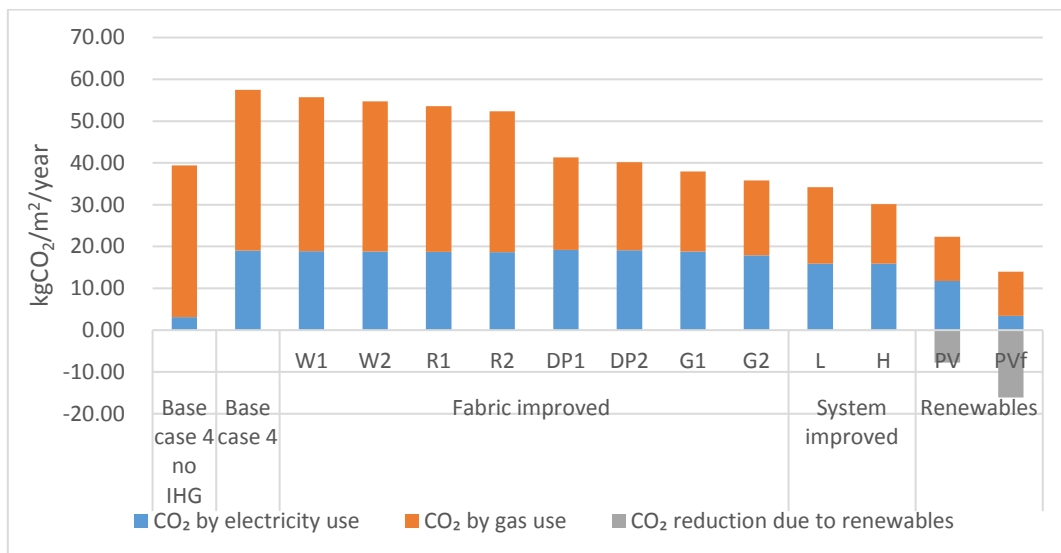


Figure 6.94 Summary of the CO₂ emissions of Case 4 for a range of retrofit measures (ref: Table 6-7)

Figure 6.94 presents the annual CO₂ emissions of Case 4. From the bar chart, we can see that the CO₂ emissions have a gradual decline with the successive application of the fabric and system retrofit packages, mainly in the decrease of gas use. In addition, the CO₂ emissions fall along with renewables use, as the electricity generated by PVs offsets some of the electricity consumption and solar thermal reduces the amount of gas for hot water use. Moreover, the PV roof and facade package has much more potential in reducing CO₂ emission than the PV roof package.

6.8.3.2.4. Operating Cost

Figure 6.95 summarises the annual operating costs, savings and the earnings from solar PVs of Case 4. First of all, for the overall operating cost, the tendency drops as the retrofit packages increase, with the most marked reductions coming from draught proofing and PVs. Second, the draught proofing package brings the most reduction in gas cost of 17.3 CNY/m². In addition, the renewables have great performances in decreasing both electricity and gas cost. Moreover, with the increasing level of retrofit from fabric to renewables, the cost savings gradually improve, with a total annual saving of 58.3 CNY/m².

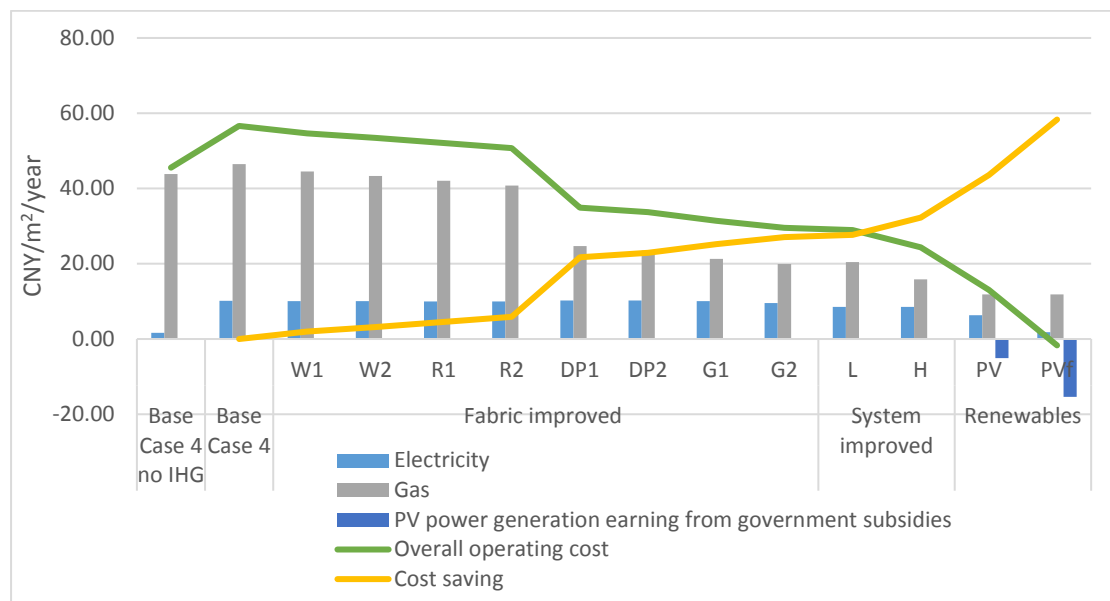


Figure 6.95 The summary of the operating cost and saving of Case 4 for a range of retrofit measures (ref: Table 6-7)

6.8.3.2.5. Percentage of Improvement

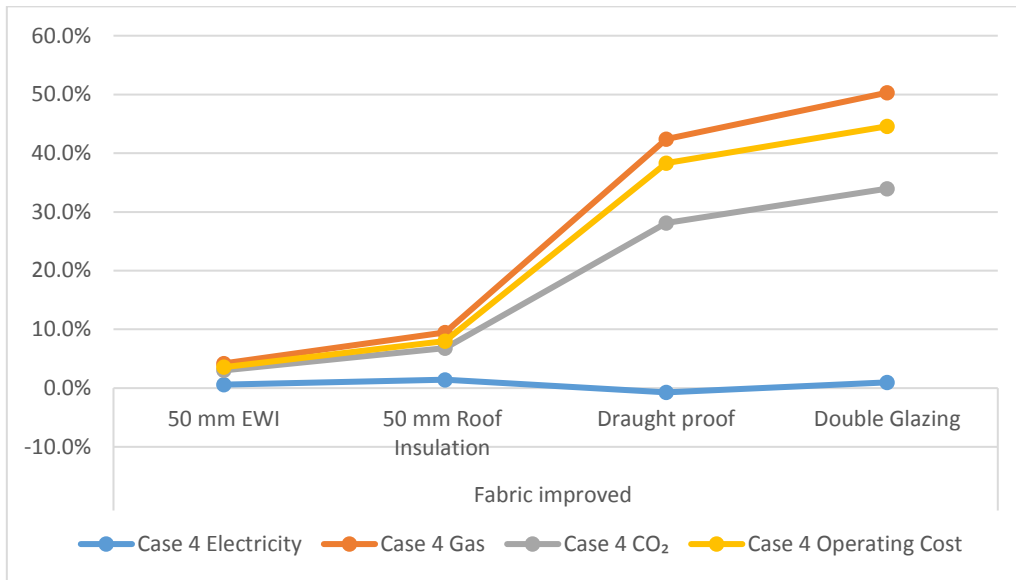


Figure 6.96 The percentage of improvement of Case 4 with 50 mm insulation

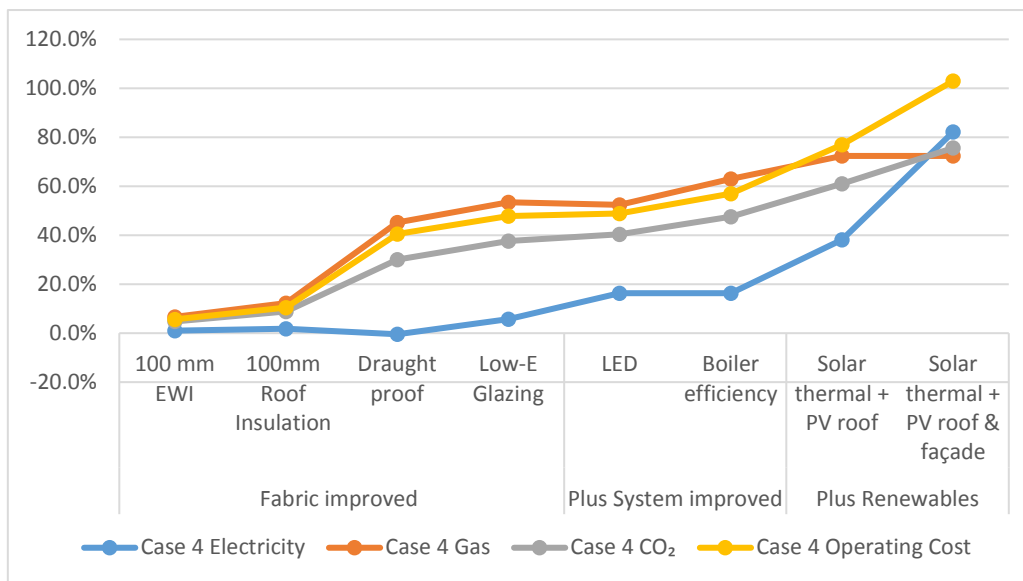


Figure 6.97 The percentage of improvement of Case 4 with 100mm insulation

Figure 6.96 and 6.97 compares the percentages of the retrofit improvements of Case 4, with 50mm and 100mm insulations, respectively. Firstly, improvements in electricity, gas, CO₂, and operating costs rise with the increase of the retrofit packages. Secondly, the 100mm insulation packages are slightly better than the 50mm ones.

Thirdly, the LED package saves 16.4% of the electricity and the PVs saves up to 82.2% of the electricity use. In addition, the fabric and system retrofit provide the maximum improvement in gas, where the greatest improvement lies in the measure of draught proofing, with gas reduction of more than 42.4%. Moreover, solar PV roof and facade package contributes the most in reducing electricity and operating costs, with the proportions of 82.2% and 103%, respectively.

6.9. Analysis and Comparison of the Four Cases

After analysing the modelling results of each case before and after retrofitting with different packages, it is necessary to compare and discuss the four cases together to examine the retrofit impact on residential buildings in different ages and types.

The comparison is made based on the building type and age band. Among the four cases, in terms of dwelling type, Case 1 is mid-rise, Case 2 is multi-storey, and Cases 3 and 4 are high-rises. Since Case 1 is seven floors and Case 2 is six floors, they can also be considered as lower storey buildings compared with high-rises. Regarding building age, Cases 1 and 3, and Cases 2 and 4 are in the same age range.

6.9.1. Comparison of the U-value Improvement of the Four Cases after the Insulation Retrofit

The U-values of the four cases before and after the insulation retrofit are listed in Table 6-17. From the table, we can see that firstly, the most substantial reduction in U-value is through the roof and window retrofit. More specifically, for roof retrofit, the U-values of the four cases have reductions of 2.27 to 2.68 with the 50 mm roof insulations and 2.45 to 2.85 reductions with 100 mm roof insulations. Secondly, for the EWI, the U-values of the four cases before retrofitting were in the range of 1.04 to 2.53, while after retrofitting with 50 mm EWI, the values decrease to 0.39 to 0.51, and after retrofitting with 100 mm EWI, the numbers decline to the range of 0.26 to 0.32. Additionally, for window retrofit, the U-values drop from 5.32 before retrofitting to

3.27 with double glazing, and to 2.66 with low-E glazing. Last but not least, Case 2 has the best improvement through roof retrofit, and Case 3 improves the most by EWI.

Table 6-17 Construction details of the four cases before and after the insulation retrofit

Construction	Improvement	Insulation thickness (mm)	U-Value (W/m ² /°C)			
			1987 floor 7	1996 floor 6	1983 floor 18	2001 floor 20
External Wall	Insulation with Expanded polystyrene (EPS) board	/	1.06	1.04	2.53	1.22
		50	0.39	0.39	0.5	0.51
		100	0.26	0.26	0.31	0.32
Roof	Insulation with composite polyurethane board	/	2.67	3.06	2.86	2.8
		50	0.4	0.38	0.36	0.36
		100	0.22	0.21	0.21	0.21
Window	All single glazed windows replaced by double/ Low-E glazing	6	5.32	5.32	5.32	5.32
		6+3N+6 *	3.27	3.27	3.27	3.27
		6+3L+6 *	2.66	2.66	2.66	2.66

* N-normal; L-low-E

6.9.2. Comparison of the Energy Demand, Energy Supply and CO₂ Emissions of the Four Cases

Figure 6.98 shows the energy demand of the four cases before and after the retrofitting. According to the chart, firstly, the heating demands of the four cases decrease dramatically after retrofitting. Secondly, the cooling demands are higher in high-rise buildings than in lower storey buildings before and after the retrofitting, which have great declines in lower storey buildings after retrofitting due to the applications of the GSHPs. In addition, for Cases 1 and 3, which are within the same age range, the high-rise has more energy demand than mid-rise. However, this does not apply to the Cases 2 and 4. This is because Case 4 had already had insulation on external walls before retrofitting, which made the heating demand lower in the base case. Furthermore, for Cases 3 and 4, which are of the same dwelling type, the newer one has lower energy demand after retrofitting whilst the older one has more retrofit potential, especially in heating demand reduction.

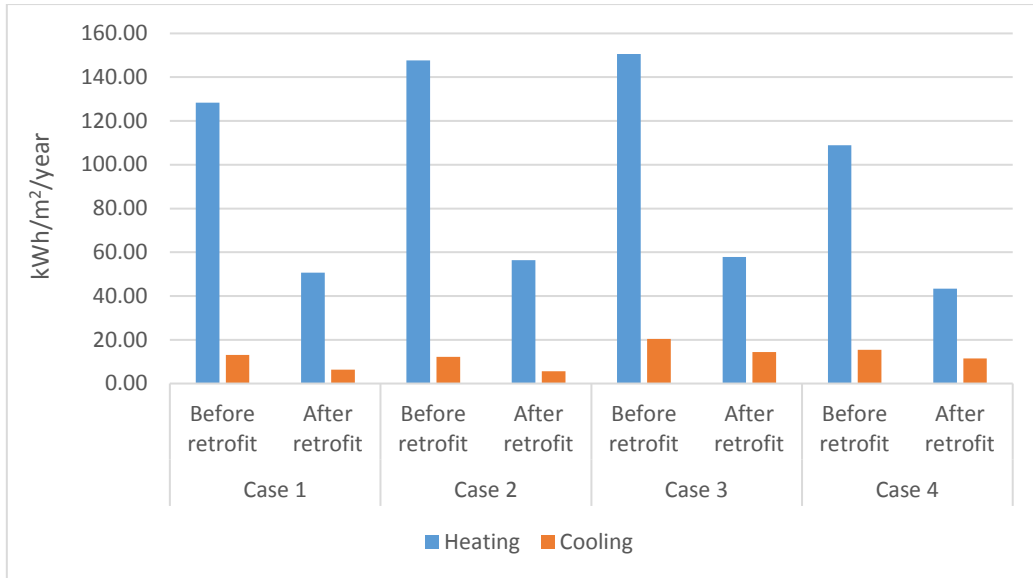


Figure 6.98 Heating and cooling demand of the four cases before and after retrofitting

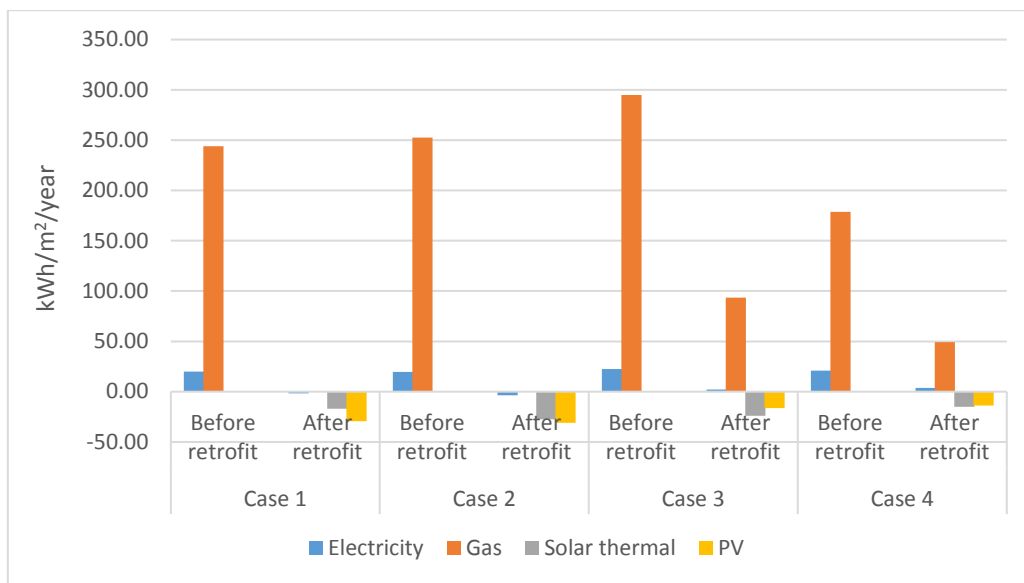


Figure 6.99 Energy supply and solar potential of the four cases before and after retrofitting

Figure 6.99 illustrates the energy supply before and after retrofitting and the solar potential of the four cases. As can be seen from the graph, first of all, the energy supply decreases significantly after retrofitting, particularly in gas use. Second, before retrofitting, the gas consumption in older building (Case 3) is higher than that of the newer one (Case 4) with the same building type. Third, after retrofitting, the gas supply reduces to zero in Cases 1 and 2 due to the application of the GSHPs. In addition, the

electricity use of the four cases is of a similar amount before retrofitting and decreases less in the high-rise buildings than in the two cases with fewer storeys after retrofitting. Besides, in terms of the solar PVs, the lower storey buildings (Cases 1 and 2) have twice more electricity generation by PV than the high-rises (Cases 3 and 4), because the proportion of high-rise roofs is relatively smaller than that of the lower storey buildings.

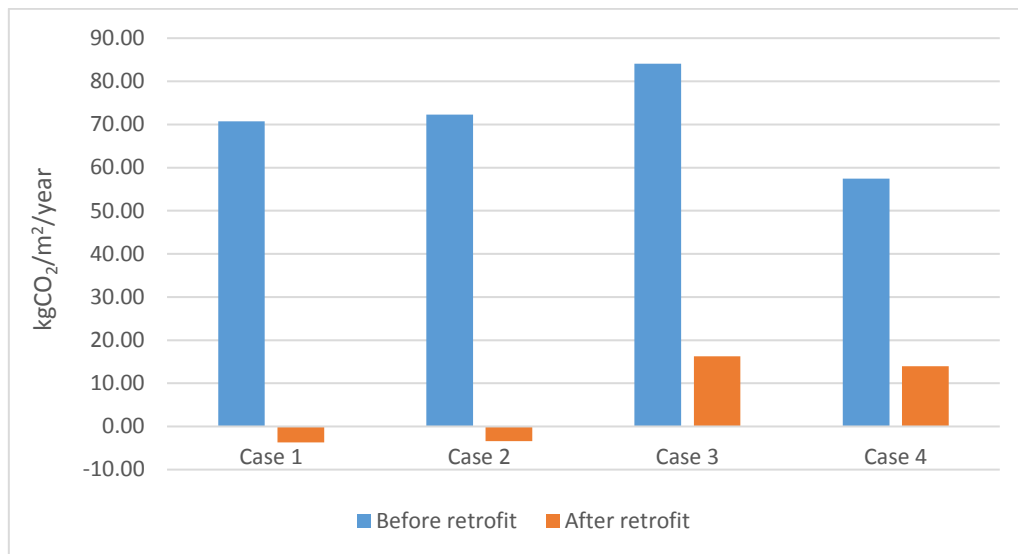


Figure 6.100 CO₂ emissions of the four cases before and after retrofitting

The CO₂ emissions of the four cases before and after retrofitting are presented in Figure 6.100. We can see from the chart that Cases 1 and 2 have better performance in CO₂ emissions reduction due to the GSHP installation. Also, buildings that were built relatively early (Cases 1 and 3) have larger CO₂ emissions reductions after the retrofitting, with the reductions of 105.2% and 80.6% compared with the newer ones (Cases 2 and 4), with 104% and 75.6%, respectively. Moreover, Case 4 is the newest building, with the lowest CO₂ emission before retrofitting, and its retrofit potential is also the most limited.

6.9.3. Comparison of the Operating Cost, Retrofit Cost and Payback Year of the Four Cases

Figure 6.101 summarizes the operating costs and savings of the four cases before and after the retrofitting. First of all, before retrofitting, Case 3 has the highest operating cost. Second, after retrofitting, lower storey buildings have lower overall operating costs and more savings than high-rises due to larger proportions of roof area and the installations of GSHPs. Third, the gas costs decline significantly after retrofitting for all cases, of which Cases 1 and 2 have no gas cost as a result of applying the GSHPs. Furthermore, the lower storey buildings have more electricity cost reductions than the high-rise ones, because larger proportion of roof areas enable solar PVs to produce more electricity. The lower storey buildings generate almost twice as much electricity as the high-rise ones of the same age band.

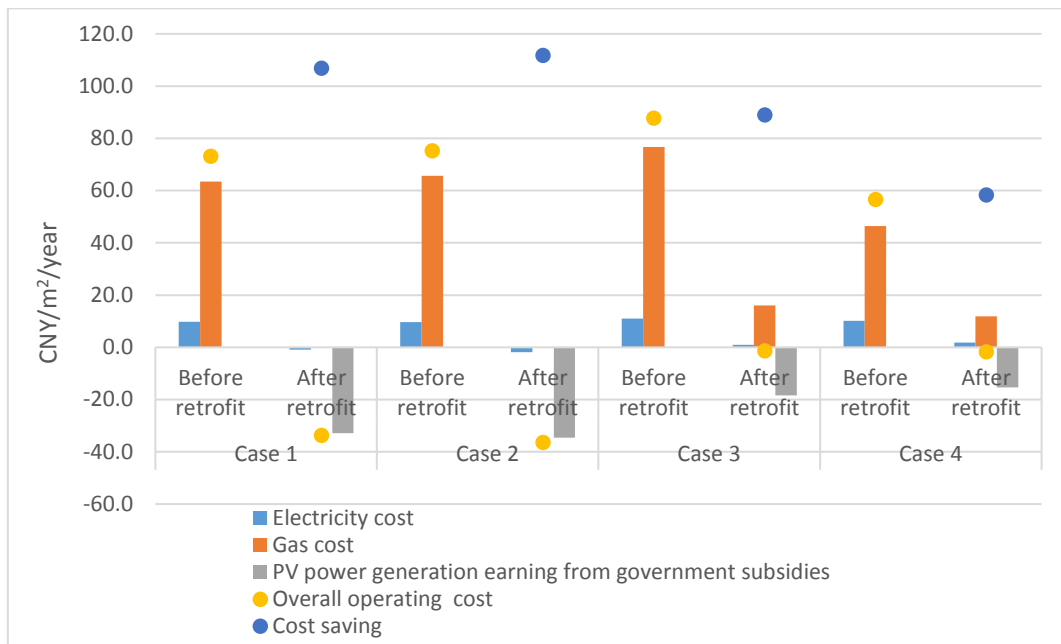


Figure 6.101 Operating cost of the four cases before and after retrofitting

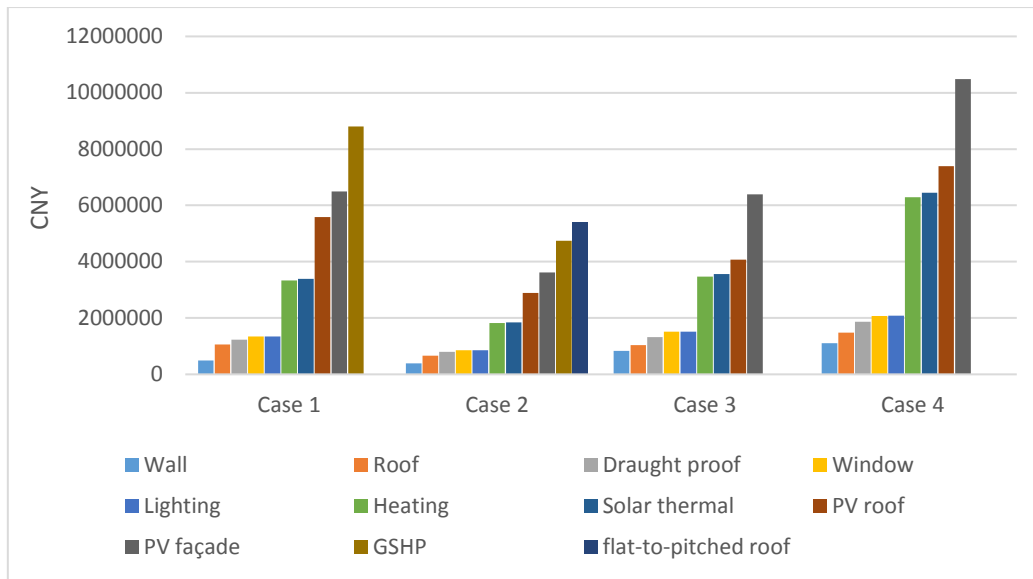


Figure 6.102 Retrofit cost comparison of the four cases on different retrofit packages

Figure 6.102 compares the retrofit costs of the four cases with different retrofit packages. The costs are based on the technical and economic indicators for the retrofitting of the existing residential communities in Beijing (Beijing Municipal Commission of Housing and Urban-rural Development 2017), which can be seen in Table 2-4. In general, the retrofit cost increases with the accumulation of the retrofit measures. When adding the solar PVs, the retrofit costs rise sharply. Also, heating system improvement, solar PV and GSHP have relatively higher retrofit costs than other measures. In addition, for the solar PV facade, high-rise buildings have a much greater retrofit costs because relatively larger facade areas can be considered for PV installation. Moreover, of the four cases, Case 4 has the highest retrofit cost due to it having the largest total floor area.

The total retrofit costs and pay back years of the four cases are listed in Table 6-18.

From Table 6-18 we can see that firstly, for the retrofit of fabric, system and solar thermal and solar PV, the costs are higher and the payback periods are more extended for high-rises than mid-rise and multi-storey buildings. Secondly, for Case 2, the cost of the flat-to-pitched roof retrofit is 1,077.91 CNY/m², so the flat-to-pitched roof retrofit cost is 656,447.19 CNY. If this measure is added, the payback time increases from 8.3–8.4 years to 9.8–9.9 years. Additionally, for Cases 1 and 2, if applying the

GSHPs, the retrofit costs grow and the payback years increase to 10.4–12.2 years and 10.9–12.6 years, respectively. The overall payback times are much shorter than the UK. This is mainly due to the relatively low cost of residential building retrofit in China. The cost per square metre of the whole-house retrofit is equivalent to the level of UK elemental retrofit.

