Welsh School of Architecture

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An Affordable Nearly-Zero-Energy Townhouse Prototype for China's Future Low-Carbon Housing

Real-case Validation in the Suburban Area of Xi'an City

Thesis for the degree of Doctor of Philosophy

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Dedicated to my son Haoze Liang

who inspired, encouraged and enabled me to more than I can be

Abstract

As part of the 11th Five Year Plan on Energy Development (2006-2010), China once set up a 65% target for reducing the energy consumption of residential and public buildings by 2020. Then in 2016, the State Council of China directly referenced nearly-zero-energy buildings and PV micro-generation on the roof as the critical solutions to enhance building energy conservations and carbon emissions reductions. Most recently, in January 2019, China's Technical Standard for Nearly Zero Energy Building (GB/T51350-2019) has been launched for implementation. All these policies aim to promote low-carbon buildings in China.

However, in China's housing sector, affordability has been a profound obstacle to implement low-carbon technologies. China's high-rise high-density housing strategy also technically impairs the deployment of cost-effective micro renewable generations. Therefore, the main challenges not only lie with the cost of low-carbon technologies but the fundamental reform of housing strategy to enable building integrated renewable generation.

This research aims to provide a new approach for future low-carbon housing in China. It proposes an affordable nearly-zero-energy townhouse prototype in suburban area, which integrated affordable and replicable energy demand, energy storage and renewable energy supply solutions.

This research has two main aspects of contribution to the existing literature. Firstly, on the theory side, this research fills the research gap on the low-rise low-carbon housing in China. It not only formulated the terminology and prototype of the affordable nearly-zero-energy townhouse but also provides a conceptual design framework to guide the design and integration process. Secondly, on the practical side, this research provides evidence for the large scale rollout of the approach by carrying out a real project case study. The case study covers the whole design, construction and commissioning process. It validated the applicability of this prototype at the regional and project level. It also evaluated the achieved indoor thermal and energy performances of the constructed house against its costs.

This research proved that the affordable nearly-zero-energy townhouse prototype could apply in a wide range of cities' suburban area in China, and it suits for the majority of climate zones. The embedded integration strategy of low-carbon technologies and the proposed design process are implementable in practice. The parameters defined in the national level prototype are competent to guide the development of project-level baseline building. The benchmarks set in the national level prototype are also capable of promoting affordable nearly-zero-energy performances with a reasonable cost in real practice.

List of Publications

Zhang, K., Jones, P. and Stevenson, V. 2018. **An optimisation design *framework for residential buildings integrating air-source heat pump multi-supply system, active thermal storage, and onsite renewable energy.*** Presented at: Second International Conference for Sustainable Design of the Built Environment: Research in Practice, The Crystal, London, 12-13 September 2018 Presented at Elsharkawy, H., Zahiri, S. and Clough, J. eds. International Conference for Sustainable Design of the Built Environment SDBE 2018: Proceedings. p. 729-740.

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Chapter 1

Introduction

‘Quantitatively, China has achieved remarkable success in housing development, especially over the last twenty years. But…there has been a considerable shortage of knowledge and practice about housing types and systems…Consequently, we see very few examples of housing projects that reflect the future direction of modern architecture with, for instance, consideration of local climate, culture, community, economics and technological conditions.’

--- Wu (2001)

“When a city lacks stable and affordable housing, community members have to move frequently, resulting in stress and health issues and a weakened sense of community cohesion…Additionally, communities need to make sure that there is adequate affordable housing available in convenient and safe locations to access jobs and community assets like schools. Communities without affordable housing are often segregated by income and family background, contributing to growing inequality and destabilizing the community.”

--- Helling and Shaver (2018)

1.1 Research background

Within the built environment, housing is one of the essential parts of daily life, if not the most important. One can be knowledgeable without any education in schools, and one can work without being in factories and offices. Still, one can never live happily without a home. As commented by Vale et al. (2014):

> *‘Specifically, housing can help residents address the struggle to maintain economic livelihood, the threats of a changing climate, the challenges of urban violence, and the inequities of governance. In this way, the affordability of housing is inextricably connected to the resilience of cities.’*

For the above reasons, affordable housing is a critical area to ensure social stability and equity, and governments widely deliver the relevant schemes all over the world. Most commonly, the affordability issues are tackled through public or social housing schemes to make sure low-income-group people have their shelters. However, in the 21st-century, housing affordability issues gradually extend to be a problem of even medium-income-group people in many countries.

On the one hand, this is because people pursue higher living standards through higher requirements of housing. However, on the other hand, this phenomenon is the result of increasingly scarce natural resources (e.g., land, construction materials, energy), and a more vulnerable society (such as the ageing population, lack of labour force in the construction industry).

Furthermore, there are natural hazards caused by climate change (e.g., freezing and hot weather, urban waterlogging, and droughts), and social chaos caused by national and international conflicts. They both make the comfort and safety standard expensive to maintain.

There was a general assumption that people's living standards would continue to rise, and they will upgrade the built environment to meet the rising requirements (Stone 1970). However, people widely understand now that ecological capacity restrains the increase of living standards, and housing consumes environmental resources. Even with such awareness, one cannot expect people to compromise by living in a cheap but low-quality house. As soon as their economic status improves, people will undoubtedly pursue better accommodation. Therefore, producing cheap but low-quality housing does not help solve the housing affordability issues. On the contrary, making high-quality housing more affordable is the way to go.

Historically, innovations of technologies and relevant infrastructures made high-quality things more affordable. The electric bulb not only lifted people's living quality and productivity but also totally changed the way people utilise energies (Matulka and Wood 2013). The relevant infrastructures to provide these energies changed consequently as well. Again, the appearance of the smartphone brought massive convenience and efficiency for communications, and it changed the infrastructures with or without people's awareness (Senthilingam 2015).

Currently, the progress of electric cars awakes people’s imagination of less polluted but safer and more convenient transport. Once more, it might bring another energy revolution, which is to replace fossil fuels for cars with renewable energy and relevant infrastructure systems (Danko 2015).

All these products of new technologies were expensive when they first came to the market and did not belong to ordinary people's daily life. However, after a few generations' iterative progress, they have become or foreseeably will become affordable to the majority of people. The driving force behind such a 'progressively cheaper' phenomenon is people's desire for a better life, as well as the increased knowledge of the world. When passion and ability work together, people could achieve a higher standard of living, both economically and environmentally.

Therefore, we should have confidence that innovative housing products can achieve the same affordable outcomes as these examples.

The housing revolution is happening in the world. There have been leading countries pushing the innovative house research from conceptual discussions to numerical (Kreuder and Spataru 2015; Fischer et al. 2016) and experimental validation (Thygesen and Karlsson 2013; Thygesen and Karlsson 2017; Lizana et al. 2018). More importantly, the research in many developed countries start to synergise and make Nearly-Zero-Energy (NZE) (Deng et al. 2014), Zero-Energy (ZE) (Hernandez and Kenny 2010; Marszal et al. 2011; Sartori et al. 2012), or even Energy-Positive (EP) houses (Jones et al. 2015) more affordable.

Such future-oriented research has not been seen in China’s affordable housing sector yet. It is not that China has not been aware of these innovative houses, or China cannot see the importance of research in this area. On the contrary, China is ambitious in energy savings and carbon emissions reductions in the buildings sector. Early in 2006, China set up a target in its 11th Five Year Plan on Energy Development, which ‘plans to reduce the energy consumption of residential and public buildings by 65% by 2020' (NHBC Foundation 2011). Then in 2016, the State Council of China (2016) directly referenced NZE buildings and PV micro-generation on the roof as the critical solutions to enhance building energy conservations and carbon emissions reductions. Most recently, in January 2019, China’s *Technical Standard for Nearly Zero Energy Building (GB/T51350-2019) has* been launched for implementation.

However, in research and real practice, NZE or ZE residential buildings are rare in China’s housing sector, and they are not seen as the path for its affordable housing either.

A leading researcher in China’s green building sector, Prof. Zhu, once commented that ZE Buildings are not suitable for China (Chen 2011). She said *'China's building forms are different from the developed countries, mainly high-density settlements. Even though ZE Buildings do not consume commercial (grid) energy, they rely on technologies such as PV and ground source heat pumps. They all consume significant areas of land.*'

Again, another leading Chinese researcher in this field, Prof. Xu, also mentioned building form as an obstacle for China to promote NZE residential buildings (Xu 2017). His point is that multi-storey and high-rise buildings with apartments are the main types of residential buildings in China. These buildings have typical characters of '*high density, high plot ratio, a large shared public area within the buildings, and frequently opened entrance.*' (Xu 2017). Thus, such buildings are challenging to be ZE or NZE. Moreover, Xu (2017) comments that the vacancy rate of the residential buildings is high (20-30% referenced by him), which causes high heat transfer between apartments. Therefore, with these characters, Xu (2017) believes that the current popular strategies of NZE houses in developed countries are not suitable when applying in China on the residential buildings.

These two Chinese researchers' comments are correct in terms of the background information they referenced. However, for the future situation in China's housing sector, their remarks can be challenged.

Firstly, for Zhu's comment on land consumption by the technologies, current practices in other countries have already overcome the difficulties through the holistic design of buildings' envelopes and systems.

For example, the SOLCER House in the UK (Jones et al. 2015) has managed to apply the air-source heat pump multi-supply system plus a PV integrated roof to deliver an energy positive dwelling. Such a residence does not need any extra land for the technologies. Furthermore, with all these low-carbon technologies on board, it is still constructed within the cost of local social housing budget (£1200/m^2, including systems, interior decorations and landscape). Therefore, down to the low-rise residential building level, land consumption of technologies, as well as technologies' availability and affordability, are no longer the main obstacles for NZE residential buildings.

Secondly, arguments could be brought up by Xu's (2017) point of high heat transfer between apartments, due to the high vacancy rate of multi-storey and high-rise residential buildings in China:

- **Are the high-rise high-density residential buildings already over-supplied?**

Existing research has shown high inventories of unsold housing (Figure 1.1) and considerable vacancies of already sold housing (Wu et al. 2016; Zhao et al. 2017). Such data seems conflicting with the general urban housing shortage in China. However, it indeed reflects two fundamental truths in China's current housing sector: 1) People who need shelter cannot afford to buy the properties available in the real estate market; 2) People who are capable of buying their housing do not want or need as many supplied high-rise apartments as in the market.

Figure 1.1 also shows that the shortage of urban private housing is mainly in tier-1 cities, which fully urbanised with adequate infrastructures, public services and job opportunities. In tier-2 to 4 cities, there have been signs of an oversupply of commercial housing, which are dominated by high-rise apartments.

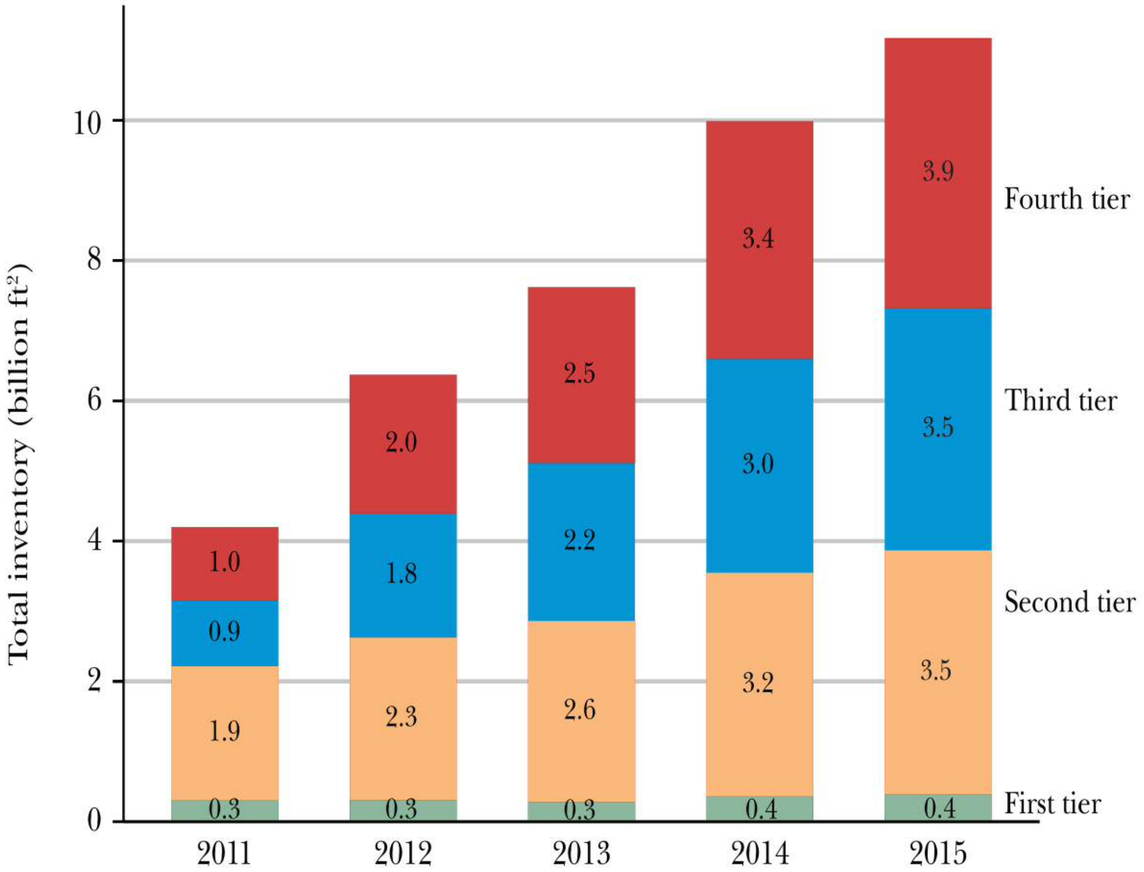


Figure 1.1 Inventory Estimates by Tiers of Cities in China (Glaeser et al. 2016)

Note from the source: Developer inventory data is from the local housing bureau (Fangguanju), and compiled by Soufun. Because the data does not cover all the cities, our estimates of inventory in each tier are based on inventory per capita by tier multiplied by urban population in each tier. Because the data do not have many Tier 4 cities, the authors also assume the Tier 4 cities have the same inventory per capita as the Tier 3 cities. In total, the estimates cover 262 prefecture-level cities: 4 cities in the first tier, 34 in the second tier, 84 in the third, and 140 in the fourth.

Therefore, it can be reasonably arguable whether China needs such a massive amount of high-rise high-density residential buildings in tier-2 to 4 cities. Again, even for tier-1 cities, it is also arguable whether 100% of high-rise residential building is the way to go.

- **Does China have enough land to build low to multi-storey housing for its population?**

There is a famous Population Density Demarcation Line (Hu Huanyong-Line), which separates China into two parts (Figure 1.2).

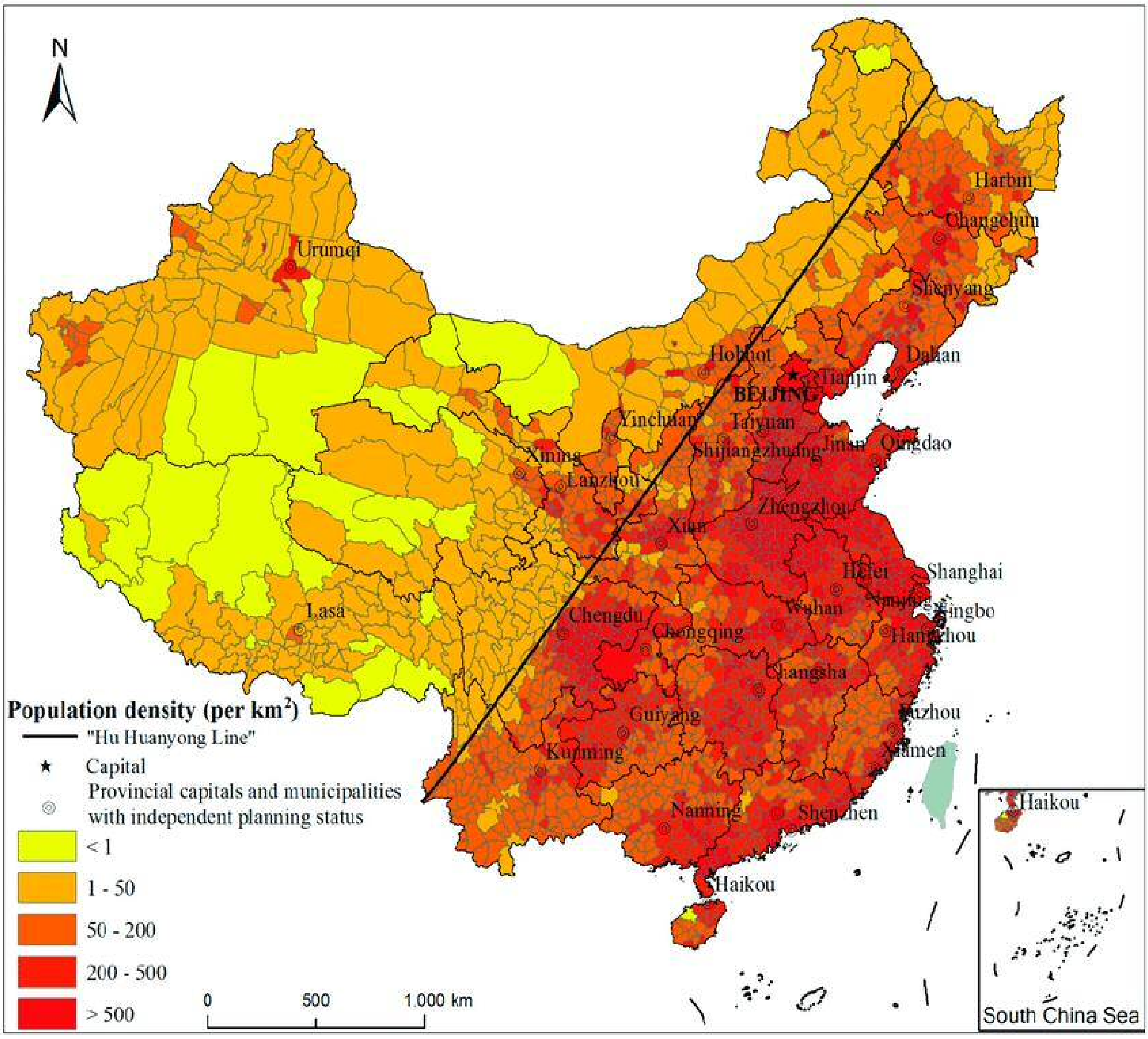


Figure 1.2 Population distribution by the two sides of Hu Huangyong-Line

Source: (Li et al. 2018)

China's renowned geographer Huanyong Hu drew this Line in 1935, and it describes the extremely uneven distribution of China's population. At that time, his calculation concluded that 36% of China's land raised more than 96% of the people on the south-east side of the 'Line'; on the contrary, 64% of China's land raised less than 4% of the people on the north-west side of the 'Line' (Guo et al. 2016a).

This Line still exists now, even though 80 years have passed (Table 1.1). According to (Li et al. 2018), China's average population density in 2015 is about 314.85 people/km^2 on the south-east side of the 'Line' and 15.34 people/km^2 on the north-west side of the 'Line'. Because the majority of China's cities are on the south-east side of the 'Line', China's current urban population density is then roughly 315 people/km^2.

Table 1.1 Population distribution on the two sides of the Hu Huanyong-Line reproduced from (Guo et al. 2016a)

	Percentage of Total population	
	The south-east side of the Line	**The north-west side of the Line**
1935	96.79	3.21
1964	95.33	4.67
1982	94.21	5.79
1990	94.08	5.92
2000	93.84	6.16
2010	93.49	6.51

However, as shown in Figure 1.3, even only comparing the dense part, China's population density is still less than its neighbour Japan (348 people/km^2) and South Korea (528 people/km^2). For these two countries' capital cities Tokyo and Seoul, there are still considerable low-rise and multi-storey residential buildings for the low-to-medium income group people.

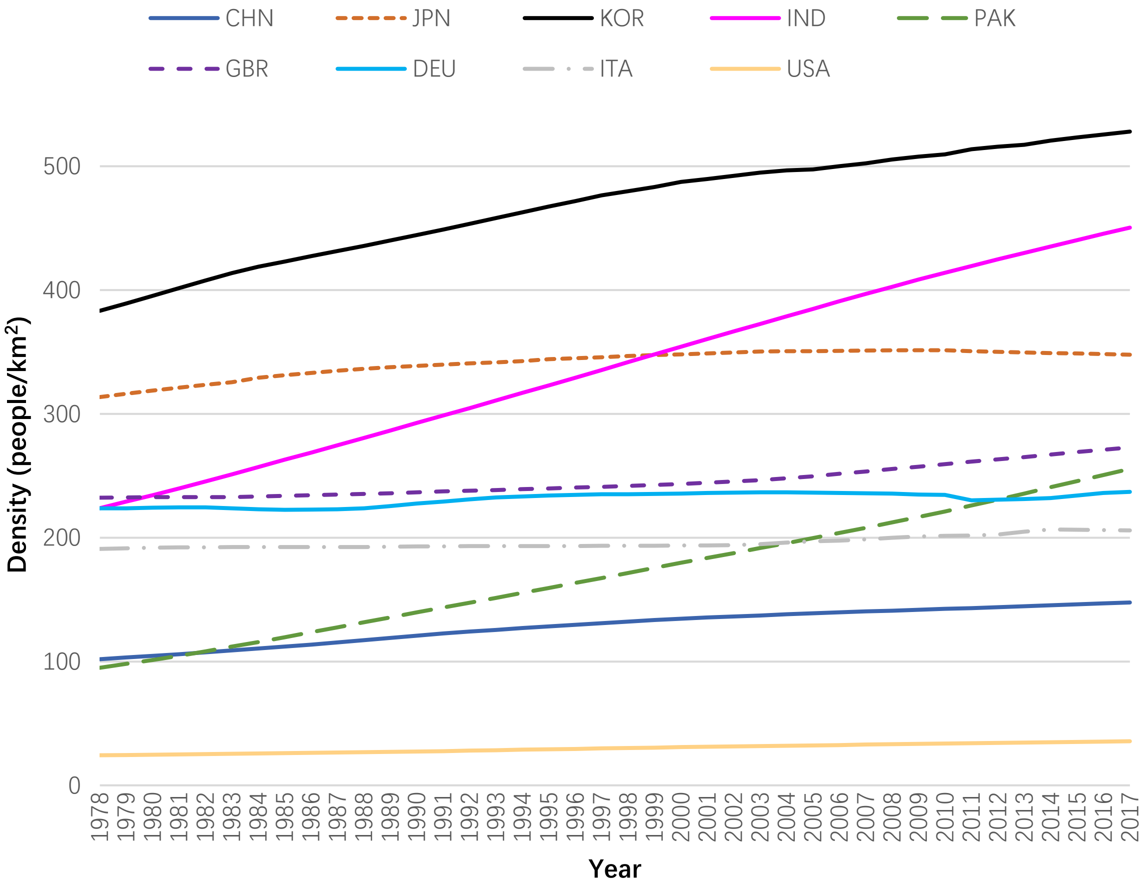


Figure 1.3 Population density of countries

Note: 1. Diagram reproduced by the author based on the data from World Bank (The world bank database 2018)

2. CHN-China, JPN-Japan, KOR-Korea, IND-India, PAK-Pakistan, GBR-Great Britain, DEU – Germany, ITA-Italy, USA-USA

Figure 1.3 also shows that China's national population density is not high compared with many other counties, and it did not increase in a sharp trend either. Until 2017, even with China's most distinguished record of population density, it is still less than many other counties in the diagram of comparison.

Reviewing the countries presented in Figure 1.3, the high population density developing countries (e.g. India and Pakistan) do not appear to have the whole-country extremely high-rise high-density urban form. Neither in the high population density developed countries (e.g. UK, Germany, and Italy) the mainstream housing is high-rise high-density.

Therefore, China should have sufficient land to build low to multi-storey housing for its population, even in its high population density cities.

- **Is high-rise high-density housing the only solution for high population density cities?**

In this world, there are two high population density regions which only construct high-rise residential buildings - Hong Kong and Singapore. Both of them have only a small area of land for development. One thing needs to note, however, that Hong Kong and Singapore are all located in low latitude area with subtropical or tropical rainforest climate. For such environments, the small distance between high-rise buildings provides benefits for shading each other and the roads. On the contrary, such settlement and building form will be harmful to the high latitude area. The apartments in these buildings will not be able to get enough daylighting, as well as sunlight for passive heating. Thus, it is essential to acknowledge that Hong Kong and Singapore's settlement and building form may not be an excellent example for other cities in high latitude.

Moreover, a high-density city could mainly have low-rise and multi-storey buildings. London is such a case, which is a famous high-density city with only a few high-rises residential buildings. London once built a few high-rises affordable housing in the 1970s and 1980s (Li 2013). However, ultimately London chose to mainly develop low-rise and multi-storey residential buildings in its urban area. Over half a century, it managed to create a high-density city in such pattern well.

Therefore, it is fair to say that settlement and building form is the humanmade choice, rather than a standard development trend for solving high population density's housing problems.

Early in the 1970s, Martin and March (1972) had answered the question - 'How was it that one form of building with a floor area to ground space ratio (plot ratio) of 3:1 could be accommodated in 8-storey buildings, whereas elsewhere, in some situation, the same plot ratio required tall towers?'. With thorough mathematical and architectural illustration, his 'court' form solution via low-rise and multi-storey buildings provides both high density and high land-use efficiency. He also proved that such settlement and building form could bring many environmental benefits. Such solution laid the foundation of London's modern urban space and structure, and still have its influence until now.

In the same period, Stone's works (Stone 1970; Stone 1973) explored future housing choices for the UK. His research took the social-economic point of view, and focussed on population density and associated housing form, in responding to its population projections done in the 1970s (expectedly rapid growing and quick ageing). He made a series of thorough assumptions about housing strategies based on the relevant land use, costs, capacity of construction industry and administration issues. Moreover, he concluded that for the lifecycle cost of residential buildings '*flatted blocks are more expensive than houses and bungalows; their costs rise with the number of storeys in a block, and it is this rather than the resulting density which mainly determines costs*'. Stone is the pioneer in the housing affordability area who extends the costs of housing from construction to broader socio-economic issues.

The above two types of research have not been seen in China's housing sector yet. Even though the urbanisation process is significantly different between the UK and China, Chinese towns in not fully built suburban area could learn from some of London's experiences. Also, the research of China's context can undoubtedly reflect the critical research questions discussed by Martin and Stone.

China itself is a country with a rich history of low-rise high-density settlements. Its traditional settlements all follow structured 'court' form and prove to have multiple social and environmental benefits (Soflaei et al. 2017). However, China lost such settlement and building form in the modern urbanisation process. There was a short period at the beginning of the 21st century when townhouses were fashionable in the market. However, developers mainly built these townhouses for 'rich' people. They neither aimed for being affordable to low-to-medium income group people, nor for being high density as a solution for the general urbanisation. That is why the Chinese government tightened its policy on the land supply for such projects (Ministry of Land & Resources and State Development & Reform Commission of China 2006). The '*prohibited use of construction land for a housing project with plot ratio less than 1.0 or floor area per unit more than 144 m^2*' policy has made pure townhouse projects rarely able to get planning permit since 2006. As a result, the 'townhouse communities' become rare in the housing market since then.

Now the research outcomes in China have demonstrated that it is possible to achieve a plot ratio of more than 1.0 with modern living standards purely by court form townhouses (Figure 1.4).

Unit area / Plot ratio

Small unit area & **High** density

Large unit area & **Low** density

Figure 1.4 Achievable plot ratios by low-rise court form townhouses in 1 hectare (VANSN 2016)

Note: In this graph, the grey areas are buildings, the green places are courtyard, and the white are roads.

Also, the UK's pilot project has shown that it is possible to get the cost of EP townhouse down to the current affordable housing level (Jones et al. 2015). Therefore, it is vital to investigate the possibility of affordable NZE townhouse as a solution for future low-carbon housing strategy in China. Such solution focuses not only on providing shelters for low-to-medium income group people, but also enhancing the sustainability and resilience of urban housing as a whole.

However, there is a significant research gap in affordable NZE townhouse in China.

On one side, China's green building policy has set up the *Technical Standard for Nearly Zero Energy Building*, the requirement of which is competitive to the developed counties' standards. However, there have been comments about this Standard that it is very challenging for high-rise high-density buildings to achieve the set targets (Chen 2011; Xu 2017).

On the other side, the existing researches on the townhouse in China mainly focus on improving liveability by building form (Li 2005; Xu 2007; Liu 2008; Ma 2011) or specific design features (Gao 2001; Li 2006). Neither of these research addressed the affordability issues of the townhouse, nor did they explore the possibility of the townhouse to be low-carbon housing. Especially, after the land supply policy tightened in 2006 (Ministry of Land & Resources and State Development & Reform Commission of China 2006), the research about townhouse become rare as well.

Thus, the study on the prototype of affordable NZE townhouse in China's suburban area is an urgent need, because such research can fill in the research gap on China's future affordable low-carbon housing solutions.

1.2 Research aim, questions and objectives

Low-carbon housing is vital for climate change mitigation and adaptation, which is a shared priority of both sustainability and resilience. NZE house is a sub-type of innovative housing product in the low-carbon housing category. However, low-carbon housing is a broad concept, which has not been well defined yet. Currently, research is merging from different areas to refine the definition. For example, construction materials, the energy utilisation within and beyond the building boundary, water usage, transportations of both people and goods, people's lifestyles and general socio-economic status. These are all crucial issues to be considered in the design of low-carbon housing. If without a prototype to extract the priorities while paying attention to affordability issues, the creation of NZE townhouse will lose its focus along the process. Furthermore, if there is only a prototype of NZE townhouse, the design process cannot be structured around the key elements to deliver integration for lower costs. Therefore, among the gaps of studies on the affordable NZE townhouse, a prototype and its conceptual design framework are the priorities.