Table 6-18 Retrofit costs and pay back years of the four cases

Retrofit cost	Case 1	Case 2	Case 3	Case 4
Fabric, system, plus solar thermal and solar PV (CNY)	6.5– 6.6 million (786.9– 802.3/m ²)	3.6–3.7 million (900– 915.1/m ²)	6.4–6.6 million (782.6– 804.6/m ²)	10.5–11.1 million (597.9– 616.7/m ²)
Payback year	7.6 - 7.8	8.3 - 8.4	11.5 - 11.8	11.1 - 11.4
plus Flat-to-pitched roof (CNY)	—	4.3-4.4 million (1063.4– 1078.6/m ²)	—	—
Payback year		9.8 - 9.9		
plus GSHP (CNY)	8.8–10.3 million (1066.9– 1252.3/m ²)	4.7–5.5 million (1179.9– 1365.1/m ²)		
Payback year	10.4 - 12.2	10.9 - 12.6		

6.10. Summary

This chapter examined several individual and combined retrofit measures related to energy saving including EWI, roof insulation, draught proof, window replacement, lighting improvement, heating system upgrade, solar thermal, solar PV, and GSHP. Through a series of simulations, the impacts of different retrofit measures and combinations on the improvement of the existing residential buildings can be clearly seen. A summary can be made as follows:

- The improvement of different individual retrofit measures and combination of retrofit packages on existing residential buildings are listed in Table 6-19 as follows:

Table 6-19 Improvement of different retrofit measures and packages (ref: Table 6-7)

Retrofit measures			Individual retrofit measure				Retrofit package				
			Demand	Electricity	Gas	CO ₂	Demand	Electricity	Gas	CO ₂	Operating cost
Fabric	EWI	• Has better retrofit results in high-rise buildings than lower storeys; • 100mm insulation is slightly better than 50mm	5.7%–10.7%	1% – 2.3%	6.7%–12.2%	4.8% – 9.7%	5.7% – 10.7%	1% – 2.3%	6.7% – 12.2%	4.8% – 9.7%	5.6% – 14.3%
	Roof insulation	• Has better effects on multi-storey and mid-rise buildings than high-rises; • 100mm insulation is slightly better than 50mm	3.9% – 11.9%	0.4% – 5%	4.5% – 12.8%	3.5% – 10.4%	10.6% – 20.9%	1.9% – 6.5%	12.3%–22.4%	8.8% – 18.2%	10.4% – 25.5%
	Draught proofing	• Contributes the most in reducing energy demands and gas use	20.2% – 25.9%	-0.9% – 1.6%	23.6%–33%	17.5%–21.6%	34.9%–41.1%	-0.5% – 5.1%	42% – 47.2%	30.1%–36.3%	40.5% – 45.1%
	Window retrofit	• Low-E glazing has better performance than double glazing	6.2% – 10.5%	4.8% – 7.3%	5.5% – 10%	5.5%–9.4%	45%–48.8%	5.8% – 11.1%	52.4% – 54%	37.7%–42.9%	47.8% – 51.4%
System improvement	LED	• The second efficient measure to reduce electricity supply	0.5% – 0.7%	9.5% – 10.8%	-0.7%–-1.1%	1.8%–2.7%	45.9%–51.1%	16.4% – 22%	51.6% – 53.1%	40.4% – 45%	48.9% – 52%
	Heating system	• The second best measure to reduce gas supply • Has better results in older buildings than newer ones	0	0	22.2%–33.3%	14.9%–25.1%	45.9%–51.1%	16.4% – 22%	62.3%–68.7%	47.5%–56.6%	56.9% – 64.6%
Renewables	Solar thermal	• Reduces gas consumption for hot water use	0	0	11.6%–15.5%	8.1% – 11.6%	45.9%–51.1%	82.2% – 179.2%	72.4%–77.3%	75.6%–100.5%	101.5% – 135.5%
	Solar PV	• The most efficient measure to reduce electricity uses, CO ₂ emissions, and operating costs	0	65.8% – 157.1%	0	17.8%–50.7%	45.9%–51.1%				
	GSHP	• Would significantly improve the energy performance by combining with solar PV	/	/	/	/	45.9%–51.1%	93.7% – 118.9%	100%	101% – 105.2%	144.1% – 148.4%

- The impact of different retrofit measures and packages on existing residential buildings with different ages and types:
 - a. Draught proofing has the most considerable improvement in reducing energy demand, followed by roof insulation in lower level buildings and EWI in high-rise buildings.
 - b. Heating system improvement and draught proofing are the two best-performing retrofit measures for reducing gas consumption, where heating system upgrade for older buildings has better performance than newer ones.
 - c. EWI has better retrofit results in high-rise buildings than in lower storey buildings. On the contrary, roof insulation has better effects on multi-storey and mid-rise buildings than on high-rises. The reason is that the high-rise buildings have a larger proportion of facade area and a smaller proportion of roof area than lower level buildings.
 - d. The effect of the 100 mm insulation boards is slightly better than that of the 50 mm ones, which is mainly reflected in the reductions of the heating demand.
 - e. Low-E glazing has better performance than double glazing in reducing energy demand, supply, CO₂ emissions and operating cost. The double glazing mainly reduces heating loads, while the low-E glazing has coating, so can reduce both heating and cooling loads.
 - f. The effect of increasing the thickness of the insulation boards from 50 mm to 100 mm is not as good as replacing the window from single glazing to double glazing.
 - g. The flat-to-pitched roof retrofit increases the roof area so that increasing the solar potential. Also, pitched roof has less energy demand and energy supply than flat roofs.
 - h. The installation of LED lighting could reduce electricity supply by 9.5%–10.8%, but also increase the gas consumption by 0.7–1.1% due to less heat gain from the LED lamps compared with the incandescent lamps.
 - i. Solar PV is the most efficient retrofit measure to reduce electricity use.
 - j. Draught proof and solar PV are the two best measures in reducing CO₂ emissions for newer buildings, while for older ones, heating system upgrade is also a significant measure for CO₂ reduction.

- k. Solar PV contributes the most in reducing electricity use, which has better results in lower storey buildings than the high-rises due to larger proportion of roof areas. It also provides the greatest reduction in overall operating cost, considering both operating cost reductions and earnings for renewable energy generation and export.
- l. Installing the GSHP and PV in multi-storey and mid-rise buildings would significantly improve the energy performance by displacing electricity-related emissions, depending on access to appropriate installation space.
- m. Case 4 already has a better base performance than other three cases before retrofitting due to its wall insulation. Therefore, it has the lowest potential for improvement.

- Reducing energy demand is a significant way to reduce energy consumption, which provides the potential for adopting renewable energy such as solar PV to achieve most of the energy supply needs.

- IHG is one of the main stable heat sources throughout the year, and it is necessary to take into account in order to get more accurate and realistic results. Also, precise hourly IHG data is essential to ensure the accuracy of the dynamic energy simulation and analysis.

- The retrofit performance improved with increasing level of retrofit packages. The fabric retrofit measures, including EWI, roof insulation, draught proofing, and window replacement exhibit good performance in improving existing residential buildings with previous poor insulation.

- The fabric retrofit measures are more cost-effective for older buildings with poor insulations and airtightness, while solar PV and GSHP are the most efficient retrofit measures to improve existing residential buildings and reduce CO₂ emissions.

- The best retrofit results can be achieved by applying the highest specification with a whole-house approach which combines the fabric, system, and renewable retrofit measures. This, however, may not be feasible for every retrofit project due to budget and limitations on installing renewables.

Chapter 7 Case Study in China at the Community Scale

7.1. Introduction

This chapter provides the energy simulation of the four China cases at the community scale and highlights multiple benefits as well as broader related issues. It begins with the introduction of the basic information of the four communities and retrofit measures and procedure for simulation, followed by the simulation of four communities before and after the retrofitting. Then a comparison is made between the four communities and different scales, and the effects of the 'whole-house' retrofit packages are evaluated. Lastly, the research question 'how to improve the existing communities in China through sustainable housing retrofit to create a high-quality living environment?' is analysed and discussed in its social, environmental and economic aspects.

The four communities for simulations are the communities in which each of the four cases is located. There are three community types: mid-rise communities (Community 1), high-rise communities (Community 4) and mixed communities (Communities 2 and 3). Community 1 has only mid-rise buildings of the same type as Case 1, and Community 4 has only high-rise buildings of Case 4 type. Communities 2 and 3 are mixed communities of two building types: Community 2 is mixed with multi-storey buildings of the Case 2 type and high-rise buildings built in the same year, and Community 3 is mixed with high-rises of the Case 3 type and multi-storey buildings of the same age.

The simulation procedure contains two stages. The first is to simulate each community without IHGs and with IHGs to see the impact of IHGs on different heat gains and thermal performance in community scale. The second stage is to simulate the retrofit packages including the fabric, system retrofit and renewables at the community scale to see the combined effects.

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Table 7-1 Retrofit measures for simulation in community scale

Retrofit measure	Strategy package		
a. 100mm EWI	Fabric		a.b.c.d.
b. 100mm Roof Insulation			
c. Draught Proofing			
d. Low-E Glazing			
e. LED Lighting	System	Lighting	a.b.c.d.e.
f. Boiler Efficiency Improved		Heating	a.b.c.d.e.f.
g. Solar thermal + PV Roof	Renewable	PV roof	a.b.c.d.e.f.g.
h. Solar thermal +PV Roof + Façade		PV roof + façade	a.b.c.d.e.f.g.h.
i. Ground Source Heat Pump (COP 4.6)		GSHP	a.b.c.d.e.f.g.h.i.

The fabric retrofit measures involve EWI with 100 mm expanded polystyrene (EPS) boards, roof insulation with 100 mm composite polyurethane boards, draught proofing (the infiltration rate is reduced from 1.0 to 0.5 and the occupied ventilation rate is changed from 2.0 to 1.0) and window replacement with low-E glazing. The system improvement consists of upgrading the lighting to LED lamps and improving the heating system efficiency to 90%. The renewable package includes the installation of the solar thermal (50% efficiency) to the roof and solar PV (15% efficiency) to the roof and the south facade above the third floor, and the GSHP system with COP of 4.6. As the GSHP is more suitable for places with low plot ratios, it has been applied to Cases 1 and 2 on a building scale. Communities 1, 2, and 3 are mainly composed of multi-storey and mid-rise buildings; therefore, the GSHP is installed for Communities 1, 2, and 3 in the simulation of the community scale.

7.2. Modelling of Community 1

7.2.1. Introduction of Community 1

Community 1 is Changqingyuan Community located in the southeast of Beijing. There are fourteen buildings in this community, which are all mid-rises with seven floors. The buildings were built in 1987, and the conditions before retrofitting were the same as Case 1. The 3D model of Community 1 with colour faced for solar radiation and the shading mask of the south roof of Case 1 are demonstrated in figure 7.1. It can be seen

from the picture that most of the buildings are facing south, while two buildings have an east–west orientation, and there are four buildings with pitched roofs as Case 1; the others are flat roofs.

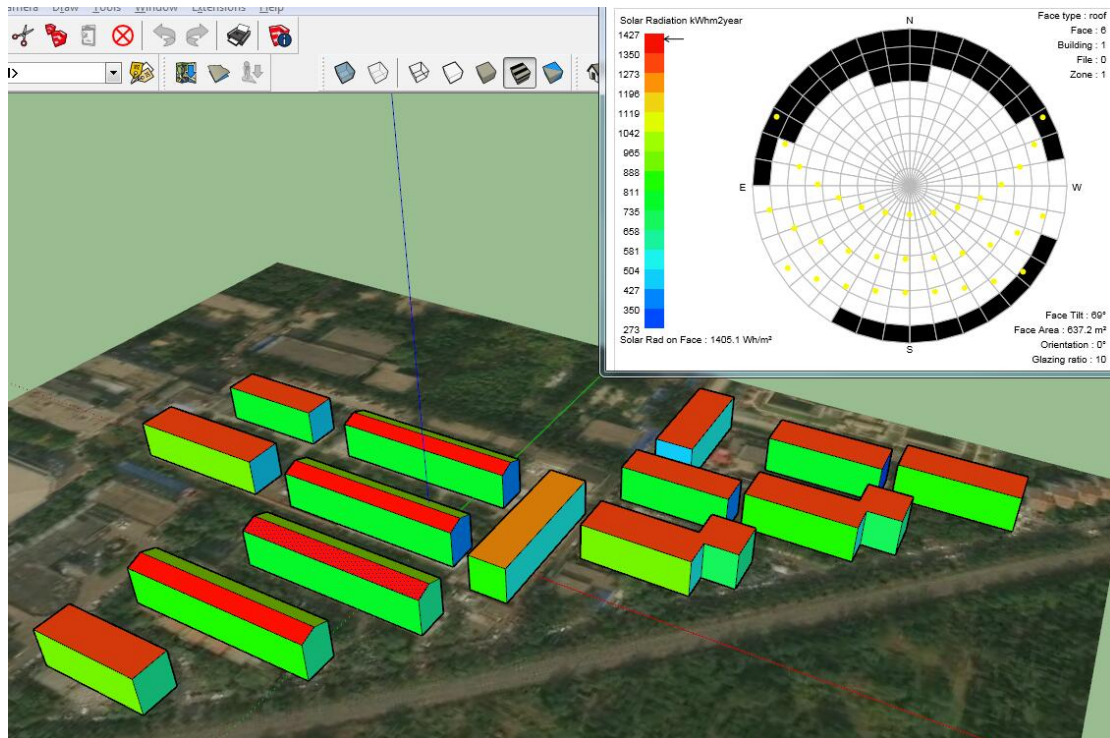


Figure 7.1 The 3D model of Community 1

7.2.2.Simulation Results of Community 1

The simulation results show the average monthly gains of Community 1 without and with IHGs before retrofitting (Figures 7.2 and 7.3), and after fabric retrofitting (Figure 7.4), including heater gains, cooler gains, internal gains, solar gains, ventilation gains and fabric gains. To be specific, first, the heater gain is the main heat source in winter before retrofitting, which decreases after adding IHGs due to the effects of the heat generated by occupants, lighting and appliances in the building. After fabric retrofitting, the heater gain dramatically drops. Secondly, the cooler gain accounts for a small amount without IHGs, which increases more than three times after considering IHGs before retrofitting, and has a slightly reduction after fabric retrofitting. Thirdly, the solar gain is generally stable before retrofitting throughout the year, and after

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fabric retrofitting, it reduces to less than half of that before retrofitting. In addition, the ventilation gain and fabric gain increase with IHG, and decrease by half after the fabric retrofitting. Furthermore, it can be seen that the IHG occupies a considerable part of the heat gains when taking it into account before retrofitting, and becomes the main heat source after retrofitting.

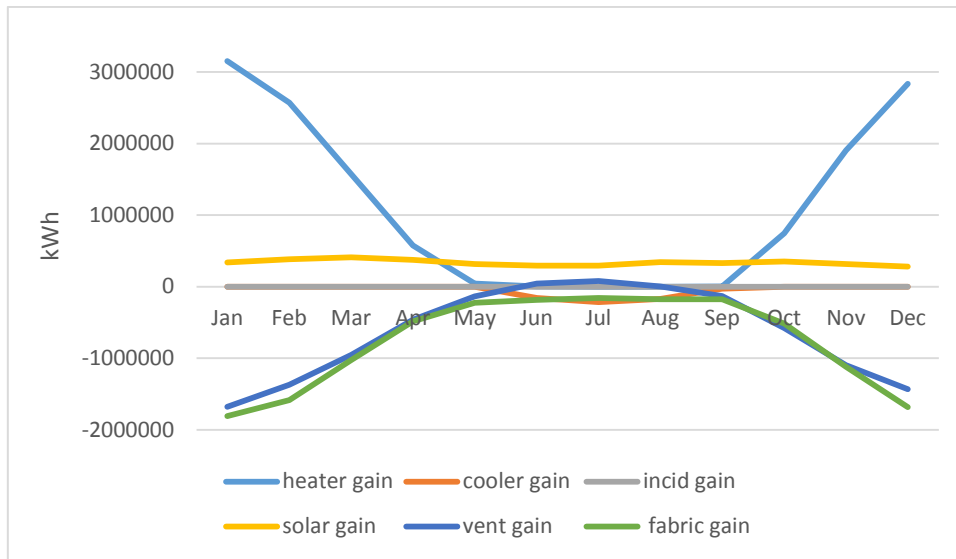


Figure 7.2 Monthly gains of Community 1 without IHGs before retrofitting

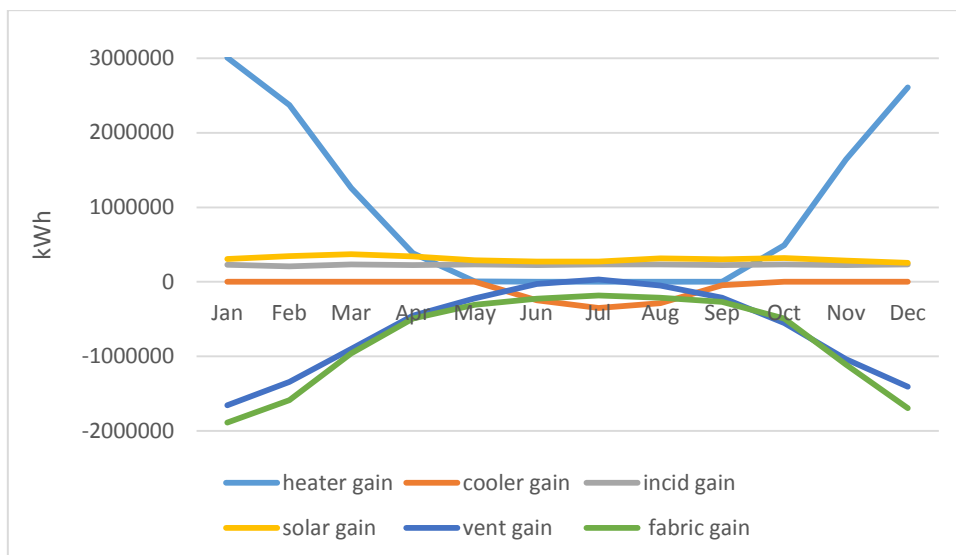


Figure 7.3 Monthly gains of Community 1 with IHGs before retrofitting

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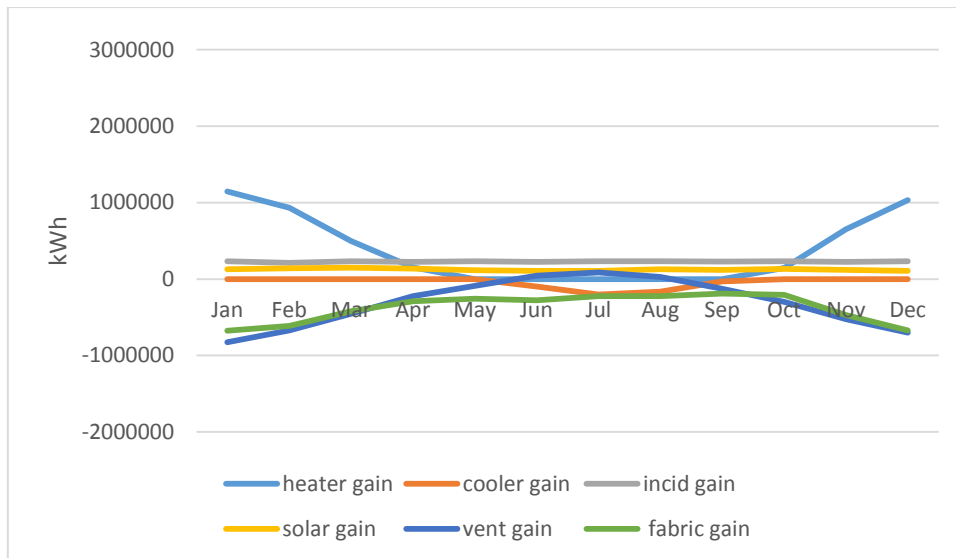


Figure 7.4 Monthly gains of Community 1 after fabric retrofitting

Figure 7.5 illustrates the annual energy demand breakdown of Community 1 before and after retrofitting. From the graph, it can be seen that first, the changes of heating and cooling demand are consistent with those described in the monthly gains. Second, the energy demand does not change much with system retrofit and renewables installation, only lighting demand is reduced by 69% when replacing all the lights with LEDs.

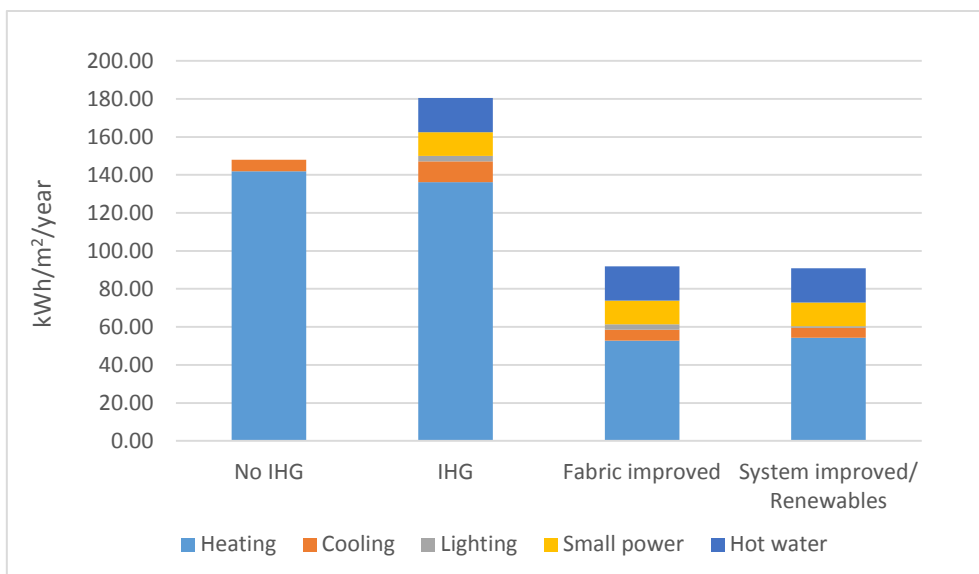


Figure 7.5 Annual energy demand breakdown of Community 1

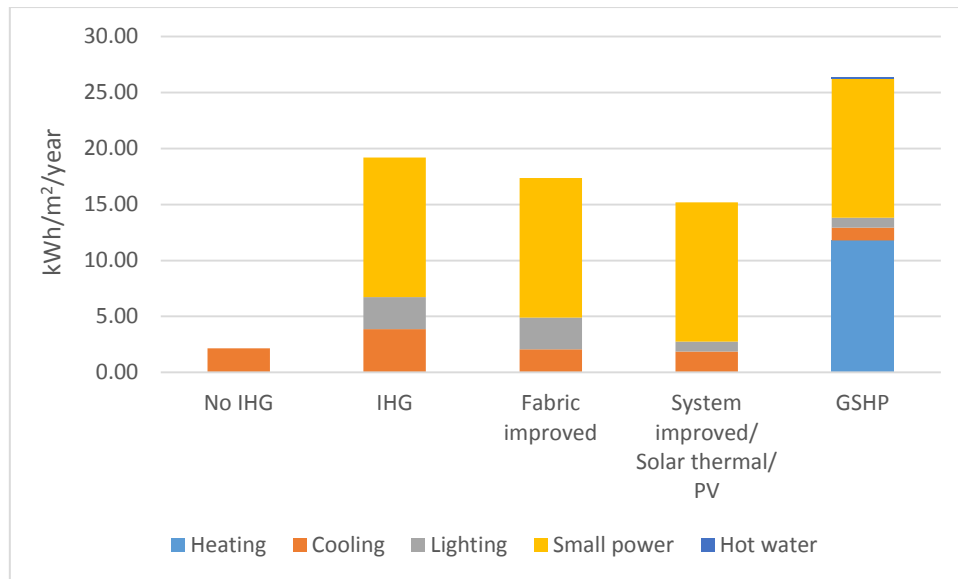


Figure 7.6 Annual electricity supply of Community 1

Figure 7.6 demonstrates the annual electricity supply of Community 1. According to the bar chart, first of all, the electricity use is only 2.2 kWh/m² without IHGs, while after adding IHGs, it jumps dramatically to 18.8 kWh/m². Second, the electricity used for cooling has a modest decline after fabric retrofitting, and a more decrease when using GSHP. Third, the lighting improvement reduces the maximum electricity use, while other retrofit packages do not contribute much. Also, small power occupies the major proportion of electricity consumption. Moreover, the heating and hot water do not consume electricity except the GSHP, which has less electricity consumption than that after fabric retrofitting, but still uses more electricity than that after system retrofitting.

In terms of gas supply, as shown in Figure 7.7, firstly, the most significant improvement is through the fabric retrofit, with an annual reduction of 135 kWh/m², all for space heating. Secondly, the gas consumption is higher without IHGs even if there is no hot water use, which shows that the IHGs are a large part of the heat source. Additionally, system improvement also contributes to the reduction of gas use for space heating. Moreover, the use of solar thermal offsets a large part of the gas use for hot water. Lastly, the GSHPs do not use gas at all, so the gas consumption is zero.

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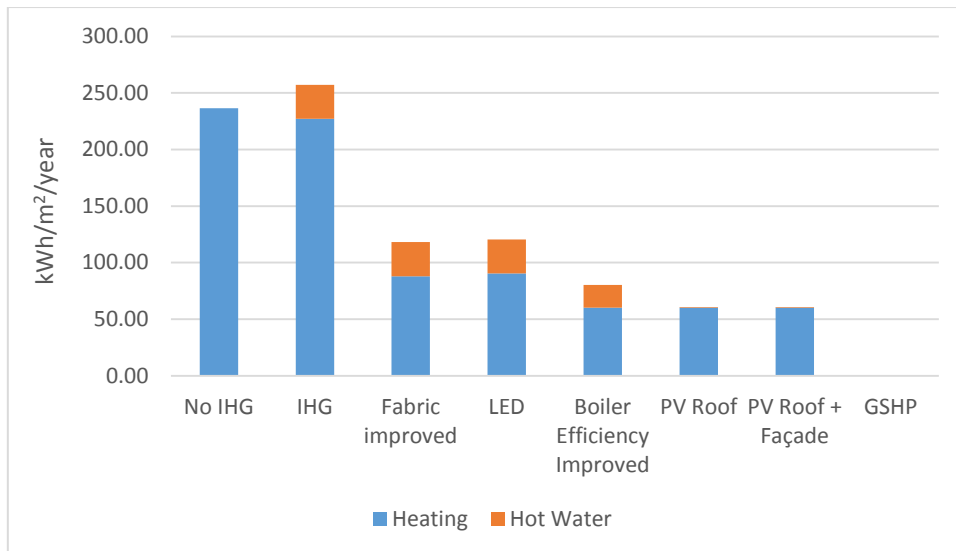


Figure 7.7 Annual gas supply of Community 1

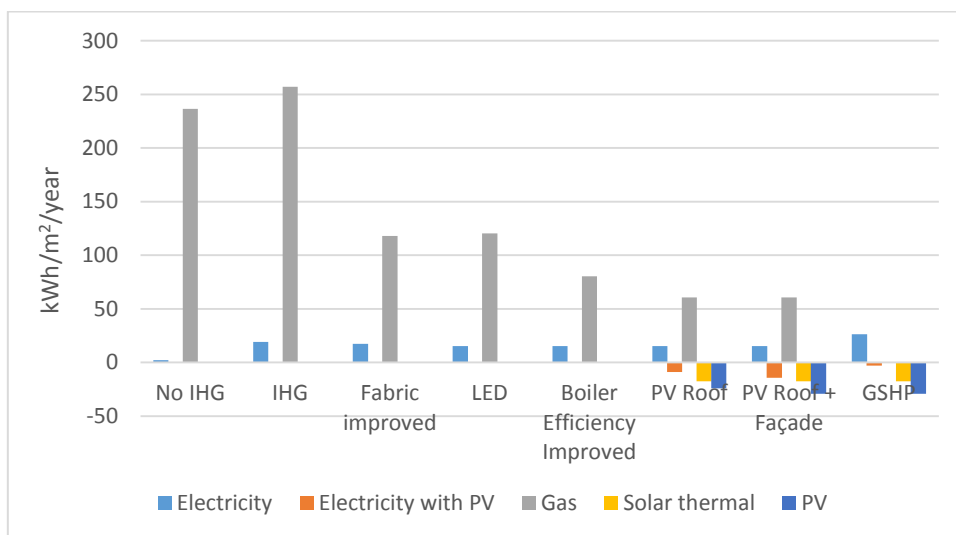


Figure 7.8 Summary of annual electricity and gas supply and renewables of Community 1

Figure 7.8 summarises the annual energy supply, the electricity generated by solar PV and the gas reduced by solar thermal. To begin with, the gas consumption decreases significantly after fabric retrofitting compared with the electricity use, because of the reduction of space heating through the fabric improvement. Second, the electricity consumption shows a substantial decrease after applying the solar PVs, which drops from 15.2 kWh/m² to -8.81 kWh/m² with PV roof package and to -14.1 kWh/m² with PV roof and facade package. The negative values indicate the amount of electricity

that can be exported to the national grid. Third, the GSHP has the best overall performance after retrofitting. Although the electricity use increased from -14.1 kWh/m² with PV roof and facade package to -3 kWh/m² with GSHP package, the total energy use including electricity and gas drops from 76.2 kWh/m² with the PV roof and facade package to 48.3 kWh/m² with the GSHP package. Because the GSHP system does not consume gas, this significantly reduces the total energy use.

Figure 7.9 illustrates the annual CO₂ emission reductions with a series of retrofit measures of Community 1. The surplus PV power to grid contributes to a negative carbon emission. First, the annual CO₂ emissions without IHGs are less than half of those with IHGs. The CO₂ by electricity use is only 2 kg/m² without IHGs. Second, the CO₂ emissions gradually decline with the successive application of the fabric, system, and renewable retrofit packages. Third, the two major reductions of CO₂ emissions are through the fabric retrofitting and PV roof installation. Besides this, the GSHP emits the least amount of CO₂ due to the most CO₂ reductions from renewables. Although the GSHP produces slightly more CO₂ by electricity use than the PV roof and facade package, it does not have CO₂ emissions by gas use, so the total amount is much smaller than the PV packages.

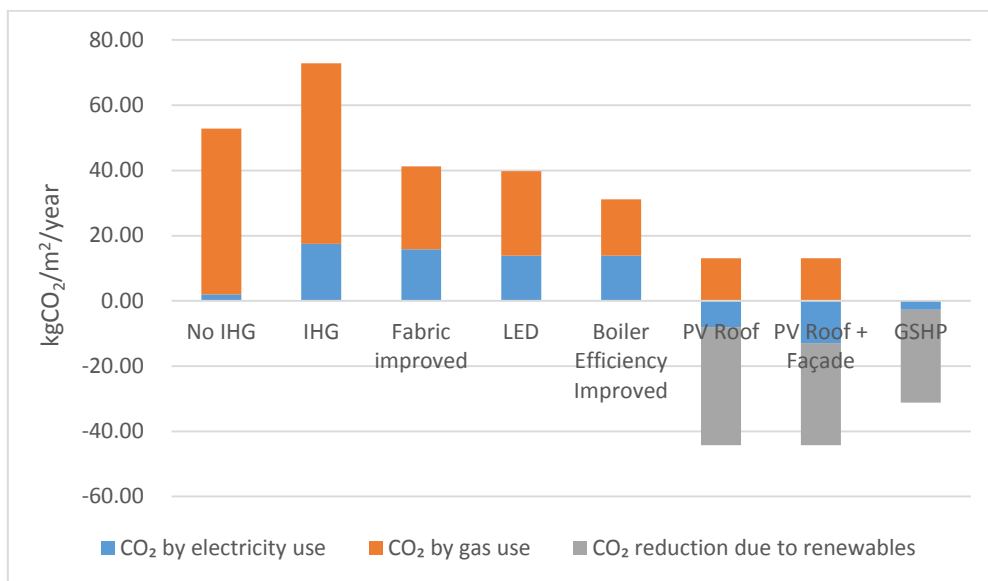


Figure 7.9 Summary of annual CO₂ emissions of Community 1

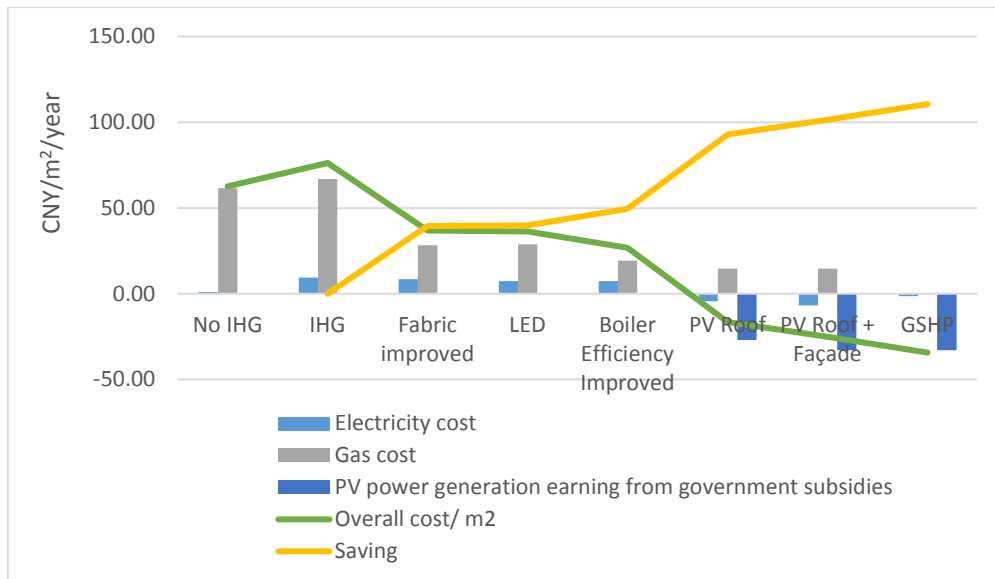


Figure 7.10 Summary of annual operating costs and savings of Community 1

Figure 7.10 shows the annual operating costs and savings of Community 1. The negative value indicates the incomes of electricity generation by solar PV and export to the grid. As can be seen from the chart, first, for the annual cost of electricity and gas, the tendency is consistent with the CO₂ emissions reduction. Second, the gas cost declines as the retrofit measures increase, with the most reduction in fabric retrofit, while the electricity cost has not changed much until installing the renewables. Third, for the renewables, the GSHP has slightly less operating costs than the PV packages. Moreover, the overall cost drops from 96 CNY/m² before retrofitting with IHGs to -9.5 CNY/m² after retrofitting, which carries savings of 110%.

7.3. Modelling of Community 2

7.3.1. Introduction of Community 2

Community 2 is Nanshatan Community located in north Beijing. There are seventeen buildings in this community, including thirteen multi-storey buildings with six floors and four high-rises with eighteen floors. The buildings were built in 1996. The conditions of the multi-storey buildings before retrofitting were the same with Case 2. As Cases 2 and 4 are in the same age group, the high-rises in Community 2 before

retrofitting adopted the construction materials of Case 4 for simulation. The 3D model of Community 2 with colour faced for solar radiation and the shading mask of the south facade of Case 2 are demonstrated in Figure 7.11. As shown in the figure, all buildings are facing south with flat roofs.

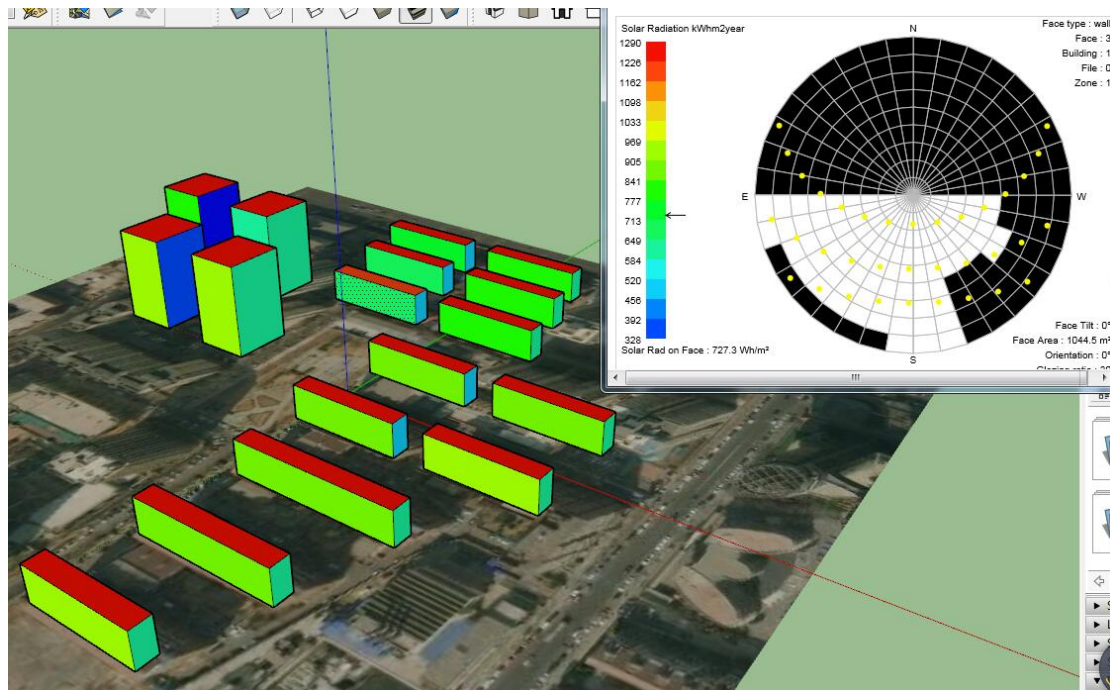


Figure 7.11 The 3D model of Community 2

7.3.2. Simulation Results of Community 2

The modelling results present the average monthly gains of Community 2 without IHGs and with IHGs before retrofitting (Figures 7.12 and 7.13), and after fabric retrofitting (Figure 7.14). From the charts, it can be seen that, first of all, the heater gain dominates in winter before retrofitting, which slightly declines after considering the IHGs and decreases drastically after fabric retrofitting. Secondly, the cooler gain occupies a small proportion without IHGs, which increases after adding the IHGs before retrofitting, and has a moderate dip after fabric retrofitting. Thirdly, the solar gain remains stable before retrofit, and drops by half after the fabric retrofit. Similarly, the ventilation gain and fabric gain rise with IHG and fall by half after the fabric

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retrofitting. Furthermore, it can be seen that the IHG makes up a non-negligible part of the heat gains before and after retrofitting.

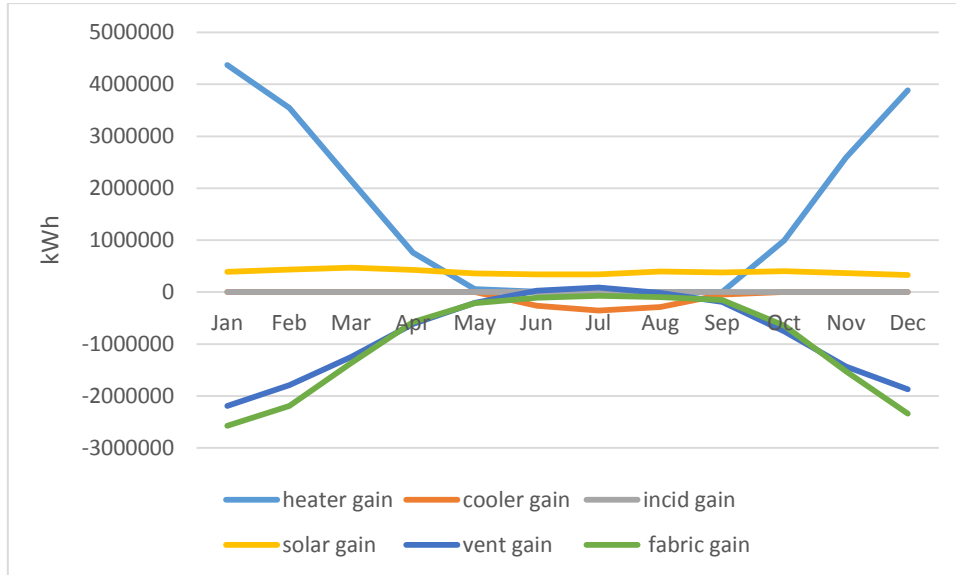


Figure 7.12 Monthly gains of Community 2 without IHGs before retrofitting

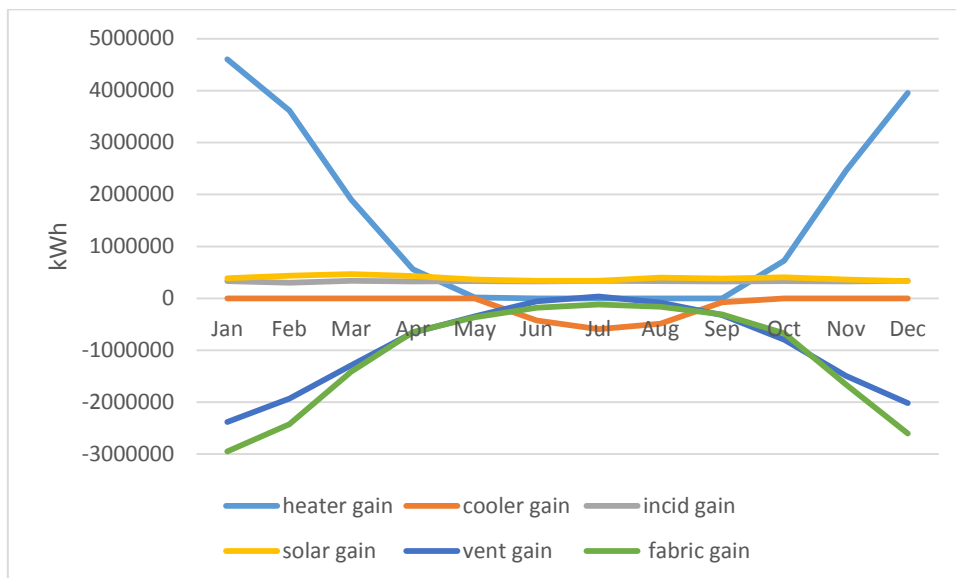


Figure 7.13 Monthly gains of Community 2 with IHGs before retrofitting

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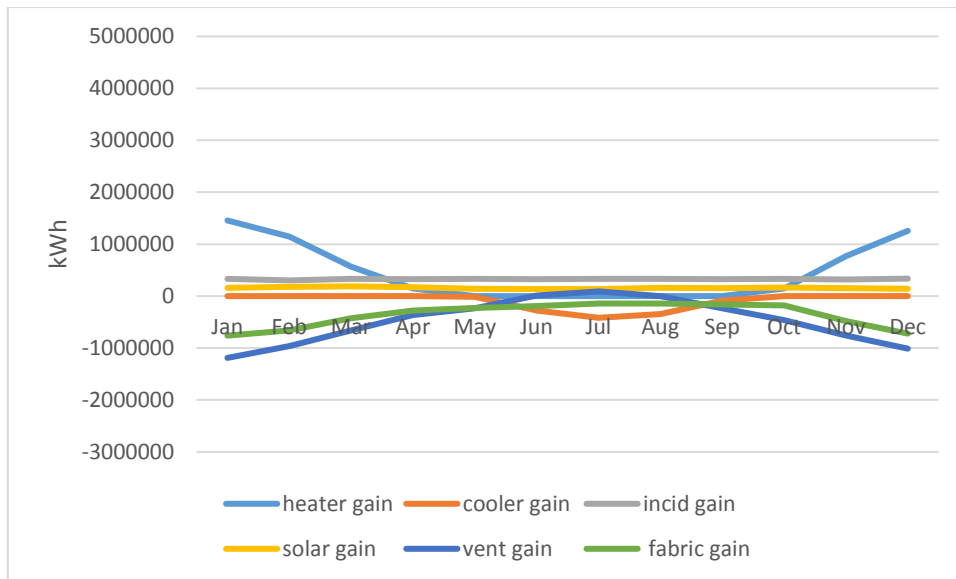


Figure 7.14 Monthly gains of Community 2 after fabric retrofitting

Figure 7.15 indicates the annual energy demand breakdown of Community 2 before and after retrofitting. As shown in the chart, first, the changes of the heating and cooling demand are the same as those illustrated in the monthly gains. Second, the annual heating demand decreases from 143.9 kWh/m² before retrofitting to 44.3 kWh/m² after fabric retrofitting. In addition, the energy demand basically has no reduction with system improvement and renewable application except lighting, which accounts for a small amount of energy demand.

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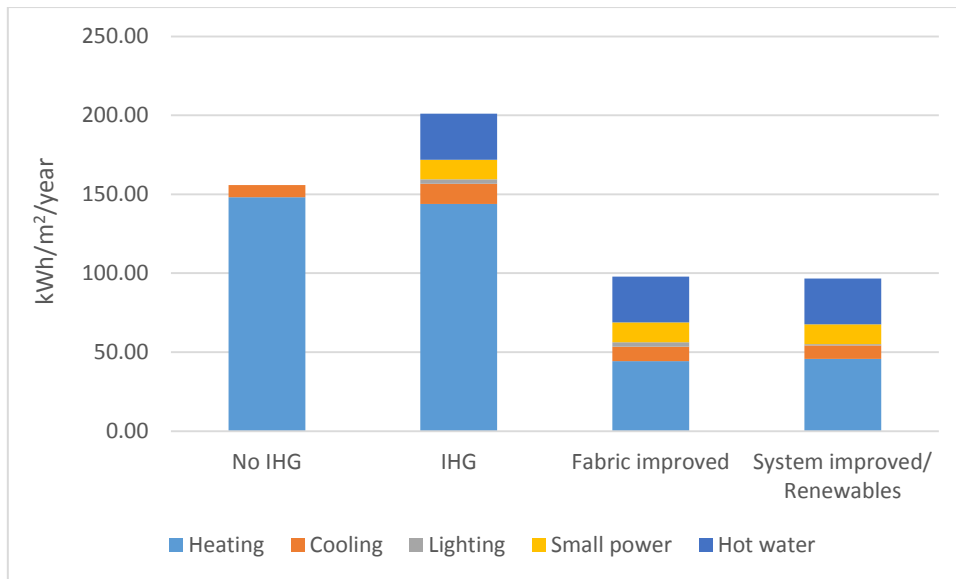


Figure 7.15 Annual energy demand breakdown of Community 2

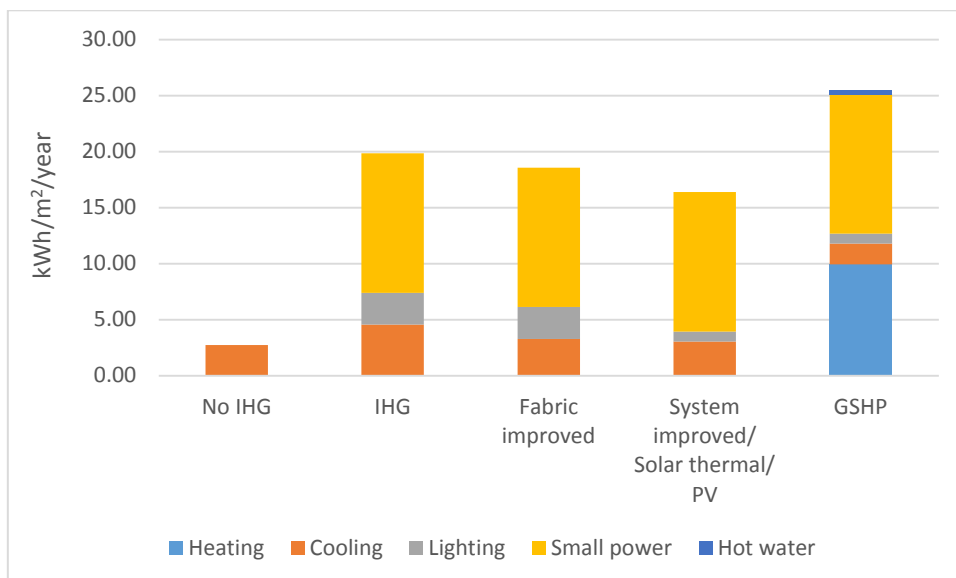


Figure 7.16 Annual electricity supply of Community 2

Figure 7.16 illustrates the annual electricity supply of Community 2. In the chart it can be seen that, first, electricity use goes up dramatically from 2.8 kWh/m² without IHGs to 20 kWh/m² with IHGs. Second, the electricity used for cooling has a slight decrease with fabric retrofitting, and a large reduction with GSHP. Third, the most significant reduction in electricity consumption is in lighting improvement, whereas other packages do not reduce much. In addition, small power occupies the majority of the

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electricity use. Moreover, only the GSHP uses electricity for the heating and hot water, which has the highest electricity use than other scenario.

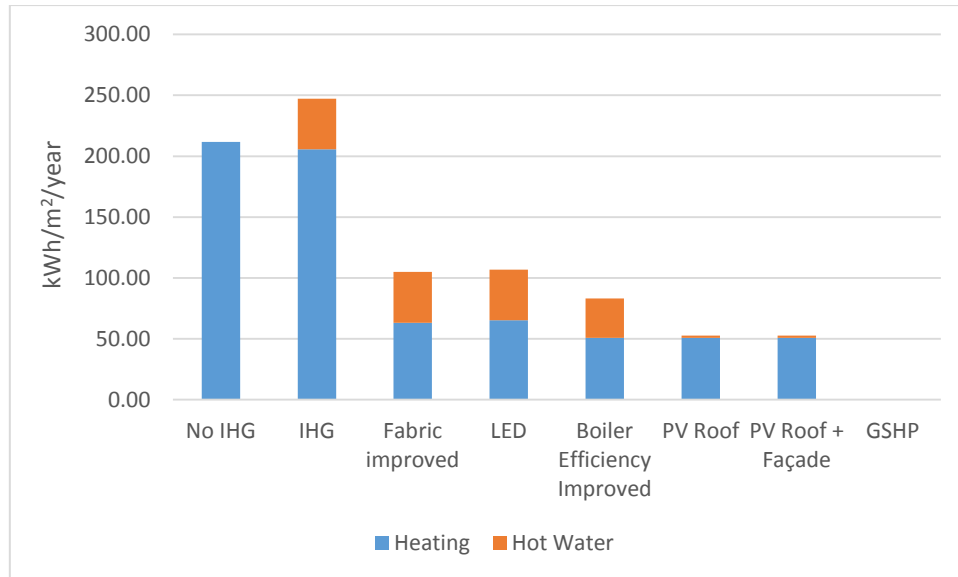


Figure 7.17 Annual gas supply of Community 2

The annual gas supply is demonstrated in Figure 7.17. According to the chart, first and foremost, the most significant improvement is through the fabric retrofit, which reduces the gas use from 247.2 kWh/m² before retrofitting with IHGs to 104.9 kWh/m² after fabric retrofitting. This is due to the fact that the improved envelope lessens the building's heating demand, thereby greatly reducing the gas consumption for space heating. Second, the gas supply is also reduced apparently through heating system improvement and solar thermal, of which the former mainly reduces the gas consumption for space heating and the latter decreases the gas use for hot water. Additionally, there is no gas use in the GSHP system.

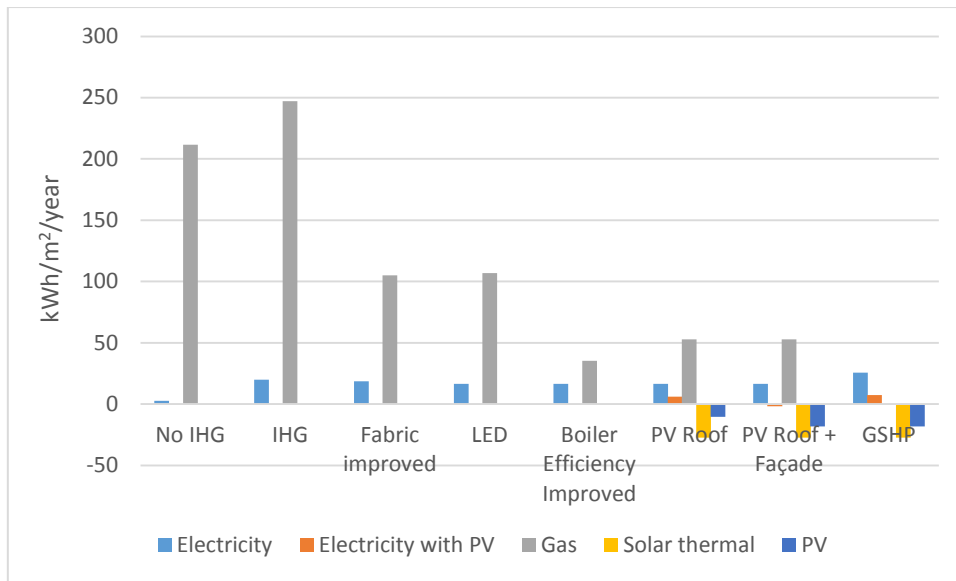


Figure 7.18 Summary of annual electricity and gas supply and renewables of Community 2

Figure 7.18 summarises the annual energy supply, the electricity produced by solar PV and the gas reduced by solar thermal. Firstly, the gas supply consistently decreases due to the fact that the heating loads for space heating decrease through fabric and system improvement and solar thermal installation. Secondly, the electricity supply remains stable with fabric and system retrofit, except a small visible drop with lighting improvement. Thirdly, the electricity consumption is reduced after adding the solar PVs, with the drop of 10.4 kWh/m² for PV roof and 18.3 kWh/m² for PV roof and facade package. Finally, the GSHP with PV has the best performance after retrofitting as there is same amount of electricity generation and no gas use, thereby significantly reduce the total energy consumption.

Figure 7.19 shows the annual CO₂ emissions of Community 2. From the chart we can see that, first, the CO₂ emissions increase significantly after taking into account the IHGs. Second, the CO₂ emissions decrease with the continuing adoption of the fabric, system and renewable retrofit packages, where the most marked reductions are with fabric retrofit and PV addition. Because the fabric retrofit cuts off a large proportion of the gas use for space heating and the electricity created by the PVs offsets a majority of the electricity use, CO₂ emissions are substantially reduced. Moreover, the GSHP has slightly more CO₂ emissions from electricity but less total CO₂ emissions than the PV roof and facade package.