For the above reasons, this study aims ***to formulate a prototype and its conceptual design framework for the low-carbon housing development in China and test their effectiveness of promoting affordable Nearly-Zero-Energy performances in real practice.***

The fundamental research question raised in this research is:

What type of NZE housing can be affordable for China to promote low-carbon housing in the future?

This fundamental question can further divide into four sub-questions:

1) *Why developed countries promote affordable low-carbon housing with the priority of NZE, ZE or even EP houses, and how that links to China's own needs of future housing development?*

2) *Can China promote affordable low-carbon housing in suburban area by NZE townhouses? If so, what are the main characters of such a residential building?*

3) *If delivering the affordable NZE townhouse in China via the proposed technical route, what type of conceptual design framework can enable holistic and economical design for local conditions?*

4) *How do we know whether or not the proposed prototype and conceptual design framework enable affordable NZE performances? If not, what are the problems and reasons?*

Several objectives are derived as follows to achieve the main aim of this research and find answers for the research questions:

1) To investigate the reasons for NZE housing development in developed countries, and find out what design principles China can adopt

2) To formulate an affordable NZE housing prototype and a conceptual design framework to deliver the summarised design principles

3) To implement the prototype and the conceptual design framework in a real project, to understand how the local conditions are applied

4) To validate the effectiveness of the prototype and the conceptual design framework by simulating and monitoring the energy & indoor thermal performances, so that the costs for achievable performances are clarified

The two fundamental contributions of this research are:

Firstly, this research provides a fresh new approach for future affordable low-carbon housing in China's suburban area. Such an approach helps the cities to develop low-carbon energy infrastructures alongside housing constructions, which enhances the sustainability and resilience of the whole urban built environment.

Secondly, the real project case study in this research presents the detailed process of applying such a prototype and conceptual design framework. Therefore, anyone who wants to adopt the prototype and use this conceptual design framework can be well informed and prepared in the planning, design and construction of such projects.

1.3 Thesis structure

This thesis consists of seven chapters which can divide into four parts. Chapters 1 to 3 constitute the first part. This part introduces the research background, raises the research questions, and develops a feasible methodology for the study as a whole. Chapter 4 is the second part, which establishes the prototype and its conceptual design framework. Chapters 5 to 6 constitute the third part, which carries out the empirical study on the application and validation of the prototype and conceptual design framework. Chapter 7 forms the fourth part. It reviews the significant research findings, synthesises all the conclusions in response to the research questions, summarises the limitations of this study, and provides recommendations for the future research and practice of the affordable NZE townhouse.

Chapter 2 focuses on the literature review. Section 2.2 clarifies the definitions of sustainability and resilience. It also explains how they link to the affordable low-carbon housing and NZE houses in the built environment. Section 2.3 is to find out China's fundamental housing problems to date by analysing China's housing status and strategies. Section 2.4 reviews China's housing policies to explore future housing development directions. Section 2.5 is about challenges and driving forces, which distils the critical areas for a breakthrough in the future. Then the research gaps in the essential breakthrough areas are summarised in Section 2.6.

Chapter 3 establishes the research framework and methodology. It firstly proposes a theory-practice integrated approach (section 3.2). Then, it sets up a multi-methods framework to deliver the theory-practice integrated study (section 3.3). Section 3.4 explains the specific strategy for each research method in details, and it also clarifies the data collected under each method. Section 3.5 clarifies the data resources, access and collecting process. Section 3.6 discusses the reliability, validity, and generalisability of this research. Finally, section 3.7 declares that ethical issues are not relevant to this research because of the methods used.

Chapter 4 focuses on concept development. Section 4.2 formulates the prototype of the affordable NZE townhouse, based on China's critical needs of affordable low-carbon housing, as well as developed countries' design principles of NZE houses. Section 4.3 compares the commonly used prototypes to find the most appropriate structure for the baseline building. It also reviews the popular technical routes of the affordable NZE houses in developed countries and China to find out the most suitable one for the prototype. Section 4.4 forms a conceptual design framework to visualise the technical route and organise the design process.

Chapter 5 is the concept implementation. The first part examines China's statistic data to find out the suitable cities for implementing the prototype (section 5.2). It also presents the local conditions of the chosen project to explain its appropriateness for being the case study of this research (section 5.3). The second part shows the process of formulating the project scale reference building (section 5.4), and the integration of detailed design strategies (section 5.5). These works in this chapter validate the applicability of the prototype and the conceptual design framework.

Chapter 6 is the validation of performances. Section 6.2 exams the energy and indoor thermal performances of the baseline building through modelling. Section 6.3 evaluates the same performances of the project's actual design by modelling too. Section 6.4 assesses the house's actual performances in the commissioning of the cooling season via monitoring. Section 6.5 compares all these assessment results, and section 6.6 analyses the relevant costs for the achieved performances.

Chapter 7 is the conclusion. It examines the research aim, summarises the significant findings, and synthesises the answers to the research questions. On this basis, it highlights the critical issues for future projects to better apply such a prototype and use the conceptual design framework. It also discusses the limitations of this study and makes suggestions for future research schemes.

Chapter 2

Literature review: Sustainability, resilience, and their links to affordable Nearly-Zero-Energy townhouse in China's suburban area

'Our new homes need to be part of the solution to climate change; not part of the problem.'

--- Department for Communities and Local Government, UK (2007)

'Well-designed affordable housing involves more than the provision of safe, decent, and inexpensive shelter; it needs to be central to the resilience of cities... To maximize its capacity to support the resilience of cities, affordable housing should engage as many as possible of the following four criteria: (1) support the community social structure and economic livelihoods of residents, (2) reduce the vulnerability of residents to environmental risks and stresses, (3) enhance the personal security of residents in the face of violence or threats of displacement, and (4) empower communities through enhanced capacities to share in their own governance.'

--- (Vale et al. 2014)

2.1 Introduction

This chapter aims to understand where the concept of NZE house comes from, and what role it plays in enabling sustainability and enhancing resilience in the built environment. It also explores whether China could promote its affordable low-carbon housing through NZE townhouses in its suburban area.

Section 2.2 clarifies the definitions of sustainability and resilience. Moreover, it explains how the research of these two fields results in the NZE houses in developed countries. Section 2.3 reviews China's current housing status and its high-rise high-density housing strategy. Section 2.4 analyses the context and influences of China's housing policies. Section 2.5 summarises the challenges to overcome and driving forces to result in changes in China's future housing sector. Section 2.6 analyses the gaps of the affordable NZE housing research in China.

2.2 Affordable Nearly-Zero-Energy housing: the combined need for sustainability and resilience in the built environment

Firstly, this section clarifies the definitions of sustainability, resilience, built environment and NZE housing. Secondly, it analyses the connections between these concepts and explains how the previous research in the sustainability and resilience fields merged in the built environment - how the built environment evolved for climate change mitigation and adaptation, and why the housing sector plays the leading role of low-carbon buildings. Finally, this section summarises the principles of NZE houses in developed countries.

2.2.1 Climate change mitigation and adaptation in the built environment: the coherent goal of sustainability and resilience

Both sustainability and resilience are comprehensive and general concepts. Sustainability, as the most widely referenced, is 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs (The World Commission on Environment and Development 1987). Resilience, as referenced by Helling and Shaver (2018) of U.S. Green Building Council, is 'the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.' The research of the built environment did not develop these two concepts. Nor were these two concepts overlapped in any research topics of the built environment in the 20th century.

However, Hassler and Kohler (2014) pointed out that sustainability debates raised the awareness of climate change's risks and their impacts on the existing built environment. As a result, climate change mitigation and adaptation in the built environment become the overlapped area of sustainability and resilience research in the 21st century. Sustainable and resilient design of buildings is now one of the intensively studied topics in this area. As Kosanović et al. (2018) once commented, 'the two approaches offer opportunities for synergies and reciprocal benefits.' They summarised the cooperation process of the two approaches in Figure 2.1.

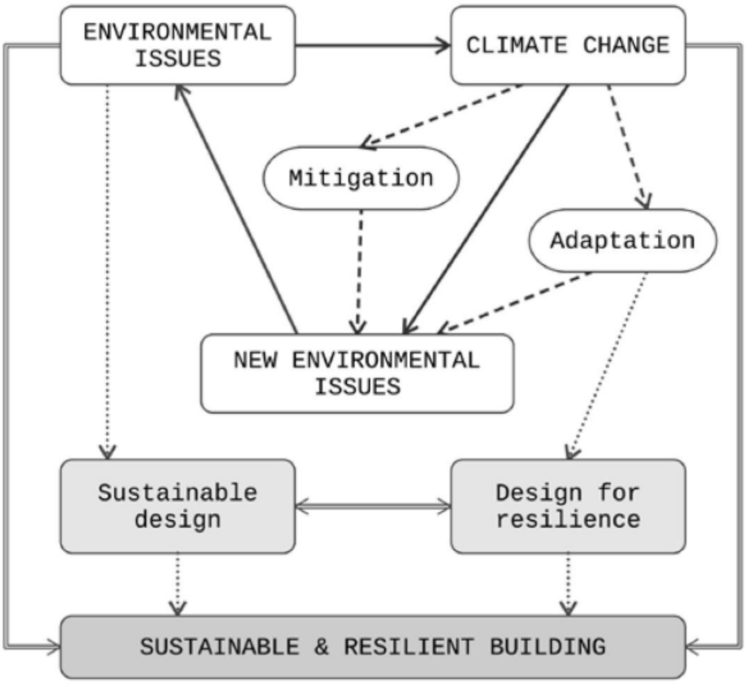


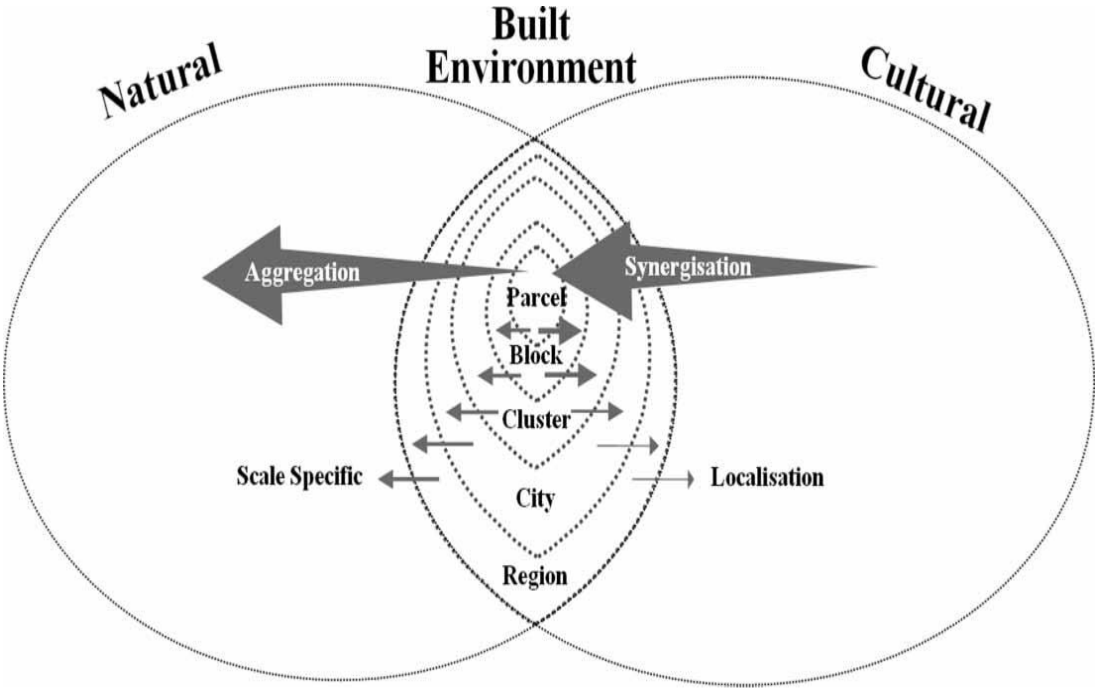
Figure 2.1 Causal relations between environmental issues, climate change, and design responses (Kosanović et al. 2018)

As a result, the current design and practices of buildings commonly embrace such cooperative approaches and have made a lot of positive changes. On one side, these newly designed and constructed buildings make efforts to reduce environmental impacts for the sake of future sustainability. On the other side, they pay attention to overcome the current difficulties caused by environmental and climate change, aiming to enhance the whole built environment’s resilience.

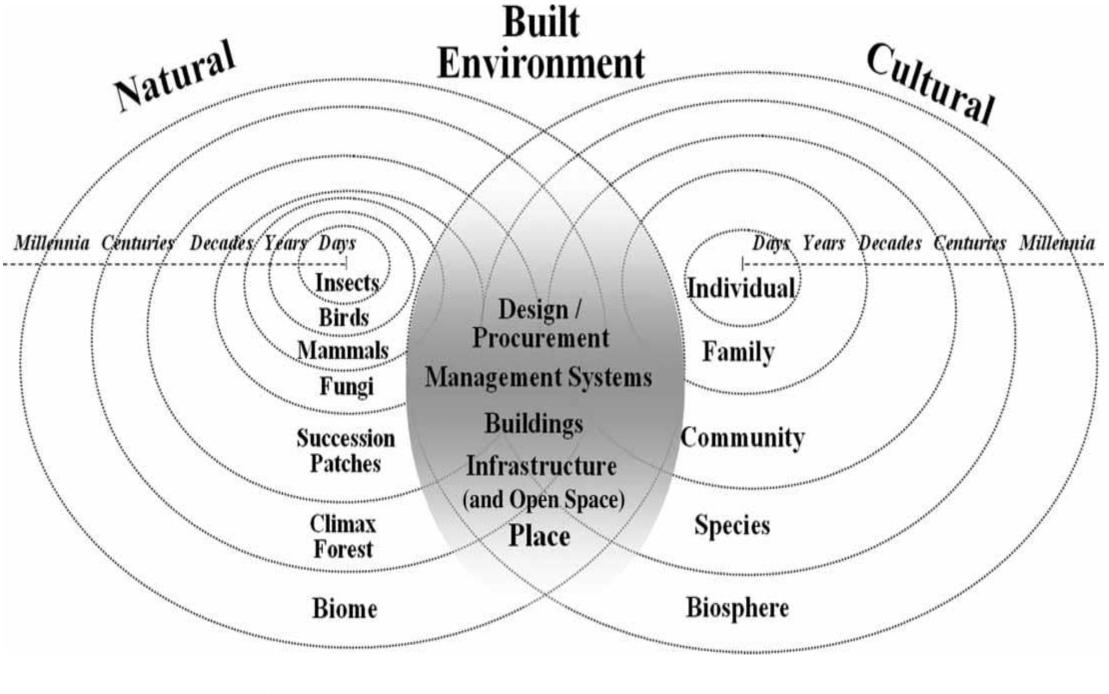
2.2.2 Definition of the built environment, its evolution, and its influences on the design of modern buildings

It is necessary to clarify the definition and the scale of the built environment to understand why the design of buildings has changed.

Moffatt & Kohler (2008) reviewed the research on the built environment from the 1970s to the beginning of the 21st century, both in social science and engineering fields. Based on the findings, they formulated a conceptual framework (Figure 2.2 a and b) to present the relationships among nature, built environment and human society. They also conceptualised a social-ecological system to define the built environment.



(a) *As spatial scales change, some physical effects are aggregated, while others are scale specific; some decision-making begins at the most local scale and seeks to maximise self-reliance, while other decision-making begins at the macro-scale and seeks to enable positive synergies*



(b) *Robust and adaptable systems require interaction across the time rings (logarithmic scale). For ecosystems, the rings are occupied by keystone species that provide responsiveness and continuity. For society, the rings reflect the simultaneous loyalties for humans, as individuals, and as members of larger collectives. For built environments, the material and cultural realms are combined, with the fast pace of the social processes (design, assessment, contracting, management) balanced by the longer-term influences of buildings and landscapes*

Figure 2.2 The conceptual framework of the built environment as a social-ecological system
(Moffatt and Kohler 2008)

Moreover, Moffatt & Kohler's work (2008) further explained the interactive mechanism among nature, built environment and human society - through the built environment, human's social and economic activities influence the whole ecosystem's sustainability, either positively or negatively. Equally, the ecosystem's changes affect the built environment, and then economic activities and human society are influenced consequently. According to Moffatt & Kohler's model (Figure 2.3), there are five scales of the built environment: Parcel, Block, Cluster, City and Region. Moreover, 'building' and 'infrastructure' are two functional elements in the built environment.

In the past ten years, the debate in urban planning and building design continuously engaged resilience. More specific topics are developed in both Urban Sustainability (US) and Urban Resilience (UR) domains to enable positive changes in the built environment. Zhang and Li (2018) reviewed 60 relevant papers' discussions and conclusions (mainly published after 2008). They summarised these papers' topics under 'items' (features) of the built environment, and then further grouped them under different physical scales (Table 2.1).

Table 2.1 Comparison of the built environment models in 2008 and 2018

(Moffatt and Kohler 2008)		**(Zhang and Li 2018)**	
Scale	**Item**	**Scale**	**Item (of the built environment)**
Not available	• Design / Procurement • Management System • Buildings • Infrastructure (and Open Space) • Place	Global	Ecological environment
			Resource protection and utilisation
			population and health
Region		Reginal	Regional economic structure
			Reginal resource flow
			Regional resource carrying capacity
City		Urban/city	Urban governance
			Urban system
			Urban security
Cluster		Community	Residents demand
			Neighbourhood
			Community management
Block		Facility	Infrastructure management
			Transportation
			Building
Parcel		**Not available**	

According to Zhang and Li's (2018) summary, the built environment research recently merged 'parcel and block' into one 'facility' scale. They also extend the up-limit edge of physical scale from 'region' to 'global' (see Table 2.1 for detailed comparison).

Such changing of scales and development of scale-related sub-topics are not because of different perceptions from researchers. They reflect the evolution of the built environment, in terms of scale-related synergies and physical effect aggregations.

- **Evolution 1: Macro-scale synergies of actions for climate change mitigation and adaptation - influencing the building design targets**

Since the late 1990s, there have been intensive debates about the causes and influences of climate change. Coming to the 21st century, the science of climate change develops to a new level. Scientists now can quantify the relationship between human activities involved Green House Gases (GHGs) emissions and the average mean temperature rising of the Earth's surface. The conclusion is that if the average mean temperature of the Earth's surface continues rising at the current rate, extreme climate change at global scale may not be avoidable (IPCC 2018). As a result, the sustainability of the whole ecological system will be under serious threat.

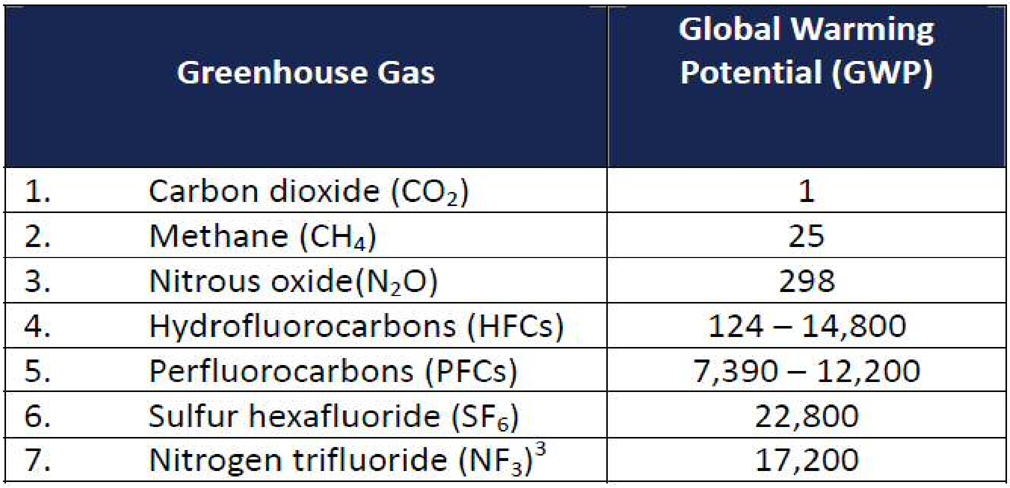
IPCC (2018) also pointed out that:

> 1. *'Impacts on natural and human systems from global warming have already been observed (high confidence). Many land and ocean ecosystems and some of the services they provide have already changed due to global warming (high confidence).'*
>
> 2. *'Increasing investment in physical and social infrastructure is a key enabling condition to enhance the resilience and the adaptive capacities of societies.'*

Therefore, climate change's impacts on the ecological system, and consequently on the built environment and human society are well understood now. Consequently, global scale rules are made for climate change mitigation and adaptation.

The Kyoto Protocol was adopted in 1997 and entered into force on 16 February 2005. Then on 8th December 2012, at the end of the 2012 United Nations Climate Change Conference, an agreement was reached by nearly 200 nations to extend the Protocol to 2020. Further, at the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. This legal agreement sets out a global action plan to put the world on track to avoid dangerous climate change by limiting global warming to well below 2°C (European Commission 2016). On 22nd April 2016, the 'International Mother Earth Day', 175 parties (174 countries and the European Union) signed the Paris Agreement (COP21-CMP11 2016). Paris Agreement is by far the most significant number of countries ever to sign an international agreement on a single day, which firmly launches the 'low-carbon development' agenda at the global level.

Low-carbon development so far has no formally agreed definition. In the context of United Nation's conventions, the term low-emission development strategies (LEDS - also known as low-carbon development strategies, or low-carbon growth plans) is used more frequently after 2010 (Clapp et al. 2010). Such phrasing is to avoid misusing of the term 'carbon' to present the whole GHGs because there are seven regulated GHGs in the Kyoto Protocol (Figure 2.3). These regulated GHGs in the Kyoto Protocol are the most relevant to human activities in the built environment.



	Greenhouse Gas	Global Warming Potential (GWP)
1.	Carbon dioxide (CO_2)	1
2.	Methane (CH_4)	25
3.	Nitrous oxide(N_2O)	298
4.	Hydrofluorocarbons (HFCs)	124 – 14,800
5.	Perfluorocarbons (PFCs)	7,390 – 12,200
6.	Sulfur hexafluoride (SF_6)	22,800
7.	Nitrogen trifluoride (NF_3)[3]	17,200

Figure 2.3 Kyoto GHGs (Brander 2012)**, referenced** (IPCC 2007)

The term 'low-carbon' is short for low - Carbon Footprint (CFP), which is an approach created by scientists to simplify the calculations of GHGs emissions. Scientists group all the legally bound GHGs and work out the total amount of heat trapped by them. Then, they calculate the amount of carbon dioxide that would be needed to cause a similar effect. This amount of carbon dioxide is carbon dioxide equivalent – CO_{2e} (Brander 2012), which mostly used in international negotiations and agreements.

The globally binding CO_{2e} emissions targets have profound influences in the industrial sectors, as each of them needs to set up its sub-targets for climate mitigation obligations. In the construction industry, the existing research has analysed buildings' lifecycle CO_{2e} emissions in order to understand its impacts during the whole producing process. For example, in the UK, BIS (DBIS 2010) once concluded that buildings' in use CO_{2e} emissions account for about 83% of their lifecycle total emissions (Table 2.2).

Such building lifecycle CO_{2e} emissions research brings the focus of current building design on their energy performance. Because the in use CO_{2e} emissions of buildings mainly come from their energy consumptions for heating, cooling, hot water, ventilation, lighting and appliances. As a result, NZE buildings become the most intensively researched topic in developed countries' building sector since the beginning of this century.

According to the National Assembly for Wales (National Assembly for Wales 2018), an NZE building is defined as:

> *'...a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.'*

As seen from Table 2.2, if a building can achieve nearly zero-energy consumptions during its operation stage, the majority of a building's lifecycle CO_{2e} emissions would disappear. That is why such building is believed to be 'low-carbon' and could play a vital role in climate change mitigation.

Table 2.2 CO_{2e} emissions of the construction industry's sub-sectors reproduced from (DBIS 2010)

Sub-sector	% of the total	Category
Design	0.5%	Embedded CO_{2e} emissions
Manufacture	15%	
Distribution	1%	
Operations on-site	1%	
In use	83%	Operational CO_{2e} emissions
Refurb / Demolition	0.4%	Maintenance and end of life CO_{2e} emissions

Note: the % of CO_{2e} emissions bases on the UK's $MtCO_{2e}$ calculated out from the research's data resources in 2008. Each country may vary in the percentages due to the local construction materials and the building forms (high-rise buildings have a higher percentage of embedded CO_{2e} emissions). However, in general, such distribution of CO_{2e} emissions is applicable world widely.

Therefore, the modern design of buildings has further narrowed its targets from lifecycle 'low-carbon (footprint)' to NZE in use.

- **Evolution 2: Micro-scale aggregations of physical effects - influencing the building design purpose**

Previously, buildings' (blocks) simplex functions (parcel), such as office, school, and dwelling, would define the types of buildings. However, in the recent ten years, more and more multi-functional buildings occurred. The most obvious example is the large commercial buildings in the urban complex, which names as HOPSCA (Hotel, Office, Park, Shopping mall, Convention and Apartment). Such building certainly pushes the aggregation of the built environment to a more complicated level. That is why in Zhang and Li's (Zhang and Li 2018) classification, 'facility' becomes the smallest scale of both Urban Resilience (UR) and Urban Sustainability (US) topics. Such aggregation increases the land use and transport efficiencies because people can get comprehensive services by the same building (facility).

However, with the breakthroughs of technologies in the past five years, the aggregation does not stop at the 'parcel + block = facility' level. Within the facility scale, innovations of technologies have made the boundaries among infrastructure, transportation, and building very vague.

The electric cars open the prelude of renewable energy powered 'clean transportation'. In the meantime, it also provides an abundant source of electricity storage for gird load shifting (Institute of Physics 2018) and supply (Walton-Warwick 2017) for both buildings and grid as power banks. Again, the buildings which generate, store and use energy at the same time cannot be seen as just buildings anymore. The appearance of these two 'facilities' also accompanies the arising of the smart grid, which enables these facilities being distributed and utilised dynamically at the community (cluster) scale.

Such aggregation increases the energy use efficiency and reduces fossil fuel consumptions. When these facilities working with the smart grid, micro-renewable-generation can utilise on a larger scale for more functions.

Therefore, now when designing a building, it would aim to have its local renewable energy generation(s), and get connected to the gird for reciprocal benefits – so-called 'buildings as power stations'.

- **Evolution 3: Medium-scale synergies of the cultural domain through new business models - influencing the building usage**

The massive changes of physical effect at the 'facility' scale also push the synergies in the social domain. Because when the resources and facilities are distributed and utilised in the community (cluster) or even city (urban) scale, the boundaries among individual, family and community (Figure 2.3a) are weakening as well. The current business models in many countries and sectors corroborate such a change (Iersel 2013). These business models aim to enable greater convenience in the built environment, with fewer emissions than standard practices, and more new job opportunities. These business models grouped and created a 'Low-Carbon Economy'.

For example, vehicles and bikes are shared by a large number of people through short term renting rather than directly purchasing. Such business model reduces the total amount of facilities needed at the community or city scale, by increasing the using frequency and occupying rate of them.

The similar business model in the building sector has appeared too, which trades building generated renewable energy with grid-supplied energy. Such business model encouraged renewable generations being installed on individual buildings, therefore, saving the land from installing PVs. In such a case, buildings become power stations, alongside their normal functions. However, the renewable energy business models involving buildings are still under investigation. The main problem is that the 'renewable-power-generating' buildings are not affordable to the medium to low-income groups yet.

In a word, the perception of the built environment has changed fundamentally since the 1970s. The scales of the built environment also evolved. These changes all together resulted in new types of facilities to serve the goal of climate change mitigation and adaptation. NZE buildings are the resulted innovative facilities to serve such evolutionary built environment.

2.2.3 The role that affordable NZE houses play in the evolutionary built environment

As explained above, the evolution happening in the built environment was to meet the conjunct need for sustainability and resilience. It brings low-carbon (footprint) requirements to current and future design of buildings.

The existing research of low-carbon buildings found that NZE or ZE building integrated renewable energy generations in association with heat pump systems and thermal storage is the critical area for a breakthrough. Such a strategy:

- does not need extra land for energy generations (Attoye et al. 2018)
- produce less carbon-intensive energies and use them locally (Luthander et al. 2015)
- has fewer distribution losses (Fischer and Madani 2017)
- has higher energy transfer efficiency (Arteconi et al. 2012)
- has immense flexibility of energy utilisation, so more resilient to hazardous weathers (Kosanović et al. 2018)
- is more cost-effective to build and operate (Arteconi et al. 2012; Fischer and Madani 2017)

The above strategy can apply to all type of buildings. However, in the developed countries, the breakthrough of NZE and ZE buildings in the housing sector so far leads the construction industry's low-carbon agenda.

Moreover, it has pushed the standard higher to even EP houses (Jones et al. 2015). As summarised by Lu et al. (Lu et al. 2015), the reason is straightforward:

> *'As a rule of thumb, the target of zero net energy is easy to be achieved for low rise buildings with less energy use intensity and large roof space for solar photovoltaic.'*

Such a conclusion also is drawn by the research in the USA based on currently available technologies. Among all the construction areas which could achieve the ZE standard in the USA, 88% of them is buildings with four or fewer storeys. To further break down these 88%, 3 – 4 storeys buildings only take 12%, and 1 – 2 storeys buildings take 76% (Figure 2.4). Such figures narrow the choice of ZE building design to low-rise. The similar situation applies to the EU as well.

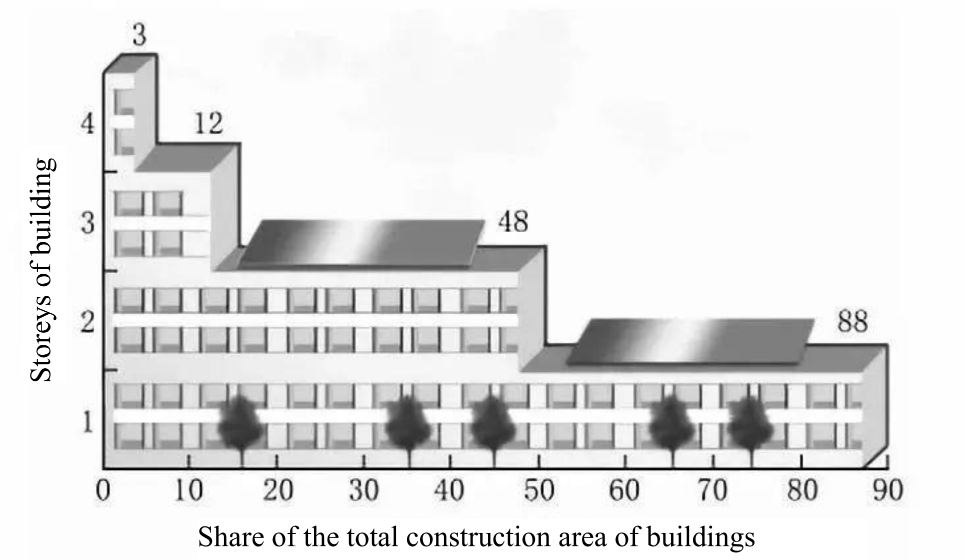


Figure 2.4 Storey of buildings v.s. the share of constructions areas which can achieve NZE standards – the USA conditions (Green buildings in the EU and USA 2018)

The majority of housing are low-rise buildings in the EU. The NZE and ZE buildings are therefore most easily to deploy in the housing sector. That is why early in 2010, the EU Directive has set up its NZE building standard, and assign funds for helping the housing sector to achieve such standard (National Assembly for Wales 2018). Since then, many of the leading countries in the EU (such as the UK, Germany, and Switzerland) have required their new build houses to achieve NZE or ZE performance.

Thus, even though 'low-carbon (footprint)' building is the ultimate goal for climate change mitigation, NZE or even higher energy performance buildings are the most popular ones in the current practices. They not only significantly reduce the building sector's CO_{2e} emissions but also vastly enhance the infrastructure's resilience to climate change events. Among all types of NZE or above buildings, the house is now the flagship in the developed countries because they are most cost-effective to achieve such standards.

Moreover, comparing with other types of buildings, housing has closer links to social sustainability. The significantly reduced energy in use also means minimised bills, which is essential to eradicate fuel poverty. The improved comfort level by such housing can also significantly improve the health and well-being of low-income-group people. That is why in many of the developed countries, the new build social houses are required to achieve NZE or above performance.

2.2.4 Summary: the principles of current affordable NZE houses in developed countries

Based on the above sections, the breakthrough of current affordable NZE house follows the principles as below:

- **Design pattern and feature** – they are low-rise, driven by energy performance, with building-integrated renewable energy generation as a default feature
- **Scale** – they are seen as a part of the low-carbon infrastructures and need to work with the smart grid to integrate renewable energy supply, storage and local usage
- **Standard** – the standards of comfort and well-being are high, but only consuming a little energy, so the houses have to be at least NZE
- **Cost** – the lifecycle costs need to be competitive to the current standard practice so that they could be affordable

Believably, these principles can be adopted by China with adjustments according to the country's circumstances.

2.3 China's current urban housing status and its high-rise high-density housing strategy

This section investigates China's current housing status by analysing the existing literature and statistic records. Section 2.3.1 reviews the main problems of China's current housing sector. Section 2.3.2 analyses China's high-rise high-density housing strategy in order to find out why it did not resolve these problems effectively. Section 2.3.3 summarises the critical areas for a breakthrough in order to achieve low-carbon housing in the future.

2.3.1 China's current housing status and concerned issues.

2.3.1.1 Facts of supply and affordability

Urban housing shortage and unaffordability occurring along urbanisation are the common problems of many countries in the world. China has gone through the rapid urbanisation stage within only twenty years, which is much shorter than many of the developed countries. On top of the speed is its rural-to-urban immigration scale. Therefore, some common housing problems are extremer than in other countries at the same urbanisation stage.

In order to catch up with the rapid urbanisation rate, China has built an immense amount of housing since the late 1990s (Figure 2.5). Especially coming to the new century, affordable housing was supplied intensively - only between the 11th and 12th five-year-plan period (2006-2010 and 2011-2015), China has constructed over 40 million units of new affordable housing (Tan 2017). The intensive construction of affordable housing continues in the 13th five-year-plan period.

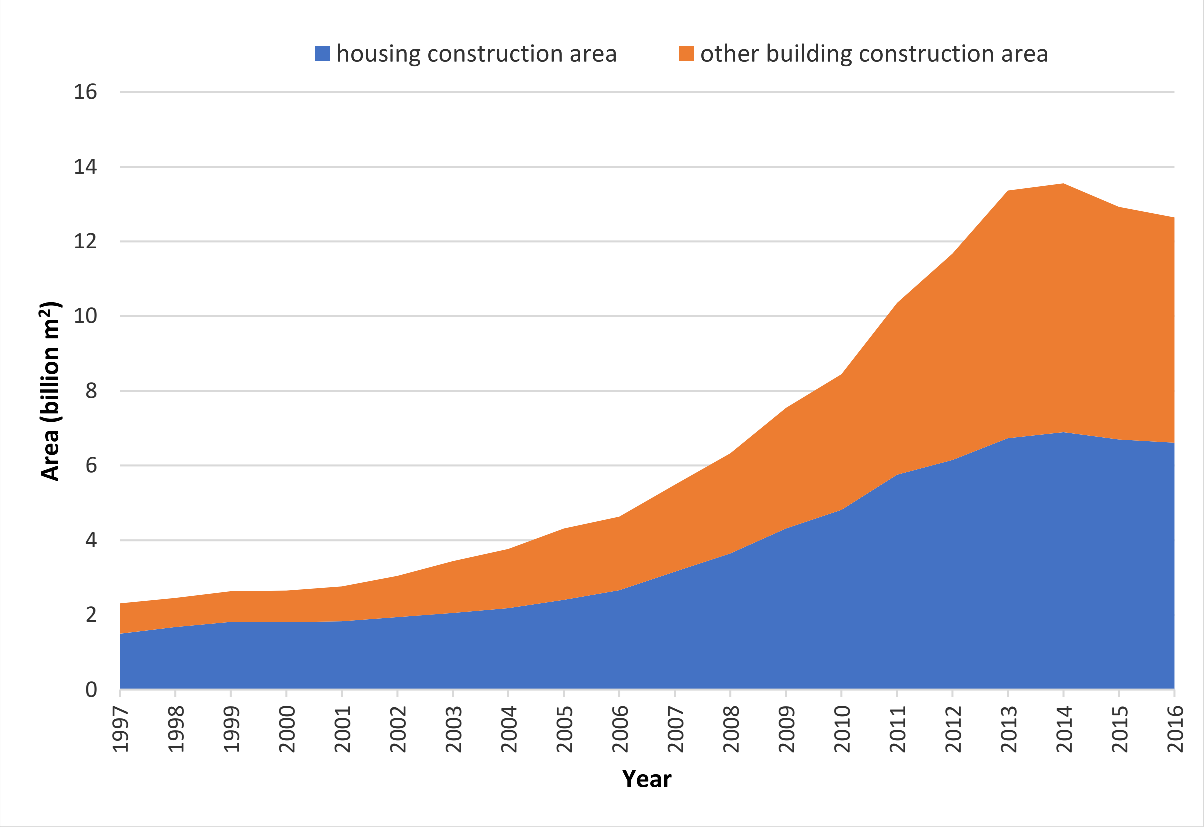


Figure 2.5 The constructed building areas in China 1997 – 2016

Data Source: China Statistical Yearbook, 1998 – 2017

However, this enormous amount of housing supply did not manage to ease the housing price increase. In the past 20 years, China's housing price has been increasing quickly and continuously (Figure 2.6).

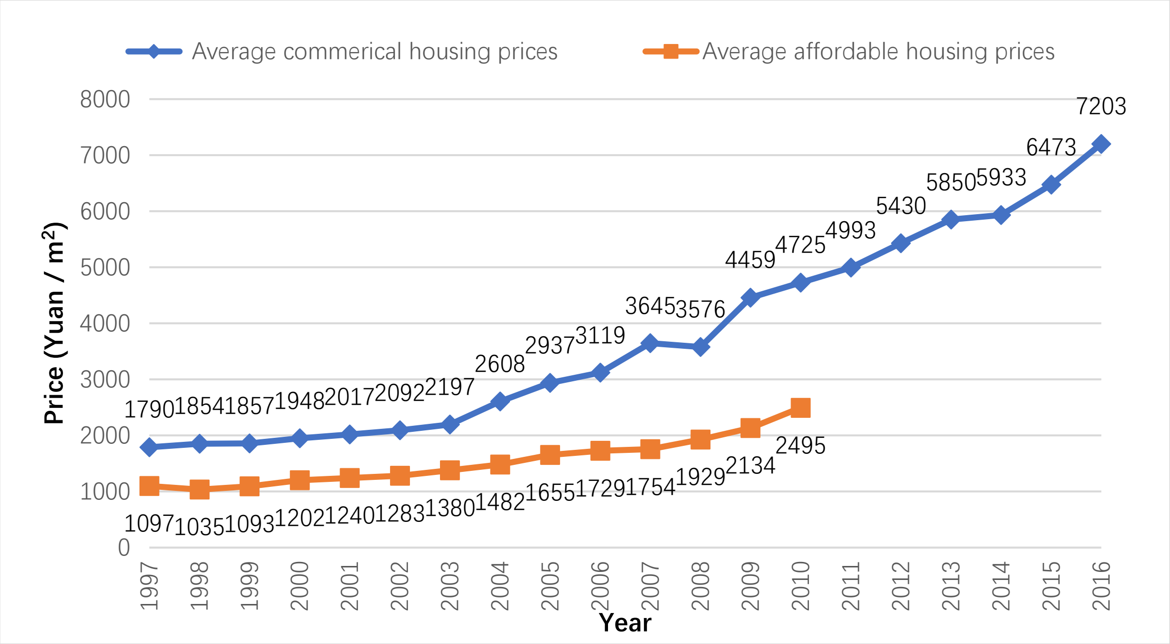


Figure 2.6 Average commercial and affordable housing prices in China 1997 - 2016

Data Source: China Statistical Yearbook, 2011 & 2017

Note: National Bureau of Statistics of China no longer records affordable housing price after 2010, because the policy switched from price-cap housing to government-subside housing from 2011. With the new policy, the price of affordable housing started to vary largely with local economic status. In that case, the national average price of affordable housing no longer reflects the true situation across the country.

With all types of affordable housing programmes on board (Table 2.3, more detailed descriptions and analysis of these programmes are in section 2.4.1), the private housing's price still increased to 4 times the price 20 years ago. In the meantime, the average household disposable income has not increased at the same rate and is still far behind the housing cost (Table 2.4).

Table 2.3 Main programmes of China's affordable housing policies (Zou 2014)

Programs		**Period**	**Housing tenure**	**Target groups**
Peaceful Living Project (PLP)		1995–1998	Ownership	Low- and moderate-income households
Social Housing	Cheap-Rent Housing (CRH)	1994-present	Rental	Indigent households
	Economical and Comfortable Housing (ECH)	1998-present	Ownership	Low- and moderate-income households (before 2007); Low-income households (after 2007)
	Price-Cap Housing (PCH)	2007-present	Ownership	The middle class who cannot afford market housing
	Public Rent Housing PRH)	2010-present	Rental	Low- and moderate-income households; new employees, and eligible migrants in some cities

Table 2.4 Comparison of average household disposable income (£) by group between China and the UK in 2017

China				UK			
Income Group	Annually	Monthly	Ratio quintile	Income Group	Annually	Monthly	Ratio quintile
High (20%)	20923	1744	10.9	Top	70,684	5890	5.3
Medium-high (20%)	11132	928	5.8	4th	41,058	3422	3.1
Medium (20%)	7248	604	3.8	3rd	29,667	2472	2.2
Medium-low (20%)	4461	372	2.3	2nd	21,436	1786	1.6
Low (20%)	1920	160	1	Bottom	13,392	1116	1

Note: China's data convert to pound with the change rate of 9:1, and an average of 2.9 people per household

Source: 1. China's data from *Statistical Communique of the People's Republic of China on national economic and social development in 2017*

2. UK's data from *Household disposable income and inequality in the UK: financial year ending 2017*, UK - Office for National Statistics

Table 2.4 presents the average household disposable income by groups in China in 2017 and compares it with the figures of the UK. It clearly shows that the ratio quintile among the top, medium and bottom is much higher in China. Therefore, although China's general economy has grown tremendously, the majority of Chinese people are still struggling to purchase housing as their primary consumable.

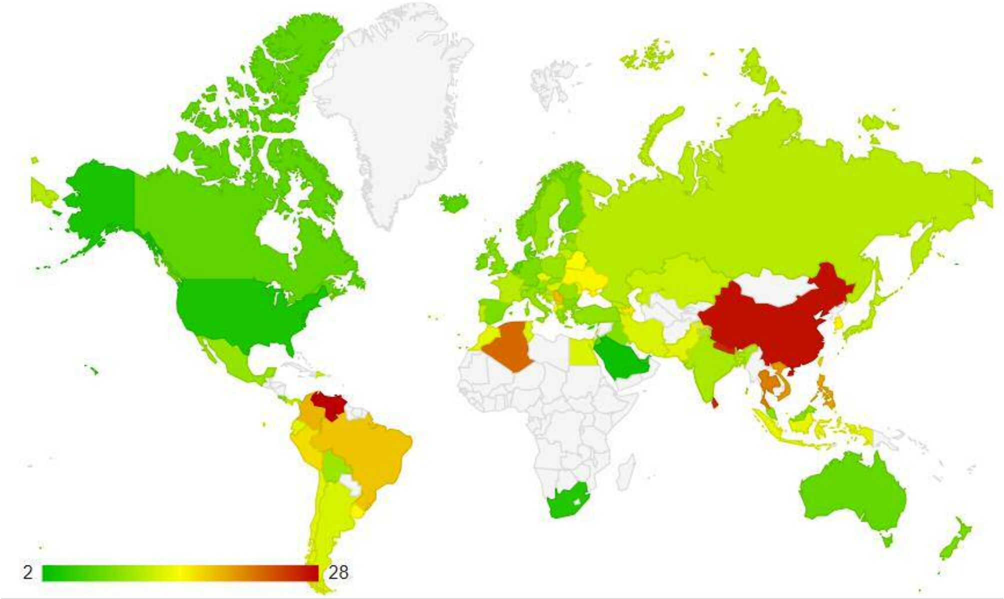


Figure 2.7 House price to income ratio of countries, 2018 Mid-Year (NUMBEO 2018)

Table 2.5 Comparison of House Price to Income Ratios among the world's major cities

Order in the world (302 entries in total)	City	Country	House to income ratio	Mortgage as a percentage of income
2	Hong Kong	China	46.89	293.60
3	Beijing	China	44.34	350.17
4	Shanghai	China	44.00	344.54
5	Shenzhen	China	39.86	316.52
7	Mumbai	India	30.99	339.93
10	Rio de Janeiro	Brazil	24.58	295.91
11	Guangzhou	China	23.10	191.40
17	Singapore	Singapore	21.18	130.05
18	Taipei	China	21.08	127.31
22	London	UK	20.58	139.47
28	Paris	France	18.51	111.29
31	Seoul	South Korea	17.79	125.01
61	Stockholm	Sweden	14.20	87.39
79	Tokyo	Japan	12.97	72.74
94	New York	USA	11.93	87.32

Source: NUMBEO, 2018, https://www.numbeo.com/property-investment/rankings_by_country.jsp?title=2018-mid [Access on 24/08/2018]

Note: The table only includes the Chinese tier 1 cities to be compared with other key cities in the developed countries or similar level developing countries

China's housing affordability level is inferior compared with other countries around the world. Figure 2.7 shows when the House Price to Income Ratio is averagely 8.89 in the UK in mid-year 2018, the figure is 27.17 in China. Even such a high ratio is only about 60% of China's tier 1 cities' average (Table 2.5).

It might by default be thought that the shortage of housing would naturally push up the property price. Therefore, if China needs to accommodate such a lot of people in the urban area within such a short time, the high price is reasonable. However, the truth is that China's shortage of housing is not as extreme as indicated by the housing price. Neither is the housing shortage a universal phenomenon in the whole country.

As introduced in Chapter 1 (Figure 1.1), existing research shows that the shortage of private housing is only in tier 1 cities of China. From tier 2 to 4 cities, there are different levels of private housing oversupply, the majority of which are high-rise apartments.

Meanwhile, the average housing area per person in China has reached 36.6 m^2 (Figure 2.8), while the usual level of developed countries' is 35 m^2 (Zhu and Li 2015). Such a figure means the already constructed housing in China has been sufficient to provide Chinese people with decent living space.

This phenomenon begs the question - why did the housing price did not reduce when supply was sufficient? The answer is the ineffective housing supply and high costs of infrastructure.

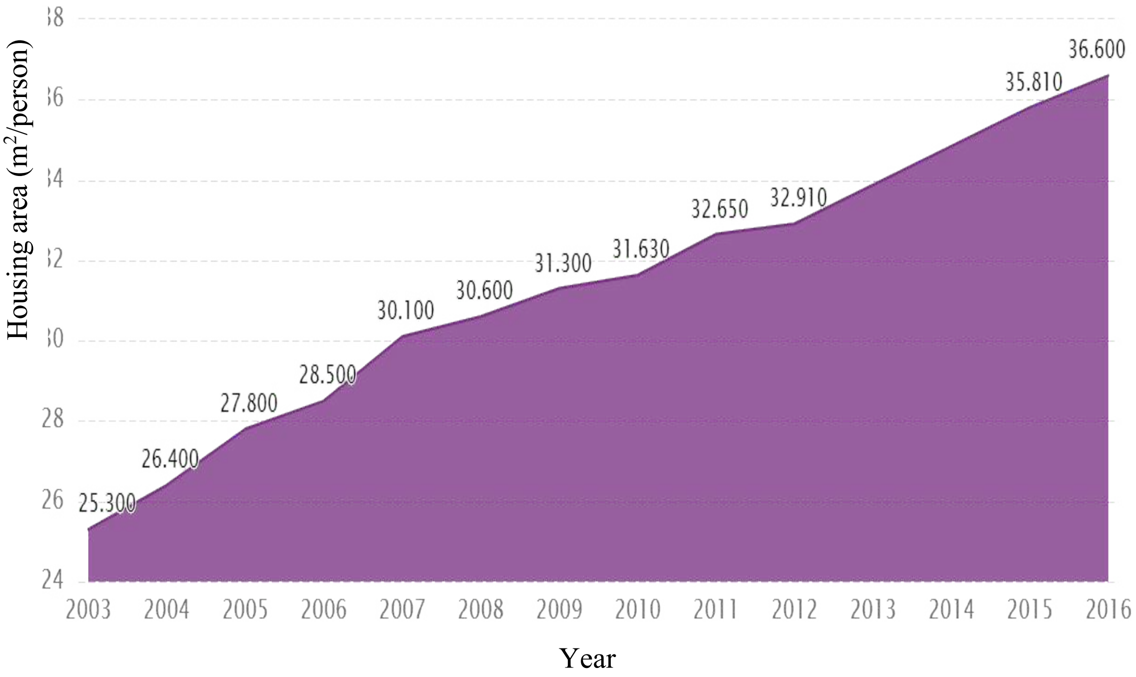


Figure 2.8 The average housing area per person in China 2003 – 2016 (CEIC 2018)

Source: National Bureau of Statistics, China, 2018

The vacant rate reflects the ineffectiveness of housing supply.

For commercial and ownership-oriented ECH & PCH housing, there is no direct, consistent and credible data on vacancy rate at the national or local level. However, 10% - 30% is a widely referenced range in the mainstream financial and economic media, e.g. PhoenixNet, (Bai 2018); and Tencent (Wang 2018).

For public and social rental housing, because the majority of fund comes from the government, there is officially released data. With the audit result, in 2016 '*Nationwide, 128,700 almost completed affordable housing (public + social) units cannot be delivered for more than one year, due to the delay of supporting infrastructure construction. There have been 272,400 apartments completed and checked for approval, but vacant for more than one year, due to the remote location and unreasonable apartment design*' (Notice of follow-up audit results of the government-subsidised housing project in 2016, referenced by China Economic Net, (China Economic Net 2017)). The national vacant rate of public and social rental housing is not specific yet, but even if the rate is not high, it is still essential to avoid. Because without the effectiveness of affordable housing provision, the more unnecessary cheap housing constructed, the more natural resources and public funds wasted.

For such a situation, there would be a relevant percentage of energy infrastructures wasted too. Because for the real estate development, either the government or the developer needs to match the energy infrastructures with the potential end-user demand. Usually, this part investment is before the housing constructions. If the end-user demand is over-estimated, there would be significant over-sizing of energy infrastructures too. This part extra cost will ultimately be passed to the home-owners when they buy the properties, which makes the housing price higher than it actually should be. The hidden and wasted infrastructure costs add burdens to affordability.

Southwestern University of Finance and Economics (Survey and Research Center for China Household Finance 2017) also concluded that '*40% of the existing annual housing supply is enough to meet additional (commercial) housing demand*'. If this research's conclusion is reasonably accurate, it means two significant changes needed in the future private housing development. Firstly, the new build private housing no longer needs as high plot ratio as the current standard practice. In that case, there will be more chances to develop low and multi-storey residential buildings. Secondly, the future energy infrastructures will have the chance to reduce the needed size and cost further, as well as decrease its embedded and operational CO_{2e} emissions. This is based on the fact that building-integrated low-carbon energy infrastructures could be built along with the NZE or above houses to enable costs savings.

Table 2.6 summarises the existing literature' conclusions about why the recent affordable housing programmes (both ownership and rental) failed to enable affordability and satisfy people's living requirement.

Table 2.6 The reasons for China's affordable housing programmes' failure

Programme	**Reasons for not being effective**	
	(Zou 2014)	(Cao and Keivani 2014)
Peaceful Living Project (PLP, Ownership)	1. both local governments and developers lacked incentives to invest in the PLP program 2. the housing mortgage system offered unfavourable terms 3. the PLP program left intact the link between housing provision and work units. Households continued reliance on housing provision by work units (if one changes job, the allocated house will be taken back by the work unit)	1. Inadequate financial support (from central and local governments) and legislation led to poor location of affordable housing and a lack of public infrastructure.

Programme	Reasons for not being effective	
	(Zou 2014)	(Cao and Keivani 2014)
Cheap-Rent Housing (CRH)	1. the CRH program has imposed a heavy fiscal burden on local governments because local governments are unable to sell the CRH units to recoup the initial investment 2. local governments have to allocate additional funds as maintenance fees because low rents do not generate enough revenues to cover the upkeep.	2. The phenomenon that affordable housing does not cover migrant workers is widespread, resulting in some affordable housing empty. 3. They are commonly grouped in the sizeable affordable housing community, resulting in management problems. 4. The credit check system is not yet beneficial and lacks the human resources to screen applicants. 5. Property management is inefficient and lacks effective sanctions. 6. The lack of competition and substitution in the supply of housing reduces household choice and satisfaction (of affordable housing) to a certain extent.
Economical and Comfortable Housing (ECH, Ownership)	1. benefitted upper-income households rather than low-income ones, due to the absence of strict criteria to verify the eligibility of applicants 2. local governments complained that the ECH program impose a heavy fiscal burden	
Price-Cap Housing (PCH, Ownership)	1. local governments do not want to allocate land that could develop in other ways that yield more excellent benefits 2. local governments worry that the PCH program could compete with the market housing, thereby jeopardising the local housing market	
Public Rent Housing (PRH)	1. impose a more substantial fiscal burden on local governments than do homeownership programs 2. the private housing market, including some low-cost, informal housing in urban villages, can provide cheaper rental housing in better locations 3. local governments adopted eligibility criteria that are overly restrictive regarding income, current house condition, and the status of household registration	

These issues can further summarise as:

- **Not affordable to build**

Neither the government nor the developers have sufficient financial capacity to build such many high-rise apartments and the relevant infrastructures.

- **Not affordable to buy or rent**

The construction cost of high-rise apartments and needed infrastructures has been high on its own. Then the hidden financial and administrative costs make the ultimate cost far beyond the low-to-medium income group people’s capability to buy or rent.

- **Not affordable to live**

The remote location of affordable housing projects increases people's travelling time and costs for work. On top of this, the municipal services to these high-rise high-density housing are not stable while expensive, which are extra burdens to people's daily life.

- **Not affordable to maintain**

The cost to retrofit and refurbish high-rise buildings are high. The needed facilities and services (such as fire alarm and automatic sprinkler system, lifts, and rubbish cleaning) are expensive to be maintained to a reasonable level too. The property management fee payable by the low-to-medium income group cannot cover the administrative costs sufficiently.

However, the minimised bills and much lower maintenance costs are two distinct advantages of the NZE or above townhouses. Their construction costs are getting lower now. That is why they are widely perceived as a multi-beneficial solution for public or social housing in developed countries. In China, there have not been NZE or above townhouses involved in the housing sector yet. Therefore, the possibilities are certainly worth exploring. The critical research area then is how China could build the NZE or above townhouses with locally affordable costs.

2.3.1.2 Living conditions

Besides extreme unaffordability, the current housing does not satisfy Chinese people's requirements of living either. China's occupants often complain about the conditions which closely link to health and well-being. These complaints mainly caused by the weaknesses of high-rise apartments' liveability, which are the areas thoroughly studied since the last century. Li's (2013) review on high-rise apartments' liveability issues traced the studies back to the 1950s. From then on, western countries started to build high-rise residential buildings. Table 2.7 summarises the five main weaknesses of high-rise apartments' liveability.

Through over 60 years' practice of high-rise buildings, many of the above problems have been primarily alleviated by modern design and technologies. However, many of these weaknesses have roots in the settlement and building form, so they cannot be eradicated. In China, spatial segregation (Calthorpe 2016; Lin 2018; Ma et al. 2018) and poverty isolation (Zou 2014) created by high-rise high-density affordable housing are currently the most highlighted area in existing research. With the developed countries' experience, these two problems together can easily trigger safety and public security problems, even though they might not exist at the beginning. Therefore, there are substantial concerns about the social sustainability of China's urban housing.

Table 2.7 Identified weaknesses of high-rise apartment' liveability summarised from (Li 2013)

Weaknesses	Specific problems
Health problems of high-rise residents	• 'Sick building syndrome' (Evens, Chen et al., 2006; GoWell, 2011) • Anxiety, feeling isolated, the strain of emotion (GoWell, 2011; McCarthy and Saegett, 1978; Mitchell 1971) • Mental illness increase, such as depressive symptoms and psychological symptoms (Cappon, 1971; Freeman, 1993; Goodman, 1974; Hannay, 1981; Richman,1974)
Lack of safety	• Easily evoke the sense of fear and unsafe, such as fire, natural disaster (earthquake), communicable diseases and failures of the infrastructures (lift, water and electricity supply), even attack like 911 (Gifford, 2007; Haber, 1977; Hung, Chan et al. 2006)
Poor public security	• 'Filtering down effect', which could result in poverty concentration and form new urban slums (Beedle, 1977; Bier 2001) • Litter, graffiti and crime (Newman's, 1975)
Weakening social relations	• Social isolation (Jephcott, 1971; Korte and Huismans, 1983; Stevenson, Martin and Neill, 1968) • Loose relations and interactions among neighbours (Churchman and Ginsberg 1984; Holahan and Wilcox, 1979; Williamson, 1978) • High-rise occupants have found to have less familiarity with neighbours and lower levels of social support than other people (GoWell, 2011) • Weakened sense of community (Forrest, La Grange et al., 2002; Michelson 1977)
Negative impact on families with younger children	• Heightened family conflict, parental isolation, and behavioural and development difficulties among children (Morville, 1969a; Morville, 1969b; Sandels and Wohlin, 1960; Sheppard 1964) • Fewer contacts with playmates (Leventhal and Newman, 2010; Morville 1969b) • More depressive symptoms reported by mothers (Richman, 1974)

2.3.1.3 Residential buildings' construction materials, energy performance and endurance

As explained in Table 2.2, a building's CO_{2e} emissions are mainly from the manufacture of construction materials and the energy consumptions in use. Therefore, buildings' CO_{2e} emissions reductions mainly come from three actions: 1) use more environmentally friendly materials; 2) enhance buildings' energy performance in use; and 3) prolong the buildings' lifespan to conserve the embedded energy, water and construction materials. Unfortunately, none of the three actions has been adopted effectively in China's housing sector.

Firstly, China's construction of high-rise high-density housing mainly relies on concrete and steel, which are energy-intensive materials. When mixed, they are hard to recycle at the end of the buildings' lifespan. According to (Wang et al. 2018a), in China, 80% of the embedded energy is from the manufacturing and on-site construction of concrete and steel.

China did make efforts to reduce these two materials' CO_{2e} emissions and has made significant progress (Figure 2.9). However, with the nature of these two materials and the amount needed in practice, the embedded energy of China's residential buildings is challenging to reduce significantly. Therefore, unless China could involve low and multi-storey residential buildings in the future, the further reduction potential of housing's embedded energy will be minimal. The reason is that many environmentally friendly materials cannot apply in high-rise buildings as the main structure.