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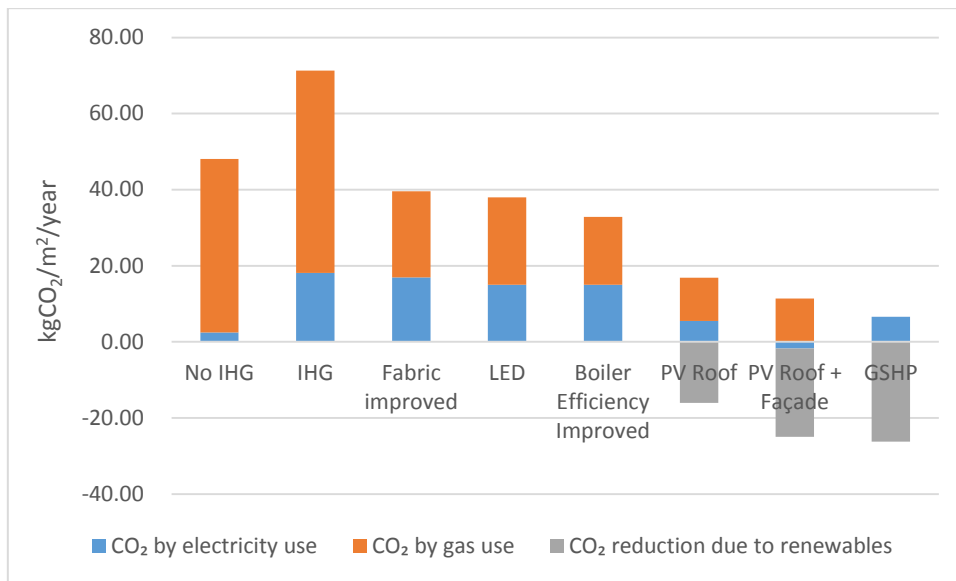


Figure 7.19 Summary of annual CO₂ emissions of Community 2

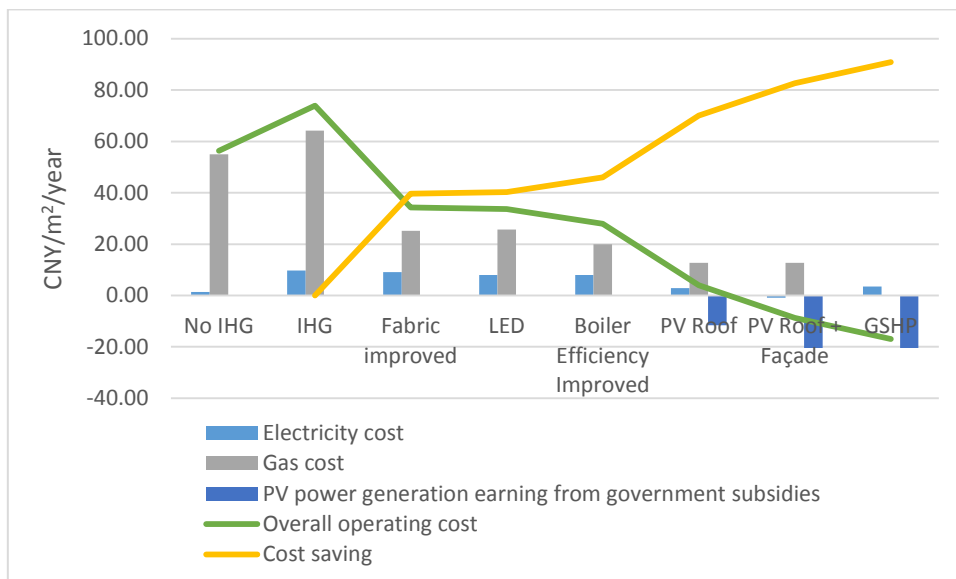


Figure 7.20 Summary of annual operating costs and savings of Community 2

Figure 7.20 outlines the summary of the operating costs and savings of Community 2. According to the chart, first of all, the overall operating cost decreases along with the increasing retrofit measures except those without IHGs before retrofitting. Second, the most significant reductions are in the renewable packages, while the savings rise accordingly. Third, the gas cost has a maximum reduction by fabric retrofitting, which reduces from 64.3 CNY/m² to 25.2 CNY/m². In addition, the electricity cost has not

changed much by the fabric and system retrofitting until renewables are installed. Moreover, the GSHP has less overall operating cost and more savings than the PV roof and facade package. Furthermore, the overall operating cost is reduced from 74 CNY/m² to -16.9 CNY/m², with an annual cost saving of 90.9 CNY/m².

7.4. Modelling of Community 3

7.4.1. Introduction of Community 3

Community 3 is Dongsishitiao Community built in 1983 located in the northeast of Beijing. There are fourteen buildings in this community, involving ten mid-rises with seven floors and four high-rises with eighteen floors. The conditions of the four high-rise buildings before retrofitting were the same with Case 3. Since Case 3 and Case 1 are in the same age band, the construction materials of the mid-rises in Community 3 before retrofitting used the construction materials of Case 1 in the simulation. The 3D model of Community 3 with colour faced for solar radiation and the shading mask of the south facade of Case 3 are demonstrated in Figure 7.21. From the graph we can see that all of the buildings are facing south, and the mid-rise buildings have pitched roofs as Case 1.

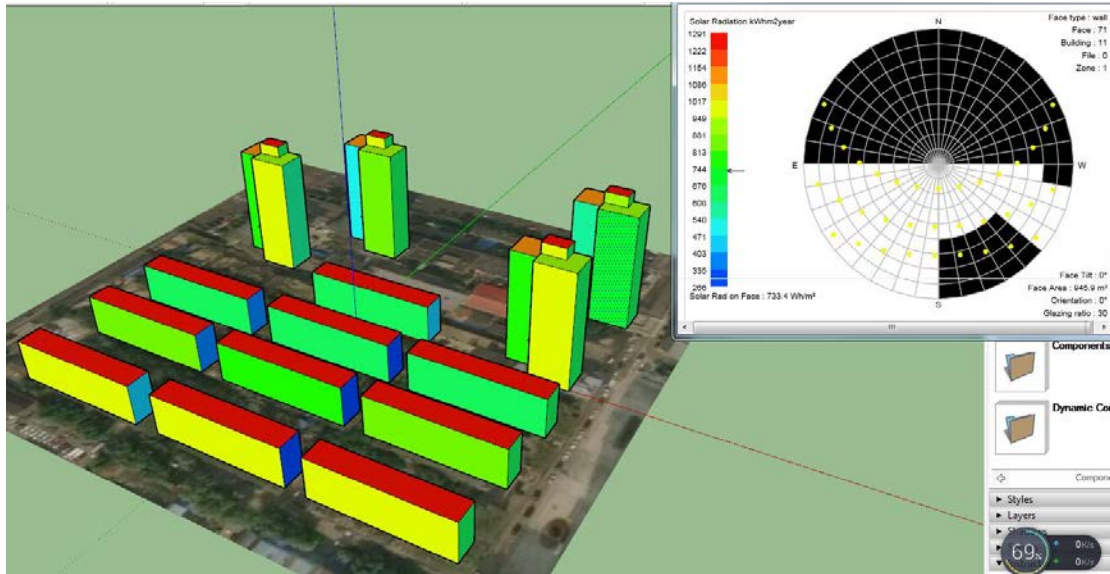


Figure 7.21 The 3D model of Community 3

7.4.2. Simulation Results of Community 3

The modelling results show the average monthly gains of Community 3 without IHGs and with IHGs before retrofitting (Figures 7.22 and 7.23), and after fabric retrofitting (Figure 7.24). More specifically, first, from October to April, the heater gain is the leading heat source before retrofitting, which slightly declines after adding IHGs and then drops steeply after fabric retrofitting. Second, from May to September, the cooler gain accounts for a small proportion without IHGs, which grows after adding IHGs before retrofitting, and slightly declines after fabric retrofitting. Further, the solar gain stays stable before retrofitting, and cuts down by half after the fabric retrofitting. Likewise, the ventilation gain and fabric gain increase with IHG and are reduced by half after the fabric retrofitting. Besides, the IHGs occupy a non-negligible part of the heat gains when they are taken into account before and after retrofitting.

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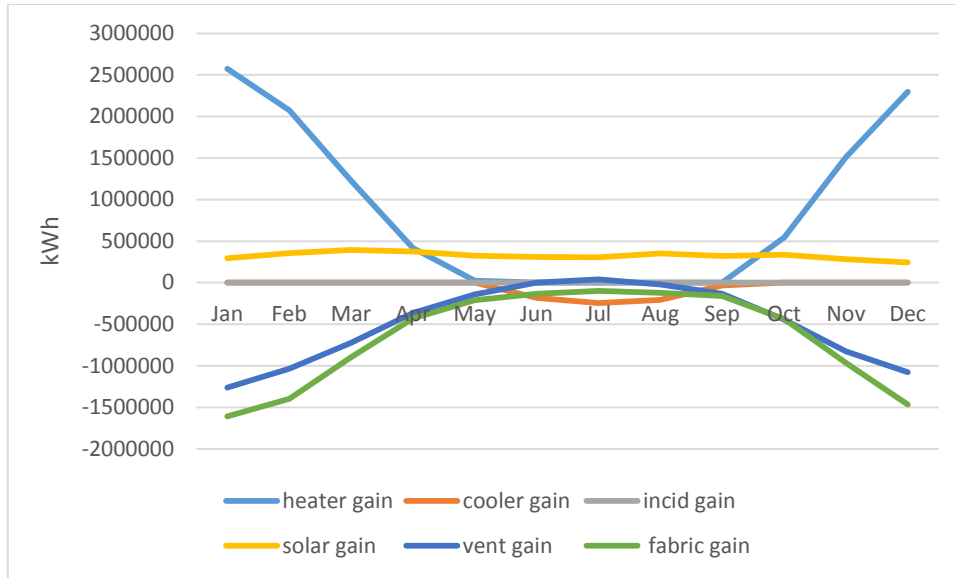


Figure 7.22 Monthly gains of Community 3 without IHGs before retrofitting

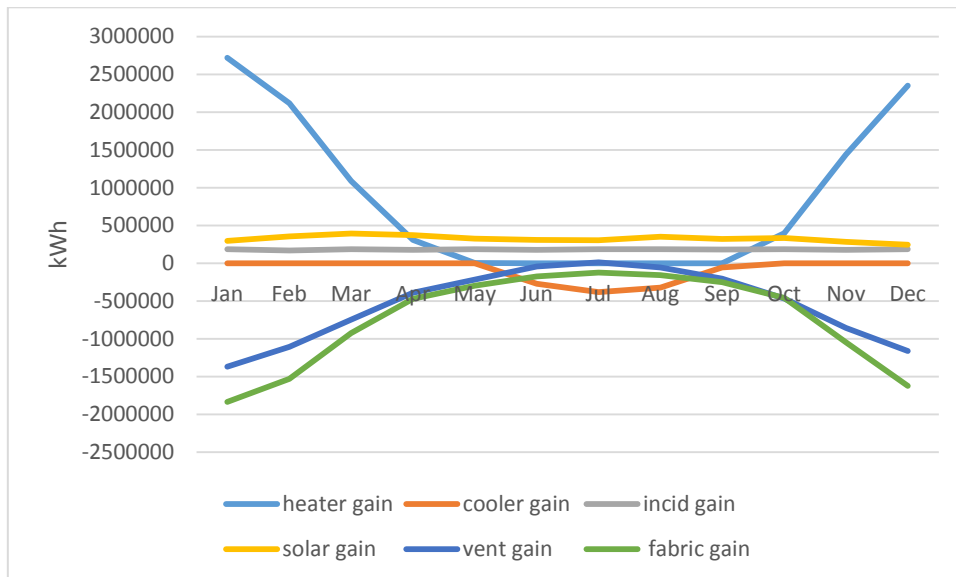


Figure 7.23 Monthly gains of Community 3 with IHGs before retrofitting

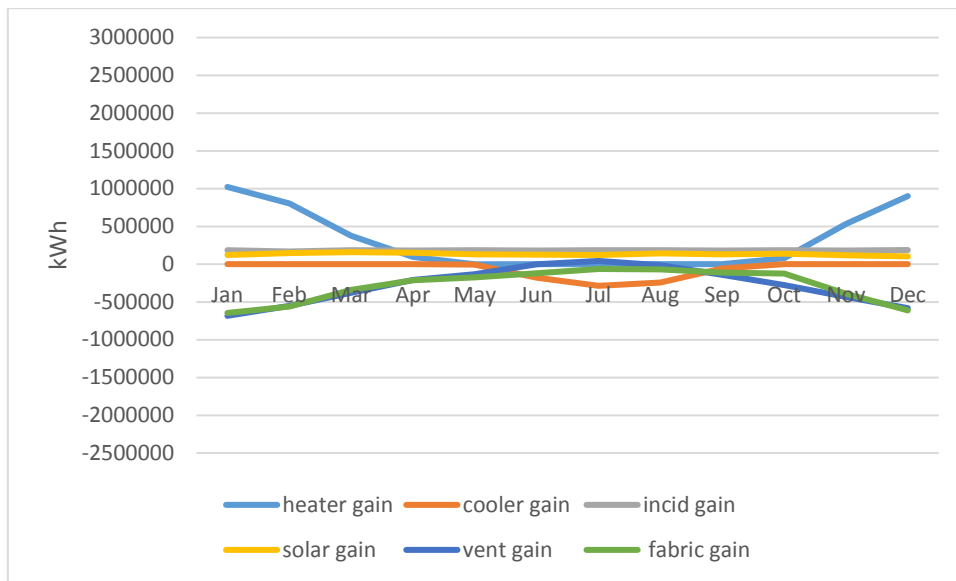


Figure 7.24 Monthly gains of Community 3 after fabric retrofitting

Figure 7.25 illustrates the energy demand breakdown of Community 3. From the graph we can see that, first, the heating and cooling demand are consistent with the monthly data. Second, the energy demand decreases rapidly from 208 kWh/m² before retrofitting to 108.1 kWh/m² after the fabric retrofitting. Third, the cooling demand is reduced very little after fabric retrofitting, and stabilises at 10.3 kWh/m² after retrofitting. Furthermore, lighting improvement slightly reduces the energy demand, while heating system retrofit and renewables result in no reduction in energy demand.

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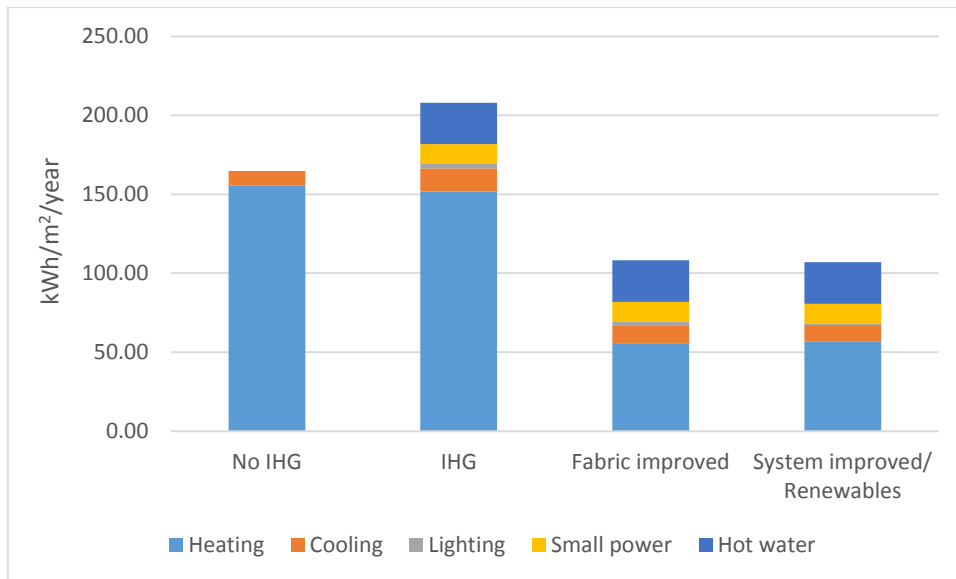


Figure 7.25 Annual energy demand breakdown of Community 3

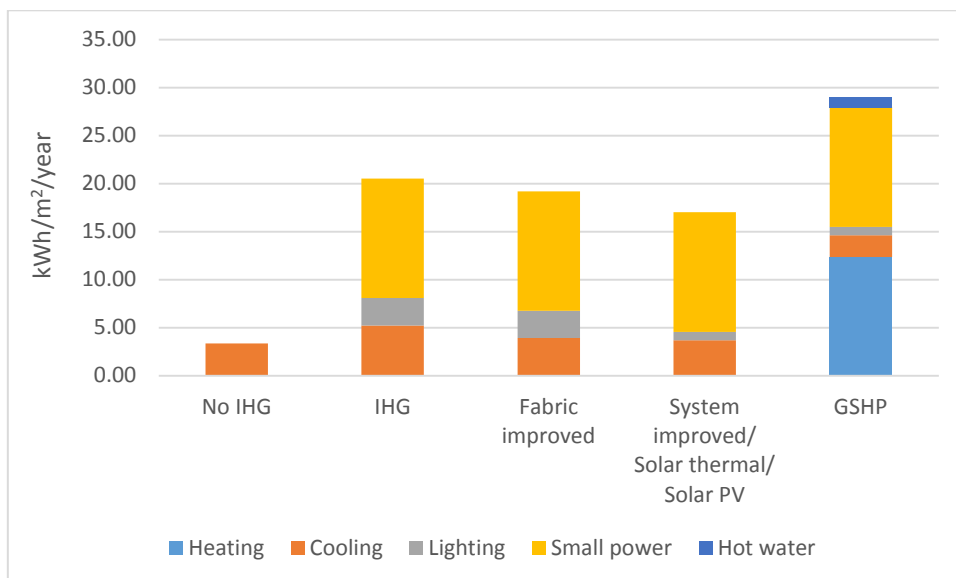


Figure 7.26 Annual electricity supply of Community 3

Figure 7.26 demonstrates the annual electricity supply of Community 3. To begin with, the electricity used for cooling has a modest decrease with fabric retrofitting, and a great decline with GSHP. In addition, the electricity is stable for small power, which accounts for the largest proportion of the electricity supply. Also, lighting contributes the most to reduce electricity use, with a decrease of 2.2 kWh/m². Moreover, only the GSHP package uses electricity for space heating and hot water, thus, it consumes more electricity than others.

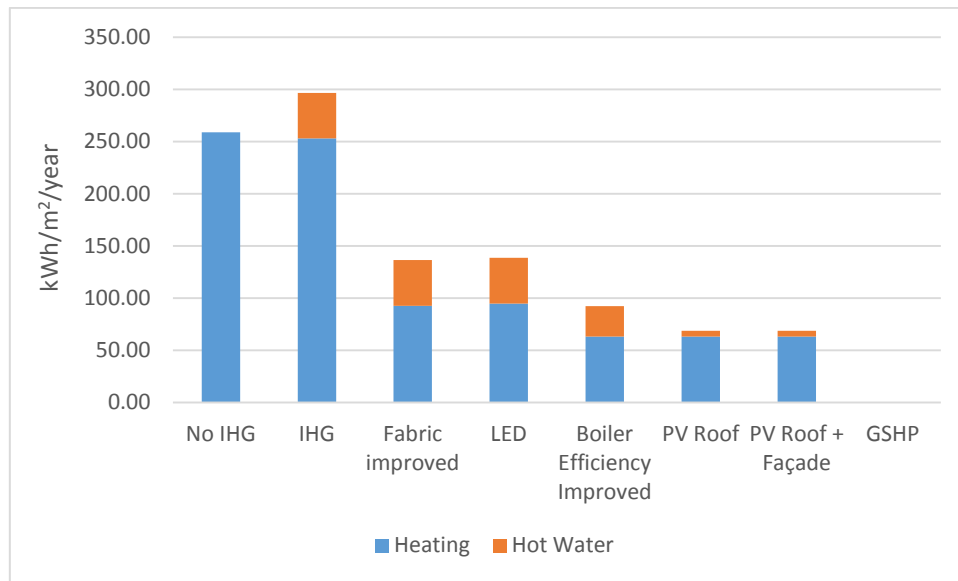


Figure 7.27 Annual gas supply of Community 3

Figure 7.27 shows the annual gas supply of Community 3 declining through different retrofit packages. First of all, fabric retrofit appears to be the most significant improvement, with the annual gas reduction of 160.3 kWh/m². Second, there is more gas consumption for heating without IHGs than with IHGs, which means the empty rooms consume more gas for space heating compared to the rooms with occupants, lighting and small power. Third, the second largest gas reduction is contributed by the GSHP, which does not consume gas at all, and so greatly reduces the gas use. Besides this, the gas use has also decreased by heating system improvement and solar thermal installation, where the former mainly decreases gas use for space heating and the latter decreases the gas supply for hot water.

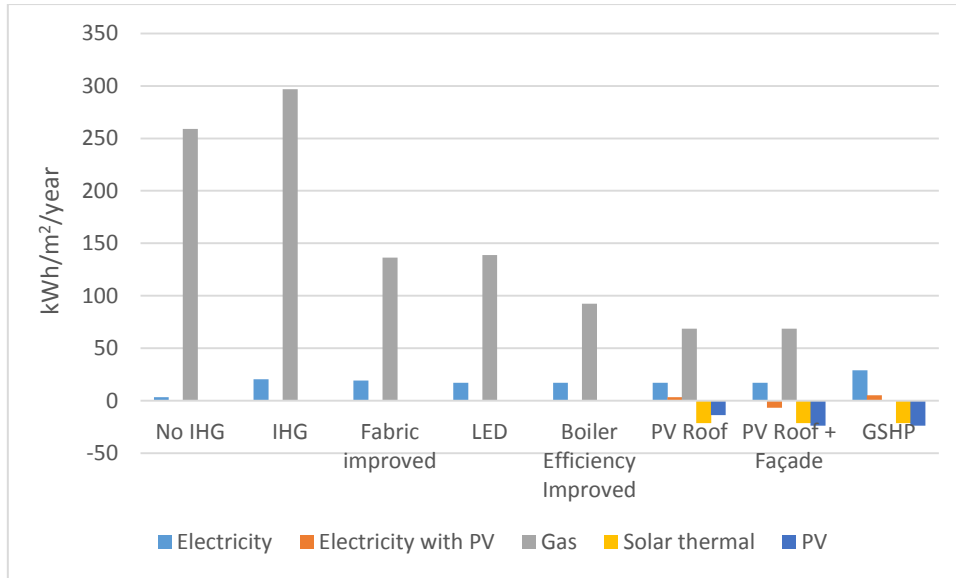


Figure 7.28 Summary of annual electricity and gas supply and renewables of Community 3

Figure 7.28 presents a summary of the annual energy supply, the electricity generated by solar PV and the gas reduced by solar thermal. Firstly, the gas supply consistently decreases, with the greatest decline in fabric retrofit. Secondly, the electricity use mainly remains stable through fabric and system retrofit, with a little reduction in lighting improvement. Thirdly, the electricity consumption drops when applying the solar PVs, with the drop of 13.5 kWh/m² for PV roof and 23.7 kWh/m² for PV roof and facade. Finally, the GSHP has the least energy consumption and much better performance than other retrofit packages, which has the total energy use of 5.3 kWh/m², compared to the PV roof and facade package with 62.1 kWh/m².

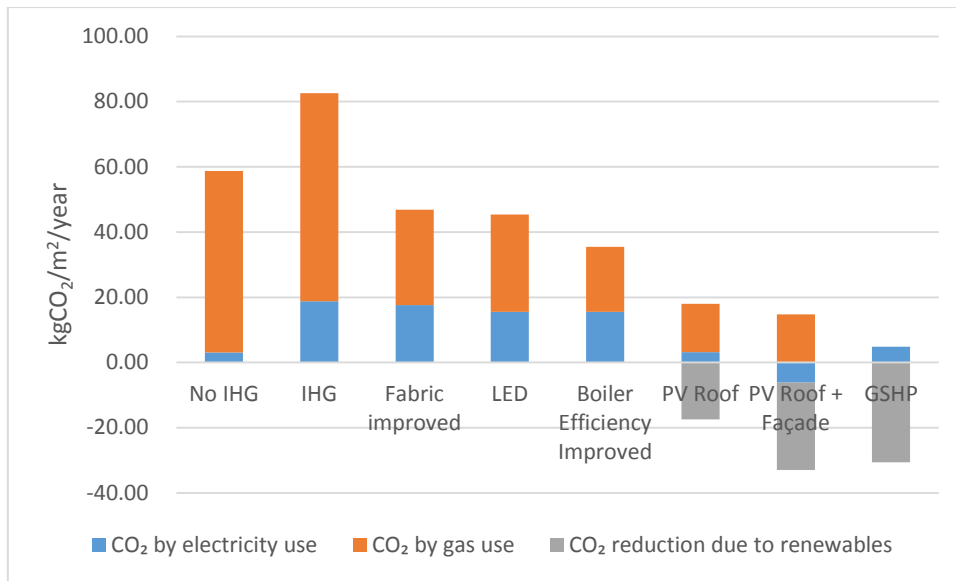


Figure 7.29 Summary of annual CO₂ emissions of Community 3

Figure 7.29 shows the summary of annual CO₂ emissions of Community 3. As can be seen from the chart, first, the CO₂ emissions with IHGs are substantially higher than those without IHGs, mainly because of electricity use, whilst the CO₂ emissions from gas use are slightly lower with IHGs than without IHGs. In addition, the annual CO₂ emissions experience a downward trend with the successive adoption of the retrofit packages, with the largest reduction in fabric improvement. Furthermore, the annual CO₂ emissions are reduced from 35.4 kg/m² after system improvement to 18 kg/m² with solar PV panels to the roof and 8.7 kg/m² with PV installed on the roof and the south facade above the third floor. Besides, the GSHP has slightly more CO₂ emissions from electricity but has the least total CO₂ emissions of 4.8 kg/m².

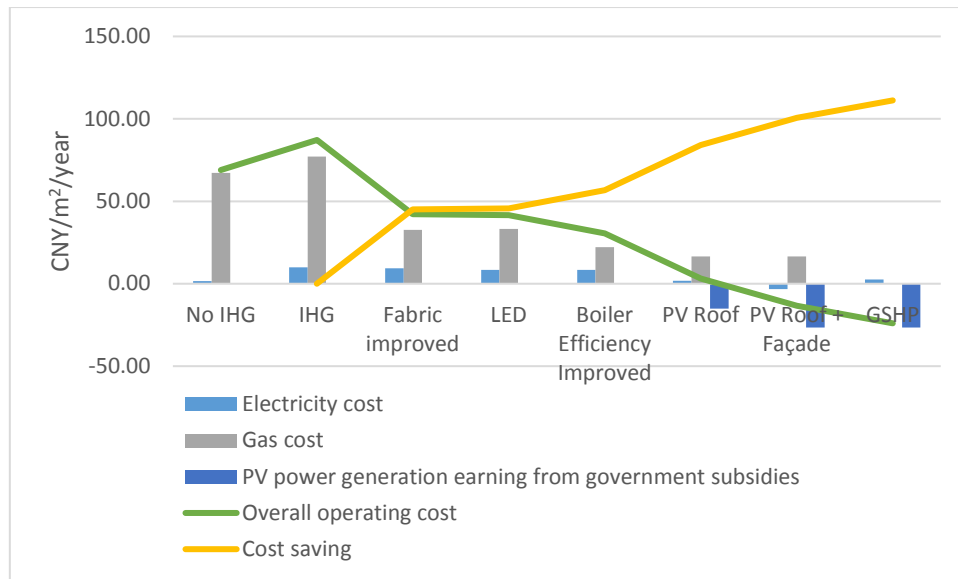


Figure 7.30 Summary of annual operating cost and savings of Community 3

The annual operating costs, savings and earnings from solar PVs are summarised in Figure 7.30. Firstly, for the annual electricity and gas costs, the tendency is consistent with the CO₂ emission reductions. Secondly, the electricity cost is slightly reduced from 10 CNY/m² with IHGs before retrofitting to 9.4 CNY/m² after fabric retrofitting and 8.3 CNY/m² after system retrofitting. Thirdly, when installing the renewables, the electricity costs significantly decrease to 1.7 CNY/m² and -3.3 CNY/m² with a solar PV roof and a PV roof plus facade, respectively. Additionally, with the income from solar PV generation and government subsidies, as well as no gas cost, the GSHP has the lowest overall operating cost of -24 CNY/m², with an annual savings of 111.2 CNY/m² in total.

7.5. Modelling of Community 4

7.5.1. Introduction of Community 4

Community 4 is Xinfengjie Community located in north Beijing. The community has eight high-rise buildings with twenty floors each. The buildings were built in 2001, and the conditions before retrofitting were the same as in Case 4. The 3D model of

Community 4 with colour faced for solar radiation and the shading mask of the south facade of Case 4 are demonstrated in Figure 7.31.

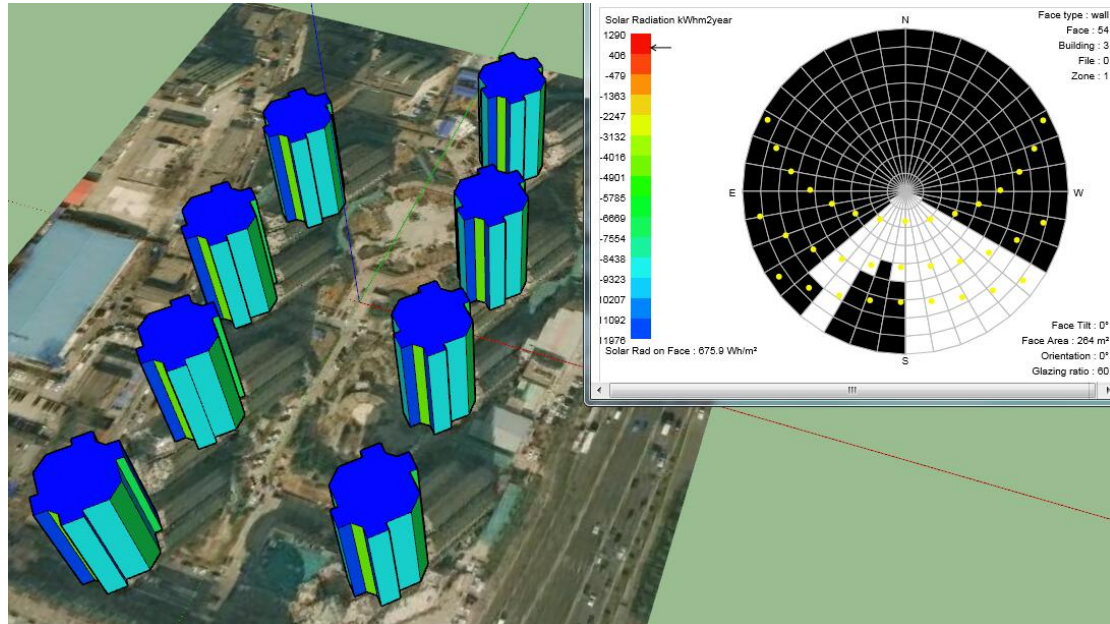


Figure 7.31 The 3D model of Community 4

7.5.2. Simulation Results of Community 4

The simulation results present the average monthly gains of Community 4 without and with IHGs before retrofitting (Figures 7.32 and 7.33), and after fabric retrofitting (Figure 7.34). To be more precise, firstly, the heater gain is the primary heat source in winter before retrofitting, which is higher without IHGs than with IHGs, and dramatically declines after adding IHGs due to the effects of the heat generation from occupants, lighting and small powers. Secondly, the cooler gain makes up for a small proportion in summer without IHGs, which rises with IHGs, and has a moderate reduction after fabric retrofitting. Thirdly, the IHG occupies a part of the heat gains that cannot be ignored when taken into account before and after retrofitting. Furthermore, the solar gain remains stable before retrofitting throughout the year and decreases by half after retrofitting. Besides, the ventilation gain and fabric gain are slightly higher with IHG, and decline by half after the fabric retrofitting.

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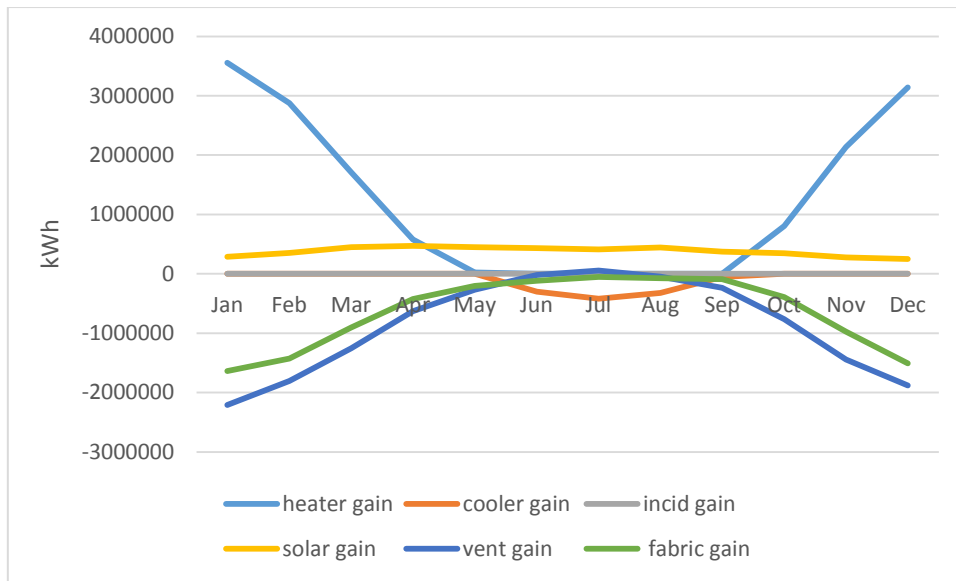


Figure 7.32 Monthly gains of Community 4 without IHGs before retrofitting

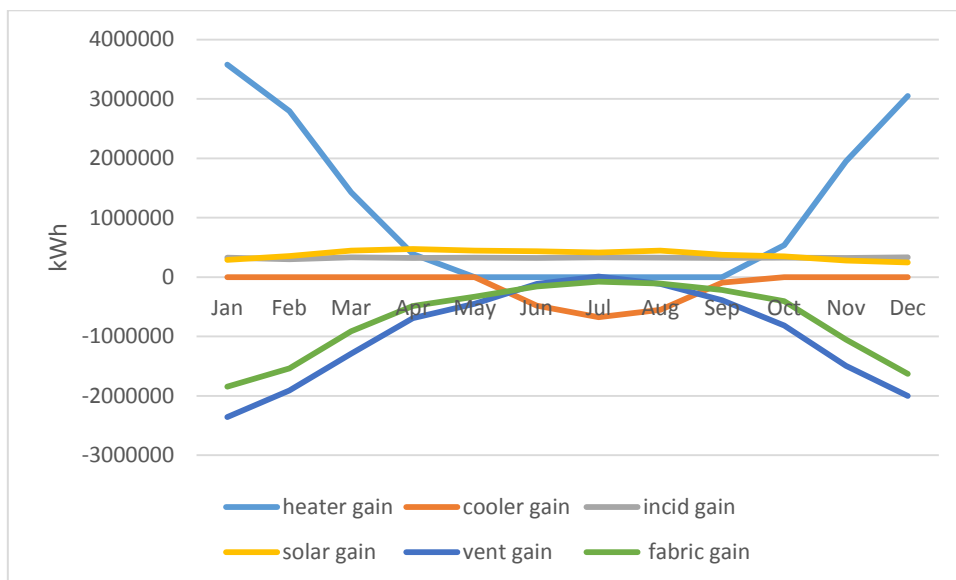


Figure 7.33 Monthly gains of Community 4 with IHGs before retrofitting

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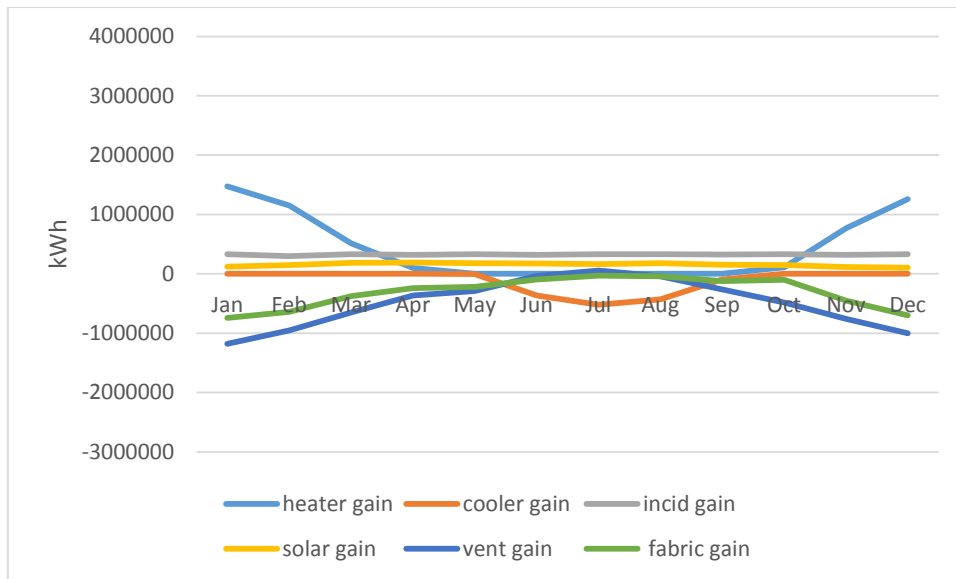


Figure 7.34 Monthly gains of Community 1 after fabric retrofitting

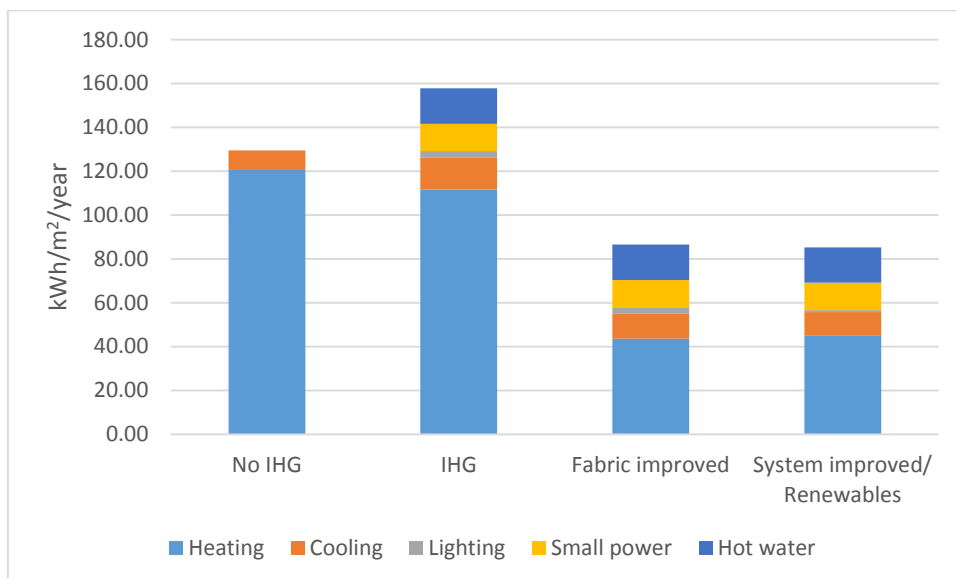


Figure 7.35 Annual energy demand breakdown of Community 4

Figure 7.35 describes the energy demand of Community 4. As can be seen from the graph, to begin with, the variation trend of the heating and cooling demands is the same with the monthly data. Also, the fabric retrofit has the most significant improvement on energy demand, mainly in reducing heating demand. In addition, the cooling demand levels off at just over 11 kWh/m² with different retrofit packages. Moreover, the package of lighting improvement has a marginal decline of energy

demand while the heating system upgrade and renewables show no reduction of energy demand.

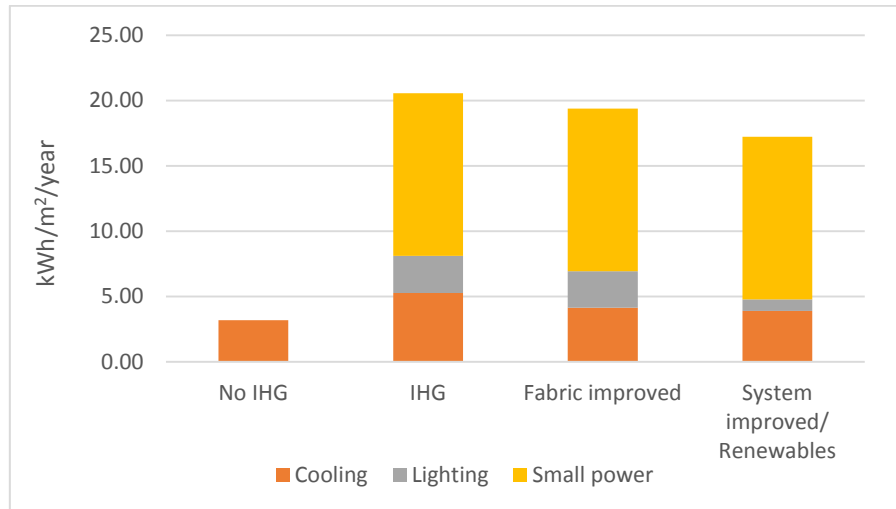


Figure 7.36 Annual electricity supply of Community 4

Figure 7.36 outlines the annual electricity supply of Community 4. From the graph it can be seen that, first, electricity is used for cooling, lighting, and small power. Second, small power accounts for the greatest proportion of the electricity use. In addition, the lighting improvement has the largest electricity decrease, whereas other retrofit packages do not contribute much.

The annual gas supply is demonstrated in Figure 7.37. According to the chart, first, the gas consumption for heating is higher without IHGs than with IHGs, which indicates that the rooms without occupants, lighting and appliances need more gas for space heating. Second, the most considerable reduction is through the fabric improvement, which reduces the gas use by 97.2 kWh/m². Third, the gas supply also drops through the heating system improvement and solar thermal packages, of which the first mainly decreases the gas use for space heating and the second reduces the gas consumed for hot water.

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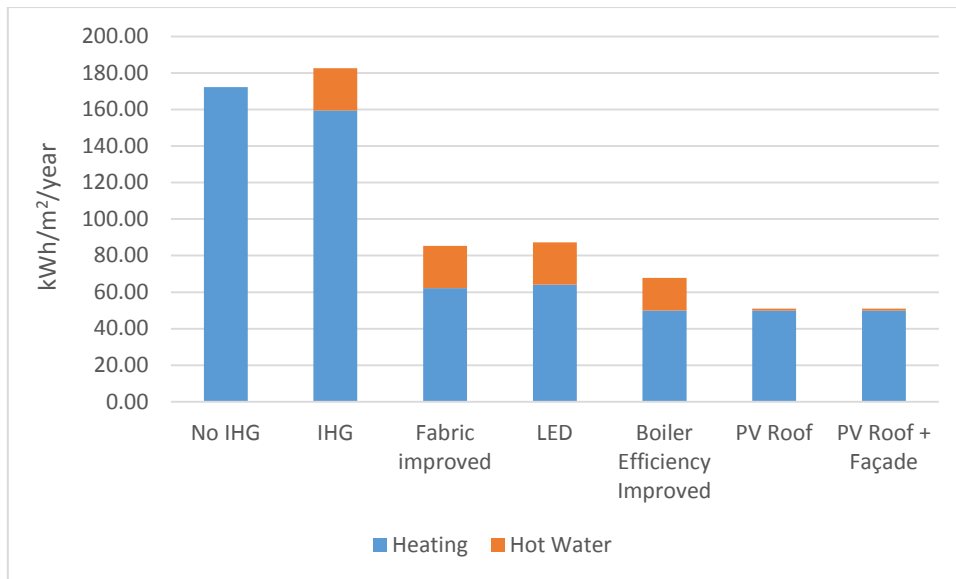


Figure 7.37 Annual gas supply of Community 4

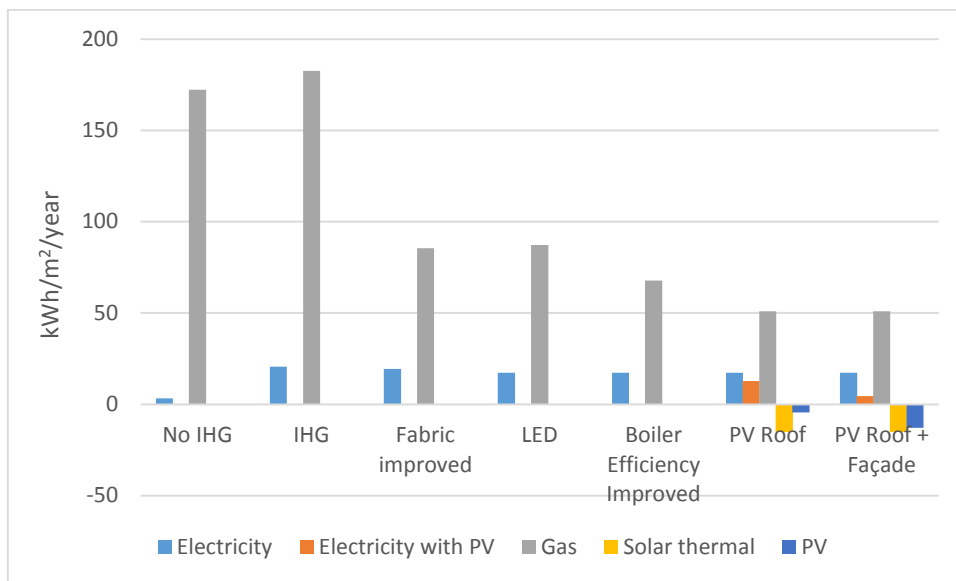


Figure 7.38 Summary of annual electricity and gas supply and renewables of Community 4

Figure 7.38 summarises the annual energy supply and the energy generation by renewables. To be more exact, first, the gas consumption declines gradually with the retrofit packages applied while the electricity consumption mainly remains stable after the fabric and system retrofitting. Second, after installing the solar PV, the electricity supply gently drops from 17.2 kWh/m² to 12.7 kWh/m² with the PV roof

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package and 4.4 kWh/m² with the PV roof and facade package. Besides this, the gas use decreases by 16.9 kWh/m² when solar thermal is installed.

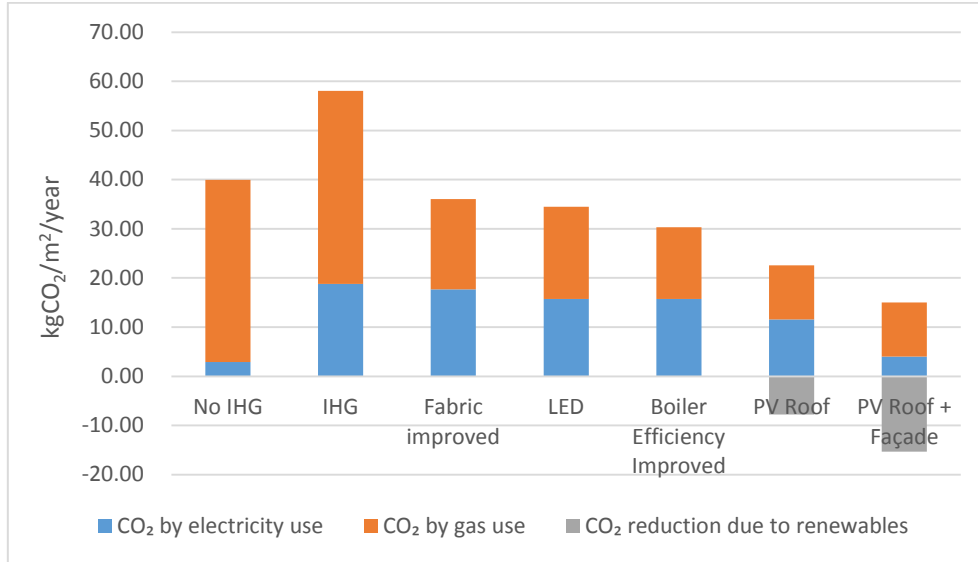


Figure 7.39 Summary of annual CO₂ emissions of Community 4

Figure 7.39 illustrates the annual CO₂ emissions of Community 4. As can be seen from the bar chart, first, the CO₂ emissions with IHGs are approximately one third more than that without IHGs. Second, the CO₂ emissions show a steady decline with a series of retrofit packages. In addition, the CO₂ emissions decrease apparently when adding the renewables, with the reductions of 7.8 kg/m² with PV roof package and 15.3 kg/m² with PV roof and facade package. This is because the electricity generated by the solar PVs offsets a part of the consumption and the solar thermal reduces a portion of the gas use for hot water.

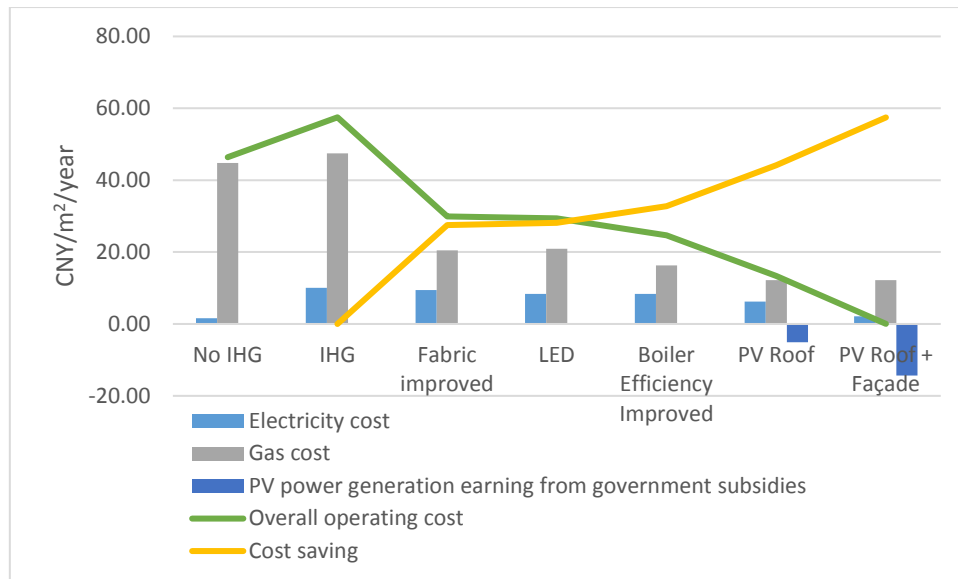


Figure 7.40 Summary of annual operating cost and savings of Community 4

Figure 7.40 summarises the annual operating costs, savings and the earnings from PV powers of Community 4. As shown from the graph, first, the overall operating cost is 11.1 CNY/m² higher with IHGs than without IHGs. Second, as the retrofit packages increasingly applies, the operating cost gradually declines, with the largest reductions in fabric improvement. Third, fabric retrofit brings the most decrease in gas cost of 27 CNY/m². Moreover, the renewables also have great performances in both electricity and gas cost reduction. Besides, with an increasing level of retrofit from fabric to renewables, the savings gradually increase, with a total annual savings of 51.2 CNY/m².

7.6. Analysis and Comparison of the Four Communities

After analysing the simulation results of each community, it is necessary to compare the results of the four communities to discuss the retrofitting impact on energy demand, energy supply, CO₂ emissions and operating costs and savings.

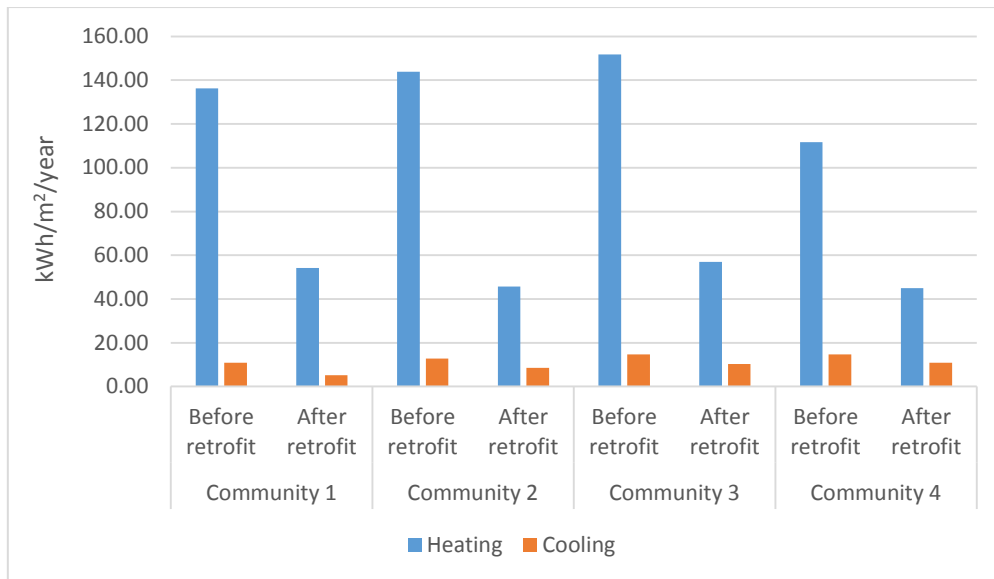


Figure 7.41 Annual heating and cooling demand of the four communities before and after retrofitting

Figure 7.41 illustrates the energy demand of the four communities before and after the retrofitting. According to the chart, first, the heating demands of the four communities are reduced drastically after retrofitting. Second, the cooling demands are not decreased much compared with the heating demands, where Community 1 of only mid-rise buildings declines the most, while Community 4 of only high-rises has the least reduction, which is similar to the result of the building scale.

Figure 7.42 describes the annual energy supply before and after retrofitting and the solar potential of the four communities. As can be seen from the graph, first of all, the energy supply declines dramatically after retrofitting, especially in gas consumption. Second, before retrofitting, the gas consumption in the older communities (Communities 1 and 3) is higher than that of the newer ones (Communities 2 and 4). Third, after retrofitting, the gas consumption drops to zero in Communities 1, 2 and 3 because of the installation of the GSHP system. Additionally, the electricity use in the four communities is similar before retrofitting. However, after retrofitting, Community 1 has the most significant reduction in electricity use, while Community 4 has the least reduction, and Communities 2 and 3 are in between. This is because Community 1 with only mid-rises has a larger proportion of roof area, so it has the

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greatest electricity generated by PV, whereas Community 4, with only high-rises, has the least amount of electricity generation.