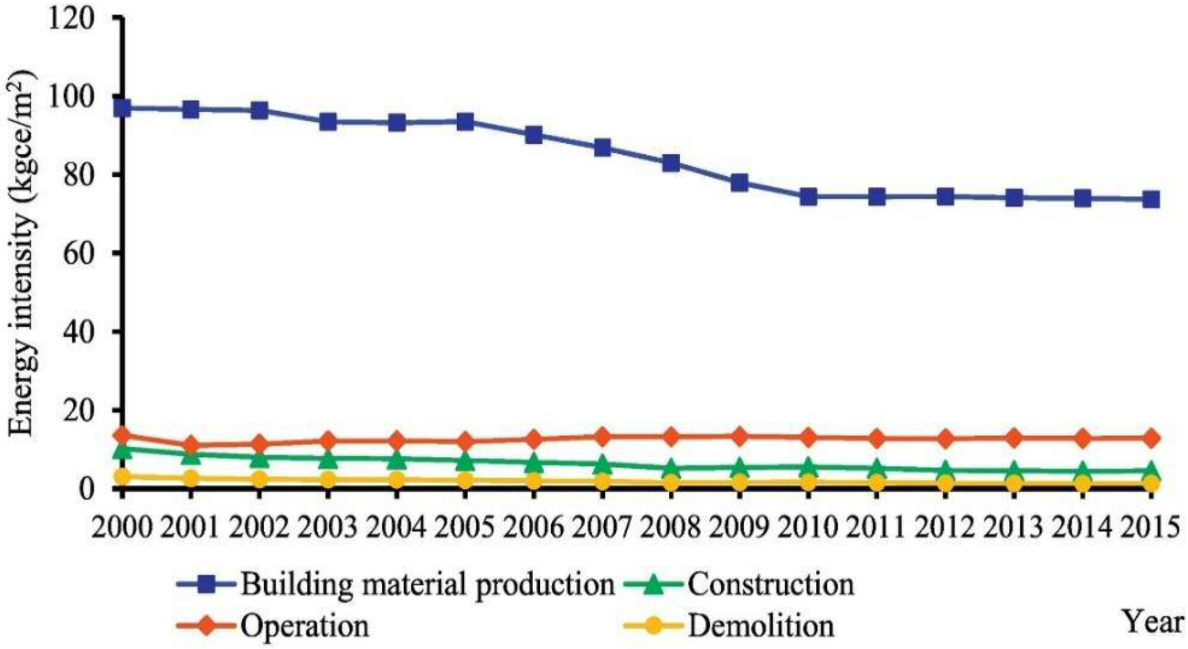
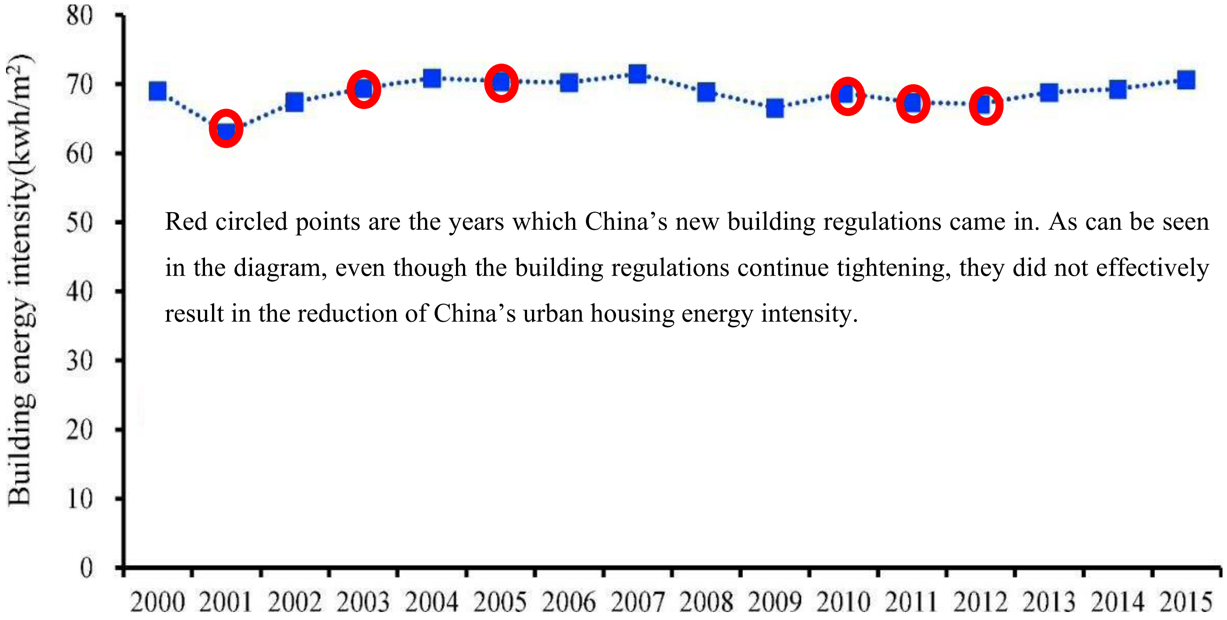


Figure 2.9 The energy intensity for urban residential buildings in China 2000–2015
(Huo et al. 2019b)

Note: kgce/m^2 is a Chinese unit which converted all the energy use into equivalent standard coal defined in Chinese regulation.

Secondly, China's general energy performance in the urban housing sector did not improve alongside the launches of building regulations (Figure 2.10).



Red circled points are the years which China's new building regulations came in. As can be seen in the diagram, even though the building regulations continue tightening, they did not effectively result in the reduction of China's urban housing energy intensity.

Figure 2.10 The operational energy intensity of the urban residential buildings in China 2000 – 2015 (reproduced from (Huo et al. 2019a)**)**

Comparing residential buildings' operational energy intensity with the developed countries', China's current level is low per m^2 floor space (Huo et al. 2019b). The reason behind is that Chinese people's current living standard is still significantly lower than the developed countries ((Jiang 2018; Huo et al. 2019b). However, even with such low per square meter operational energy intensity, China has already ranked second in urban residential operational energy consumptions (Figure 2.11).

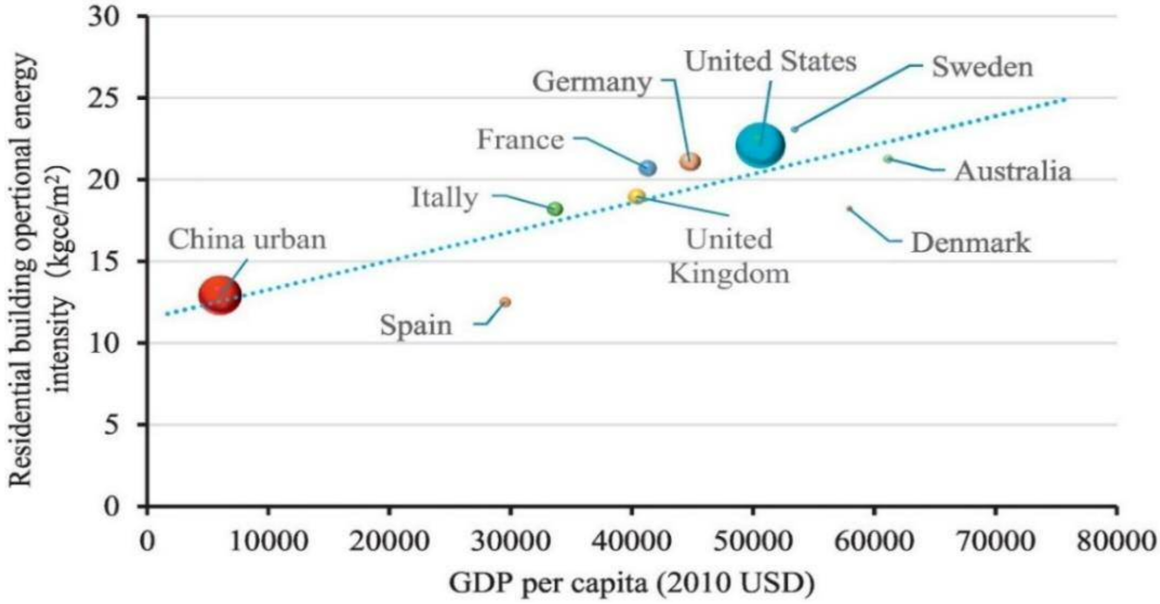


Figure 2.11 Comparison of the residential building operational energy intensity and GDP per capita in the world in 2014 (Huo et al. 2019b)

Note: The size of the ball represents the residential operational energy consumption

Data source: IEA database: https://www.iea.org/classicstats/statisticssearch/; (Huo et al. 2019b)

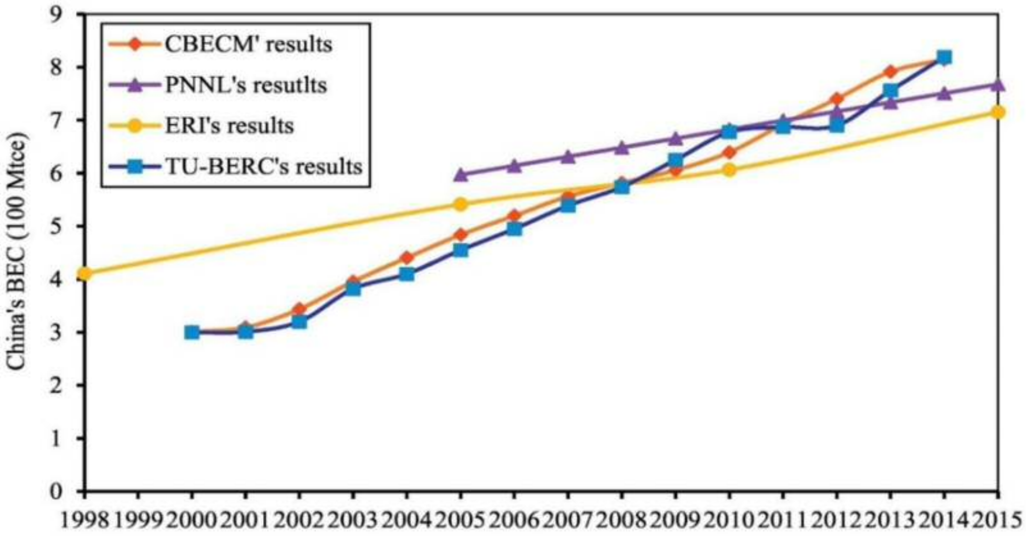


Figure 2.12 Comparison with other studies as for the building operational energy consumption in China (Huo et al. 2019b)

Data source: (Huo et al. 2019b), PNNL (Pacific Northwest National Laboratory), ERI (Energy Research Institute), TU-BERC (Tsinghua University-Building Energy Research Centre).

Note: Mtce is the Chinese unit for energy, which is Mega Tonnes of Coal Equivalent

In the past 20 years, China's residential operational energy consumption has increased considerably due to the rising comfort level (Figure 2.12). Foreseeably, China's living standard will continue rising. If the energy performance of its housing sector does not improve significantly, China will quickly overtake the USA to be the highest residential operational energy consumption country in the world.

Thirdly, China has the shortest building lifespan in the world (Table 2.8), which wastes an enormous amount of embedded energy, water and construction materials.

Table 2.8 Statistical data of building lifespans in China and other countries (reproduced from (Wang et al. 2018c)**)**

Country	Lifespan	Country	Lifespan
China	30	Switzerland	71
USA	44	Austria	80
Germany	64	France	102
Spain	77	UK	132.6
Belgium	90.0	Austria	80.6
Netherlands	71.5		

One of the crucial reasons is that China demolishes and rebuilds, rather than retrofitting, old housing stock to satisfy the modern living standard. As reported by Shepard (Shepard 2015), '*Between 2005 and*

2010 alone, China dismantled more than 16 per cent of its housing stock. That is more than 1,850km^2 *of floorspace – enough to blanket Greater London*'.

Among those 16 per cent dismantled buildings, there are still many low and multi-storey building constructed in the 1960s and 1970s (Wang et al. 2018c). If China replaces them with high-rise high-density housing, keeps the vacant rate high, and then demolishes them within 30 years, the resulted wastes and environmental impacts will be unbearable.

Moreover, high-rise high-density housing is hard to retrofit. The warnings come from two high-rise residential building fire disasters - 28 floors residential building, Jiao Zhou Road, Shanghai, 15th November 2010, 58 died and 71 injured; 24 floors Grenfell Tower, London, 14th June 2017, 72 died. Both of the disasters occurred during or just after retrofitting the external insulation of the two buildings.

Therefore, even if China could guarantee its future residential buildings' lifespan for 50 years, if they are still high-rise high-density, it will be hard for them to stand any longer by retrofitting. Both the layout and the envelopes of such buildings are hard to adjust.

In total, the above content in this section proves that there are two critical problems of China's housing sector: 1) the lack of effective and affordable housing supply; and 2) the high CO_{2e} emissions of residential buildings.

2.3.2 The current high-rise high-density affordable housing strategy in China

The review in section 2.3.1 presents the systematic failure of current affordable housing strategy. However, before criticising such a strategy, it is essential to understand why and how China implemented such a strategy.

World wide it is not only China which uses high-rise high-density strategy to deal with the housing shortage and affordability problems. Early in the 1840s western countries' cities had started to show signs of growing upwards, and modern high-rise housing reached its peak in western countries in the 1960s to 1970s (Li 2013). During this period, high-rise housing was built up quickly in the vast regions from Europe, North America, and Australia to several developed Asian countries (Li 2013). Because World War II (1939-1945) adversely affected many western countries' economy, most of the high-rise housing built during this period were affordable housing (council housing and public housing). Moreover, they were often part of the 'Slum Clearance' programmes (Li 2013). However, with such 'first-aid' approach of high-rise housing supply, consequent problems quickly appeared.

After the mid-1970s, the problems of high-rise housing became evident, and many of those ‘Slum-Clearance Programmes’ became ‘New Slums’ (Li 2013). Such a situation caused a quick decline of new-build high-rise housing, and it was not a rare case or only in one country that people knocked down the existing high-rise buildings for further development (Li 2013).

Since then, the high-rise high-density housing strategy becomes an intensively debated area in academia. On one side, places like Singapore and Hong Kong managed to develop well relying on such strategy, and even city like London is starting to build high-rise apartments again in the 21st century. However, on the other side, a vast amount of research addressed the negative impacts of such a housing strategy. Also, modern design and technologies cannot solve many of the existing problems fundamentally.

China successfully used the high-rise high-density housing strategy to cope with the most dramatic urbanisation process in the world over the past 20 years. Nevertheless, due to the new population trend and new urbanisation stage, China now stands at the crossroad to choose its future housing strategy. Before exploring the future housing strategy, it is essential to distinguish whether it is the current strategy creating these problems, or just the poor implementation in practice.

Therefore, section 2.3.2.1 carries out a detailed case study on China’s biggest affordable housing project. Through this case study, this research investigates the strengths and weaknesses of the current high-rise high-density strategy for affordable housing.

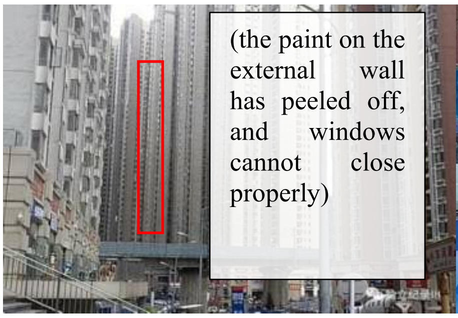
2.3.2.1 Flower Orchard Project, the epitome of China’s current practice of high-rise high-density affordable housing

The best way of distinguishing whether it is the current strategy creating problems, or just the poor implementation in practice, is to investigate the actions in practice. Therefore, this research studied the biggest affordable housing project in China. This project was once seen as the ultimate way to go for China’s affordable housing projects and achieved great success in terms of governmental and commercial results. However, after ten years’ construction and operation of the community, the problems of liveability and livelihood became evident. These problems also threaten the sustainability and resilience of the community. Such a situation reflected the housing history in the western countries after the mid-1970s. Therefore, this case is also an excellent example to investigate whether China repeats the mistakes of western counties, or China has different circumstances.

Figure 2.13 shows the original, newly built, and a few years later situation of the Flower Orchard Project.

a. The original shanty community at Flower Orchard Project site

b. The new high-rise city complex built up at Flower Orchard Project site



(the paint on the external wall has peeled off, and windows cannot close properly)

Quickly degraded buildings

Unsafe pavement occupied by cars and motorbikes

Messy onsite parking Poor safety management Dangerous construction operation

C. The outbreak of problems at Flower Orchard Project site

Figure 2.13 Images of Flower Orchard Project

Source:

(a) Focus real estate network. 2018. Flower Orchard Project in Guiyang: Who was hit in the face by the "rise" of the super Asian real estate development project? http://sc.house.hexun.com/News/details/id/113343.html [access 7th August 2018]

(b) Zhihu Online Forum. 2018. How to evaluate China's biggest real estate development project 'Flower Orchard' in Guiyang https://www.zhihu.com/question/46642458 [access 5th August 2018]

(c) Sohu Online News. 2018. Flower orchards: a new shanty life under pseudo-ecology. http://www.sohu.com/a/240629826_429684 [access 12th July 2018]

There is no doubt that this project successfully turned the original messy and dirty shantytown (Figure 2.13, a) to a fresh new community (Figure 2.13, b). When it is newly finished, one cannot tell quickly whether this is a typical Chinese urban commercial community or an affordable housing community (Figure 2.13, b). However, just within ten years' operation, the degradation quickly shows up, and the community's management starts to lose control (Figure 2.13, c).

The following contents present some facts and figures for this project.

According to the news reported by China Business (China Economist 2018b), the original shanty community on-site has over 4,000,000 m^2 slum housing and occupied more than 20,000 households. With over 100 billion Yuan investment from government and other commercial resources, the developer cleared out the original shanty community. Then, they constructed over 250,000,000 m^2 high-rise buildings onsite within eight years (2010-2017). These buildings consist of housing, business, offices, community centre and hotels. With one police station and six public security offices, plus 23 mini fire stations and over 40 bus lines running daily, this area has developed from a simplex affordable housing project to a city complex. China Economist (China Economist 2018b) also referred to a local government officer's statement that *'after eight years' construction and development, now (2018) there have been more than 220 buildings under operation…There are more than 132,000 households, about*

400,000 people, living there. More than 6400 companies run their business, and over 13,200 shops sell their products in this area, which provide more than 150,000 jobs locally'.

Indeed, from a governmental and commercial point of view, this project has achieved great success. Because on top of the above figures, the housing price of this project had maintained much cheaper than the average local housing until 2016 (Zhihu Forum 2018). Furthermore, even with such low profit per m^2, the developer still successfully grew from a small unknown company to the top 20 developers in China just by this single project (Zhao 2012).

However, since 2015 there have been warnings from academia and planners that such mega high-density settlement could bring series troubles to the cities. For example, Nan Shi, the secretary-general of Urban Planning Society of China, reminded that *'when huge amount of population crowded in a small area of a city, the need of infrastructures such as transport, grid and water supply will explode in a short time, which may even make the city's main infrastructure systems collapsed. In that case, such an area would become the burden, or even the tumour, of a city'*(Economic Information Daily 2015). Also, Peng Wu, the former deputy director of Tianjin Urban Management Bureau, concerned that *'When a residential area is too big, the property owners committee will be hard to elect out, which makes the local social stability a big hidden problem'*.

The reality quickly corroborates the concerns. With the available information so far, all sorts of predicted problems have come one after another. Firstly, housing prices become no longer affordable. According to China Economist (China Economist 2018b), the latest new build housing price of this project has reached 15,000 Yuan / m^2, which is even higher than the city's average private housing price. The sharply arising price primarily links to the land price increase in the third phase of this project.

It also needs to note here that the 6.8 plot ratio makes the majority of high-rise residential buildings of Flower Orchard Project 44 floors. Moreover, each building has more than 1,000 households living inside (China Economist 2018b). Therefore, it is not hard to imagine the pressure this single project created to the whole city's infrastructures and municipal services.

Early in 2015, the local planning officer had stated that the existing infrastructures in this area are not sufficient to support such quick and extreme high-density housing development (Yan et al. 2015). Moreover, the occupying rate of the project's third phase reduces to 60%, due to lack of parking place and chaotic traffic status at peak time (China Economist 2018b). The city government has to call for multi-department meetings to discuss how to improve the environment of this area (China Economist 2018a). Because *'the daily output of domestic wastes is about 450 tonnes, which is equal to a middle-size city's rubbish production. Nevertheless, the current capacity of environmental sanitation* *equipment in this area is only about 100 tonnes'*, said Gang Chen, the chief director of Urban Management Bureau of Nanming District (administrative division area of Flower Orchard Project).

These facts and figures recalled the memory of Manhattan, New York's development from about 100 years ago. Just because of the better infrastructure and improved technologies after 100 years, Flower Orchard Project managed to push this project to a larger scale within only eight years. However, comparing with the situation of western countries after the mid-1970s, outcomes of this project do not show fundamental improvements in terms of sustainability and resilience.

Apart from Singapore and Hong Kong, the majority of countries in the world have implemented a diverse housing type strategy in the 21st century. Moreover, high-rise high-density housing is no longer the mainstream strategy used in western countries. Therefore, China needs to reflect on the housing history of other countries. It is critical to evaluate the gains and losses before carrying on such a strategy in the future.

2.3.2.2 Strengths and weaknesses of China's high-rise high-density affordable housing strategy

The pros and cons of high-density communities widely discussed around the world (Table 2.9). China's particularity is its extreme high-rise building form on top of very high-density, which pushes both the advantages and disadvantages of such housing strategy to an extreme level.

Comparing Table 2.9 with Flower Orchard Project's facts and figures, it shows that the early successes of this project all benefit from the advantages of high-rise high-density strategy.

The 400,000 people living in this single project have been more than a major city in western countries (such as Cardiff, the ninth-largest city of the UK). Without the high-rise high-density housing strategy, it is not possible to use so small area of land to occupy so many people. According to (You 2018), this project uses only 4.0 km^2 land, which is about 1% of the local city's construction land, to occupy about 10% of the city's total population.

Till the second phase of this project, the density was high but bearable by the local infrastructures and public services (or the catching up speed). Because of the saved land cost, even the local medium-low income group could afford to buy the apartments. Therefore, this project only used eight years to occupy the population, which might need to settle in other countries for over 50 years. Such real estate development and brought in demographic dividend did benefit the local region – Guiyang city's economy figures have been shining since 2010, and Guizhou province has the quickest GDP increase rate in China in 2017 (You 2018).

Table 2.9 The impacts of high-density living mode (Chen et al. 2004)

Advantages	Disadvantages	Environmental issues to be concerned
• Save land, and reduce the damage to the natural environment around the cities • Save construction materials (because compact form housing generally consumes fewer envelope materials, such as roof, foundation and party walls) • Save operational energy, because compact form housing generally has a smaller building shape coefficient • Reduce transport distance. Could reduce GHGs emissions by less private car use and more convenient public transport • Can help to raise enough consumers for services nearby, such as local jobs, shops, entertainment facilities, educations. • Reduce the distance of the service of infrastructures and roads, so improving the efficiency of them, and save both capital resources and operational energies • Increase the open spaces and green lands nearby to improve the microclimate • Create more opportunities for the residents' communication so that that the community could cultivate its culture, and increases the sense of security	• When the community is too compact, the outdoor activity spaces will be insufficient • in order to build high-density communities, increasing the amount of high-rise residential buildings and large-volume buildings will increase the use of high embedded energy materials such as steel and concrete • high-density living environments generally do not guarantee adequate indoor ventilation and daylighting effects. Hence the electrical load of lighting and air-conditioning will be an increase • the use of equipment such as elevators for high-rise residential buildings increases the operational energy of buildings • the high-density residential areas induce considerable traffic pressure around - aggravate road congestion, prolong commuting time and worsen air quality are the expected results • The crowded living environment tends to make residential areas dirty and messy, which increases the possibility of disease transmission. And the crime rate tends to be higher too • In crowded living environments, conflicts are more likely to cause 'bad neighbourhood effects', because people would fight for limited resources • The reduced privacy of living and noisy environment significantly increases psychological and mental stress	• The effectiveness of land use • Consuming high embedded-energy materials • Residential energy consumption • Property management and maintenance costs • Traffic conditions nearby • The sufficiency of surrounding urban functions • The efficiency of urban infrastructure • Indoor and outdoor air quality • Access to daylight and sunlight • noise • The indoor space utilisation rate • The flexibility of interior space • Community greening and landscape • Accessibility of internal roads in the community • Convenience and safety of the internal road system in the community • Privacy in the community • The comprehensiveness and convenience of public facilities in the community

Source: The table was a summary of the authors' literature review result of Newman and Kenworthy, 1989a, 1989b; ECOTEC, 1993; Katz, 1991; Calthorpe, 1993; Hillman, 1996; Thomas and Cousins, 1996; Breheny, 1996; Pun, 1994; Travers, 2001; Pacione, 1989; Rudline and Falk, 1999; and Burton et al., 1996

Moreover, the dwelling units designed to be identical, so that the machinery operations of cast concrete could quickly build them up. Such simplified housing largely shortened the process of construction. Furthermore, the extremely compact settlement form makes the public services to be located in convenient distance easily, which reduces the reliance on private cars. So, in the short term, this project did promote the affordability, liveability and livelihood of the original shanty community. Comparing with the affordable housing projects in the western countries during the 1960s and 1970s, the real estate development efficiency of this project has progressed to a much higher level.

However, this project also made the drawbacks of the high-rise high-density housing impossible to cure.

The third phase of this project pushed the density to a level which cannot be held by the city's existing and new infrastructures. The over-simplified high-rise buildings did not attract enough medium to high-income group people to settle. Hence, all sorts of disadvantages of high density arose in recent years. Due to the extremely high-rise solution of all residential, public and commercial buildings, it creates double-negative impacts on infrastructures and energy use:

- Firstly, the peak energy use has already been high because of high-density but lifting the services to 44 floors all over the site only make it much worse.
- Secondly, such extremely high-rise high-density form excludes the possibility of onsite renewable energy generations.
- Thirdly, such extremely high-rise building is hard to maintain and upgrade for better end-user efficiency of municipal services.

Together, the above three infrastructures and energy issues make such community hopeless to be a low-carbon residential area in the future. They created many vulnerabilities for the city and the residents to defend the climate change events. Therefore, despite a short period of eye-catching rewards at the beginning, this project causes more and more concerns or even criticisms from academia and residents.

Therefore, the above review reminds us to carefully think about the full meaning of living quality, when planning and designing an affordable housing community. Without broader considerations of sustainability and resilience, many decision-makings would become short-sighted. They would create more troubles in the long term than they may have solved in the short term.

2.3.3 Summary: the main problems of China's current housing sector

From the review in section 2.3.1 and 2.3.2, the critical barriers of China's housing sector to be low-carbon can summarise as follows:

1) high-rise high-density settlement and building form exclude the possibility of on-site renewable generation
2) the peak energy use is at a very high level, which is not possible to be satisfied by the local or nearby renewable generation

3) it is hard to reduce the embedded energy because the construction of high-rise high-density housing relies on energy-intensive materials
4) it is very challenging to increase the current residential buildings' energy performance and liveability through retrofitting and refurbishment

2.4 The influences of China's housing policies and building regulations

Market and policy are the two main drivers for low-carbon housing development, and between these two the former has more influences on the private housing sector, while the latter on affordable housing sector (Zhang et al. 2018). Therefore, before proposing a new type of affordable housing, it is necessary to understand what China's housing policies emphasise in terms of affordability and low-carbon.

2.4.1 Affordable housing policies

Governments around the world have a common goal to provide affordable housing. However, the details, terminology, definitions of poverty and other criteria for allocation vary within different contexts. Even within the same country, the policies of affordable housing change along with the country's economic and social status. Therefore, it is essential to review the background of China's affordable housing policies in order to understand their impacts on China's current housing affordability status.

In China, the affordable housing policies have gone through several reforms since 1978. Before the 1990s, the concept of affordable housing was called 'indemnificatory housing' (*Fu Li Fang*), which was mainly provided by state work units to their employees as part of the social welfare system (Wu 1996).

In 1994, the Chinese government introduced the concepts of 'Economic and Comfortable Housing (ECH)' (*Jing Ji Shi Yong Fang*) and 'Cheap-Rent Housing (CRH)' (*Lian Zu Fang*) to ease the ever-increasing pressure of urban housing shortage (Table 2.10, document 1). The challenging part of the policy is ECH programme. '*From welfare housing allocation to housing commercialisation is a dramatic transition in China's economic history. At that time, the decision-makers did not have much confidence in the success of the reform*' (Tan 2017). Therefore, CRH is the other part of the reform to provide a period of transition (Tan 2017). Providing rental subsidy, providing low-rent house directly, or providing rent rebate were the three essential strategies to implement the CRH programme in different cities (Ju 2002).

The central government knew that ECH programme needed to push top-down. Hence, in 1995 'Peaceful Living Project (PLP)' (*An Ju Gong Cheng*), China's first ownership-oriented affordable housing program was launched (Zou 2014). Despite the failure of the PLP programme (Zou 2014), the central government is still determined to promote housing commercialisation. In 1997, the Asian Financial Crisis broke out. As a response, China motivated to promote domestic consumption through increasing investment in affordable housing (Wang, 2001, referenced in (Zou 2014)). In 1998 the ECH programme was formally launched (Table 2.10, document 3). In the second half of the year, the allocation of ‘indemnificatory housing’ entirely stopped (Yao 2010). However, the ECH programme was not as successful as the government expected (Man 2011; Tan 2017)

In 2003, the government formally gave up ECH as the necessary type of post-reform housing (Man 2011). In 2006, the development of ECH was transformed from previously sales only, to the rental to low-income groups as well (Yao 2010). In 2007, the reform of urban housing system in China entered into a new stage, which transformed from addressing housing ownership only to emphasise equally on both housing guarantee and housing commercialisation (Yao 2010; Cao and Keivani 2014). ‘Price-Cap Housing (PCH)’ (*Xian Jia Fang*) was also introduced to the market at the same time, to ease the housing affordability problems. *‘PCH units are lower than market-rate houses but higher than the ECH units’*; however, *‘it was still too expensive for low-income households’* (Zou 2014).