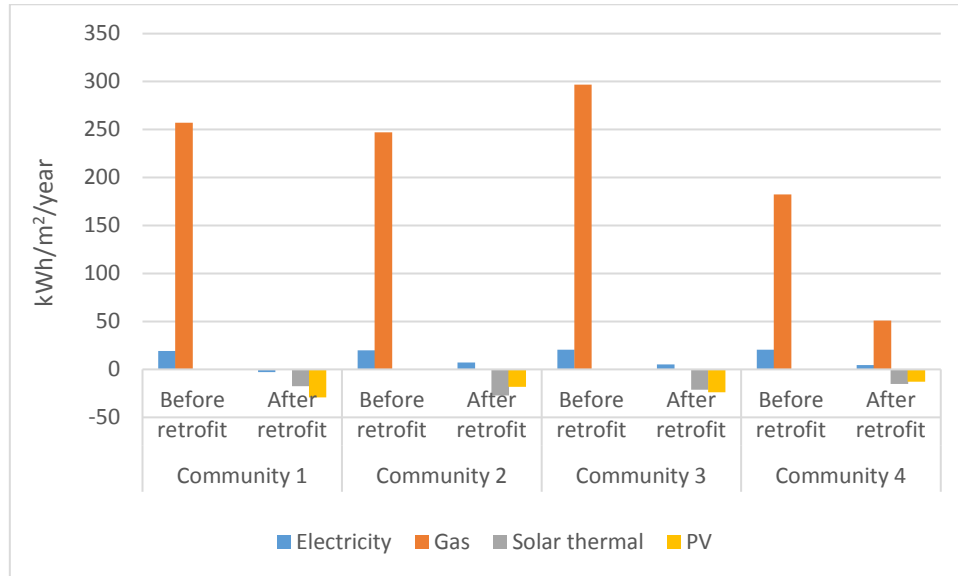


Figure 7.42 Annual energy supply and renewables of the four communities before and after retrofitting

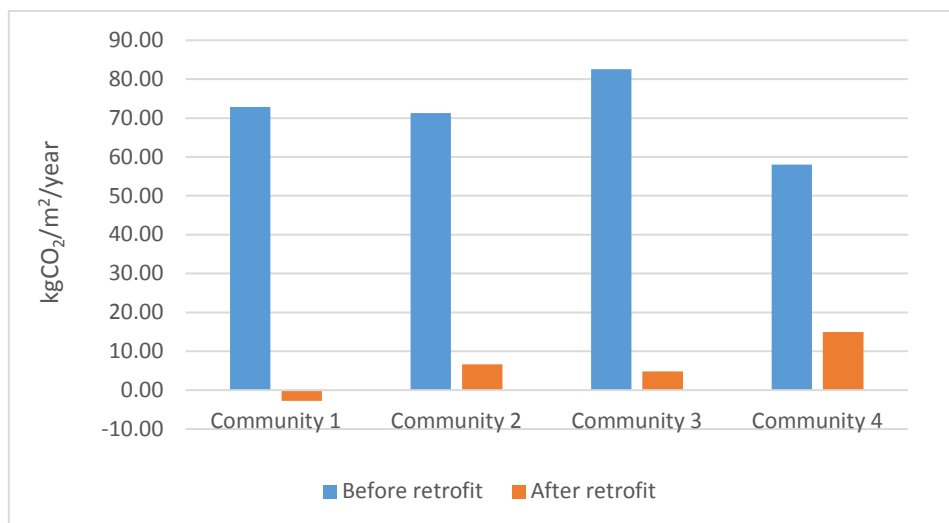


Figure 7.43 Annual CO₂ emissions of the four cases and communities before and after retrofitting

The annual CO₂ emissions of the four communities before and after retrofitting are shown in Figure 7.43. According to the chart, first, before retrofitting, newer communities (Communities 2 and 4) have lower CO₂ emissions compared to older

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ones (Communities 1 and 3), and Community 4 has the best performance. After retrofitting, Communities 1 and 3 have better performance than Communities 2 and 4 and Community 4 emits more CO₂ than the other three communities. In other words, older communities have more potential in reducing CO₂ emissions and the most recent built community has the most limited retrofit potential. Second, in terms of community type, Community 1, with its mid-rise buildings, has the greatest reduction of CO₂, whereas Community 4 with its high-rises, has the lowest CO₂ reduction, and the mixed communities are in between.

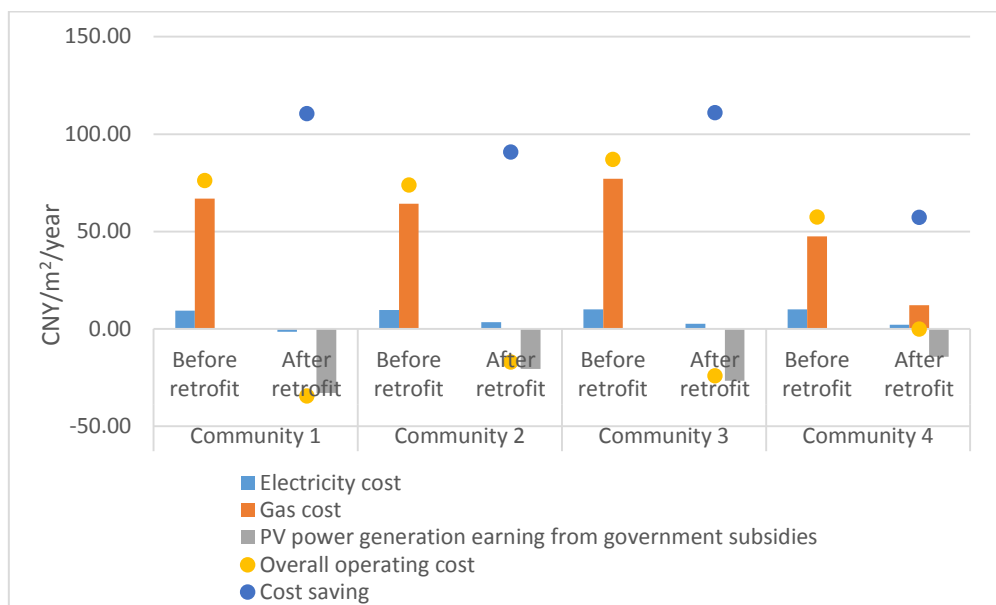


Figure 7.44 Annual operating cost and savings of the four cases and communities before and after retrofitting

Figure 7.44 summarizes the operating costs and savings of the four communities before and after the retrofitting. From the chart it can be seen that, first, older communities have higher overall operating costs before retrofitting, where the oldest, Community 3, has the highest. After retrofitting, the older communities have lower operating costs and more savings than the newer ones. Second, after retrofitting, Community 1, with its mid-rises, has the greatest electricity cost reduction and the lowest overall operating costs, whereas Community 4, with its high-rises, has the least electricity cost reduction and the highest overall operating cost. This is because a larger proportion

of roof areas in Community 1 enable solar PVs to generate more electricity, and this reduces electricity costs and overall operating expenses. Third, the gas costs drop dramatically after retrofitting, where Communities 1, 2 and 3 have no gas cost as a result of the GSHP installation.

7.7. Comparison of the Simulation Results between the Community and the Single Building

A comparison between the communities and single buildings of the same building type should be carried out. As Communities 2 and 3 are mixed, with two building types of multi-storeys and high-rises, they cannot be compared with either Case 2 or Case 3. Therefore, only Communities 1 and 4 can be compared with Cases 1 and 4 to see the difference between the two scales.

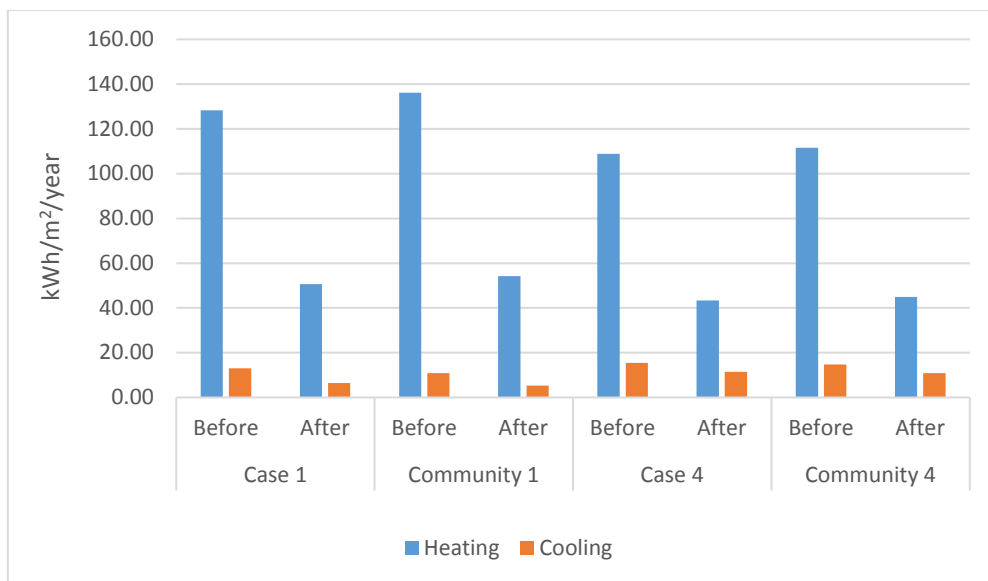


Figure 7.45 Annual heating and cooling demand between the community and single building

Figure 7.45 compares the annual energy demand between the communities and the single buildings. From the bar chart we can see that, first, the heating demands in communities are slightly higher and the cooling demands are moderately lower than those of the cases in building scale, as the effect of overshadowing by adjacent

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buildings increases the heating demand and decreases the cooling demand. Second, the difference between Case 1 and Community 1 is more obvious than that between Case 4 and Community 4, because the distance between buildings in Community 1 is closer than that in Community 4. Third, the community scale has more energy demand reduction than the building scale, with those of Communities 1 and 4 decreasing by 87.7 kWh/m² and 70.5 kWh/m², respectively, compared to those of Cases 1 and 4 by 84.4 kWh/m² and 69.5 kWh/m², respectively.

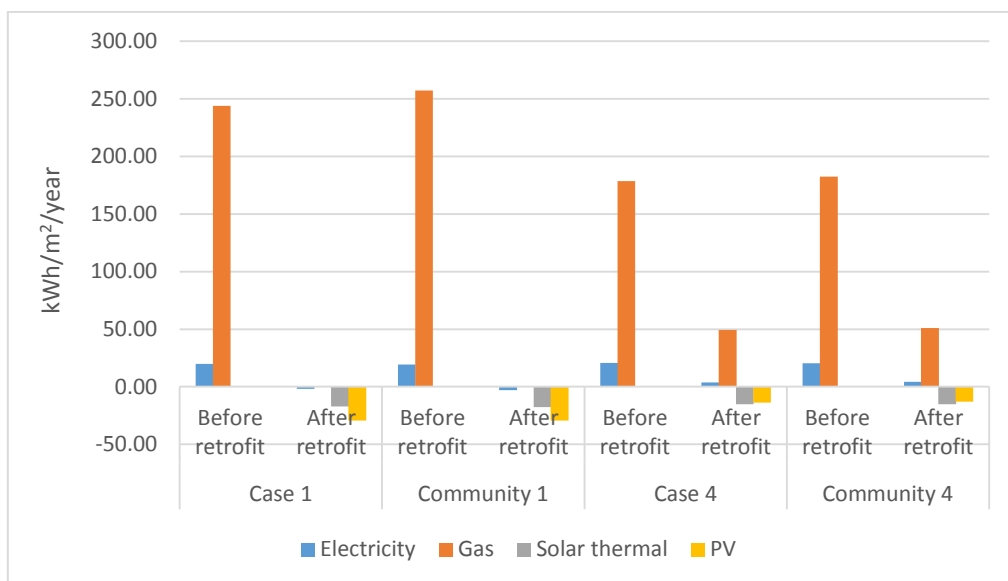


Figure 7.46 Annual energy supply and renewables between the community and single building

Figure 7.46 shows the annual energy supply and renewables between the communities and the single buildings. As can be seen from the chart, firstly, the electricity consumptions in communities are slightly lower and the gas consumptions are higher before retrofitting than those of the cases in building scale. This is also due to the effect of overshadowing by adjacent buildings, which increases the heating demand and decreases the cooling demand. The increase in heating demand increases the amount of gas use, and the reduction in cooling demand reduces the amount of electricity consumption. Secondly, it is worth noting that the amount of gas increase in community scale is larger than that of the electricity reduction, as the heating demand in northern China is greater than the cooling demand; the effect of overshadowing on heating loads is thus greater than that of cooling loads, and

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therefore the impact on gas is greater than electricity. Thirdly, the difference between Case 1 and Community 1 is more obvious than that between Case 4 and Community 4, especially in gas supply. In addition, the community scale has more reductions in energy supply than the building scale, with those of Communities 1 and 4 decreasing by 279.3 kWh/m² and 147.7 kWh/m², compared to Cases 1 and 4 by 265.7 kWh/m² and 146.5 kWh/m², respectively.

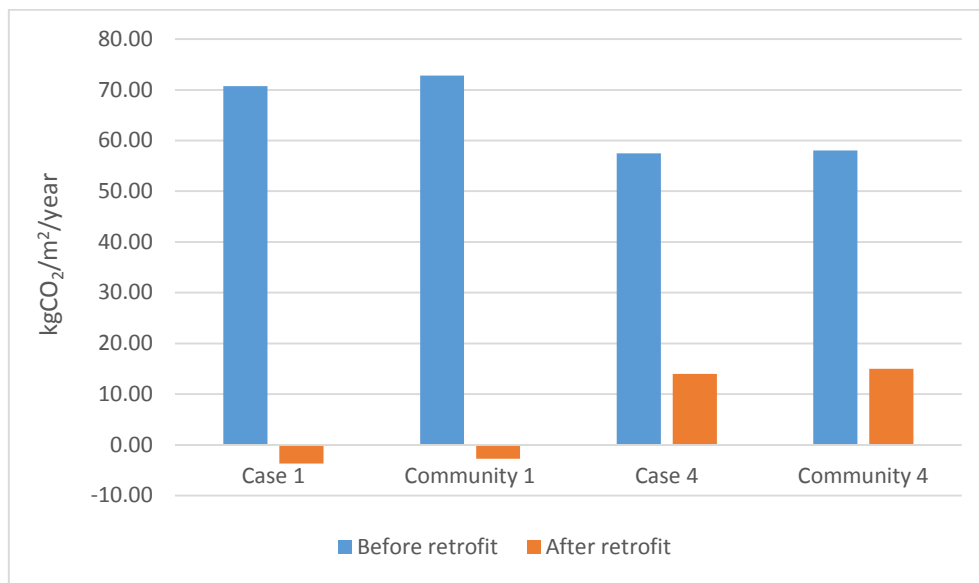


Figure 7.47 CO₂ emissions between the communities and the single buildings

Figure 7.47 demonstrates the annual CO₂ emissions between the communities and the single buildings. From the chart, first, the CO₂ emissions in communities are modestly higher than that of the cases in building scale before and after retrofitting, since the amount of gas increase is larger than that of the electricity reduction, the overall energy consumptions are slightly increased, and thus the annual CO₂ emissions are slightly higher at the community scale. Second, the communities have more CO₂ emission reductions than single buildings, with those of Communities 1 and 4 being reduced by 70.1 kg/m² and 73 kg/m², respectively, compared to Cases 1 and 4 by 67.1 kg/m² and 71.5 kWh/m², respectively.

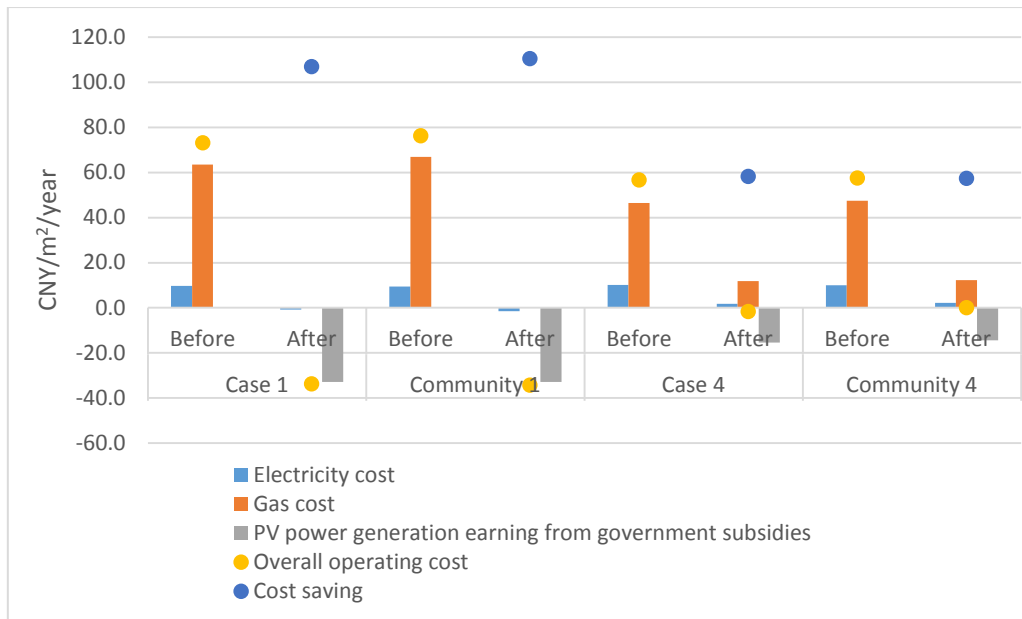


Figure 7.48 Annual operating cost and saving between the community and single building

Figure 7.48 summarises the annual operating costs and savings between the communities and the single buildings. Firstly, the electricity costs in communities are slightly lower and the gas costs are higher before retrofitting than those of the cases in building scale due to the impact of overshadowing. Secondly, the overall operating costs are moderately higher at the community scale than at the building scale before retrofitting, while after retrofitting, the results are different. The annual operating cost of Community 1 is lower than that of Case 1, whereas Community 4 is slightly higher than that of Case 4. Moreover, the annual savings of Community 1 is greater than Case 1, while Community 4 has slightly less savings than Case 4.

In terms of retrofit cost, it is suggested that the cost is 10% to 20% lower for large scale due to labour efficiency and transport savings (Palmer et al. 2017). The cost of construction material is also cheaper for large scale retrofit than those at the building scale due to economies of scale. Table 7-2 lists the retrofit costs and payback years for the four communities. It can be seen from the table that the payback years for the four communities are in the range of 10.2 to 14.4 years. After taking off 20% savings from large scale retrofit, the payback years decrease to 8.1–11.5 years.

Table 7-2 Retrofit costs and payback years for community scale

	Community 1	Community 2	Community 3	Community 4
Retrofit cost (CNY)	101–119 million (1073–1259/m ²)	126–148 million (1014–1194/m ²)	80–95 million (1092–1305/m ²)	84–87 million (598–617/m ²)
Payback year	10.2 - 11.9	12.2 - 14.4	10.2 - 12.2	10.7 - 11
Retrofit cost with 10% saving for large scale (CNY)	81–95 million (966–1133/m ²)	101–118 million (912–1074/m ²)	64–76 million (983–1175/m ²)	67–69 million (538–555/m ²)
Payback year	8.1 - 9.5	9.8 - 11.5	8.2 - 9.8	8.6 - 8.8

7.8. Multiple Benefits

Similar to the UK large scale retrofit case studies, the retrofitting of existing residential buildings at community scale in China also has multiple benefits beyond the purely environmental improvements.

7.8.1. Social Benefits

- **Job Creation**

Regarding job creation, take the research outcome by Janssen and Staniaszek mentioned in the UK case study for reference, 19 new local jobs would be created by every €1 million invested in retrofitting, which means that for every 1 million CNY spent on retrofitting, 2.4 new jobs would be created (currency: 1 EUR=7.8 CNY) (XE 2018). Thus, the four community retrofitting could create 748 to 860 new jobs for local people, which could increase the annual community income of 42.8 to 49.3 million CNY. Moreover, there are many indirect jobs generated from the supply chain, maintenance services and supporting industries.

• **Health Improvement**

In terms of health, according to the surveys and interviews in China, there are many elderly people living in the existing communities, who are at higher risk of illnesses due to cold, humid homes. According to a recent research (Jaakkola et al. 2014), every 1°C decrease in indoor temperature increases the risk of upper respiratory tract infections (URTI) by 4%, flu by 2% and laryngitis by 2%. As shown in Table 7-3, retrofitting can improve the indoor temperature of 1.8 °C to 2.1 °C, which could reduce the risk of URTI by 7.2% to 8.4%, flu by 3.6% to 4.2%, and laryngitis by 3.6% to 4.2%.

Table 7-3 Average indoor temperatures of four cases and communities before and after retrofitting

Scale	(Unit: °C)	1	2	3	4
Case at the building scale	Before retrofitting	20.6	20.4	20.7	20.8
	After retrofitting	22.4	22.2	22.6	22.9
Community	Before retrofitting	20.5	20.2	20.3	20.7
	After retrofitting	22.3	22	22.1	22.8

The statistics data shows that the average annual health care expenditure of urban residents in Beijing is 2,630 CNY per person. Therefore, the retrofit can reduce the health care cost up to 221 CNY per person each year, which would amount to 2.7 million CNY for the four communities.

In addition, when the indoor conditions get better, people are more willing to invite friends to their home, which is good for their physical and mental health of the residents.

• **Comfort enhancement and other social benefits**

There are more social benefits to existing community retrofit. For example, the indoor thermal comfort is improved due to increased room temperature and reduced humidity in winter. Also, the replacement of windows can reduce the noise from outside. Moreover, the awareness and willingness of residents to save energy can be increased. When they see other residents in the same community benefiting from the

retrofit, many residents of other buildings will start to express their willingness and support of energy efficiency retrofit.

7.8.2. Economic Benefits

- **Energy bill reduction**

The economic benefits of sustainable retrofit are reflected in reducing the energy bills due to the reduction of heating and cooling demands as well as the savings from renewables. According to the data published by Beijing Municipal Bureau of Statistics in 2016, the average annual income of the urban residents in Beijing is 57,275 CNY, and the income of the low income households is 25,812 CNY per person. The average annual expenditure of for living is 12,128 CNY per person, where the expenses for low income families is 5,548 CNY per person. The annual savings of the four retrofits at the community scale are in the range of 7.8 million to 10.3 million CNY. Therefore, each resident can save 2,452 to 9,957 CNY per year of their living costs through retrofit, which also reduces fuel poverty on the other hand.

- **GDP Growth**

In addition, if referring to the UK's estimation that every £1 invested in energy efficiency measures, there would have a payback of £3.20 to the government through increased GDP (Washan et al. 2014), then for the four retrofit projects at community scale with total retrofit cost of 312.3 million to 358.7 million CNY, the payback would be 999.4 million to 1,147.8 million CNY.

- **Asset Values Increasing**

Moreover, the asset value of the properties can be increased by retrofit. According to a report from *The Beijing Times* (2018), since the existing communities are relatively well located, the average increase in house prices is generally more than 10% after retrofitting, and the maximum increase in a single community is close to 50%. The rent rises 1,000 to 2,000 CNY per month after retrofitting, which is a 15% to 30% increase.

7.8.3.Environmental Benefits

- **Renewable Potential Increasing**

Communities have a larger potential for applying renewable energy than individual buildings. First, for communities mixed with multi-storey, mid-rise and high-rise buildings, there is more potential for using solar energy than single high-rise buildings, as the multi-storeys and mid-rises increase the proportion of the roof areas of the community, thereby increasing the total electricity generated by solar PV. For instance, Case 3 as an individual building has an annual electricity generation from solar PV of 16.4 kWh/m², which increases to 23.7 kWh/m² in Community 3.

Also, as a high-rise building with high plot ratio, Case 3 at the building scale is not suitable for applying GSHP, whereas at the community scale, the installation of GSHP becomes possible with other mid-rise buildings.

In addition, some buildings without an optimal orientation for solar PV as single buildings can benefit from the net electricity production within the community if combined with energy battery storage and the reasonable distribution of government subsidies.

- **Air Quality Improvement**

Beijing, as the capital of China, has suffered from serious air pollution for many years. Sustainable retrofitting can improve the energy efficiency, so that can significantly reduce the CO₂ emissions from building sectors. The total annual CO₂ emission reduction of the four community retrofits is 26.9 million tCO₂. The benefits will increase when the scale becomes larger.

- **Resource Saving**

Improving energy efficiency through retrofit can save both renewable and non-renewable resources such as electricity, gas and water.

There are more environmental benefits of existing community retrofit, such as energy delivery improvement, and the improvement of the aesthetics of community environment.

7.9.Lessons and Retrofit Suggestions of Existing Community Retrofit

7.9.1.Policies and Regulations

Policies and regulations are essential to retrofitting existing communities. The following suggestions and issues should be considered:

- The targets, policies and regulations should be optimised specifically for retrofit. Appropriate preferential policies should be established to encourage more companies to actively participate in the existing community retrofit. Meanwhile, for some newly issued policies and regulations, the supporting documents should be issued as soon as possible to explain in details.
- The speed of updating relevant retrofit standards should be increased in order to adapt to the development of the situation of the sustainable retrofitting of existing residential buildings.
- The heating system reform should be carried out as soon as possible. The energy bills should be charged according to usage instead of housing area. After the improvement of building envelope, the effect of energy saving by occupants becomes more obvious. Only by linking energy saving with the economic interests of the residents can the final energy saving effect be guaranteed.
- Relevant evaluation and supervision standards should be developed for existing residential building retrofit, and the evaluation, supervision and management process should be put into practice to ensure the retrofit effect.

7.9.2.Retrofit Measures

- When selecting the retrofit technologies, the appropriate, practicable combination of technologies should be adopted according to different climate zones, locations, the building types and ages, as well as the occupants' behaviour, long term maintenance, and funding availability.
- Fabric improvement should be given priority for the buildings with poor insulation, while for newer buildings with better insulation and airtightness, it is good to consider renewables for more energy savings and CO₂ emissions reduction. In order to achieve the best retrofit results, it is suggested to use the whole-house approach when there is enough funding.

7.9.3.Implementation

- A detailed survey should be made as early as possible to obtain accurate data, which are critical to ensure that appropriate retrofit measures can be identified.
- Modelling is a good way to design and decide upon the most appropriate energy efficient and cost effective retrofit solutions. The IHG over time has a large impact on accurately simulating the real-time energy performance, which should be taken into account when doing the simulations.
- Professional and systematic training should be provided to the builders before the retrofitting to ensure the construction quality and retrofit performance.
- The implementation process should be effectively organised and managed, and the construction time should be well-planned.
- It is significant to monitor the works before, during and after the retrofitting to precisely evaluate the retrofit quality, performance and to solve problems in time.
- If the budget is sufficient, it is suggested to adopt the 'whole-house' approach for retrofitting the existing residential buildings, and it should be ideally carried out at one step to make it more cost-effective and save time and resource.

7.9.4.Financing of Retrofit

- Since most of the residents in the existing communities are low and middle income people, it is recommended to use funds from government and local authorities as the main retrofit funding and the remaining funds to be shared by the beneficiaries in order to motivate the enthusiasm of residents to participate in the retrofit. Meanwhile, new financing channels should be developed such as financial institution loans and market financing.
- It is crucial to plan and assess the retrofit costs, carefully including the fixed capital costs and operating costs for maintenance and project management.
- Regarding the distribution of solar PV generation, it is suggested that the construction cost should be jointly funded by the government, local authorities, residential property management, property owners, and grant support mechanisms. The income from electricity generation and government subsidies can be managed and distributed by the property management in the community and deducted from property management fees on a monthly or yearly basis. This not only makes it easier to manage and collect property management fees, it also makes it easier to avoid unnecessary disputes between residents.

7.9.5.Working with Residents

- Publicity work should be done well before the retrofit, focusing on the multiple benefits brought by the retrofit, so that residents can fully understand the retrofit process and effects.
- A survey should be made before the retrofit in order to learn about the opinions of the residents towards retrofit.
- When it comes to the indoor work, construction work should be arranged appropriately to minimise the impact on the daily lives of the residents. For example, the window replacement can be arranged together with the heating system retrofit

to increase the work efficiency and minimise the duration that workmen have to enter the property.

- In the process of retrofit, communication and coordination with residents should be maintained to resolve the contradiction between the construction team and the residents.
- After retrofit, a follow-up survey should be made with residents in order to obtain their feedbacks in terms of the implementation process.
- Training and guidance should be given to residents, so they can learn to use and maintain the energy efficient facilities. It is essential to provide easily understandable information about the building for the occupants. This is a prerequisite to best ensure the designed retrofitting strategy has a chance to become an actual strategy.

7.10. Summary

This chapter provided the energy simulation of the four Chinese cases at the community scale and broader related issues.

Comparing the simulation results of the communities with cases at the building scale, there are two differences worth noting. The first is that the heating demands of the communities are slightly more than the cases at the building scale, while the cooling demands of the communities are less due to the overshadowing of buildings by adjacent buildings. The second is that the energy reduction is higher at the community scale than at the building scale: with 13.6 kWh/m² higher for Community 1, with only mid-rise buildings and 1.2 kWh/m² higher for Community 4, with only high-rise buildings.

This chapter also examined the effect of the 'whole-house' retrofitting approach and discussed it with multiple benefits across social, economic, and environmental aspects. The multiple benefits of the existing residential building retrofitting in China are referred to the UK case studies and summarised in Table 7-4 as below.

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Table 7-4 Multiple benefits of existing residential building retrofitting in the UK and China

Multiple benefits		UK	China
Social benefits	fuel poverty alleviation	<ul style="list-style-type: none"> • 291,000 houses suffering from fuel poverty. • As homes become more energy efficient, residents can have more and better energy services with lower energy bills. 	<ul style="list-style-type: none"> • Many residents living in the existing communities are low income people. • Save the living cost through lower energy bill by retrofit.
	Job creation	<ul style="list-style-type: none"> • 160,050 person-years of employment in total for the local area with £7,275 million investment on whole house retrofit for welsh houses in fuel poverty. • increase the income of around £4148 million for local residents. • Some people benefited from the trainings and started their own companies after that. 	<ul style="list-style-type: none"> • The four community retrofits could create 748 to 860 new jobs for local people. • Increase the annual income of 42,841,700 to 49,256,500 CNY for local residents. • Many indirect jobs generated from the supply chain, maintenance services and supporting industries.
	Health improvement	<ul style="list-style-type: none"> • For £7,275 million investment in whole house retrofit to remove fuel poverty in Wales, it would have an expected annual NHS saving of £3055.5 million. • Improve physical and mental health of the residents by improving the indoor air quality and providing warmer and more comfortable indoor environment through retrofit. 	<ul style="list-style-type: none"> • Improve the indoor temperature of 1.8 °C to 2.1 °C, which could reduce the risk of URTI by 7.2% to 8.4%, flu by 3.6% to 4.2%, and laryngitis by 3.6% to 4.2%. • Reduce the health care cost up to 221 CNY per person each year, which is 2,735,538 CNY for the four communities. • People are more willing to invite friends to their home, which is good for the physical and mental health of the residents.
	Comfort enhancement	<ul style="list-style-type: none"> • Increase the internal temperature of 1°C or 2°C to the existing housings, improving the thermal comfort of the occupants. • Improving the air tightness would reduce draughts in the house. 	<ul style="list-style-type: none"> • The indoor thermal comfort is improved due to increased room temperature and reduced humidity in winter.

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Economic benefits	Energy bill reduction	<ul style="list-style-type: none"> It is estimated that in the UK, £8.61 billion spent on energy bills could be saved if the EPC ratings of all households were increased to band C by 2035 through retrofit. Retrofitting the 291,000 Welsh houses in fuel poverty could save more than £180 million on their annual energy bills. 	<ul style="list-style-type: none"> The annual savings of the four retrofits at community scale are in the range of 7,790,420.76 CNY to 10,284,949.32 CNY. Each resident can save 2,452 CNY to 9,957 CNY per year of their living cost through retrofit.
	GDP growth	<ul style="list-style-type: none"> For £7,275 million investment in the 291,000 Welsh houses in fuel poverty would be returned of £23 billion to the government via increased GDP, and £9 billion in tax revenues. 	<ul style="list-style-type: none"> For the four retrofit projects at community scale, the payback would be 999,417,952.7 CNY to 1,147,811,166 CNY.
	Asset values increasing	<ul style="list-style-type: none"> The property value and rental level of existing buildings could be increased. Individuals and businesses are willing to pay rent or sales for more energy efficient properties. 	<ul style="list-style-type: none"> The average increase in house prices is more than 10% after retrofit, and the maximum increase in a single community is close to 50%. The rent rises 1,000 to 2,000 CNY per month after retrofit, which is 15% to 30% increase.
Environmental benefits	Energy delivery improvement	<ul style="list-style-type: none"> Investing in energy efficiency in housing will reduce 26% of natural gas imports in 2030, which will save £2.7 billion in that year. 	<ul style="list-style-type: none"> Energy providers can save their costs on the operation and increase their profit margins as well as provide better service to their customers.
	Resource saving	<ul style="list-style-type: none"> With local suppliers and contractors involving large-scale retrofit can save more cost, time and resources in transportation, installation, maintenance, and management process. 	<ul style="list-style-type: none"> Improving energy efficiency through retrofit can save both renewable and non-renewable resources such as electricity, gas and water.

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	Air quality improvement	<ul style="list-style-type: none"> • Improve the air quality due to the air pollutions emission being reduced at the energy generation stage as well as the direct fuel combustion stage in houses 	<ul style="list-style-type: none"> • Improved energy efficiency can significantly reduce the CO₂ emissions from the building sectors. • The total annual CO₂ emission reduction of the four community retrofits is 26131.53 tCO₂.
	Renewable potentials increasing	<ul style="list-style-type: none"> • Large scale retrofit has a lager potential for applying renewable energy than the individual building. 	<ul style="list-style-type: none"> • For some buildings without an optimal orientation, roof area proportion or plot ratio for solar PV or GSHP as single build can benefit from the community.

Moreover, this chapter put forward some suggestions and guidance based on the research outcomes for the retrofiting of existing residential buildings in China. The suggestions revolve around five topics including policies and regulations, retrofit measures, implementation, financing of retrofit, and working with residents. These suggestions provide a reference for the future retrofiting of existing residential buildings in China.

Through this chapter, the research question of ‘how to improve the existing communities in China through sustainable housing retrofit to create a high-quality living environment’ has been answered.

Chapter 8 Conclusion and Recommendations

8.1. Introduction

This chapter begins with brief summary of the research process. It then describes the main findings, the implications of research outcomes, the limitations of the study, and recommendations for future research. This chapter closes with a short conclusion to the thesis.

8.2. Conclusion

As discussed in Chapter 1, the aim of this research is:

‘to investigate the retrofit projects in Wales, UK to explore the retrofitting of existing residential buildings at the community scale in Beijing, China to find out how and to what extent the retrofit technologies and processes can be transferred from the UK to China, and the most suitable, sustainable, cost-effective combination of retrofit strategies to improve energy efficiency and sustainability’.

There are five objectives in order to achieve the research aim:

1. To identify the definition, development, reason and importance of sustainable retrofit;
2. To explore the UK’s retrofit methods, implement processes, technologies, financial schemes, and multiple benefits through the examination of practical projects;
3. To discover the problems of the current retrofitting of existing residential buildings in China to find out the gap between the UK and China;

4.To identify the most suitable, sustainable, cost-effective retrofit approaches in transferring the technologies and processes from the UK to China to improve existing housings and communities;

5.To discuss research outcomes with more social, economic aspects and multiple benefits to provide suggestions and guidance for retrofitting residential buildings in China to create a high quality living environment.

The conclusion is structured according to the five objectives.

8.2.1.Definition, Drivers and Reasons for Sustainable Retrofitting in China

Through the literature review, it is found that, firstly, sustainable retrofit can be defined as ‘incremental improvements to the building fabric and systems with the primary intention of improving energy efficiency and reducing carbon emissions’. Secondly, the drivers and reasons of retrofitting existing residential buildings in China are: first, the numbers of existing buildings in China are three times that in developed countries, accounting for about 50% of the world’s total, and more than 90% are high energy consumption buildings. Second, residential buildings account for more than two-thirds of the total energy consumption of building sectors. In addition, the air pollutions in recent years in China is severe, which promotes the process of retrofitting existing buildings. Moreover, retrofitting of existing residential buildings provides opportunities to reduce energy consumption and CO₂ emissions, which could improve the energy efficiency, sustainability, as well as air quality and peoples’ quality of life.

8.2.2.Low Carbon Housing Retrofitting in Wales, UK

Through the literature review and the case studies in the UK, it is found that most of the large scale retrofitting projects in the UK mainly conduct elemental retrofit, which generally uses one or two retrofit measures, such as the Warm Wales Arbed 1 and the Neath Port Talbot retrofitting programme. The retrofit costs are usually low, and the

reductions of buildings' energy consumptions and CO₂ emissions are in the range of 10% to 30%.

Meanwhile, there are some examples of deep retrofit in the UK at small scales, such as the five SOLCER retrofit projects. The CO₂ emission reductions are shown to be in the range of 50% to 70%, but the retrofit costs tend to be expensive, so that large scale deep retrofit has not been considered to be financially available. The payback years of the five SOLCER retrofit projects are from 46 to 63 years, so evaluating the energy retrofit simply by energy savings is difficult. Now the UK starts to look at multiple benefits of retrofit relating to issues like reducing fuel poverty, creating jobs, and improving peoples' health.

Therefore, the existing housing retrofitting result cannot be evaluated by simply calculating the energy savings and CO₂ emission reductions. There should be a comprehensive evaluation in combination with multiple benefits in social, environmental and economic aspects.

8.2.3. Problems and Challenges of Current Housing Retrofit in China

From the literature review and interviews in China, it is found that, firstly, there are many problems of current housing retrofit projects in China including:

- Slow updated and non-mandatory residential energy efficiency standards;
- Poor workmanship and a lack of supervision and quality control;
- The original design data and detailed information of the properties is missing;
- A low level of standardisation of building materials;
- A lack of a complete organisation system for energy efficiency retrofit;
- No long-term investment and financing mechanism;
- Heating reform has not been put into practice in most of the existing communities;
- A lack of a holistic retrofit approach for existing residential buildings;

- A lack of a systematic set of monitoring and verification criteria for existing residential building retrofit;

China also has great challenges to achieve sustainable retrofit of existing residential buildings, including high energy consumption in buildings, overloaded environmental capacity of waste absorption, low industrialisation in residential building system, poor overall building thermal performance, and insufficient understanding of energy efficiency of residential buildings.

Therefore, China may benefit from experiences from the UK, and combine these with China's situation to develop suitable retrofit strategies for China's existing residential buildings. The main experiences can be transferred from the UK to China are the whole-house retrofit approach and multiple benefits of sustainable retrofit. There are other experiences can be transferred, such as the retrofit procedure, surveys at both pre-retrofitting and post-retrofitting stages, energy consumption prediction methods, and monitoring and management mechanism.

8.2.4. Evaluating the Impacts of Different Retrofitting Measures and Packages on the retrofitting of Existing Residential Buildings at Different Ages, Types and Scales

From the case studies in China by simulation, the findings are as follows:

- Draught proofing is the most efficient retrofitting measure in reducing energy demand and gas supply. The individual measure of draught proofing can reduce energy demand by 20.2% to 25.9%, and the retrofitting package can save 34.9% to 41.1%. The individual measure of draught proofing can contribute to gas reduction of 23.6% to 33%, and the retrofitting package can reduce it from 42% to 47.2%.
- Solar PV is the most efficient retrofitting measure to reduce electricity use and CO₂ emissions. The electricity reductions are from 65.8% to 157.1% for individual measure, and from 82.2% to 179.2% for retrofitting package. The CO₂ emissions reductions are from 17.8% to 50.7% for individual measure, and from 75.6% to 100.5% for retrofitting

Chapter 8 Conclusion and Recommendations

package. In addition, the performance is better in lower storey buildings than high-rises due to a larger proportion of roof areas. In terms of the operating cost, the PV package can save 101.5% to 135.5%.

- The measure of upgrading the heating system also has good performance in reducing gas consumption, with reductions of 22.2% to 33.3% for individual measure, and 62.3% to 68.7% for retrofitting package. Also, the retrofit result is better in older buildings than newer ones.
- EWI has better retrofitting performances in high-rise buildings compared to lower storey buildings. By contrast, roof insulation shows better results in multi-storey and mid-rise buildings than high-rises due to the proportion of roof area. Moreover, the effect of increasing the thickness of the insulation board from 50 mm to 100 mm is not as good as changing the windows from single glazing to double glazing.
- Low-E glazing has better performance than double glazing in reducing energy demand, energy supply, CO₂ emissions and operating cost. Whereas double glazing mainly reduces heating loads, low-E glazing reduces both heating and cooling loads due to the coating.
- The GSHP package in multi-storey and mid-rise buildings would significantly improve energy performance, with electricity reductions of 93.7% to 118.9%, gas reductions of 100%, CO₂ emissions reduction of 101% to 105.2% and operating cost reductions of 144.1% to 148.4%.
- Reducing energy demand is a significant way to reduce energy consumption, which provides the potential for adopting renewable energy like PV to achieve most of the energy supply needs.
- The retrofitting measures will vary due to dwelling type and age when improving existing residential buildings. Older properties with poor insulation have the highest potential for improvement and need to focus on fabric measures. For properties built to more modern standards, there needs to be more of a focus on renewables such as solar PV and GSHP to achieve an improvement. The best retrofitting results can be

achieved by applying the highest specification with a whole-house approach, which combines the fabric, system, and renewable retrofitting measures.

- In comparing the community with the building scales, the heating demands of the communities are slightly more than those of single buildings, while the cooling demands of the communities are less due to the overshadowing of buildings by adjacent buildings. In addition, the energy reduction is higher at the community scale than at the building scale. In this study, the simulation showed that energy use was 13.6 kWh/m² higher for Community 1, with only mid-rise buildings, and 1.2 kWh/m² higher for Community 4 with only high-rise buildings.
- For solar energy application, there is more potential for communities mixed with multi-storey, mid-rise and high-rise buildings than for communities with only high-rise buildings, as the multi-storeys and mid-rises increase the proportion of roof area, thereby increasing total electricity generation.
- In terms of retrofit cost, at the building scale, the retrofit costs of the four cases in China are ranging from 597.9 CNY/m² to 915.1 CNY/m², and the payback years are from 7.6 to 11.8 years, with retrofit packages of fabric, system, solar thermal and solar PV. After installing the GSHP in Case 1 and Case 2, the retrofit costs increased to 1066.9–1365.1 CNY/m² and the payback years extended to 10.4–12.6 years. The costs for whole-house retrofitting in China are in the range of 597.9 CNY/m² to 1365.1 CNY/m², and the payback years are between 10.4 to 12.6 years. When scaling up to the community scale, the retrofit cost is 10% to 20% lower due to labour efficiency and transport savings, and the payback years can be reduced to 8.1 to 11.5 years.

The above findings show that the fabric retrofit measures should be given priority to the older buildings with poor insulations and airtightness, while renewables such as solar PV and GSHP are the most efficient retrofit measures to save energy and reduce CO₂ emissions, which should be developed at all scales. Although the case studies evaluated many individual retrofit measures and packages, the central idea of the thesis conclusion is to integrate all retrofit measures and design a suitable retrofit solution based on factors such as housing type and age. The best retrofitting results can be achieved by applying the whole-house approach which combines the fabric,

system, and renewable measures. As the whole-house retrofit scales up in numbers, the retrofit costs will be further reduced.

8.2.5. Multiple Benefits of Existing Housing Retrofitting

Through the case studies in the UK and China, this research has illustrated that the retrofitting of existing housing stocks can not only improve energy efficiency and reduce CO₂ emissions but also bring multiple benefits in environmental, social and economic aspects.

In the social aspect, the benefits include fuel poverty alleviation, job creation, health improvement and comfort enhancement. In the economic aspect, the benefits are energy bill reduction, public health spending reduction, and increases in disposable income, GDP growth and asset values. In the environmental aspect, there are the benefits of energy saving, CO₂ emissions reductions, natural resource saving, community appearance improvement and air quality improvement. The multiple benefits from existing housing retrofitting manifested across different levels, from the building level to the international level. The benefits of whole-house retrofitting, especially on a large scale, could go beyond the purely environmental achievements.

8.3. Suggestions for Retrofitting Existing Residential Buildings in China to Create a High Quality Living Environment

From the UK case study, it was found that accurate surveys and assessments at the early stage, audits and communications with residents during the whole process, and follow-up works and advice services after the retrofitting are essential throughout the retrofitting process. In addition, it was found that it is important to apply retrofitting measures according to the age, type, tenure, and size of properties. The suggestions for retrofitting existing residential buildings in China are listed in Table 8-1 below:

Table 8-1 Suggestions and guidance for existing housing retrofit in China

Policies and regulation	<ul style="list-style-type: none"> • The targets, policies and regulations should be optimised specifically for retrofitting. • The speed of updating relevant retrofitting standards should be increased. • The heating system reform should be carried out as soon as possible. • Relevant evaluation and supervision standards should be developed for retrofitting and put into practice.
Retrofitting measure	<ul style="list-style-type: none"> • The retrofitting technologies should be adopted appropriately and practically according to location, weather, building type, age, occupants' behaviour, maintenance, and funding availability. • Fabric improvement should be given priority to the buildings with poor insulation. • Newer buildings with better insulation should consider renewables for more energy saving and CO2 reductions. • When funding is available, applying the 'whole-house' approach at one time can achieve the best retrofitting result.
Implementation	<ul style="list-style-type: none"> • A detailed survey should be made as early as possible to obtain accurate data. • Modelling is a good way to design and decide the most appropriate energy-efficient and cost-effective retrofitting solutions. • Professional and systematic trainings should be conducted to the builders before the retrofitting. • The implementation process should be effectively organised and managed, and the construction time should be well-planned. • Monitoring and supervision should be conducted throughout the retrofitting process. • The retrofit should be carried out using 'whole-house' approach as one step to save time and resource.
Financing of retrofitting	<ul style="list-style-type: none"> • The funding should be shared by the government, local authorities, and the beneficiaries. • The retrofitting costs should be carefully planned. • The income from electricity generation and government subsidies can be managed and distributed by the property management in the community.

Working with residents	<ul style="list-style-type: none">• Publicity work should be done well before the retrofitting to earn understanding and support from residents.• Surveys should be made both before and after the retrofitting to learn the opinions and feedbacks from the residents.• The indoor construction work should be arranged appropriately to minimise the impact on the daily lives of the residents.• Communication and coordination with residents should be maintained throughout the retrofit.• Training and guidance should be given to residents, so they can learn to use and maintain the energy efficient facilities.
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Overall, this research not only transfers a method from the UK to investigate and evaluate the effect of different retrofitting measures and combinations on China's existing residential building retrofitting at both the building and community scales, it also discusses the multiple benefits of retrofitting in its social, economic, and environmental aspects and gives practical suggestions for the sustainable retrofitting of existing communities.

8.4.Limitations of this Research

Although this research aimed to explore the retrofitting of existing residential buildings at a community scale in China and compare it with the UK in order to improve energy efficiency and sustainability, it must be acknowledged that this research has certain limitations.

Firstly, this research focuses on four retrofitting projects at the building and community scales. Although these cases are typical residential buildings selected by building age and type, they cannot represent all existing residential buildings with different types and ages. In addition, weather conditions are closely related to energy demand, and this research investigates the climate in the UK and cold zones in China, so there are differences in climate outside the UK and other climate zones in China. Thus, some of the outcomes from this research may not apply to other contexts.

Secondly, the energy consumption and CO₂ emissions of buildings exist throughout their life cycle. This research did not consider the embodied energy during the process

of material productions and transportations from site to site, which may result in inaccuracies of the real conditions.

Thirdly, the dynamic calculation of the IHG is based on a pre-study in the UK. Although the data has been adjusted according to China's energy consumption, it must be recognised that pre-existing work was limited and the accuracy of the UK study may directly affect the accuracy of this research.

Moreover, the boundaries and scope of this research have necessarily been limited in response to available time and resources. For example, this research revolves around the existing residential buildings, so non-domestic projects are not within the scope of comparison. Another example is that this research focused on typical, non-historical existing residential buildings, so the research outcomes cannot be compared with historical buildings.

Lastly, this research did not compare the simulation results with monitoring data, as it is not possible to carry out the retrofitting monitoring in China without a series of government approvals and cooperation with urban planning departments, architectural design institutions, community property managements and residents. There are also problems like the availability and installation of monitoring equipment and the complexity of data collection afterwards.

8.5. Recommendations for future studies

The findings of this research have suggested a number of potential paths for future research.

Firstly, this research focused on the retrofitting of existing residential buildings, so more simulation for different building types such as commercial and industrial buildings can be explored and discussed. In addition, some retrofitting measures were not included in this research such as mechanical ventilation and combined heat and power cogeneration due to the limitations of building types and the research object. Future studies could investigate the energy performance of existing building retrofitting in different climate zones and at larger scales such as the urban scale.

Secondly, this research suggests that the technical tools can be improved continuously by taking more variables into account like microclimates at the urban scale. Also, wider aspects and issues can be considered and calculated together when investigating urban retrofitting such as heat gains from transportation and urban heat islands, parking in the community, and building retrofitting for the elderly.

Moreover, pre-retrofitting and post-retrofitting monitoring can identify how the building performs in reality, which can be compared with the simulation results and local standards and benchmarks, to evaluate the accuracy of the simulation tools and methods, as well as to understand the energy savings achieved.

Lastly, this research outcome could be integrated with the GIS system and combined with other statistical data such as residents' income or health data to locate the areas most in need of retrofitting and evaluate the overall impact of sustainable retrofitting on community residents and the city as a whole. These all present obvious directions for further work and research in these domains could further help us to understand and analyse the optimal solutions of sustainable retrofitting to improve energy efficiency, residents' quality of life, and reduce CO₂ emissions in China and around the world.

China's sustainable retrofitting of existing communities is still in its infancy and exploration stage, and it needs to shift the retrofitting concept from simply focusing on meeting the energy indicators and CO₂ emission targets to a more holistic perspective. It is critical to comprehensively take into account the retrofitting measure integration to achieve an optimum balance between technologies and cost-effectiveness. It is also important to consider the multiple benefits of the whole-house retrofit approach especially on a large scale in terms of environmental, social and economic aspects in order to meet the energy saving related objectives and create a high-quality living environment.

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Appendix 1

This appendix contains additional information on the results of the annual heating and cooling gains, ventilation gains, fabric gains and solar gains of the four cases at the building scale after retrofitting by different measure packages in Chapter 6.

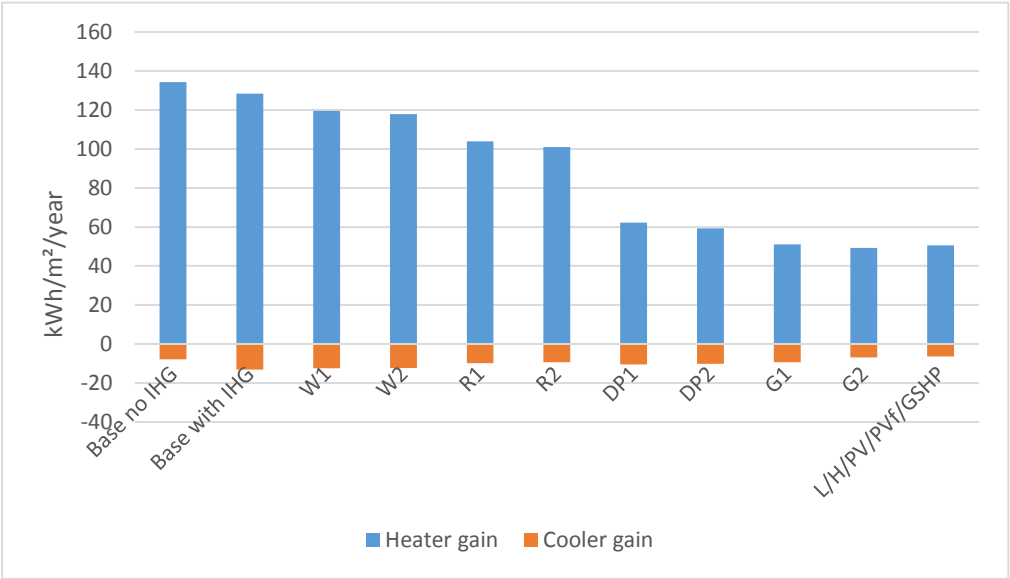


Figure A.1 Annual heater and cooler gains of Case 1 for a range of retrofit measures (ref: Table 6-7)

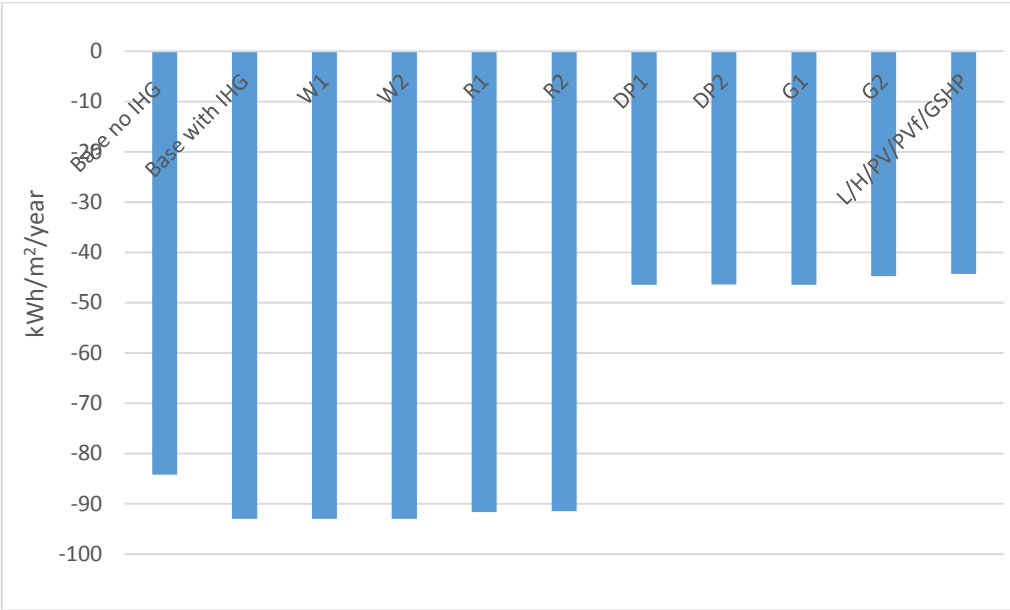


Figure A.2 Annual ventilation gains of Case 1 for a range of retrofit measures (ref: Table 6-7)

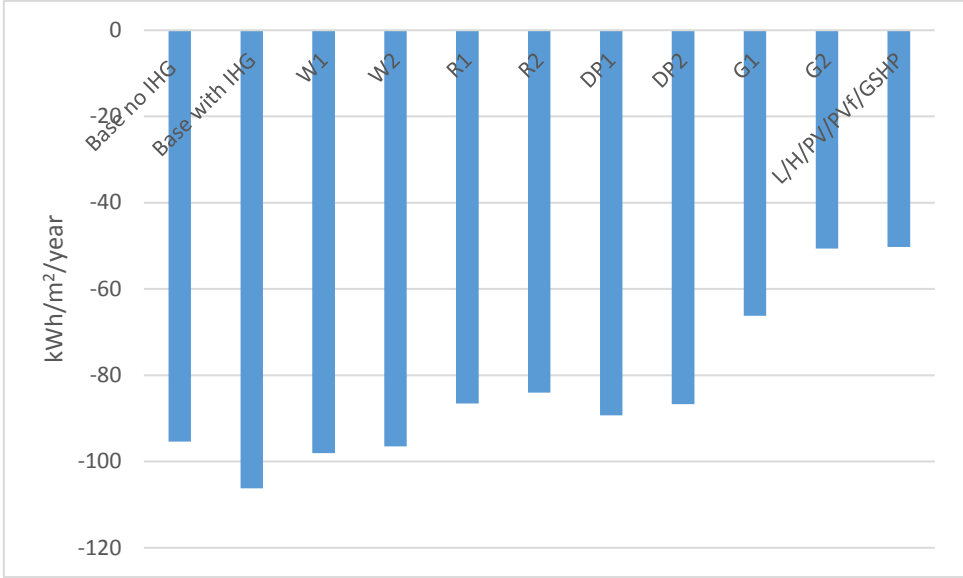


Figure A.3 Annual fabric gains of Case 1 for a range of retrofit measures (ref: Table 6-7)