In 2010, ‘Public Rent Housing (PRH)’ (*Gong Zu Fang*) was introduced to the affordable housing system, and formally become the new type of affordable housing programme (Ba et al. 2011; Cao and Keivani 2014).*‘Like previous affordable housing programmes, the Social Housing program is a top-down policy. The central government designed the policy and mandated local governments to implement it’* (Zou 2014). Between 2010 and 2014, the government focused on the construction of PRH and the renovation of shantytowns. They also set up several specific targets (Table 2.10, document 10, 11, 12, 13). During this time, the relocation of shantytown residents was mainly through the housing subsidy in kind, which means demolishing old ones and then returning new ones not on site but in another location.

In 2017 the policy suddenly turned to cash subsidy in tier 3 and 4 cities, due to the extensive inventories of private housing in these cities (Table 2.10, document 14). Such policy did manage to avoid repeated construction of housing. It significantly reduced the inventories of private housing in these cities (Liu et al. 2017b). However, it pushed up the housing prices in tier 3 and tier 4 cities (Yi 2018). Therefore, although the shantytown residents’ housing conditions are improved, the housing affordability problems are getting even worse. That is why shortly in 2018 this policy has been revised. Those cities with no or small inventory of private housing are required to come back to the real housing subsidy in-kind strategy as before.

Table 2.10 summarises the critical years and documents of China's affordable housing policies since 1994. The table shows that the relevant policies launched frequently. From the policies' contents, the quantity and cost of housing units are the main focus of China's policies. The literature referenced in Table 2.10 shows that none of the existing policies managed to ease the housing price increase in China so far. Sometimes they even pushed up the housing price.

Table 2.10 Key years, documents of policies and their impacts

Year	Document No.	Main contents of the policies	Impacts of the policies
1994	1. The State Council's decision on deepening the urban housing system reform	The core content of 'the decision' is to reform the welfare housing allocation system and replace it by monetisation and socialisation of housing allocation. The main content includes comprehensively implementing the housing provident fund system, adjusting the rent of public housing and privatising public housing. Also, the document proposes that while developing the private housing market, a housing system with the nature of social security should establish to solve the housing problems of middle and low-income families, by focusing on the construction of Economic and Comfortable Housing. According to the system design, the government should give the policy support of land, fund and so on, to guarantee the price of suitable housing matches the income level of workers at that time, gradually making it a mainstream housing source.	*'It is proposed for the first time to establish an Economic and Comfortable Housing supply system targeting middle and low-income families with social security nature, which kicked off the housing commercialisation reform and has epoch-making significance for the affordable housing system'* (Yao 2010) *'From welfare housing allocation to housing commercialisation is a dramatic transition in China's economic history. At that time, the decision-makers did not have much confidence in the success of the reform…(therefore, the government) did not address much in this document on how to set up and manage the housing market, cultivate the market customers, regulate the transaction procedures, and so'* (Tan 2017) *'…not fully implemented in practice'*(Cao and Keivani 2014)
1995	2. The implementation plan of the national Peaceful Living Project	The principle of PLP is that 'local governments assist, work units support, and households pay for the building costs'.	*'To push housing reform forward, China launched its first ownership-oriented affordable housing program - the PLP Program e - in 1995.'* (Zou, 2014)$^{02\text{-}028}$
1995	2. The implementation plan of the national Peaceful Living Project	*'When the houses completed, they will be sold directly to low - and middle-income families at the contracted price. Priority will be given to those without houses, in dilapidated houses and poor housing'.* (Yao 2010)	The critical policy which defines the delivery method for the Economic and Comfortable Housing. (Yao 2010)

Year	Document No.	Main contents of the policies	Impacts of the policies
1998	3. Circular of the State Council on Further Deepening the Urban Housing System Reform and Accelerating Housing Construction	*'In the second half of the year, the allocation of 'indemnificatory housing' stopped, and it re-emphasised that different housing supply policies should implement for different income families.'* *'The adjustment of housing investment structure was addressed, with emphasis on the development of Economic and Comfortable Housing projects.'* (Yao 2010)	*'Put forward to establish Cheap-Rent Housing system for the first time.'* *'The supply management system of Economic and Comfortable Housing and Cheap-Rent Housing was established in various large and medium-sized cities successively, marking the fundamental reform of China's urban housing system'*. *'In the course of the development of China's urban housing guarantee system, this year has a milestone significance, mainly because it abolished the 'indemnificatory housing' policy and started the fundamental transformation of housing marketisation'*. (Yao 2010) The general background is housing commercialisation (Ba et al. 2011) Economical and Comfortable Housing *'…was officially designed as the predominant type of post-reform housing provision'*. (Man 2011)
2003	4. Circular of the State Council on Promoting the Continuous and Healthy Development of the Real Estate Markets	Emphasise the adherence to housing marketisation, improve the real estate market system, and adjust the housing supply structure. It proposed to establish further and improve the system of Cheap-Rent Housing in urban areas. And the national Cheap-Rent Housing system should be extended from extremely low-income urban families to low-income urban families (Yao 2010)	Significant adjustments were made to the housing supply system, defining Economic and Comfortable Housing as the policy-oriented private housing with a public housing nature (Yao 2010) Formally gave up the idea of Economic and Comfortable Housing as the primary type of post-reform housing (Man 2011)
2005	5. Circular of the General Office of the State Council on Effectively Stabilizing Housing Prices	The economic and legal means, such as planning, land, taxation and mortgage, are used comprehensively to conduct two-way regulation of supply and demand, curb property speculation, control house purchase for investment, and reasonably guide housing consumption. Put forward a mechanism to increase the supply of private housing through planning and other means. (Yao 2010)	Partially curbed the rapid rise in housing prices. The tasks of the local government to regulate the real estate market and guarantee the housing for low-income families were clarified. (Yao 2010)

Year	Document No.	Main contents of the policies	Impacts of the policies
2006	6. Circular of the General Office of the State Council on Forwarding the Opinion of Such Departments as the Ministry of Construction on Adjusting the Structure of Housing Supply to Stabilising Housing Prices	Focus on the development of low-cost, small and medium-sized commodity housing that is suitable for the residents' self-living needs, and establish a supply mechanism to meet the basic needs of ordinary residents, through the structural adjustment of housing supply (Yao 2010)	Regulation of the upward momentum of housing prices has not achieved the desired goal. The development of Economic and Comfortable Housing was transformed from previously sales only, to the rental to low-income groups as well. (Yao 2010)
2007	7. Suggestions of the State Council on Solving Difficulties of Urban Low-income Families in Housing	Take the housing difficulties of low-income families as an essential duty of the government's public service. Clarify the responsibilities of housing guarantee work in governments at all levels. Put forward the policy system of accelerating the establishment of Cheap-Rent Housing as the focal point, and solve the housing difficulties of low-income families through multiple channels. It proposed that the Cheap-Rent Housing system should be extended from extremely-low-income families to low-income families by the end of the 11th five-year plan. Improve and standardise the system of Economic and Comfortable Housing, and shift the supply of housing from low - and middle-income families to low-income families (Yao 2010)；	It marks that the reform of urban housing system in China has entered into a new stage, which transforms from addressing housing commercialisation only to emphasise on both housing guarantee and housing commercialisation equally (Yao 2010; Cao and Keivani 2014)
2008	8. Several Opinions of the General Office of the State Council on Promoting the Healthy Development of the Real Estate Market	*'In 2008, a program of 7.5 million units of public housing was formed as part of China's stimulation package in response to the Global Financial Crisis.'* (Shi et al. 2016) Step up efforts to build Economic and Comfortable Housing and further encourage the consumption of ordinary private housing. (Yao 2010)	To increase domestic consumptions for economic crisis mitigation, the government put great efforts into constructing Economic and Comfortable Housing. This action caused a sharp increase in Economic and Comfortable Housing construction between 2009 and 2011. (Yao 2010)
2010	9. Notice of the General Office of the State Council on Promoting the Stable and Healthy Development of the Real Estate Market	Increase the supply of price-limited housing, economically affordable housing and public rental housing. It also addressed the construction scale of medium - and low-priced, medium - and small-sized price-limited housing, public rental housing, economically affordable housing and Cheap-Rent Housing. Speed up the construction of private housing with limited prices and public rental	It introduced Public Rent Housing to the public housing system (Ba et al. 2011; Cao and Keivani 2014)

Year	Document No.	Main contents of the policies	Impacts of the policies
		housing, and resolve housing difficulties for middle- to low -income families.	
2010	10. Accelerating the Development of Public Rental Housing	To develop public rental housing, and improve the housing supply system, foster the housing rental market and adjust the supply structure of the real estate market.	Public Rent Housing was confirmed to be the new type of public housing(Ba et al. 2011)
2011	11. Outline of the 12th Five-Year Plan for the National Economic and Social Development of the People's Republic of China	To construct about 3600 units of urban public housing and Shantytowns relocation housing. By 2015 the proportion of public housing in the housing sector should reach about 20%.	For the first time, specific targets set up for public housing construction.
2014	12. National New Urbanization Plan (2014-2020)	Establish a mechanism for stable government-subsidised housing at all levels and expand the significant supply of public housing. Improve the system of leasing subsidies and combine Cheap-Rent Housing with public rental housing.	Encouraged the involvement of enterprises and actors from society to provide permanent rental housing (Lin 2018)
2016	13. Outline of the 13th Five-Year Plan for the National Economic and Social Development of the People's Republic of China	Promote the shantytown rebuilt and urban village innovation to solve 100 million people’s housing in these areas within the 13th five-year-plan	Narrowed the focus of housing guarantee on solving the housing for people who live in the shantytown and urban village
2017	14. Tightening the Management and Control over Intermediate Residential Properties and Land Supply	In the third and fourth-tier cities with a large inventory of private housing and sufficient housing resources in the market, the transformation of shantytowns should focus on cash subsidy for resettlement, in order to avoid repeated construction.	The relocation of shantytown residence was changed from housing subsidy in kind to cash subsidy dominated. This change increased the capital costs of relocation, but it significantly reduces the inventory of private housing in the cities (Liu et al. 2017b) The housing price increased consequently in tier 3 and 4 cities (Yi 2018)

Therefore, it generally agreed that land provision, funds allocation, and the administrative system all have default problems, which made affordable housing policies in China not effective. Furthermore, these default problems caused remote location, lack of supporting infrastructure, and unreasonable design to the affordable housing projects. These three poor conditions significantly reduced the liveability and livelihood of affordable housing projects. As a result, many of the affordable housing projects are vacant, and the residential buildings quickly degraded. These facts show that China’s affordable housing policies did not manage to avoid the mistakes made by the developed countries in the last century.

2.4.2 Low-carbon housing policies

If affordable housing policies mainly focus on easing the housing price, low-carbon housing policies should be the driver to improve the housing sector's performances. However, just as the diverse definitions of 'low-carbon', there has not been a universal definition of 'low-carbon' housing in any county. In China, 'Green Building' (GB) is used more often in the official policies and standards. The assessment systems applied for GBs always include housing, but neither 'green housing' nor 'low-carbon housing' was used explicitly as policy terms in China.

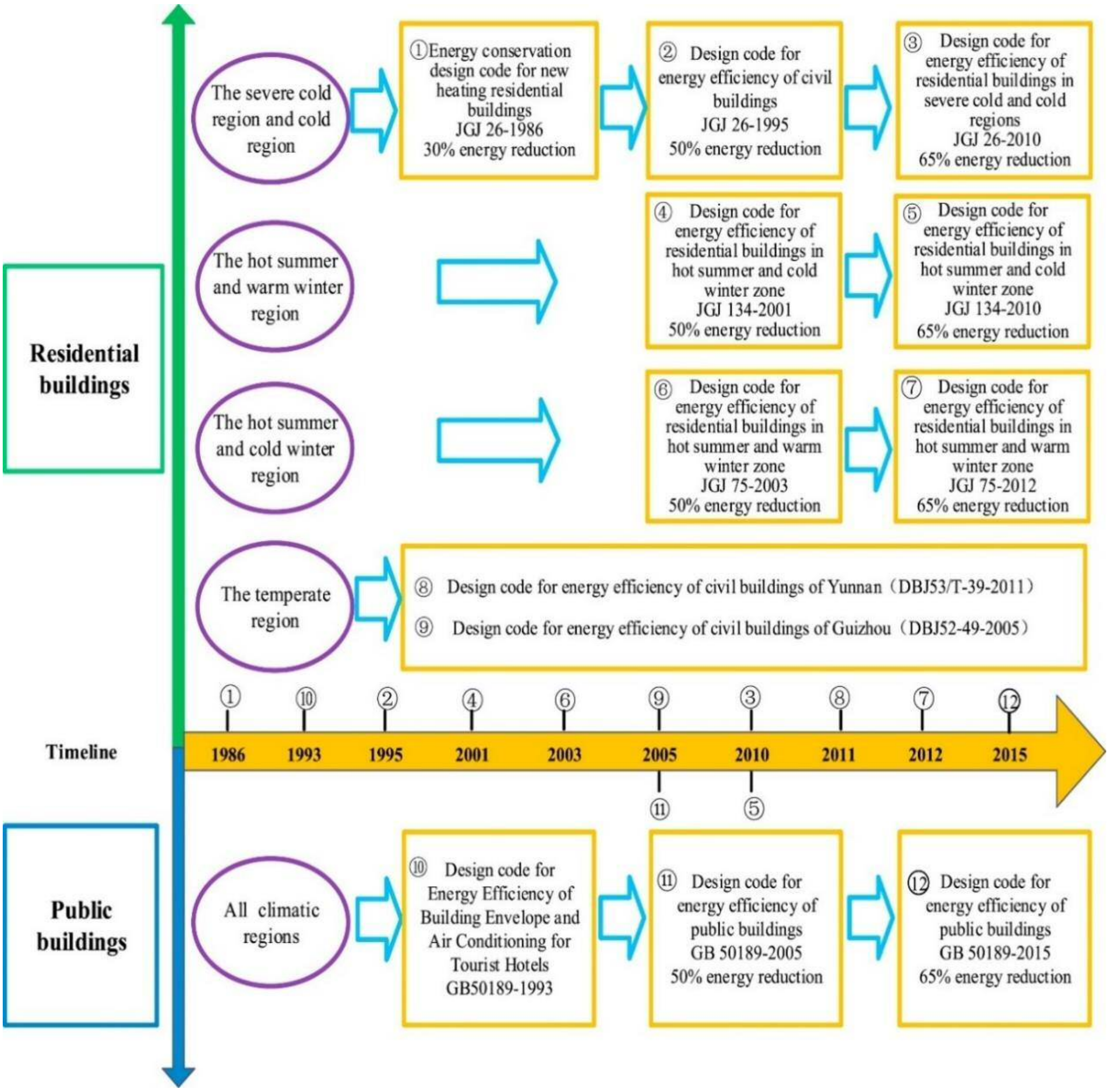


Figure 2.14 The Chinese BEE code framework (Guo et al. 2016b)

China's mandatory design codes on Building Energy Efficiency (BEE) had not been formulated until the 1980s, but the increase of standard is constant (Figure 2.14). Until 2012, the BEE standard all over the country has increased to 65% reductions compared with the buildings constructed in 1980-1981 (Guo et al. 2016b). Moreover, the 75% reduction standard launched for Severe Cold and Cold region in 2018. These standards enabled more significant share of BEE buildings in the entire housing sector (Figure 2.15), but the general building operational energy intensity in the urban housing sector did not make progress (Figure 2.10).

China's GB concept originated from BEE standards for housing in the 1980s. Then the housing energy problems were gradually emerging with urbanisation problems in the whole buildings sector. Broader sustainability issues relevant to all types of buildings came to the policymakers' eyes. Therefore, China adopted the developed countries' policies design - residential BEE standards set up baseline requirements, and are delivered through building regulations mandatorily and locally; residential GB standards raise the bar higher and are implemented through evaluation system voluntarily and nationally. Furthermore, the GB standards often reference the BEE standards on specific figures for criteria.

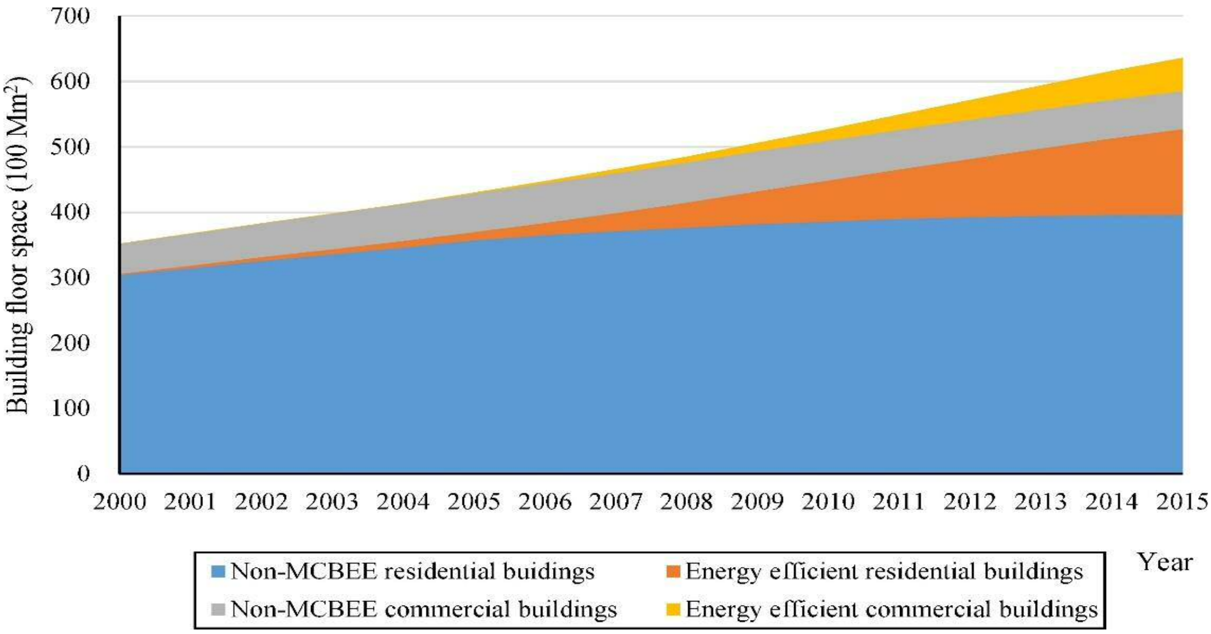


Figure 2.15 The energy-efficient and Non-MCBEE buildings from 2000 to 2015 (Huo et al. 2019a)

Note: Non-MCBEE means 'buildings not regulated by Mandatory Civil Building Energy Efficiency Codes

The formal concept of GB was not introduced into China's construction industry until the 1990s (Xiao and Qiao 2009). In 1996, *Research on Chinese Green Building System* listed as a critical funding area by the Natural Science Foundation of China (NSFC) in the Ninth Five-Year Plan. Since then, the Chinese government formulated a series of green building documents and regulations. China's green development model gradually matured at the beginning of the 21st century. The residential BEE and GB policies start to develop side by side in the 21st century (Table 2.11).

Comparing Figure 2.15 and Table 2.11, the stringent BEE standards (65% energy reduction against 1980-1981) for residential buildings have only been implemented since 2010. Moreover, it is not until 2012 that the ‘65%’ standards covered all the climate zones in China. That is why it took China ten years (2000-2009) to get a 10% share of energy-efficient residential buildings in its housing sector.

Table 2.11 The development of BEE standards and GB assessment systems

Year	**BEE standards (mandatory to the whole housing sector)**	**GB assessment systems / Low-carbon standards (volunteer to the whole housing sector)**
1986	Energy conservation design code for new heating residential buildings JGJ 26-1986 (30% energy reduction against 1980-81)	——
1995	Design code for energy efficiency of civil buildings JGJ 26-1995 (50% energy reduction against 1980-81)	——
2001	Design code for energy efficiency of residential buildings in hot summer and cold winter zone JGJ 134-2001 (50% energy reduction against 1980-81)	China’s Eco-house Technical Evaluation Handbook （version1）
2002	——	China’s Eco-house Technical Evaluation Handbook （version2）
2003	Design code for energy efficiency of residential buildings in hot summer and warm winter zone JGJ 75-2003 (50% energy reduction against 1980-81)	China’s Eco-house Technical Evaluation Handbook （version3） Green Building Assessment System for Beijing Olympic
2005	Design code for energy efficiency of civil buildings of Guizhou DBJ52-49-2005 (energy reduction rate not specified)	——
2006	——	National Green Buildings Evaluation Standard GB/T 50378–2006 (three-star standard, version 1)
2007	——	China’s Eco-community Technical Evaluation Handbook （version4）
2010	Design code for energy efficiency of residential buildings in severe cold and cold regions JGJ 26-2010 Design code for energy efficiency of residential buildings in hot summer and cold winter zone JGJ 134-2010 (65% energy reduction against 1980-81)	——

Year	BEE standards (mandatory to the whole housing sector)	GB assessment systems / Low-carbon standards (volunteer to the whole housing sector)
2011	Design code for energy efficiency of civil buildings of Yunnan DBJ53/T-39-2011 (energy reduction rate not specified)	——
2012	Design code for energy efficiency of residential buildings in hot summer and warm winter zone JGJ 75-2012 (65% energy reduction against 1980-81)	——
2013	——	Technical Guidelines for Green Affordable Housing Jianban[2013]195
2014	——	National Green Buildings Evaluation Standard GB/T 50378–2014 (three-star standard, version 2)
2015	——	The standard for Green Performance Assessment of Existing Building Retrofitting (civil buildings) GB/T 51141-2015 Technical Manual on Evaluation of Green Buildings (trial)
2018	Design code for energy efficiency of residential buildings in severe cold and cold JGJ 26-2018 (75% energy reduction against 1980-81)	Technical Standard for Nearly Zero Energy Building (GB/T51350-2019) **Ultra-low energy building:** 50% energy reduction against the local standard of 2016 (82.5% energy reduction against 1980-81) **Nearly zero energy building:** 75% energy reduction against the local standard of 2016 for residential buildings in hot summer and cold winter & hot summer and warm winter zone, and 60% in the severe cold and cold zone (90% - 91.25% energy reduction against 1980-81) **Zero energy building:** annual primary energy consumption is less or equal to the renewable energy generated by the building or resources nearby

However, from 2013 on all government-funded public buildings, affordable housing in provincial capitals, and commercial buildings of more than 20,000 m^2 in size are mandatorily required to be green (The State Council of China 2013). Moreover, affordable housing was included in the GB standard system in 2013 too. Such mandatory requirement made positive impacts, and within six years (2010-2015) China doubled its share of energy-efficient residential buildings in its housing sector to 20%.

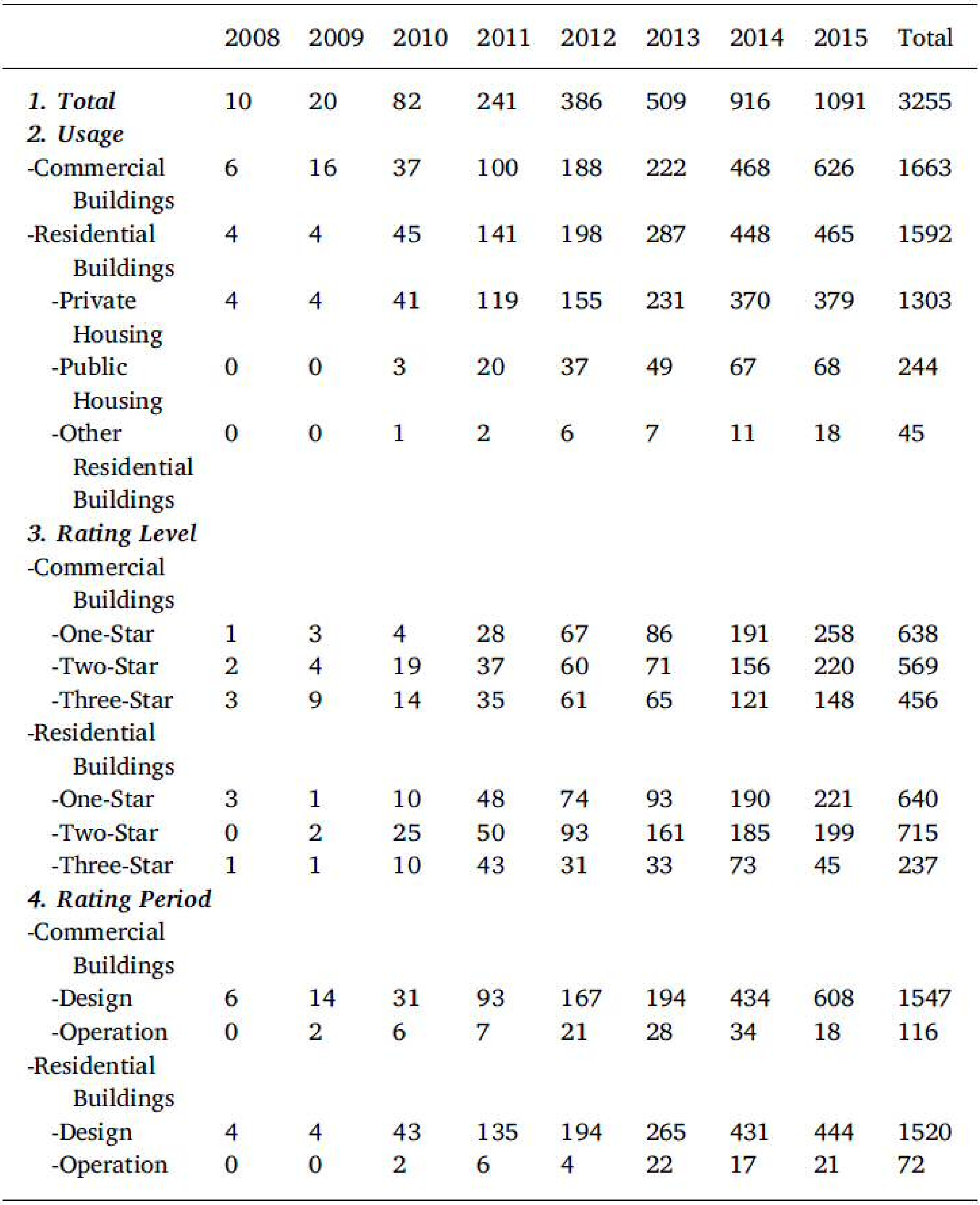
The standard for green retrofitting of existing housing was introduced in 2015 to tackle the performances of the existing housing sector. However, with all the difficulties of retrofitting high-rise high-density buildings, the Chinese government has not yet launched any policy to enforce this standard in practice.

In all the above situations, the government's policies of promoting low-carbon housing are formulated behind and around the BEE and GB standards, and mainly addressing the implementation details. However, since 2016 the government sends a strong signal that the requirements of policies will be higher than the current BEE and GB standards to take the lead on promoting low-carbon housing. These new policies are driving towards NZE or above buildings.

In 2016, the State Council of China directly referenced NZE buildings and PV micro-generation on the roof as the critical solutions to enhance building energy conservations and carbon emissions reductions (13th twelve-year-plan, (State Council of China 2016)).

Furthermore, the *Technical Standard for Nearly Zero Energy Building* was issued for consultation in 2018. In terms of energy performance requirement, this standard catches up with the ones of developed countries for their new build housing.

Green building policies are introduced to China's affordable housing sector much later than the private housing sector, so understandably will not achieve the same impacts in the short term. However, soon the housing sector's carbon emissions in China will mainly come from the affordable housing sector. The main reasons are: 1) private housing still has extensive inventories to be consumed, so will not have significant new build increase in the new future; 2) more private housing obtained green building labels than affordable housing in the past (as shown in Figure 2.16), so believably their general operational performance will be better too.



	2008	2009	2010	2011	2012	2013	2014	2015	Total
1. Total	10	20	82	241	386	509	916	1091	3255
2. Usage									
-Commercial Buildings	6	16	37	100	188	222	468	626	1663
-Residential Buildings	4	4	45	141	198	287	448	465	1592
-Private Housing	4	4	41	119	155	231	370	379	1303
-Public Housing	0	0	3	20	37	49	67	68	244
-Other Residential Buildings	0	0	1	2	6	7	11	18	45
3. Rating Level									
-Commercial Buildings									
-One-Star	1	3	4	28	67	86	191	258	638
-Two-Star	2	4	19	37	60	71	156	220	569
-Three-Star	3	9	14	35	61	65	121	148	456
-Residential Buildings									
-One-Star	3	1	10	48	74	93	190	221	640
-Two-Star	0	2	25	50	93	161	185	199	715
-Three-Star	1	1	10	43	31	33	73	45	237
4. Rating Period									
-Commercial Buildings									
-Design	6	14	31	93	167	194	434	608	1547
-Operation	0	2	6	7	21	28	34	18	116
-Residential Buildings									
-Design	4	4	43	135	194	265	431	444	1520
-Operation	0	0	2	6	4	22	17	21	72

Figure 2.16 Number of green buildings in China (Zhang et al. 2018)

2.4.3 Summary: the future housing development direction pointed out by the current policies

The review results in 2.4.1 and 2.4.2 show that China's affordable housing policies and GB policies did not merge until 2013. Before then, quantity, construction cost, and equal access are the main concerns of the affordable housing policies. Also, the low-carbon housing policies were behind the BEE and GB standards by then. However, since 2013, the affordable housing sector is required mandatorily to pursue the GB standards. Since 2016, policies have taken the lead to promote NZE or above buildings. Hence, affordable NZE or above housing will be the direction of China's future housing development.

2.5 Challenges and driving forces for China's affordable housing sector to pursue low-carbon development

2.5.1 Challenges

For sure, China needs more affordable housing now and in the future. More importantly, it needs to promote sustainable development of cities and be resilient to the ongoing climate change events. As (Wallbaum et al. 2012) summarised, affordable housing development would face the following common pragmatic challenges:

- ***Scarcity of resources*** *(e.g. land, construction materials, energy.)*
- ***Lack of sufficient funds*** *(because the tenants can hardly contribute to either the capital cost or the maintenance costs)*
- ***Time shortage due to the urgency of demand*** *(rapid urbanisation and 'metropolis effect' make a large volume of housing demand within a short time)*
- ***Shortage of skilled labour*** *(technologies that require a high skill level will face a significant problem in finding skilled and trained works among the members of the target communities)*
- ***Quality control*** *(the quality of the final products is one of the most relevant challenges)*
- ***Wastage due to inefficiency*** *(beyond the negative influence on costs, wastage also causes negative impacts on resource consumption)*
- ***Lack of added value creation*** *(the target population is usually embedded with political and social exclusion, and lived in inadequate living conditions before, so the housing projects need to contribute positively to the development of the local environment (rather than creating new poverty or social isolation))*
- ***Quality and location*** *(Low-quality products reduce the houses' life spans and increase the need for maintenance interventions. Strategic*

planning covering land use, tenure, livelihoods and services have to integrate into the method in addition to shelter construction)

These challenges are common around the world. However, to understand why China pushed high-rise high-density housing strategy to an extremer level, the specific context of China's challenges needs to be investigated.

- **Scarcity of resources (mainly appropriate land)**
    - Between 1986 and 1995, the urban expansion coefficient (the ratio of urban land growth rate to population growth rate) reached 2.29:1, which is much higher than the reasonable value of 1.12:1 determined by China's urban planning research institute. Such low land-use efficiency made later development tight of land supply for housing and far distance of commuting (Chen et al. 2004)
    - There is a decreasing supply of suitable sites for residential development (Shi et al. 2016)
    - Local governments are reluctant to allocate land to affordable housing, as they worry this policy will crowd out the construction of market-rate housing and thus decrease local government revenues. If they must, they are inclined to allocate lands in exurbs. As a result, many affordable housing projects have located in places without necessary public facilities, such as public transportation, hospitals, and decent schools (Zou 2014)
- **Lack of sufficient funds**
    - The financing of affordable housing in China depends upon funds from the Housing Provident Fund, but its deposits come from sources such as fees from land transfers that are unstable and inadequate to sustain affordable housing investment (Man 2011)
    - The central government mandates local governments to complete assigned quotas of affordable housing but bears only a small part of the cost. However, local governments are more inclined to budget funds toward infrastructure than toward affordable housing, as infrastructure is effective in attracting investment, winning the competition between regions, and promoting the local economy. (Zou 2014)
    - In the first few years of the buildings' lifespan, the pressure of maintenance on government's funds is not tremendous. But as the life of the buildings increase, the maintenance cost can become a significant financial burden (Ba et al. 2011)
- **Time shortage due to the urgent demand**
    - There have been 621 million net increased urban population between 1978 and 2017 (Figure 2.17). That is how the affordable housing crisis starts, especially for tier 1 and 2 cities in China which attract more rural-to-urban immigrants than the small cities.

- From the UN's projection, China's total urban population increase will reach its peak in 2050 (total amount reaches a peak earlier in 2035). By then, the urbanisation will make about 200 million net urban population increase from 2018 on (Figure 2.18). Because these are mainly rural-to-urban immigrants, the demand for affordable housing is still high

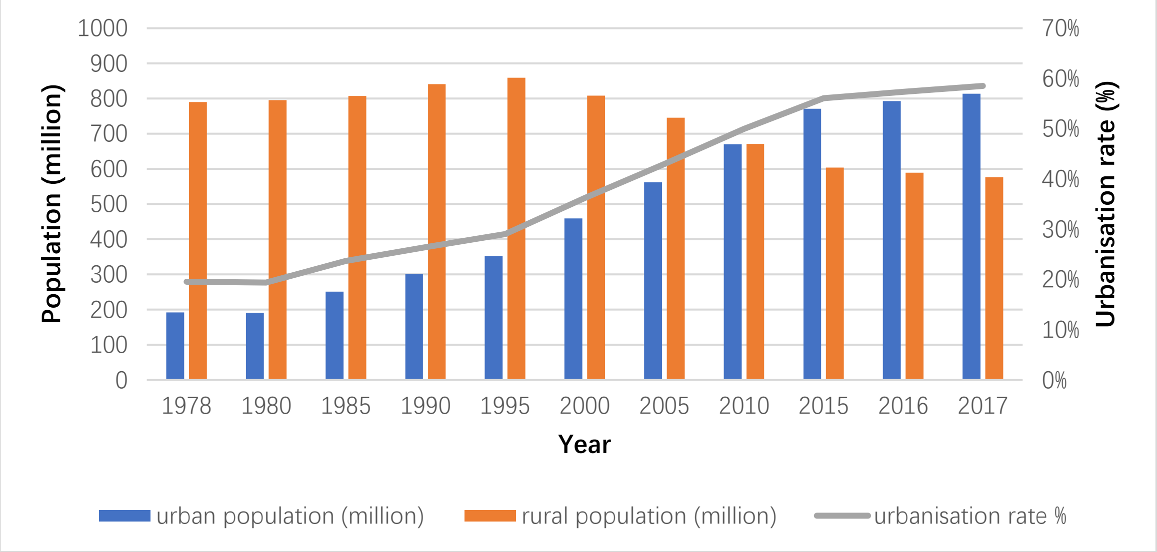


Figure 2.17 China's population 1978 – 2017

Source: *National Statistics Bureau of China (2018)*

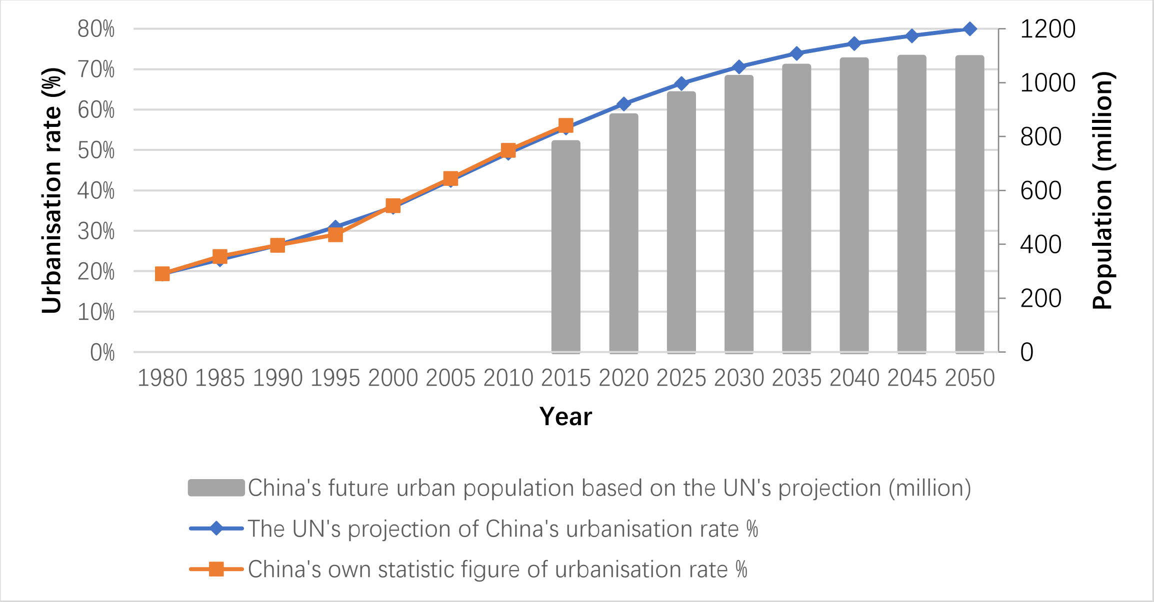


Figure 2.18 China's future urbanisation rate and urban population (median projection)

Source: (DESA 2017a; DESA 2017b; National Statistics Bureau of China 2018a)

Note: China's statistic figure of urbanisation rate calculated from its urban and rural population figures

- **Shortage of skilled labour**
  - Poor competency of labourers – the construction labourers are previously farmers and unemployed workers with low education (Zou et al. 2007)
  - Professionals of green building assessment are still scarce in China (Zhang et al. 2018)
- **Quality control**
  - A majority of Chinese contractors originated from labour and specialists, therefore, generally lacked managerial skills to contract large projects (Zou et al. 2007)
  - Because of the tight budget, using cheap materials could induce problems which influence the general construction quality (Cao and Keivani 2014)
- **Wastage due to inefficiency**
  - At present, a large number of small units of affordable housing are left vacant after being occupied a few years. (Zhu and Li 2015)
  - Because the social housing had general low construction quality, the liveability of these buildings degraded quickly. The government can only demolish and rebuild new ones. This negative cycle caused vast wastes of resources (Ba et al. 2011)
  - (China's) urbanisation relied excessively on land conversion and land financing, leading to urban sprawl and, in some cases, wasteful real estate development (Bagnasco et al. 2015)
- **Lack of added value creation**
  - In China, rating systems for the environmental performance of buildings are not formally adopted (Chegut et al. 2016)
  - Despite considerable efforts by governments to ensure the economic success of affordable housing programs, very little attention was on the sustainability of affordable housing (Gan et al. 2017)
- **Quality and location**
  - The new build projects can only continue to expand to the urban fringe and suburbs as the urban centre has been scarce of land (Chen et al. 2004)
  - There are reasons to believe that the dominance of shantytown relocation housing in recent public housing development is directly tied to the local governments' goal to promote urban redevelopment by providing low-cost housing to relocated residents (Shi et al. 2016)
  - Educational services allocated in remote affordable housing communities is usually inadequate (Zhu and Li 2015)
  - The problems include low housing quality, remote locations, and a lack of public facilities. Since the projects often generate low profits, the developer usually constructs poor quality social housing units in order to reduce the construction cost (Lin 2018)

From the above review, it can be seen that time shortage due to urgency of demand is the most apparent reason for China to pursue the extremely high-rise high-density housing strategy. However, it is easy to ignore that shortage of skilled labour, and lack of added value creation, are the top challenges of China too. Due to historical reasons, China's higher education did not resume until 1977, which creates a significant gap in preparing the planners and designers for the modern construction industry. Again, the GB standards aiming for sustainable and resilient housing were not in place until 2001 (Table 2.9), and not applied to affordable housing until 2013. Therefore, these two easily ignored challenges are more crucial in China's future low-carbon housing development.

2.5.2 Driving forces

As Shi et al. (2016) (references Chen et al., 2014) commented, the housing challenges faced by China now do not differ much from the ones of other developed countries under the same urbanisation stage. Moreover, previous mistakes are now being recognised, but not yet avoided (Ba et al. 2011).

However, this does not mean that China needs to take the same time to make fundamental changes in its housing sector. As discussed in Chapter 1 and section 2.3.2, China's current settlement and building form is the main obstacle of adopting developed countries' low-carbon housing strategies. However, this does not mean that China should wait until the same urbanisation stage as western countries to introduce NZE or above housing. Because even though the challenges are similar, the driving forces are distinct.

- **Population (social)**

With the United Nation's prediction (DESA 2017a; DESA 2017b), China's population will soon reach its peak of about 1.44 billion in 2030, and then rapidly decrease to 1.02 billion in 2100. Also, as shown in Figure 2.20, China's urbanisation speed will slow down after 2035. Shown by the review results, China has got considerable inventories of private housing in the market. Even for the existing affordable housing, there are huge vacancies due to ineffective supply. Putting all these together, it indicates that China no longer needs to build so many high-rise high-density communities within a short period.

More strikingly, some Chinese researchers recently commented that China's population has already experienced 300,000 - 1,270,000 reduction in 2018 (Yi and Su 2019). Such a conclusion has not been confirmed by official statistic resources yet, and immediately argued by many other researchers. However, in China's mainstream forum (Zhihu Forum 2019) the prediction of the inflexion point year is between 2018 and 2027 (203 comments, and many of them referenced official data resource for their calculations). This prediction is much earlier than the year 2030 predicted by the UN's median projection of China's total population (DESA 2017a).

Despite the massive uncertainty of population predictions, the signal is strong that China will soon reach its peak of population and the net amount would be less than the UN's median projection. None of the developed countries has ever experienced net population reduction in its halfway urbanisation stage. However, before their population declined, the majority of them had switched their affordable housing strategy from high-rise high-density to diverse-form high-density. Indeed, many Chinese cities will still quickly absorb more population before 2050. However, with the reduced total population, the future housing density no longer needs to be as high as currently. Therefore, it is time to think about reintroducing low and multi-storey housing in the new build housing sector for lower density.

- **Increase of living standards (economic)**

(Zhu and Li 2015) referenced Tongji University that '*The greatest demand of residents is for 90-120 m^2 of housing. And the demand for housing under 70 m^2 only accounting for 4 per cent'*. The ownership of air conditioner increased quickly in the large cities too, including those in cold climate zones, such as Beijing (Liang et al. 2016). These are the strong signals of increased living standard in China's housing sector.

Even for the low-income people, existing research shows that they are not satisfied with the living quality in current subsidised housing in China (Wei and Chiu 2018). The main problems are due to liveability (comfort and public transportation) and livelihood (public services and job opportunities) issues (Figure 2.19).

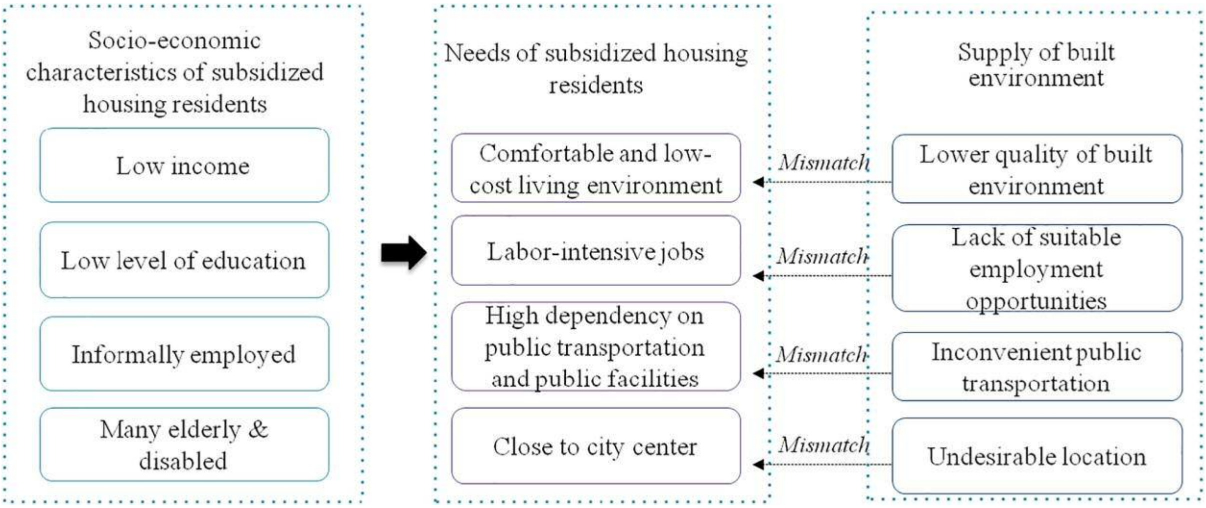


Figure 2.19 Mismatch between the needs of low-income residents and built environments of subsidised housing estates (Wei and Chiu 2018)

China's economy has been increasing for over 20 years and still expects to grow strongly. With more incomes, people will keep on raising the bar of living standard. Without good performances of residential buildings, such an increase in the living standard will create very negative impacts on the environment through excessive energy consumption.

Therefore, the future planning and design of affordable housing in China should not carry on the current practice of cheap and low-quality apartments. The innovations of social housing schemes in other countries need to be learned and adopted with adjustments to China's conditions.

- **Climate change mitigation and adaptation (environmental)**

When the developed countries were at China's current urbanisation stage (mainly 1960s to 1980s), they widely experienced energy crisis and urban pollutions. Two common phenomena occurred in these countries: 1) middle- and upper-class people moved to suburban areas for better living quality (Sun 2012); 2) heavily polluted manufacturing factories were opened in other countries to reduce their domestic pollutions (THE CONVERSATION 2017). Enhancing the new build and existing housing sector's energy and environmental performances was not an immediate adjustment made by these countries. Because at that time, climate change risks were not known by people, and the low-carbon agenda had not arrived.

The situation is different for China now. The global legal bindings of GHGs reductions have been signed, and people have thoroughly noticed the environmental impacts of industries. Therefore, China may still follow the peri-urbanisation trend, but it would have a rare chance to offshore its GHGs emissions. As a result, China must seek methods for domestic GHGs reductions.

China currently has giant housing constructions across the country, therefore generates a massive amount of CO_{2e} emissions. Both the embedded-carbon from the construction materials and the converted-carbon from operational energies contribute to the high CO_{2e} emissions.

In terms of embedded carbon, the main problem is the vacant high-rise high-density apartments. The not being used apartments wasted a lot of high embedded-carbon materials (e.g. steel, cement). Therefore, in the future, the building forms of new build housing must be adjusted to reduce the vacancies, as well as enable more use of low-carbon materials.

In terms of operational energies, residential energy consumption takes about 13% of the total energy consumption in China (NHBC Foundation 2011). 65% of the residential energy consumption in China (82% in the UK) is by heating, cooling and domestic hot water (NHBC Foundation 2011). Foreseeably, as the living standard rises, both the total energy consumption and the ones relevant to comfort in China's housing sector will increase.

2.5.3 Summary: the critical areas for breakthrough

The review in 2.5.1 and 2.5.2 shows that there is a great need and potential to reduce China's CO_{2e} emissions through promoting affordable low-carbon housing. The following three areas are the fundamental breakthroughs to make:

1) **Future settlement and building form:** on one side, the form needs to suit population distribution and density; on the other side, the form determines the strategies of low-carbon technology integration

2) **Lifecycle analysis of affordability**: not just cheap to build, but a holistic consideration of costs - build, buy/rent, operate, maintain and end of life deconstruction

3) **Renewable energy generations strategies**: how they could be integrated with residential buildings or generated nearby

2.6 Research gaps

Within the critical breakthrough area, the following research gaps identified:

2.6.1 Future settlement and building form

According to the review, the existing research about China's demographic is abundant and in great details. For example, THU DataPi (Zhang 2019) released a summary of China's population distribution and density change between 2010 and 2016.

- *Among the 633 continuously existing cities (not including the newly established or annulled cities during this period, which is 50 in total), 246 of them (38.86%) have experienced population density reduction*
- *The population density change among different scale cities is uneven (Figure 2.21). It is out of expectation that the average population density in mega-cities and big cities declined rather than increased.*
- *The construction expending speed is much quicker than the urbanisation speed. In 2000, China's urban population was 388,237,000 and the urban built-up area was 221,137,000 km^2. In 2016, China's urban population reached 402,991,700 and the urban built-up area jumped to 543,314,700 km^2. With the urban population only increased by 3.8%, the urban built-up area expanded by 145.69%.*

- *According to the State Council's survey in 2016 on 12 province's capital cities and 144 prefecture-level cities, with their current planning targets, there would need to be 3.4 billion people to fill these areas*

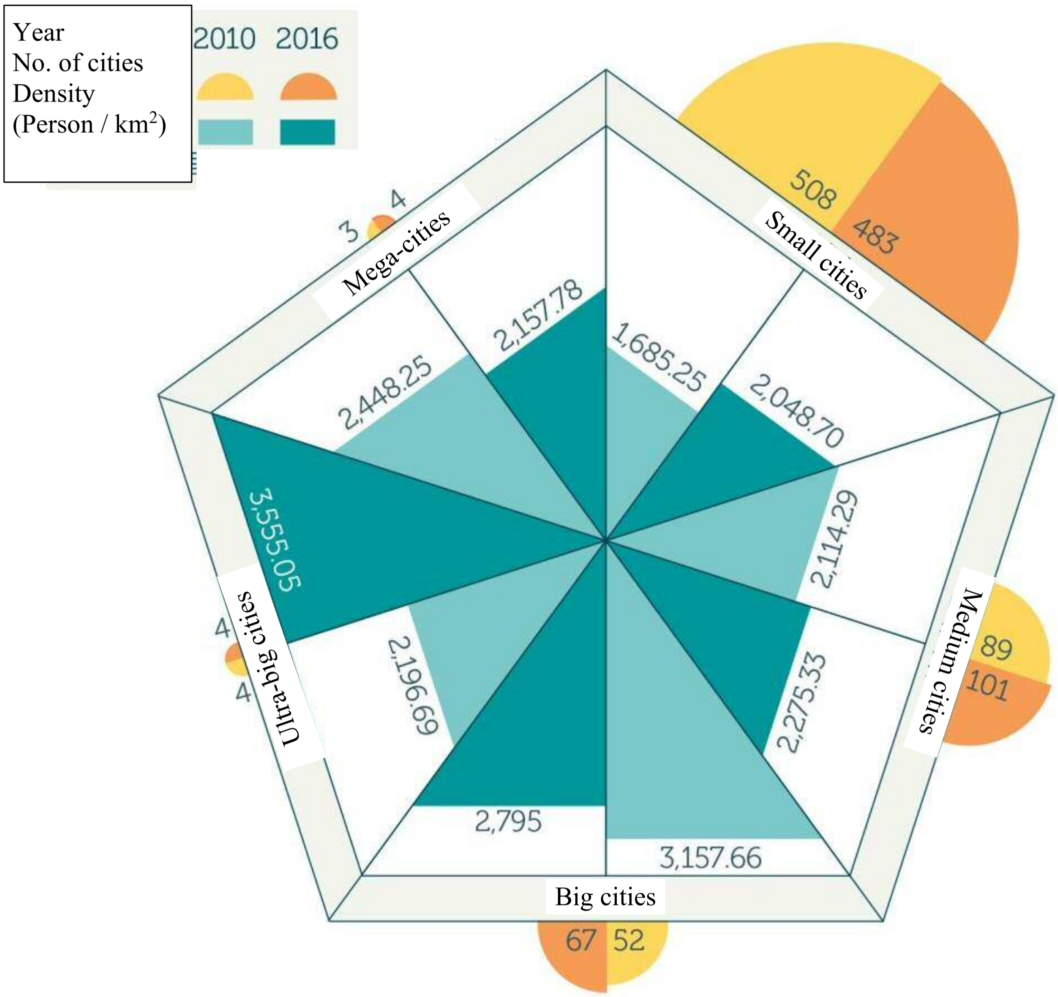


Figure 2.20 Population density changes of different scale cities in China (Zhang 2019)

Data resource: Ministry of Housing and Urban-Rural Development of the People's Republic of China. *Statistical yearbook of China's urban construction* 2010 & 2016.

Note: 1. The studied cities are all the established ones; 2. The classification of the city scale is according to *Notice of the state council on the adjustment of standards for the division of urban scale;* 3. The population density in this chart means the central city area density. Population density = (central urban permanent residents + central urban temporary residents) / central urban area. The figures in the chart are the averages for the same scale cities.

Research like THU DataPi's (Zhang 2019) points out that many cities in China over-estimated their future populations. However, so far, no research has identified how the settlement and building form could be adjusted to deal with this reduction. Then, because the default perception of settlement and building form is still high-rise high-density, the renewable energy strategy does not prefer building integrated installations. For example, Yi Jiang, the Chairman of China's Energy Conservation Association, recently (2018) commented that *'the main focus of developing renewable electricity (PV)* *should be in Northwest Gobi Desert rather than building roofs.'* He also commented that *'centralised development and long-distance transferring (of renewable energies) is more suitable for China's resource conditions'*. Such comments did not mention about the benefits that building-integrated renewable installations could bring to the housing sector. The reason behind is that the NZE or above low and multi-storey affordable housing is a blank research area in China. It is true that China's central urban area has been fully built with high-rise high-density buildings, but there is still significant land available for the development of low to medium housing in the suburban area.

2.6.2 Lifecycle analysis of affordability

The review in section 2.4 shows that the existing policies of affordable housing in China only emphasised on the capital cost (cheap to build, so affordable to buy or rent). Section 2.3 shows such policies resulted in the developers' sacrifices of infrastructure, construction materials and design quality. As a result, the liveability and livelihood of affordable housing projects are not satisfied. More importantly, when high-rise high-density affordable housing is too expensive to live in (transport costs, bills and property management fees), they are left empty. Also, when the maintenance costs raised by the difficulties of keeping and upgrading high-rise buildings, they will be not affordable to the maintainers, then the degradations show up quickly. As a result, the buildings' lifespans become shorter than they could have been. In summary, the cheaply built housing caused poor performances as well as considerable wastes in the later stages.

Such a situation once happened in the developed countries too, and that is why in the 21st century, many western countries raised the performances bar of social housing even higher than the private housing. High performances housing can significantly reduce the operation costs and create extra value for the community. Therefore, they could enable mixed living in the community for social sustainability.

So far, in the existing literature, only indicators and sustainability assessment system of affordable housing are studied in China (Gan et al. 2017). The literature did not identify how to design and build sustainable while affordable housing in a cost-effective way in China.

2.6.3 Renewable energy generations strategies

The review in 2.4.2 shows that even the newly released standards lack details to guide designers, constructers, facilities managers and other relevant occupations about *'what and how to meet corresponding provisions'* (Ye et al. 2015). For example, the most recent *Technical Standard for Nearly Zero Energy Building (under consultation)* requires renewable energy generations to be involved in *'buildings and resources nearby'*. However, within the Standards, no content is found about what are the exact technologies to be installed (e,g, PV, solar thermal, geothermal, turbines) and how to install them. On the other hand, its requirements for energy performance are not well linked to the most recent BEE standards. Because it does not explain how the buildings already in compliance with current BEE standards could further upgrade to the NZE buildings.

Such situation was pointed out by (Ye et al. 2015) that too many of the existing standards (mandatory and voluntary): 1) *'Contents in most standards largely overlap'*; and 2) *'Linkage between evaluation standards and other standards are poor'*.

It is not only China which has such difficulties of lacking implementable technical standards and feasibility studies for newly occurred technologies. Moreover, in many countries, such gaps are filled by prototype studies, which were either carried out by modelling studies or pilot project case studies. These studies created different strategies of integrating low-carbon technologies, and then explore their energy, cost and environmental performances. However, the prototype studies of NZE residential buildings in China is identified as a weak area too.

In total, this review finds that the prototype study of affordable NZE or above house in suburban area is an urgent need to help China accelerate the deployment of NZE housing. However, to emphasis China's context of urbanisation and population density, this research further narrows it down to affordable NZE townhouse. Figure 2.21explains the reason.

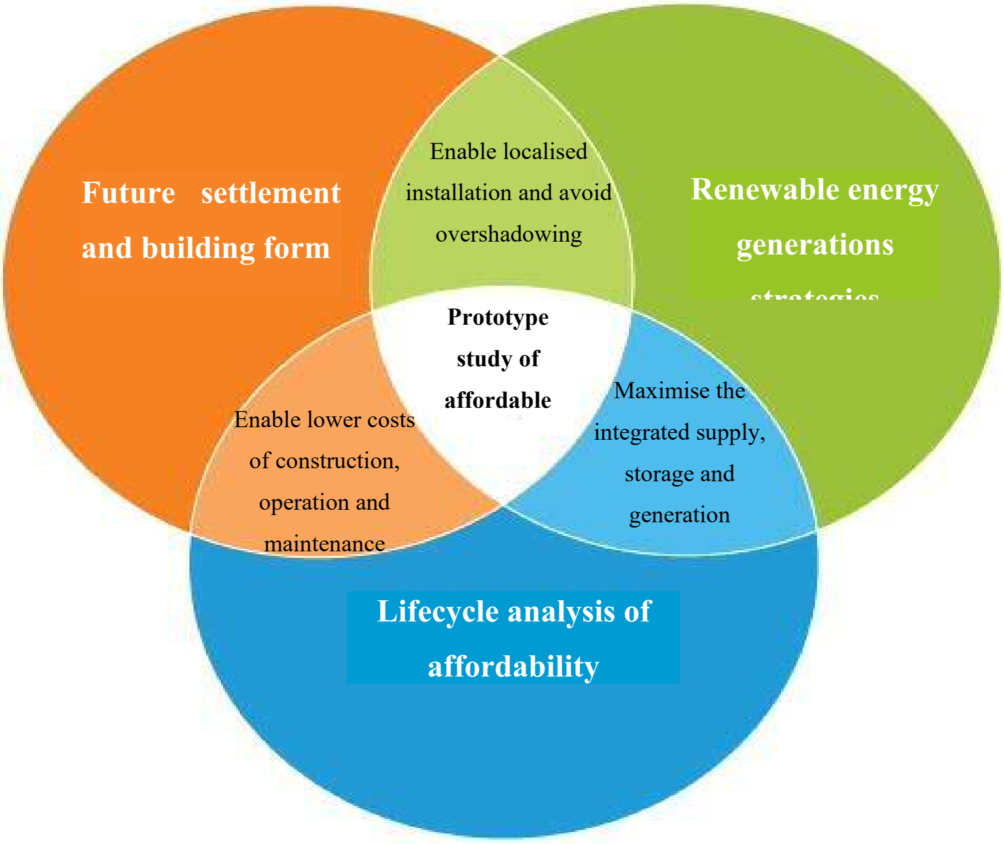


Figure 2.21 The need for the prototype study of affordable NZE townhouses

Therefore, among the merged research area, the central question of this research is raised:

What type of NZE townhouse can be affordable for China to promote low-carbon housing in the future?