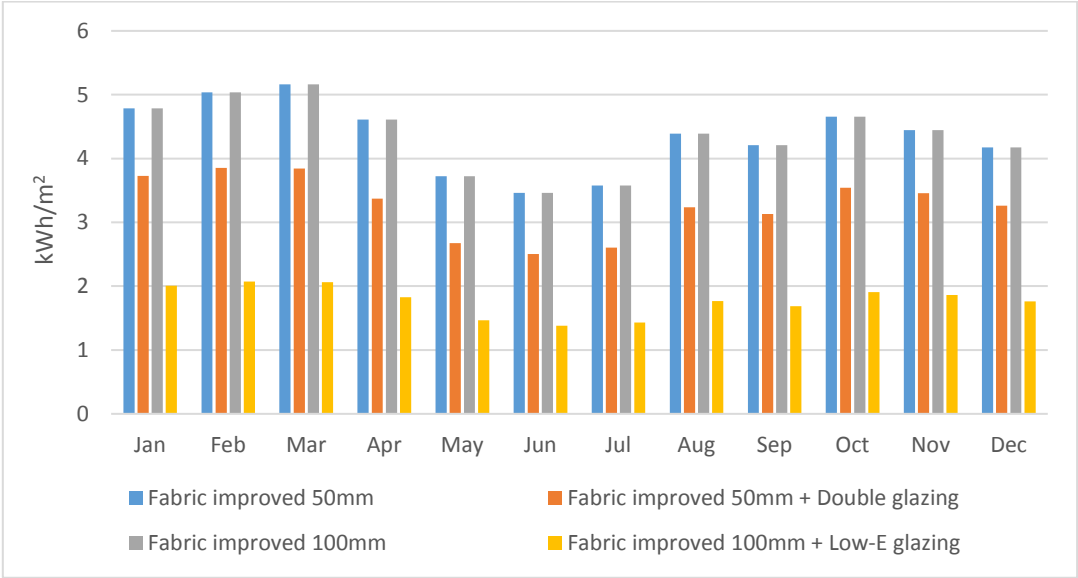


Figure A.4 Monthly solar gains of Case 1

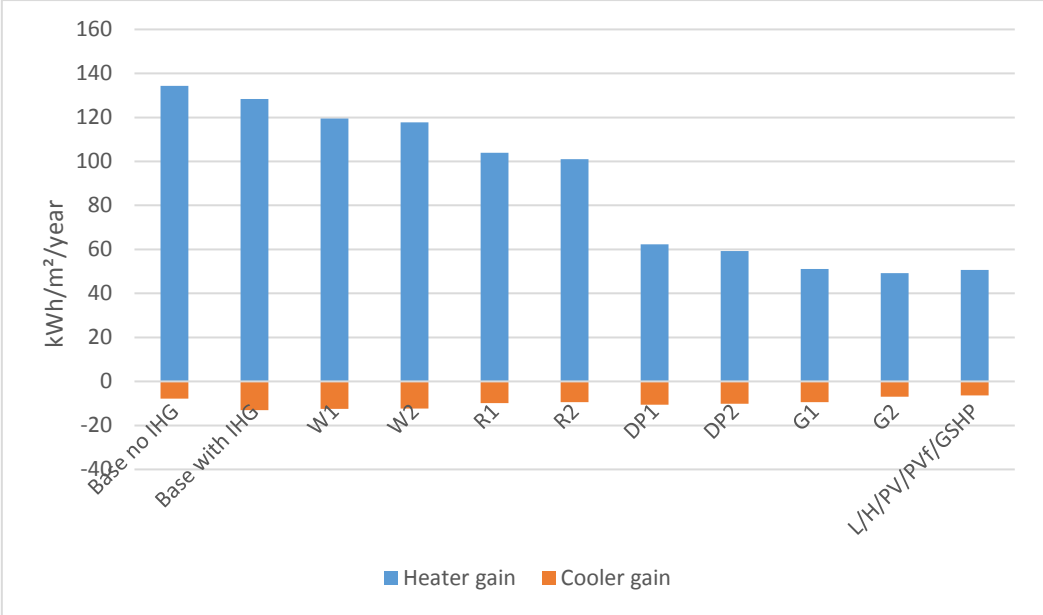


Figure A.5 Annual heater and cooler gains of Case 2 for a range of retrofit measures (ref: Table 6-7)

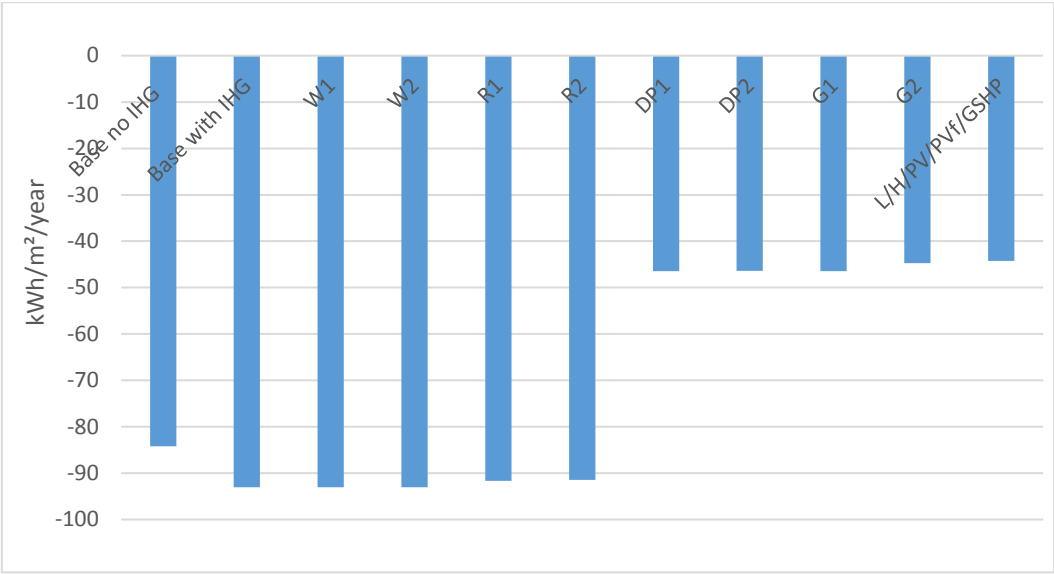


Figure A.6 Annual ventilation gains of Case 2 for a range of retrofit measures (ref: Table 6-7)

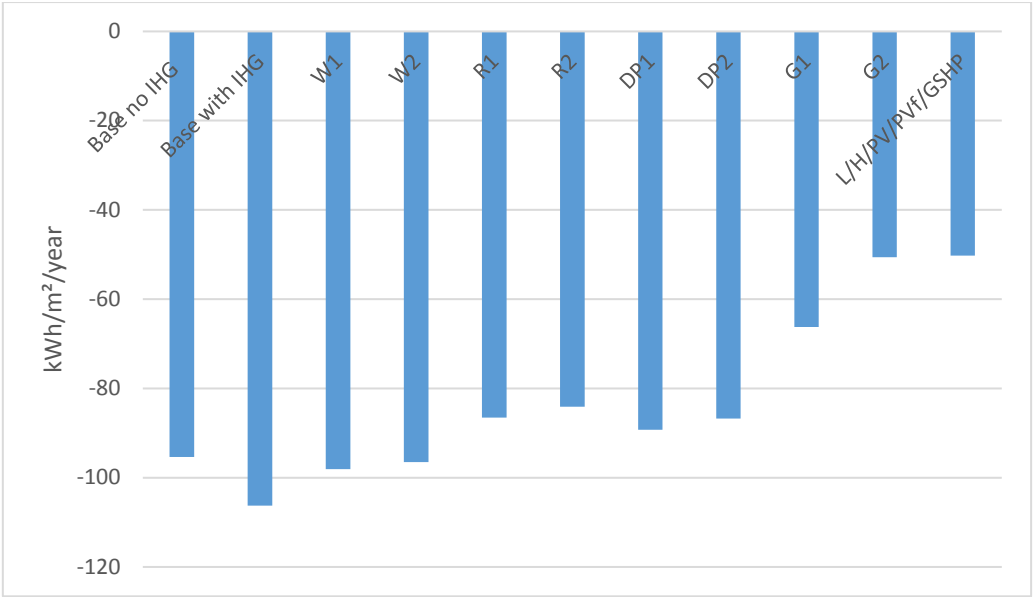


Figure A.7 Annual fabric gains of Case 2 for a range of retrofit measures (ref: Table 6-7)

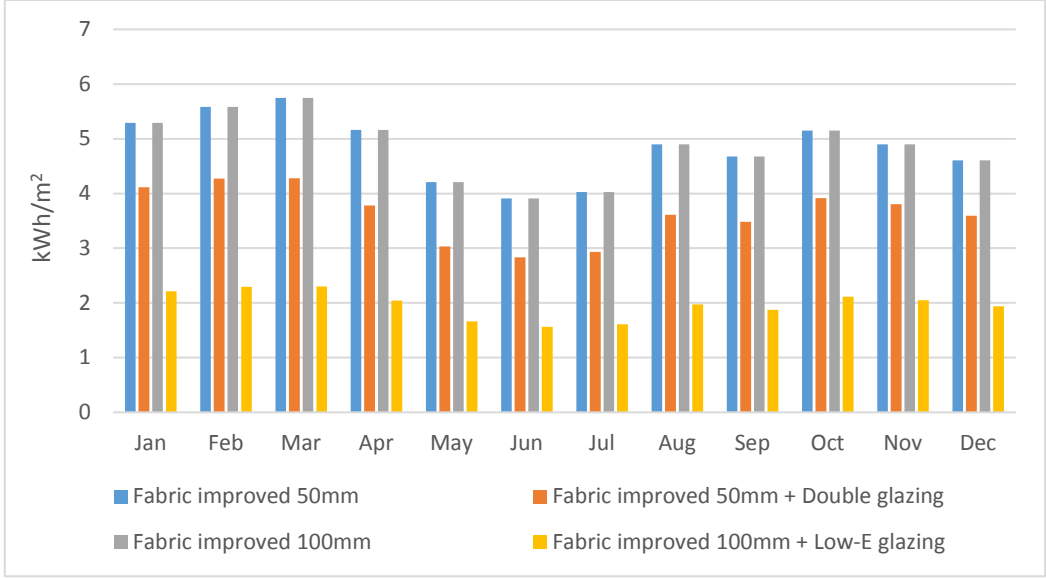


Figure A.8 Monthly solar gains of Case 2

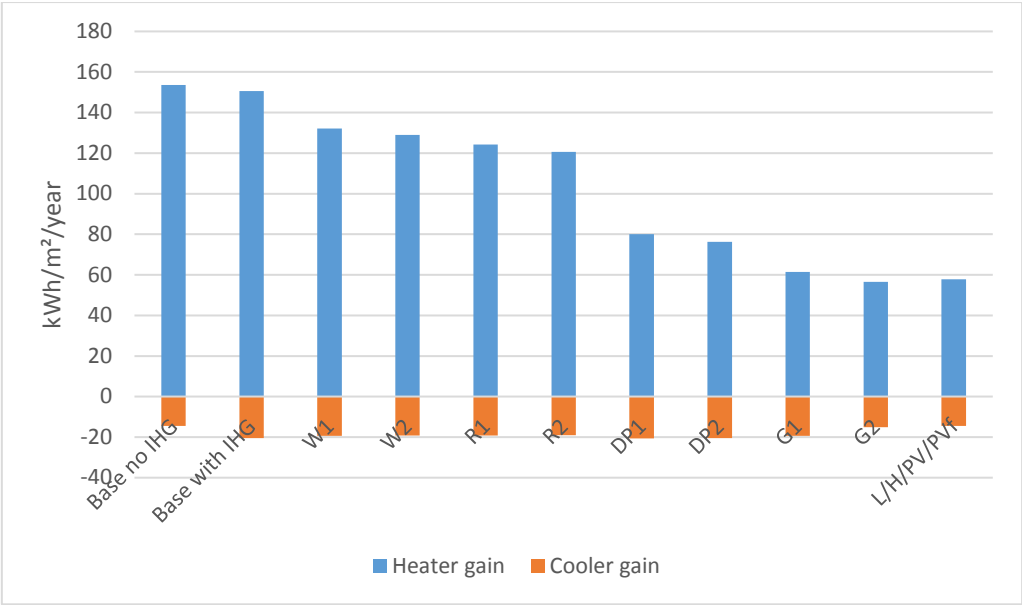


Figure A. 9 Annual heater and cooler gains of Case 3 for a range of retrofit measures (ref: Table 6-7)

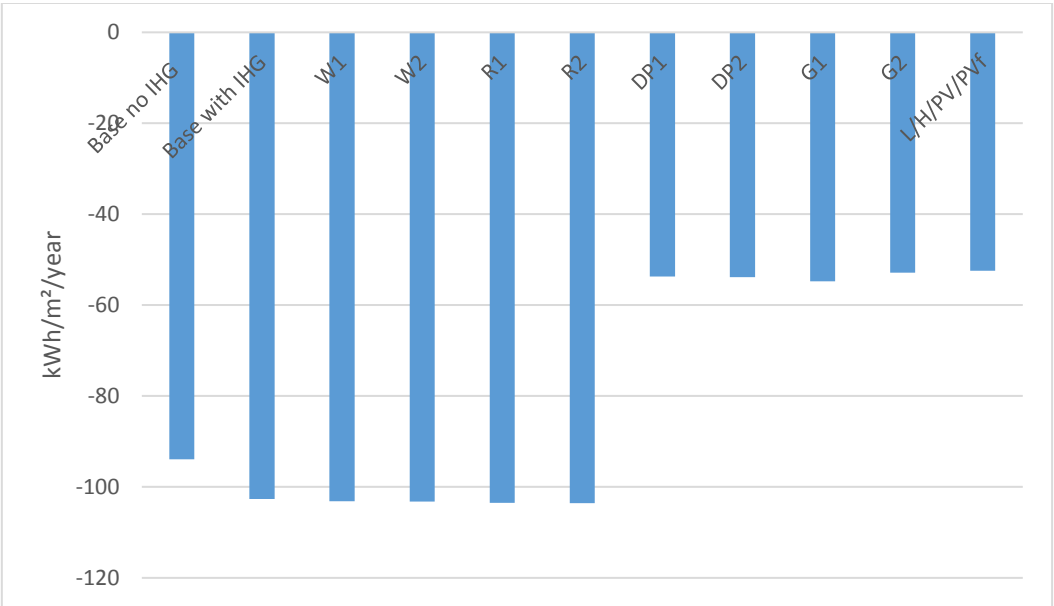


Figure A.10 Annual ventilation gains of Case 3 for a range of retrofit measures (ref: Table 6-7)

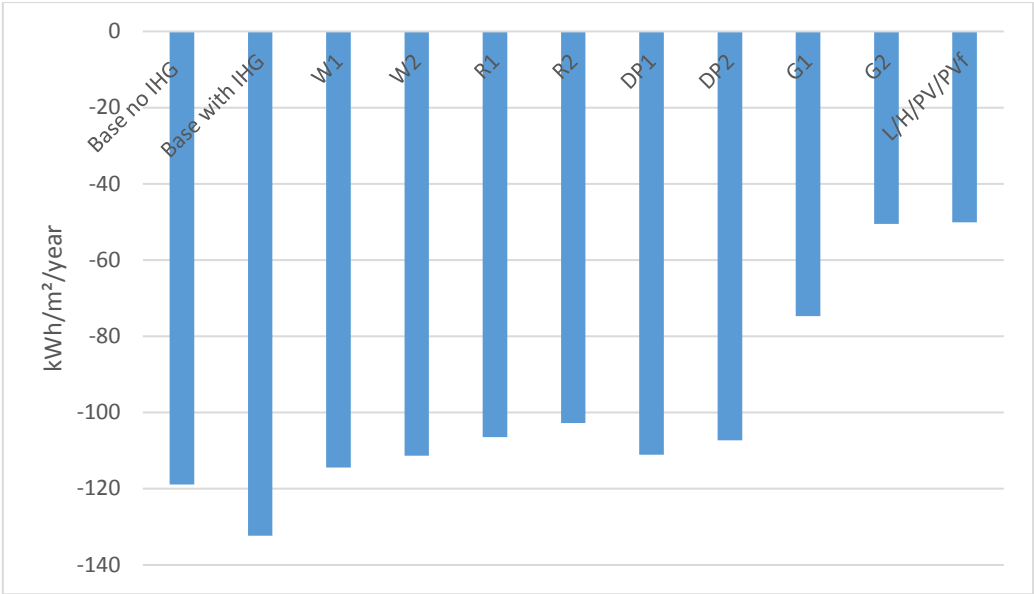


Figure A. 11 Annual fabric gains of Case 3 for a range of retrofit measures (ref: Table 6-7)

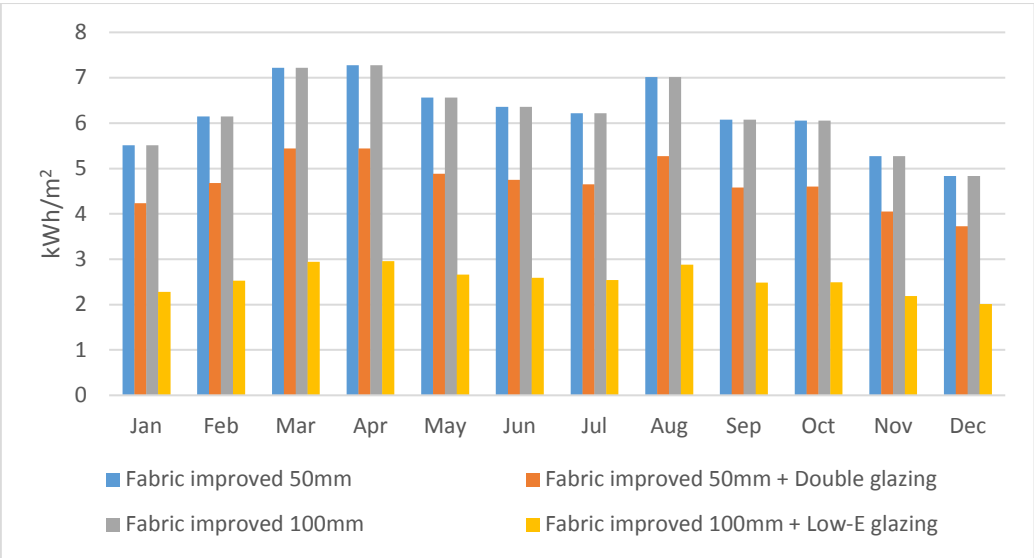


Figure A.12 Monthly solar gains of Case 3

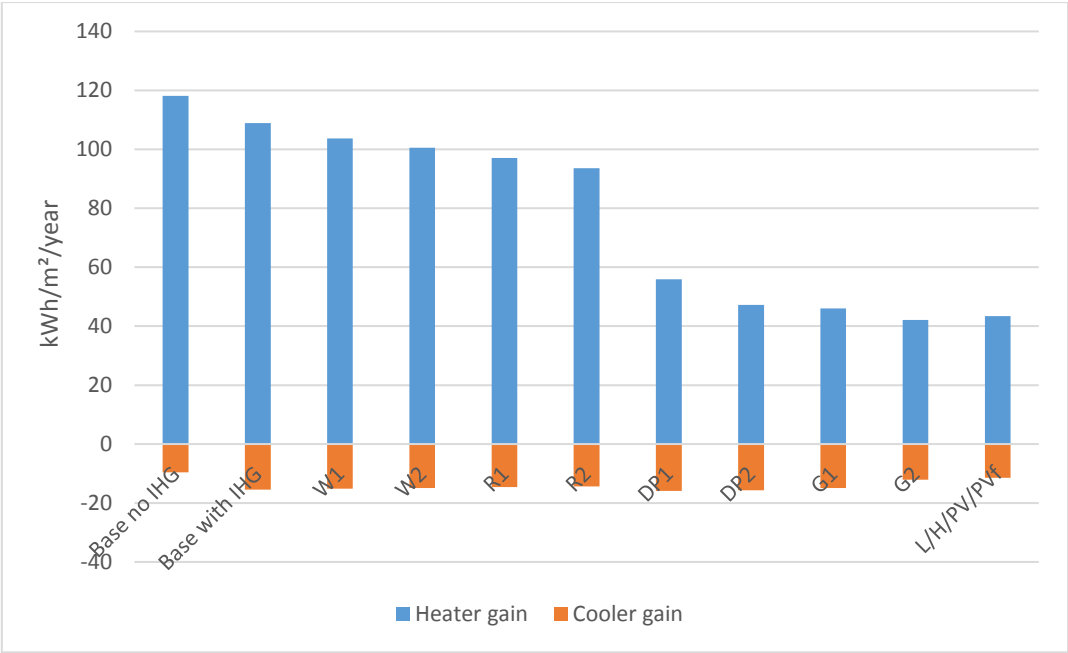


Figure A.13 Annual heater and cooler gains of Case 4 for a range of retrofit measures (ref: Table 6-7)

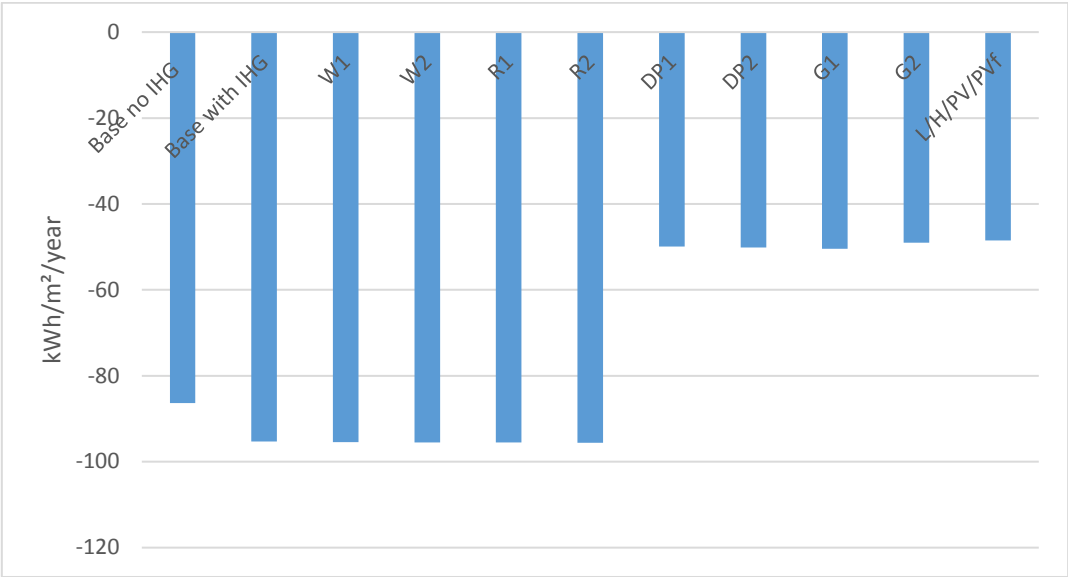


Figure A.14 Annual ventilation gains of Case 4 for a range of retrofit measures (ref: Table 6-7)

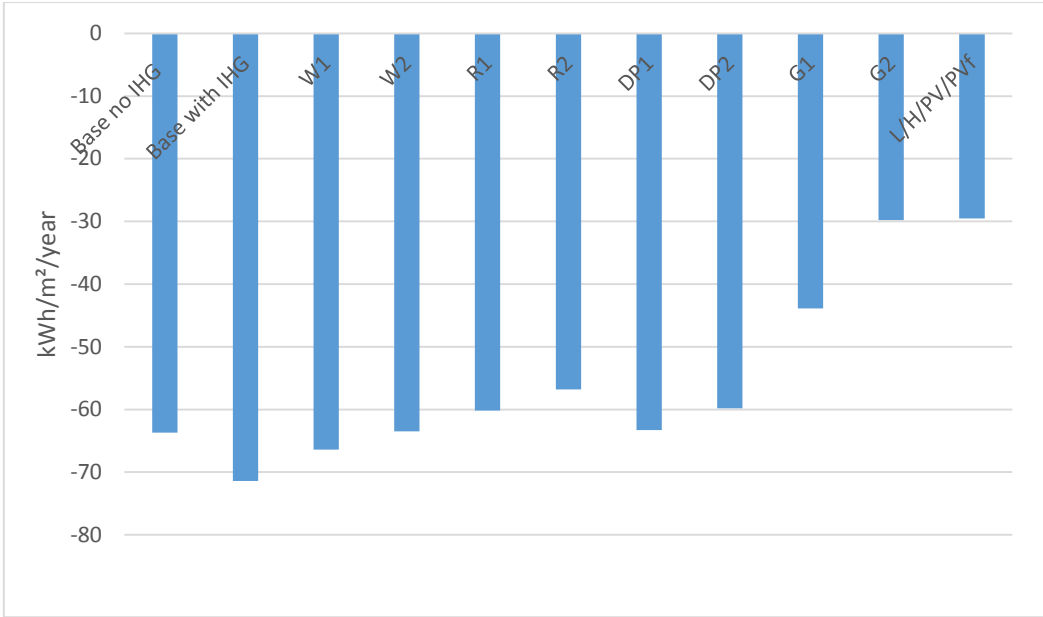


Figure A.15 Annual fabric gains of Case 4 for a range of retrofit measures (ref: Table 6-7)

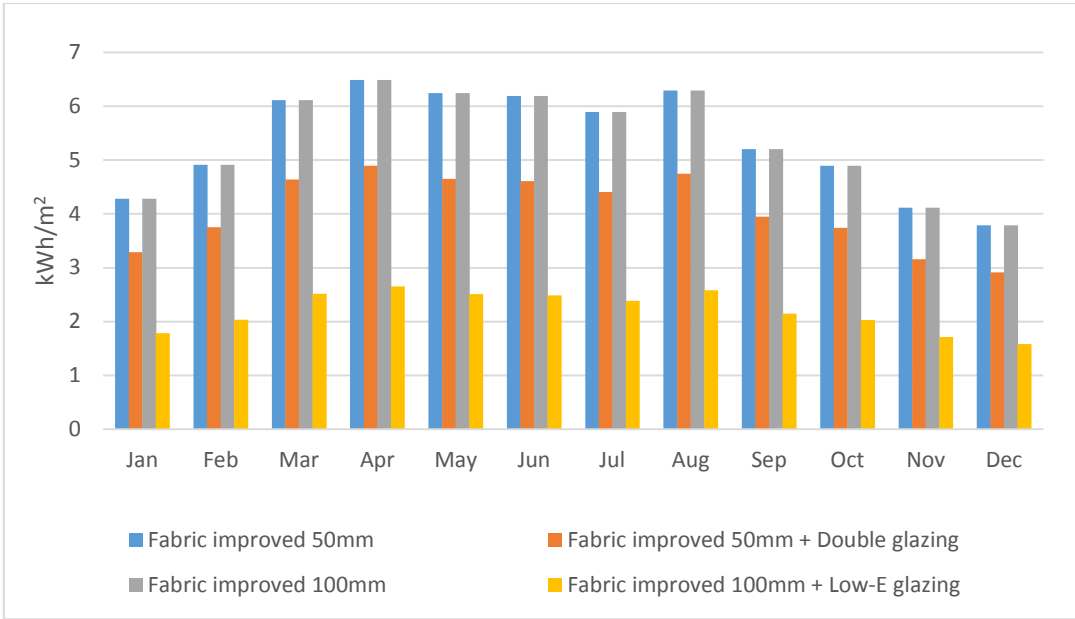


Figure A.16 Monthly solar gains of Case 4