The existing research has not yet asked such a question in China. On one side, the review shows that China's current land supply policy does not support projects only formed by townhouse, so practices become rare after 2006. One the other side, the existing research on townhouse does not include the discussions of affordability and low-carbon performances.

Now the developed countries often use NZE houses to implement social housing strategies. China's fundamental needs of housing have changed too. Thus, it is meaningful to explore the possibility of affordable NZE houses in China's suburban area.

Chapter 3

Research framework and methodology

3.1 Introduction

There are two vital criteria for judging the success of a prototype study: 1) the theoretical prototype can provide enough details for the development of the detailed designs; 2) the construction of such buildings based on the prototype can achieve the predicted performances with reasonable costs. Therefore, this research involved both the theoretical exploration of the NZE townhouse concept and the practical study of the actual project's performances and costs. In order to achieve the research aim, this research formulated an integrated approach and a holistic research framework to coordinate the research methods.

3.2 An integrated approach and the research framework

In order to develop a meaningful proposition for the affordable NZE townhouses in China, this research formulated a theory and practice integrated approach to develop and refine the concept.

For the literature-based theoretical study, it firstly investigated the gaps in China's low-carbon and affordable housing research. This work is to make sure that this prototype research contributes to China's future housing development (Chapter 2). Then, it clarified the terminology of the affordable NZE townhouse concept and defined the prototype at the national scale (Chapter 4). Finally, it formulated a conceptual design framework to guide the integration of design features and organise the design process (Chapter 4).

For the real-project-based study, it specified the criteria for the appropriate cities to implement this prototype; and it used the conceptual design framework to further develop the prototype to a baseline building for the identified case study project (Chapter 5). Then, it carried out both modelling and monitoring works to validate the actual performances of the case study project (Chapter 6). Finally, it analysed the costs of this project to achieve the monitored performances (Chapter 6). These works evaluated the prototype and the conceptual design framework' effectiveness of enabling NZE performances with reasonable costs.

With such an integrated theory-practice approach, it guarantees that this prototype study could provide useful solutions and valuable information for China's future low-carbon housing development.

Figure 3.1 presents the research framework for this study.

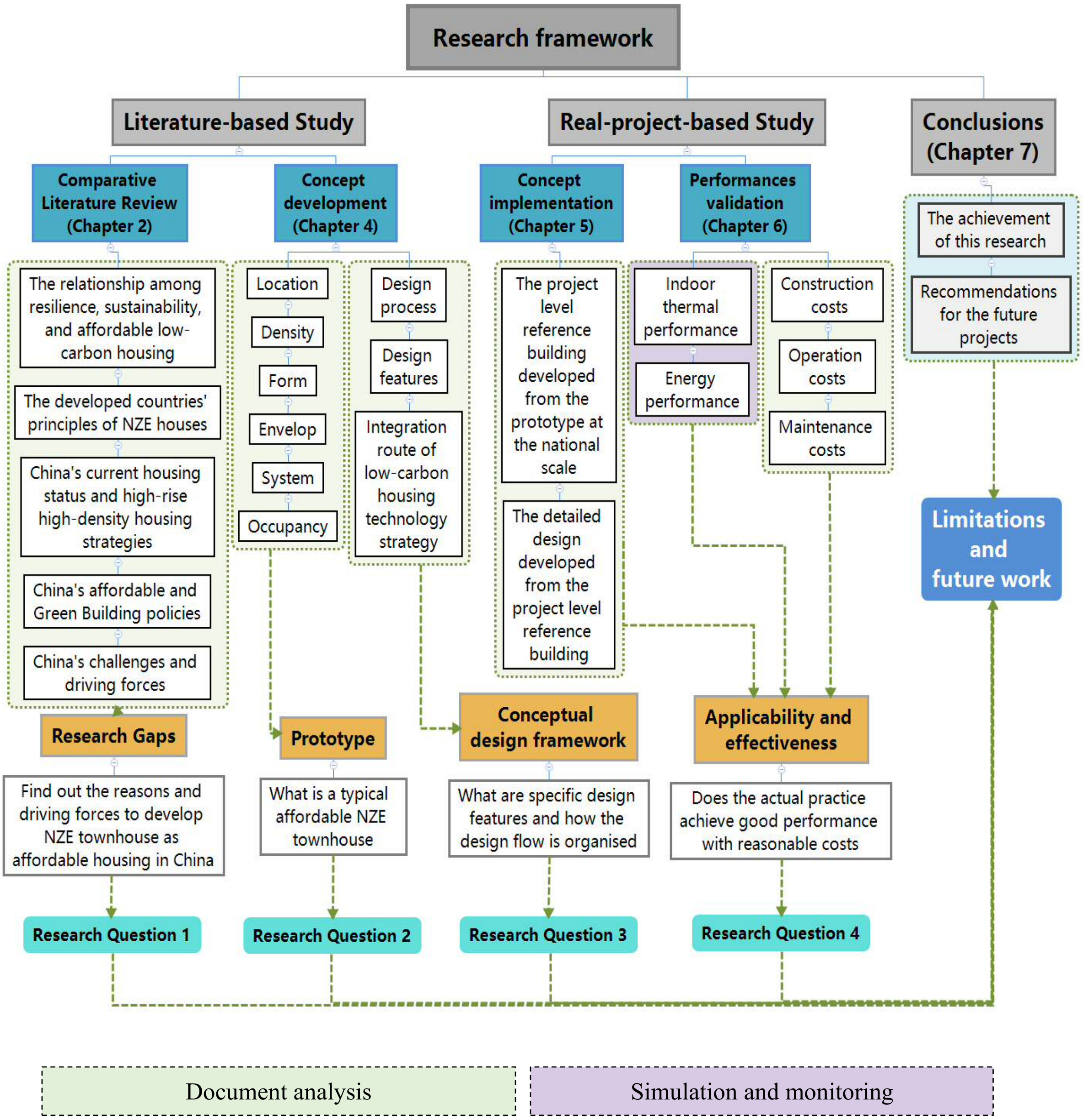


Figure 3.1 The research framework

3.3 Research strategy

In order to deliver the research framework of the thesis, this research developed a strategy mixed with both qualitative and quantitative methods. Each of the two methods has its relevance to the aim and objectives of this research (summarised in Table 3.1).

Table 3.1 Features of Qualitative & Quantitative Research (Neill 2007)

Qualitative research	Quantitative Research
The aim is a complete, detailed description.	The aim is to classify features, count them, and construct statistical models in an attempt to explain the observed phenomenon.
The researcher may only know roughly in advance what he/she is investigating.	The researcher knows clearly in advance what he/she is is investigating.
More often to be used during the earlier phases of research projects.	More often to be used during the later phases of research projects.
The design emerges as the study unfolds.	The researcher carefully designs all aspects of the study before data is collected.
The researcher is the data gathering instrument.	The researcher uses tools, such as questionnaires or equipment, to collect numerical data.
Data is in the form of words, pictures or objects.	Data is in the form of numbers and statistics.
Subjective – individuals interpretation of events is essential,e.g., uses participant observation, in-depth interviews.	Objective: seeks precise measurement & analysis of target concepts, e.g., uses surveys, questionnaires etc.
Qualitative data is more 'rich', time-consuming, and less able to be generalised.	Quantitative data is more efficient, able to test hypotheses but may miss contextual detail.
The researcher tends to become subjectively immersed in the subject matter.	The researcher tends to remain objectively separated from the subject matter.

Note: Adapted from Miles & Huberman (1994, p.40). Qualitative Data Analysis. Available at http://wilderdom.com/research/QualitativeVersusQuantitativeResearch.html

According to the literature review of research methods, mixed-method strategies are '*particularly useful when you want to reflect different perspectives on a subject*' (Saunders et al. 2012), and '*assist in increasing the validity and reliability of the research*' (My-peer Toolkit 2018). The following areas are regarded as typical by My-peer Toolkit (2018) to apply the mixed-method approaches:

- *Initiating, designing, developing and expanding interventions;*
- *Evaluation;*
- *Improving research design; and*
- *Corroborating findings, data triangulation or convergence.*

To this research, the following specific reasons determine the use of mixed-methods:

Firstly, this research aims to 'formulate a prototype and its conceptual design framework' (complete, detailed description) and test their effectiveness (explain its usefulness observed in real practice).

Therefore, it is relevant to qualitative descriptions of characters, qualitative evaluation of its applicability, and quantitative validation of the real performances.

Secondly, there was no existing research found relevant to formulate the affordable NZE townhouse concept in China. This research can only reflect on other countries' research in order to investigate their relevance and appropriateness to China's context. Therefore, the fundamental research question was only known roughly at the beginning of this research. As a result, the prototype only emerged as the literature review unfolded its main characters and the design features' benchmarks. For these two reasons, the concept development of the prototype is dependent on qualitative research.

Then, for the concept implementation of the prototype, it depended on the local delivery team's understanding of the terminology and the conceptual design framework to carry on the detailed design and construction. This part research mainly collected qualitative data of the project documents, design drawings and pictures of the completed construction work. Therefore, the analysis of the prototype and the conceptual design framework's applicability is also qualitative.

Lastly, the prototype and the conceptual design framework's effectiveness for promoting affordable NZE performances have to be validated by the actual costs and energy figures. For this thesis, the performances are validated by simulation and monitoring, both of which are typical quantitative research methods. The analysis of costs also based on numerical calculations too. These works do not involve any subjective options and can be carried on by other researchers to draw the same conclusions. Therefore, the study of the case study project's performances and costs is a piece of quantitative research.

As shown in the research framework (Figure 3.1), the literature-based study and the real-project-based study have equal weight in this thesis. As an integrated approach, they have interrelated contents too. However, each part of the work collected data by different research methods for different purposes.

The literature-based study focused on research gaps investigation and concept development. The literature review is a straightforward research method for investigating research gaps, which collects data through document analysis. Again, document analysis is the most appropriate research method to distil the main characters and technical route for the prototype and the structure for the conceptual design framework. These works entirely based on secondary data and make the literature-based study purely qualitative,

The real-project-based study implemented and validated the concept. It is carried out by a sing case study, which involves the sub-methods to satisfy its purpose. According to the literature review, there are different types of case study methods, each of which has characters and strengths to solve specific problems (Table 3.2). For the reasons below, this research adopted McDonough and McDonough’s classification (1997), referenced by (Zaidah and Zainal 2007), of ‘interpretive’ and ‘evaluative’ case study methods.

Table 3.2 Categorise of case study methods

	Literatures					
Author	**Yin (1984)**		**McDonough and McDonough (1997)**		**Stake (1995)**	
Categories	**Exploratory**	Explore any phenomenon in the data which serves as a point of interest to the researcher. These general questions meant to open up the door for further examination of the phenomenon observed.	**Evaluative**	The researcher goes further by adding their judgement to the phenomena found in the data	**Instrumental**	The researcher selects a small group of subjects in order to examine a particular pattern of behaviour
	Descriptive	Set to describe the natural phenomena which occur within the data in question. The goal set by the researcher is to describe the data as they occur.	**Interpretive**	The researcher aims to interpret the data by developing conceptual categories, supporting or challenging the assumptions made regarding them	**Intrinsic**	A researcher examines the case for its own sake
	Explanatory	Carefully examine the data both at a surface and a deep level in order to explain the phenomena in the data. Based on the data, the researcher may then form a theory and set to test this theory (McDonough and McDonough, 1997).			**Collective**	The researcher coordinates data from several different sources

Note: summarised from (Zaidah and Zainal 2007)

The ‘interpretive’ part of the case study is about the implementing process of the prototype and the conceptual framework. From sampling the cities and project locations to reviewing the design development process, the ‘interpretive’ case study serves to interpret how the prototype and the conceptual framework applied in real practice. It could highlight the critical issues in each application stage. It could also identify the problem areas where the implementation got wrong. It gets an insight into the detailed cost information for specific items too. Therefore, with the ‘interpretive’ case study method, this research could examine the applicability of the prototype and the conceptual framework.

The ‘evaluative’ part of the case study is to validate the performances and costs of the real project. It simulated the energy and indoor thermal performances of the baseline building and the final design. It also monitored these performances of the completed house in its cooling season commissioning. By comparing the modelling and monitoring results, this research could identify and analyse the performance gaps. Moreover, it analysed the costs of the project and their further reduction potentials. With this part of the case study work, this research can conclude whether the achievable performances are affordable or not.

In terms of the detailed simulation strategy, according to Swan and Ugursal (2009), the methods of investigating buildings’ energy performances can generally divide into two categories: top-down and bottom-up. The former usually based on statistic analysis and scenario projections with assumptions from economic theories. It summarises the profile or the main trends of the buildings as a group; and then, it goes into the individual level to further discuss specific topics relevant to a single building. The latter, on the contrary, often creates a virtual model (with sufficient accuracy) to form a useful representation of the actual individual building. And then, softwares are used to calculate the energy flow within and across the building’s boundary. The researcher can further analyse the simulation results of individual buildings in order to explore their influences at a larger scale. Figure 3.2 summarises the links among the sub-methods under the two categories of BES.

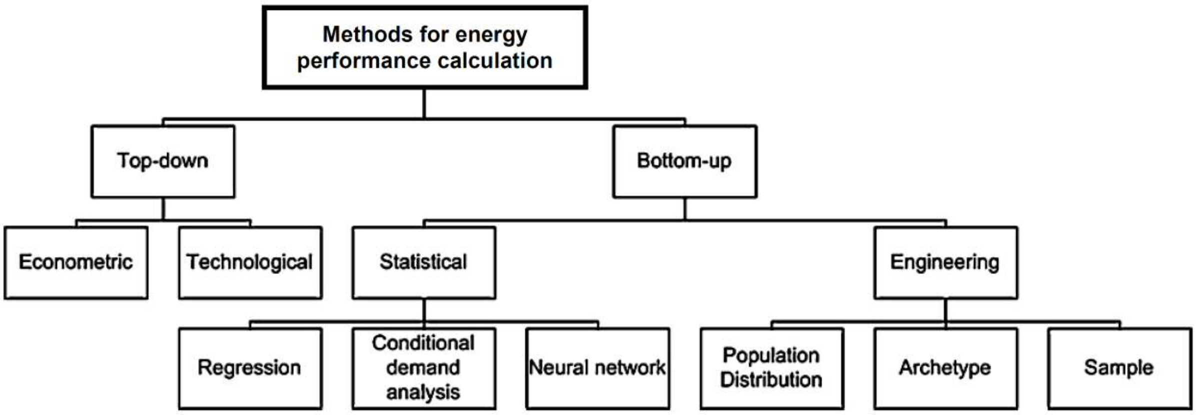


Figure 3.2 Methods for building energy performance calculation ((Lin 2013)**, summarised from** Swan and Ugursal, 2009**)**

Lin (2013) summarised the positive and negative attributes of the different types of simulation methods (Table 3.3). For this thesis, it is clear that bottom-up engineering method is the most suitable one for the research purpose. Firstly, housing has relatively stable occupant behaviour, so China’s NZE standard has defined the typical schedule of occupancy and equipment. This research just needed to follow the standard procedure. Secondly, this research followed the whole design process, so sufficient input data were available. Thirdly, the computational simulation tool for energy performance is available and applicable. Finally, at the design stage, the relationship between design features and cost factors do not need to be discussed in details. These conditions can remedy the disadvantage of the bottom-up engineering method listed in Table 3.3.

Table 3.3 Positive and negative attributes of the top-down method, bottom-up SM method and EM method ((Lin 2013)**, summarised from Swan and Ugursal, 2009**)

	Top-down	Bottom-up statistical (SM)	Bottom-up engineering (EM)
Positive attributes	1. Long-term forecasting in the absence of any discontinuity 2. Inclusion of macroeconomic and socioeconomic effects 3. Simple input information 4. Encompasses trends	1. Encompasses occupant behaviour 2. Determination of typical end-use energy contribution 3. Inclusion of macroeconomic and socioeconomic effects 4. Uses billing data and simple survey information	1. Model new technologies 2. “Ground-up” energy estimation 3. Determination of each end-use energy consumption by type, rating, etc. 4. Determination of end-use qualities based on simulation
Negative attributes	1. Reliance on historical consumption information 2. No explicit representation of end-uses 3. Coarse analysis	1. Multicolinearity 2. Reliance on historical consumption information 3. Large survey sample to exploit variety	1. Assumption of occupant behaviour and unspecified end-uses 2. Detailed input information 3. Computationally intensive 4. No economic factors

For the specific strategy under bottom-up engineering category, there are three different practices too. Table 3.4 summarises Lin’s work on the clarification and illustration of them.

This research adopted the ‘sample’ method because the simulation was just for a single case study. It aimed to examine the achievable energy and indoor thermal performances of the case study and use it to feedback the potential performances of the national scale prototype. These activities are all typical sample method related.

In terms of the detailed monitoring strategy, this research tracks both the energy and the building services systems. With both sides' monitoring results, this research could conclude: 1) how much energy is needed to achieve the monitored indoor thermal environment; 2) whether the monitor indoor environmental parameters satisfy the requirements of the baseline building. Friedman et al. (2011) once summarise the relationship between these two sides tracking as in Figure 3.3.

Table 3.4 Clarification and illustration of the sub-methods under bottom-up engineering category of building energy performance calculation (summarised from (Lin 2013)**)**

Bottom-up engineering method	Clarification	Illustration
Population distribution	• estimates the overall energy consumption at regional or national levels by aggregating the end-use of appliances • depends on the rating system for appliances, including the ownership, the use, the efficiency, and the characteristics of the appliance would not consider the interactions among different appliances	• Jaccard and Baille (1996) created a model by using the INSTRUM-R simulation tool to calculate the performance of Canadian residential houses • Kadian et al. combined micro-level data with the concept of distribution to develop a model for Delhi
Archetype	• a small number of buildings can be applied to represent a bigger group of buildings • this model often functions at three different levels by calculating minimum, average, and maximum values to give an appropriate and reasonable range • researchers can limit the number of buildings and only select relevant and useful information about energy consumption to simulate results	• MacGregor et al. (1993) set 27 archetypes in the Nova Scotia residential model • Kohler et al. (1997) built a more complicated model for the German building sector • Jones et al. (2001) developed a unique archetype model for energy prediction, which is called the Energy and Environmental Prediction (EEP) model • Carlo et al. (2003) created a model to help develop the number of archetypes used for commercial buildings.
Sample	• similar to the representative concept of archetypes, but estimates the energy performance using limited prototypes • Due to the use of real information from houses, the 'sample' technique can be in agreement with other methods and offer some practical suggestions for the building code or new technological applications	• Farahbakhsh et al. (1998) developed a model for Canadian housing, which only had 16 archetypes to calculate national consumption.

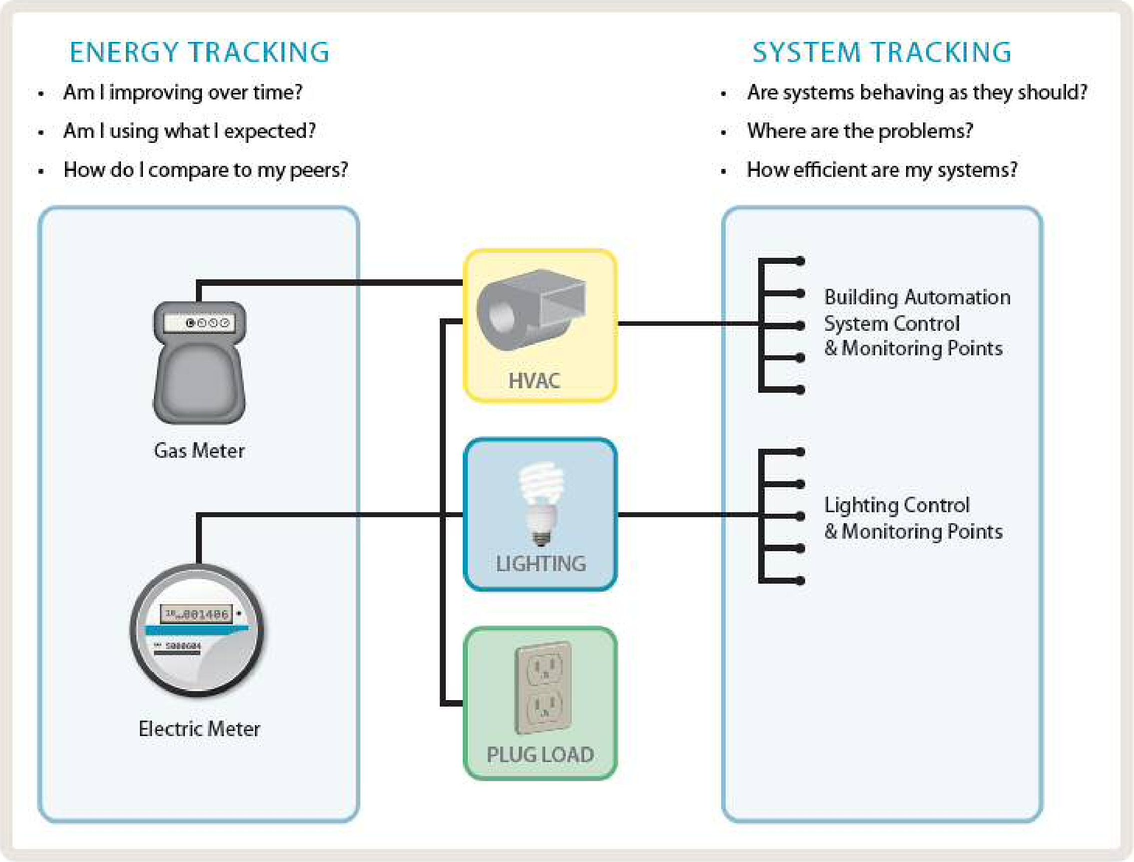


Figure 3.3 Energy Tracking and System Tracking: The Two Sides of Building Performance Tracking (Friedman et al. 2011)

The data collecting and analysis process also follow Friedman et al.'s (2011) 'four steps' procedure (Figure 3.4).

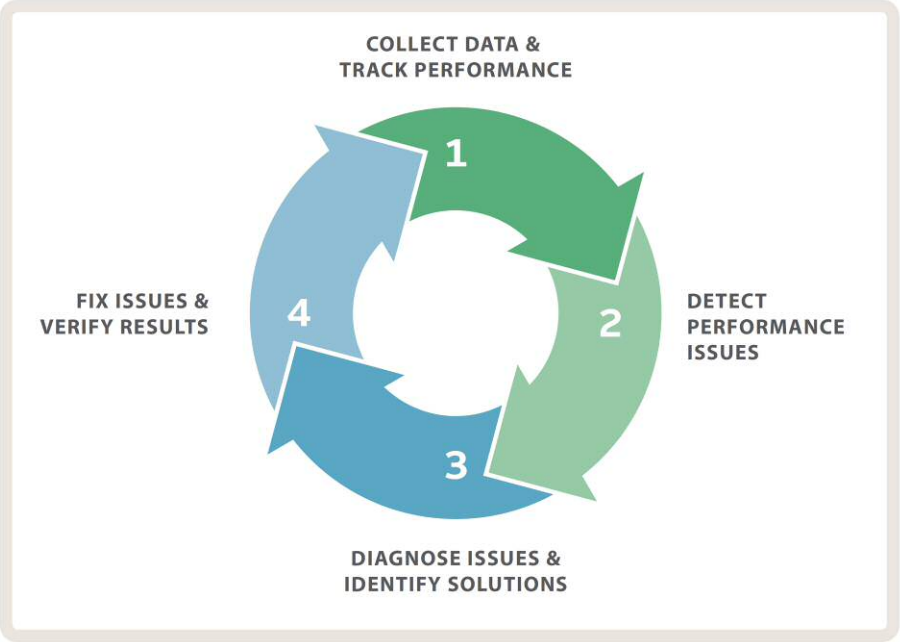


Figure 3.4: The Four Steps of Building Performance Tracking (Friedman et al. 2011)

The data collection for the 'interpretive' part of the case study is very similar to the literature review. However, there is a fundamental difference. The document analysis for the literature review was at a much broader level to collect the data for various purposes. The one for the case study was organised around a story-line to distil and interpret the data for one single purpose – whether the theoretical part research outcomes are applicable in real practice. Thus, even though this part of work in chapter 5 is in a literature review form, it is a piece of independent case study research on its own.

The data collection for the 'evaluative' part of the case study were through the simulation tool and the monitoring sensors. These data are typical quantitative numerical figures, which needs to be further processed by Excel in order to make the analysis.

3.4 Data collected under each research method and the relevant tools

The following contents provide details about how each of the methods used in the different parts of this research, and how they collected data for the different research purposes.

3.4.1 Document analysis

This research used document analysis in many parts: the literature review (Chapter 2), methodology design (Chapter 3), concept development (Chapter 4), concept implementation (Chapter 5), and performances validation (Chapter 6, cost part).

In the literature review (Chapter 2), it used the document analysis to investigate the reasons and process of the affordable NZE housing development in developed countries. The distilled principles will help China to develop its prototype for future low-carbon housing. It also brought China's current housing status, strategies, existing policies, challenges, and driving forces together for the analysis of research gaps in this area. Materials used include academic papers (journal and conference), books, news reports from all sorts of publishing resources (newspapers and websites), and relevant mainstream social media (Forums and WeChat official accounts). In the review of current affordable housing practices (Section 2.3.2.1), it also used visual data including photos, graphs, diagrams and analysis charts.

In the methodology design (Chapter 3), it used document analysis to choose the appropriate research strategy and methods for the specific research questions and objectives. Materials used include academic papers (journal), books, and articles from online resources. Words, figures and tables presented critical information summarised from the materials.

In the concept development (Chapter 4), document analysis was the primary method to inquire about the definitions of affordable NZE house, the types of prototypes, and the possible structures of the conceptual design framework. It also distilled the critical design features and technical route for the conceptual design framework. The materials used were second-hand sourced, including journal articles and books relevant to the analysis of these characters. Desk-based data including statistics yearbooks, regulations and codes of housing planning and design in China were also intensively used.

In the concept implementation (Chapter 5), it used the document analysis to present the case study's actual design and construction outcomes. It also provided the benchmarks based on local conditions and policies to set up the design targets. Materials used include planning and design archives, regulations and codes, news, social media articles, statistics yearbooks, maps and photos.

In the performance validation (Chapter 6), document analysis is used in the cost analysis section to make a comparison between the case study project and China's other low-housing projects. It also reviewed the developer's sub-contracts in order to find out the breakdown costs. This document analysis work helped to find out whether they are necessary, reasonable and affordable.

3.4.2 Building energy and indoor thermal environment simulation

In this research, there are two main parts of the modelling study.

The first part (section 5.5) used modelling analysis to assist the decision makings along the design development process. At the architectural concept development stage, climate analysis tool is used in the first place to bring the focus on the most effective passive strategies. It also gives a brief idea about during what period and to what extent the set-up comfort level has to be satisfied by HVAC systems.

The second part (section 6.3, 6.4 and 6.5) used modelling analysis to validate the energy and indoor thermal performance of the design and construction results. Besides clarifying the possible performances of the design and construction results, this part work discussed the obstacles of higher performance and highlighted the areas causing performance gap. Also, for the indoor thermal environment, unsatisfactory episodes are identified and analysed. Based on the holistic system's capacity, this research discussed methods of further improving the comfort level without excessive energy consumptions.

The two simulation tools involved in this part work are:

- **Local climate analysis – Climate Consultant 6.0**

As introduced on its official website, Climate Consultant designed to be (Milne 2008):

> *'…simple to use, a graphic-based computer program that helps architects, builders, contractor, homeowners, and students understand their local climate. It uses annual 8760 hours EPW format climate data that is made available at no cost by the Department of Energy for thousands of weather stations around the world. Climate Consultant translates this raw climate data into dozens of meaningful graphic displays'. 'The purpose is not simply to plot climate data, but rather to organise and represent this information in easy-to-understand ways that show the subtle attributes of climate, and its impact on built form.'*

For this research, the latest version of Climate Consultant 6.0 launched on 5th July 2018 is used to explore the local climate's main characters. The weather data analysis is not just used to help choose the most suitable passive strategies and relevant building form. Moreover, this research used to identify the limitations of passive strategies and to highlight the critical issues in the periods which comfort has to achieved by HVAC systems. Section 5.5 presented the figures generated by this tool and the relevant analysis.

This research used the Typical Meteorological Year (TMY) data. This data was generated through the Chinese Standard Weather Data (CSWD) method and presented with EnergyPlus Weather (EPW) File format. This data is different from the requirement of Chinese building energy-saving standards and design codes, which uses Chinese Typical Year Weather (CTYW) method. Available resources limit the compliance of the required weather data. However, existing research has confirmed the eligibility for using the CSWD method.

Li and Yang (2015) once compared the differences of using four different methods (Sandia, CSWD, CTYW, and TPCY) to generate the TMY for Xi'an city. They found that the relative standard deviation of these four methods against the 30 years' average (1971 - 2000) are very close – Sandia 12.57%, CSWD 11.11%, CTYW 10.37%, and TPCY 10.74%. The CSWD method is only 0.74% less accurate than the CTYW method for Xi'an's 30 years average value.

Therefore, despite the limited choice of weather data, there is coherence in this research to apply the same weather data in different simulation tools for analysis. Moreover, the results will be similar to the ones got by using CTYW data to repeat the same simulation.

- **Energy consumptions predictions and dynamic thermal analysis – HTB2**

There are wide ranges of modelling tools freely available or purchasable. They could be as simple as a spreadsheet, or so complicated that they need specialised knowledge to operate. It is crucial to point out that steady-state heat transfer methods are not suitable for the simulation in this research. They cannot deal with the hourly and seasonal variation of demand-side loads. Therefore, the tools which adopt steady-state heat transfer methods cannot guide the integration of the heat pump system, thermal storage, and renewable electricity generation.

This research used HTB2 (Heat Transfer in Buildings version 2) to deploy the proposed simulation of energy and indoor thermal environment performances. It is a numerical simulation tool developed at Cardiff University nearly 40 years ago, and it adopts the dynamic heat transfer approach. This tool has been extensively tested and validated, including the IEA Annex 1 (Faber and Partners 1980), IEA task 12 (Lomas et al. 1997) and the IEA BESTEST (Neymark et al. 2011; Judkoff and Neymark 2013). The SOLCER House project used it for the design of the first affordable energy positive house in the UK. The most significant advantage of this tool is that it is '…a flexible tool for studying the detailed operation of a building on a short time scale, of minutes rather than hours...' (Alexander 1997). However, other dynamic heat transfer simulation tools, such as DesignBuilder (with EnergyPlus as the calculation engine), IES-VE, DOE-2, ESP-r, eQUEST, and TRNSYS, would be equally suitable.

HTB2 can predict the internal thermal conditions and a building's energy demand under the general settings of operation. The tool was designed with the purpose of 'providing scientists/programmers, perhaps working with a research architect or design team, with a flexible tool for studying the detailed operation of a building on a short time scale, of minutes rather than hours...' (Alexander 1997). It provides users with a wide range of information, internally and externally, numerically, and graphically. Based on the provided information, researchers can thoroughly investigate the links among a building's operation parameters, its thermal performance, and its energy demand. The detailed introduction of HTB 2 is in Appendix 1.

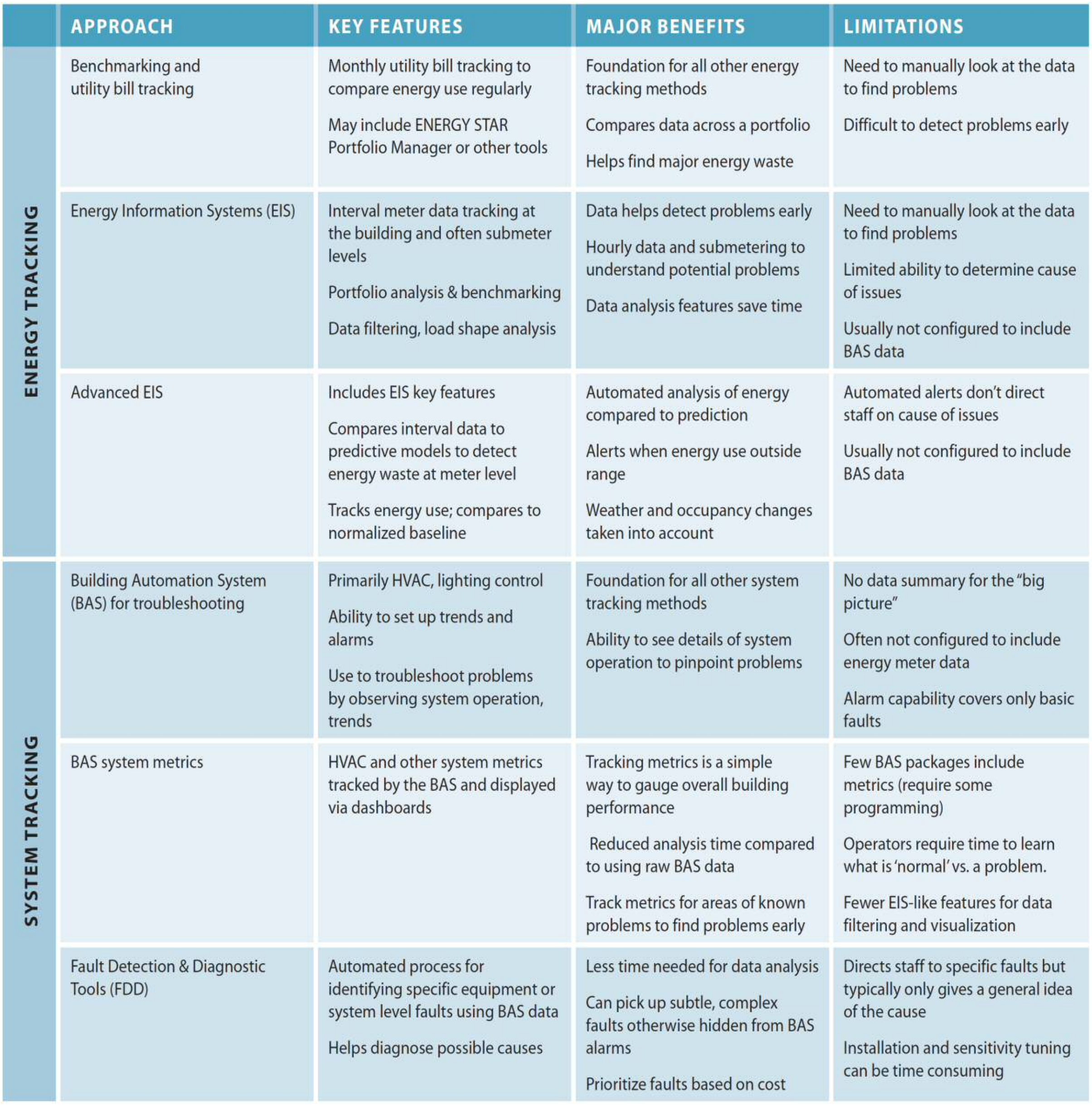
3.4.3 Building energy and indoor thermal environment monitoring

As summarised by Friedman et al. (2011), there are three sub-approaches under both energy tracking and system tracking monitoring (Table 3.5).

This research got generous sponsorship from the developer. Therefore, it could establish a medium level of energy and system tracking: Energy Information System (EIS) and Building Automation System (BAS) metrics. Such level monitoring could enable real-time data tracking and auto-control.

The following contents introduce the monitored objects and parameters. The detailed information about associated equipment, their locations of installations, and the monitored parameters is in Appendix 1.

Table 3.5 Features, Benefits, and Limitations of Building Performance Tracking Approaches (Friedman et al. 2011)



	APPROACH	KEY FEATURES	MAJOR BENEFITS	LIMITATIONS
ENERGY TRACKING	Benchmarking and utility bill tracking	Monthly utility bill tracking to compare energy use regularly May include ENERGY STAR Portfolio Manager or other tools	Foundation for all other energy tracking methods Compares data across a portfolio Helps find major energy waste	Need to manually look at the data to find problems Difficult to detect problems early
	Energy Information Systems (EIS)	Interval meter data tracking at the building and often submeter levels Portfolio analysis & benchmarking Data filtering, load shape analysis	Data helps detect problems early Hourly data and submetering to understand potential problems Data analysis features save time	Need to manually look at the data to find problems Limited ability to determine cause of issues Usually not configured to include BAS data
	Advanced EIS	Includes EIS key features Compares interval data to predictive models to detect energy waste at meter level Tracks energy use; compares to normalized baseline	Automated analysis of energy compared to prediction Alerts when energy use outside range Weather and occupancy changes taken into account	Automated alerts don't direct staff on cause of issues Usually not configured to include BAS data
SYSTEM TRACKING	Building Automation System (BAS) for troubleshooting	Primarily HVAC, lighting control Ability to set up trends and alarms Use to troubleshoot problems by observing system operation, trends	Foundation for all other system tracking methods Ability to see details of system operation to pinpoint problems	No data summary for the "big picture" Often not configured to include energy meter data Alarm capability covers only basic faults
	BAS system metrics	HVAC and other system metrics tracked by the BAS and displayed via dashboards	Tracking metrics is a simple way to gauge overall building performance Reduced analysis time compared to using raw BAS data Track metrics for areas of known problems to find problems early	Few BAS packages include metrics (require some programming) Operators require time to learn what is 'normal' vs. a problem. Fewer EIS-like features for data filtering and visualization
	Fault Detection & Diagnostic Tools (FDD)	Automated process for identifying specific equipment or system level faults using BAS data Helps diagnose possible causes	Less time needed for data analysis Can pick up subtle, complex faults otherwise hidden from BAS alarms Prioritize faults based on cost	Directs staff to specific faults but typically only gives a general idea of the cause Installation and sensitivity tuning can be time consuming

- **System specification and monitoring contents:**

The design of the case study follows a whole-house demand, storage and supply strategy. Therefore, the proposed monitoring covers all the parameters associated with the three aspects. However, due to the limits set by the on-site conditions, not all the proposed monitoring data can be collected with the research's time scale. As a result, this research can only conclude the case study project's general energy and indoor thermal performance. Moreover, detailed analysis, such as the energy use pattern, indoor air quality associated energy consumptions, HVAC system coordination, has to carry on in the future. Table 3.6 summarises the relevant details.

Table 3.6 The components of the integrated system and the monitoring methods

	Objects	Location	Category	Contents	Note
Generation	PV	Equipment box on the roof	Energy tracking	The time and amount of on-site renewable power generation	Not directly monitored because the grid license has not bee issued yet.
	Wind turbine				
Storage	Hot water tank	Equipment room on the second floor	Energy tracking	Hot water usage Recycled heat from the heat pump	Meters installed but not monitored due to no occupancy
	Water loops embedded in the fabric	Floors and the roof	Both	Heat storage capacity Condensation risk	Monitored and analysed
Demand	Occupancy	Living room, dining room, kitchen and all the bedrooms	System tracking	Detect the occupants' distribution in the house	Meters installed and data collected, but not useful because of not established occupancy
	Indoor thermal environment		Both	Record the temperature and RH, to assess the indoor thermal comfort level and associated energy consumptions	Monitored and analysed
	Indoor air quality	Portable	Both	Record the temperature, RH, CO_2, HCHO, TVOC and PM2.5 of the monitored room, to understand the ventilation associated energy consumption	Meters installed and data collected, but not useful because of not established occupancy
	Lighting	Sub-circuits	Energy tracking	Record the individual sub-circuits to get the energy consumption profile	Meters installed and data collected, but not useful because of not established occupancy
	Ventilation	Sub-circuits and equipment room	Energy tracking	Record the used electricity, and air temperature in each pipe to get the energy consumption profile and heat recovery rate	Meters installed and data collected, but not useful because of not established occupancy
	Heating and Cooling	Sub-circuits and equipment room	Both	Record the used electricity, water supply and return temperature, flow volume to get the energy consumption profile and suitable operation schedule	Monitored and analysed
	Appliances	Sub-circuits	Energy tracking	Record the individual sub-circuits to get the energy consumption profile	Meters installed and data collected, but not useful because of not established occupancy

	Objects	Location	Category	Contents	Note
External weather	Weather station	On the roof	Both	Record the temperature, RH, wind direction, wind speed, horizontal solar radiation, rainfall and the barometric pressure of the outdoor environment, to understand the outdoor conditions caused energy consumptions and thermal comfort issues	Monitored and analysed

- **Monitoring purposes, the involved calculations, and the analysis in this research**

1) The actual onsite renewable power generation and the total renewable energy utilisation rate

The easiest way of monitoring the onsite renewable power generation is to install a two-phase electricity meter on the renewable electricity supply circuit. However, when the grid licence is not issued, the supply is cut off so no data can be collected. This research used indirect monitoring to overcome this difficulty.

The wind speed and the horizontal solar radiation are monitored by the weather station on the roof to calculate the power generated by the wind turbine and PVs on the same location. Such indirect monitoring can not reflect the real system power loss during the transferring. However, the transferring loss of power is a relatively stable rate, which is well summarised by the theoretical equations. At the design stage, the theoretical renewable electricity output used the same calculations too. Therefore, the projection result based on indirect monitoring is comparable to the simulation result, which could assess the prototype's effectiveness of predicting reasonable generation output.

The weather station collects wind speed and the horizontal solar radiation on an interval of 5 seconds. With such data, this research can calculate out the hourly, daily and seasonal profile of generation.

By comparing the projected generation figures with the demand side figures, this research can also conclude the total renewable energy utilisation rate.

Chapter 6 introduces specific calculation methods in more details.

2) The house's annual energy demand

It is not possible to monitor the whole year's data within the research's available time. Therefore, this research used directly monitored cooling energy data and external weather data to predict the project's annual energy demand.

Firstly, this research went through the monitored weather data to find out the periods, which the outdoor conditions are very close to the standard weather data. Secondly, this research checked the heat pump's operation schedule and the indoor activities, to make sure that they are under a stable and controlled status. Thirdly, the best quality data is compared to the simulation results in the same period, to get the difference between the monitored and simulated results. Finally, this research used this difference ratio to multiple the simulated annual energy demand. This projected annual energy demand is used in this research as the predicted annual energy demand after commissioning.

Such a calculation can not replace the whole year monitoring for assessing the annual energy demand. However, it is a step further than the simulation prediction because the commissioning can get the prediction of the heat pump system's efficiency closer to the real situation. Even though it is still a primary performance figure based on several assumptions in both simulation and monitoring, the prediction can point out a closer range for real performance.

3) The indoor thermal environment

The monitoring for this purpose is most straightforward because the continuous indoor dry-bulb temperature and relative humidity data can reflect the indoor thermal environment. There are no occupants associated in the commissioning, so the results can not fully reflect the real occupied situation. However, in the residential environment, the internal heat and moisture gain from occupants are relatively small compared with other resources. Therefore, even without the occupants, the monitored data can be seen close to the occupied situation.

The difficulty, though, is that there are so many spaces in a house and it is not possible to install that many sensors for each of them. Besides the cost issue, it also links to the amount of collected data. Too many data without priority is not beneficial to control, because it will slow down the decision making process.

Therefore, in this research, only the four bedrooms, living room, dining room and kitchen installed the 'online' sensors. These sensors are linked to the central logger to display the real-time temperature and humidity, which are also the parameters used for the heat pump system control. Other short-term occupied spaces, such as the bathrooms, corridor and conservatory, are installed with 'offline' sensors. These sensors recorded the parameters in longer intervals of time and stored them in the embedded loggers too. These figures are not for the control of the services system but to understand the whole-house distribution of dry-bulb temperature and relative humidity.

4) The heat storage capacity and the associated condensation risk

Unless carrying on a co-heating test, it is not possible to test out the fabric's heat storage capacity in an accurate manner. Therefore, this part of the investigation used indirect monitoring as well.

The research recorded the total electricity used from kicking-off the cooling system to the indoor environment reached a stable dry-bulb temperature. During this time, the heat pump ran 24 hours schedule without stopping. Then, this research compared the electricity figure with the one which the heat pump ran in a two-shifts schedule. The compared figure was monitored under the same length of time with very similar outdoor conditions. The indoor dry-bulb temperature was also in a similar stable status as the fabric charging time.

Therefore, by deducing the heat pump's regular operation energy from the charging energy figure, the coolth stored in the fabric can be roughly calculated out. Such calculation of energy storage is not in high accuracy but is enough to make a general judgement about its capacity and cost.

Moreover, it is very unpractical and costly to install the surface temperature sensors all over the fabric. Therefore, this research assessed the fabric's condensation risk by using the indoor relative humidity (air) figures. When the indoor relative humidity is higher than 90%, it perceived as a high condensation risk. This benchmark is based on World Health Organisation's (WHO) *Guidelines for Indoor Air Quality: Dampness and Mould*. WHO ((2009), referenced Johansson 2005) '*described the material-specific critical moisture conditions for microbiological growth: the critical relative humidity (maximum long-term relative humidity allowed for non-growth) was 75–90% for clean materials and 75–80% for contaminated or soiled materials*'. Among the listed typical materials, the critical relative humidity for concrete is 90-95% (WHO 2009). In WHO's description (2009), RH > 90% is high '*for growth of selected microorganisms in construction, finishing and furnishing materials*'. In this project, the risky surfaces for condensation are ceiling, wall, and floor, which are all concrete based materials. Therefore, RH 90% is set up for the condensation risk analysis in this research. It is noted here that this benchmark is not for the comfort of occupants but for the heat pump system's control to avoid damage of indoor surfaces.

5) The energy consumption of domestic hot water and its renewable energy utilisation rate

In this case study, the heat pump system integrated the domestic hot water supply as a holistic system. The waste heat from the heat pump's compressor is recycled and delivered to the hot water tank. If still not enough, there will be an electric heater in the water tank to boost the water temperature. Such a system design makes the hot water energy consumption included in the heat pump's total energy consumption.

In order to make this part of energy consumption clear, this research installed several flow meters and water temperature sensors on the inlet and outlet water pipes of the hot water tank. An electricity meter also installed on the electric heater's circuit — Appendix 1 presented the detailed calculations of this part of energy consumption.

Unfortunately, without the occupants, it is not possible to carry on this part of monitoring, because there is no regular use of hot water. Therefore, this research did not investigate this part of energy performance with primary data. Instead, it quoted the manufacturer's figures to make a brief judgement about the potential of energy and cost savings.

6) The indoor air quality and the associated ventilation energy

This case study project installed an MVHR (mechanical ventilation with heat recovery) system. Theoretically, such a system should be able to provide enough fresh air without wasting too much energy. It can also filter out the external particles to prevent the PM2.5 pollutions. However, the literature review shows that indoor chemical caused air pollution is also high in China. Therefore, it is essential to know whether installing an MVHR system can avoid opening windows, and what level of indoor air quality such a system can provide. It is also vital to confirm whether the heat recovery rate achieves the manufacturer's declaration.

Four dry-bulb air temperature sensors are installed in the inlet and outlet pipes of the MVHR plants. These sensors collect data to calculate the heat recovery rate of the MVHR plant. A portable multi-air-pollutant sensor located in the living room, which displays the real-time indoor air quality. The control of the mechanical ventilation level also linked to this sensor's monitoring results. Whenever the air pollutants' figures higher than the set value, the mechanical ventilation will be switched to a higher level too.

However, without occupants, this proposed test can not be carried out. Therefore, this research only used the simulation results to validate the heat recovery rate benchmark set in the baseline building. Such validation will not be sufficient to reflect the real occupied situation. It is useful, though, to confirm whether the theoretical benchmark is achievable by the designed occupancy style.

7) The energy usage profile and the renewable energy autonomy rate

Besides the total energy consumption and renewable energy utilisation rate required by China's NZE standard, this research goes further to explore the energy usage profile and the renewable energy autonomy rate. When the system design changes the house's energy use from combined energy resources to purely electricity, it is essential to decarbonise the used electricity. The higher the renewable energy autonomy rate is, the less CO_{2e} emissions the house would have. It is essential to understand the profile of electricity use, and match the load with the generation, to achieve a higher rate.

For this part's investigation, this research installed both main and sub-meters on the necessary circuits to monitor the electricity use of the heating, cooling, hot water, lighting, ventilation, and appliances. It also installed flow meters and water temperature sensors in the heat pump system to analyse the relationship between electricity use and heat or coolth demand.

Again, without occupants, it is not possible to get every sub-energy use monitored, so the whole-house energy balance between demand and supply is not concludable. However, cooling energy use is sufficiently monitored on both the electricity side and the heat side. The monitoring results also provide insight into the heat pump system efficiency. Therefore, the heating energy consumption can be projected at high accuracy. The heating and cooling have the most significant share of domestic energy consumptions.

Moreover, the overlapped energy use schedule of the services system is easy to analyse. Therefore, if this big chunk of energy consumptions can be directly satisfied by the local renewable supply, the renewable energy autonomy rate would be close to the matching rate. Chapter 6 explained the detailed calculations and analysis.

3.5 Data resources, access and collecting process

In order to make sure that the theory-practice integrated approach carried out logically and coherently, this research also formulated a data collecting structure to organise the process (Figure 3.5). The resources of the needed data and the methods of collecting them are shown in Figure 3.5 directly. The contents below explained data accesses and analysis methods.

Figure 3.5 shows that this research used the inductive approach for the data analysis to test the hypothesis – the affordable nearly NZE townhouse in suburban area can be used to promote low-carbon housing in China. On the literature-based study part, it summarised other countries' research results and China's contexts to form the prototype and the conceptual design framework. On the real-project-based study part, it distilled the qualitative and quantitative results to evaluate the effectiveness of the prototype and the conceptual design framework.

There are 13 primary resources of data for this thesis. The last three (planning and design archives, contracts, and user manuals) linked to the case study. The confidential documents (e.g. the developer's contracts with the suppliers, planning permits) were provided by the developer for analysis, with the condition that specific figures and names are kept confidential. The academic papers and books were available in Cardiff University's literature and databases. All the other resources are available online to the public, which came from reliable resources such as China's central or local statistical bureaus and the UN's databases.

From these resources, this research extracted 11 types of data through three data collecting methods. Some of them were directly referenceable, and others needed to further summarise for the specific topics. This research then organised these data under the 15 codes, which built up the blocks of meaningful information for the six underlying themes of this thesis. Figure 3.5 (in next page) shows that the data for research gaps, prototype and concept design framework were only from the documentary analysis. The data for the case study was from all the three methods. In such a way, it brought theory into the practice of the case study.

After sufficient investigations of the underlying themes, this research formed four related main themes. Literature review answered the question of why, concept development answered the question of what, concept implementation answered the question of how, and lastly concept validation answered the question of how good. These conclusions all together answered the main research question with substantial evidence and provided clear clues for further studies.

3.6 Reliability, validity, and generalisability

The above data collecting structure ensured the reliability of this research because each conclusion can be traced back for its data analysis route and resources. The performances evaluation of this research based on a built-up project, so the adequacy, accuracy and accountability of performance predictions can be further validated in the future. The arguable part of this research is the capital costs. This part of data is confidential, which cannot be seen by other researchers, therefore could have involved some pre-determined bias. However, the design of the research strategy has taken the prevailing bias into account. Table 3.7 summarised the bias identified from the literature review and explained how this research handled them.

Moreover, the theory-practice integrated approach significantly enhanced the validity of such prototype research. The theory study brought a solid foundation from broader fields for the practice to rely on, while the practice provided feedback through modelling and monitoring to refine the theory study results. For this reason, such an integrated approach will lead to new ideas and solutions in line with the development of affordable NZE townhouse.

Lastly, even though the single case study was not selected randomly, the generalisability of this thesis is not reduced. Given more resources and time, such a case study can replicate in any place in China. The research findings of this specific case may not be directly replicable in other projects. However, the experiences learnt in this project about the design strategies, design integrations, the costs and performances are all very valuable to other projects. Especially for those projects in the same climate zone, the research findings of this case study can be used as benchmarks for further improvement.

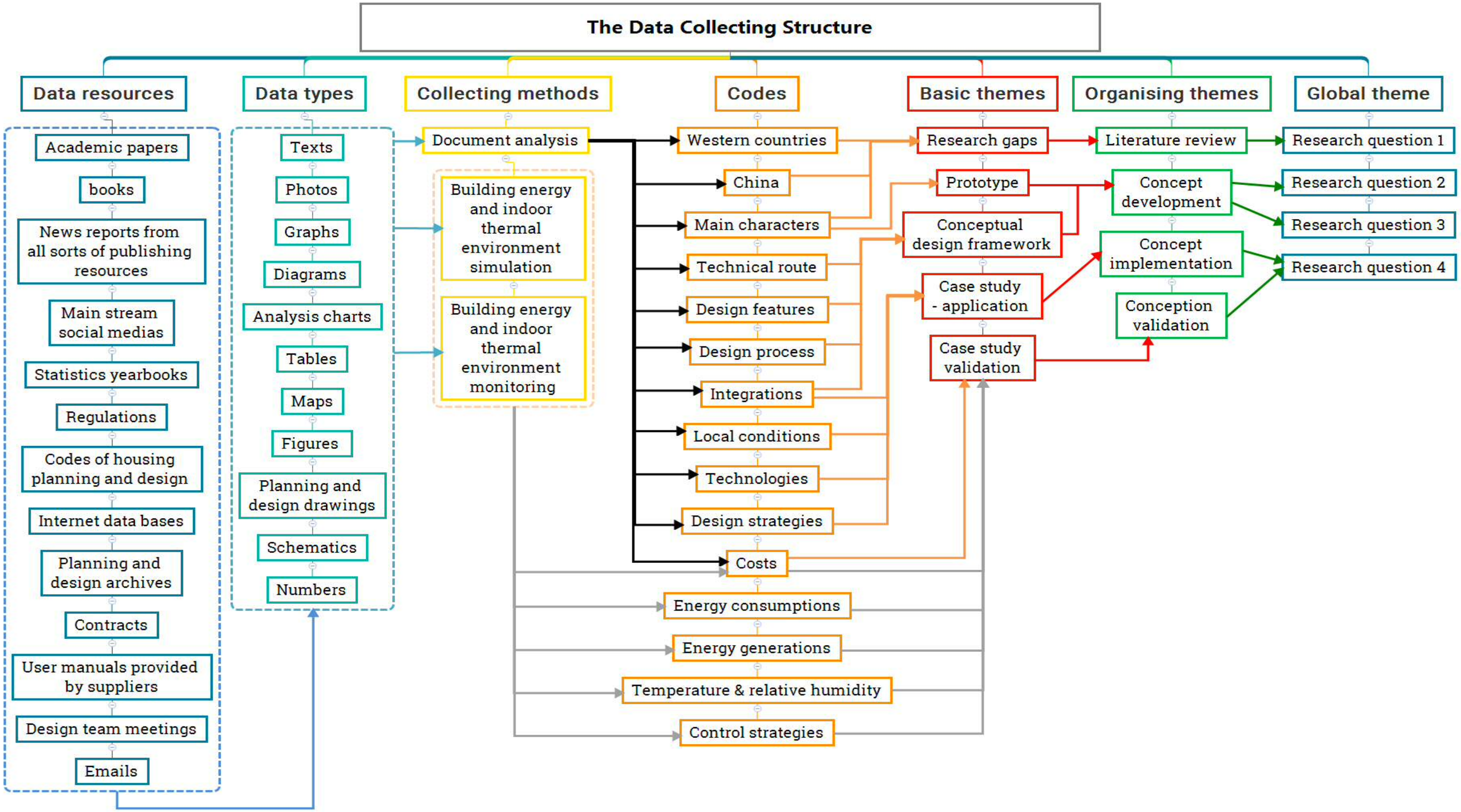


Figure 3.5 The data collecting structure

Table 3.7 Possible bias and ways to avoid them by the research design of this thesis

Possible bias		**How to avoid them in this research**
(Sarniak 2015)	(Ching 2016)	
Confirmation bias Occurs when a researcher forms a hypothesis or belief and uses respondents' information to confirm that belief	**Confirmation Bias** Unconscious act of referencing only those perspectives that fuel our preexisting views, while at the same time ignoring or dismissing opinions	The hypothesis developed from a comprehensive literature review, so has its objective theoretical foundation. The case study gives the chance to prove it not applicable and then can reject it entirely. Such a theory-practice integrated approach can avoid confirmation bias.
Culture bias Assumptions about motivations and influences that based on our cultural lens (on the spectrum of ethnocentricity or cultural relativity) create cultural bias.	**Groupthink and the Bandwagon Effect** To attain harmony, the members may agree upon a decision that deviates from the correct decision. Thus, for the sake of avoiding conflict, members agree upon a point without critical evaluation.	The concept development investigated both developed countries and China's development of theory and practices, so it distilled mutual interests and benefits. The author's position as an external participant from the UK balanced with the local team on culture awareness and way of thinking.
Question-order bias Respondents misled by the words and ideas presented in questions that impact their thoughts, feelings and attitudes on subsequent questions.	**Anchoring Bias** During decision making, anchoring occurs when individuals use the first piece of information to make subsequent judgments.	Both the prototype and the conceptual design framework were generic rather than specific, open rather than closed procedure. The implementers need to use their knowledge to develop specific design strategies according to local conditions. Therefore, the experiment's participants could start from any angle or order.
Leading questions and wording bias Are not types of bias themselves, they lead to bias or are a result of bias	**Observer Expectancy Effect** A researcher's cognitive bias causes them to influence the participants of a study subconsciously	Not relevant
The halo effect Moderators and respondents tend to see something or someone in a particular light because of a single, positive attribute.	**Selection Bias** This bias occurs when the researcher decides which type individuals or the number of individuals to participate in the study.	The case study is a commercial rather than a research pilot project, so the design team and sub-contractors were chosen by the developer rather than the research.
	Clustering Illusion & Reporting Bias Clustering Illusion occurs when we tend to look for patterns in a pool of random data. Reporting bias occurs when the direction or statistical significance of results influences whether and how research is reported	The performances results were checked both by the author and the developer. Other researchers can further validate them in the future.

Note: Because this thesis did not involve survey, interview or questionnaire, the 'respondent bias' summarised by Sarniak (2015) are not relevant.

3.7 Ethical issues

The research does not involve any study on human-beings or human activities. All the information needed are documents based and the conclusions drawn does not refer to any names or personal opinions.

Chapter 4

Concept development: The terminology of affordable Nearly-Zero-Energy townhouse in China, its prototype, and the conceptual design framework

4.1 Introduction

The literature review found that there are considerable political and social driving forces to promote NZE housing in China. As yet there are no prototypes, guidelines or definitive targets set to create the necessary step-change in the housing industry. The current housing solutions in China have not yet provided cost-effective methods to achieve higher environmental credentials. While the goal of NZE housing is government policy, there is currently little additional guidance or funding to enable this to be achieved in practice. Moreover, while the cost is the main barrier to NZE housing in developed countries, the most difficult barrier is the settlement and building form in China. The current strategies to achieve NZE or above performances in the developed countries do not apply to the high-rise high-density residential buildings in China.

However, the review also shows that China now has sufficient social, economic and environmental appeals to promote NZE housing. When the policies and definitions are not yet clear enough to guide practices, prototypes can accelerate the deployment of NZE housing. Therefore, the urgent need is the prototype study of affordable NZE housing in China. Among all the possible prototypes of NZE housing, the findings in review further narrow the priority down to affordable NZE townhouse for China. Such concept addresses the two priorities of housing in China – affordability and reasonable density - while driving the energy performance of such housing to NZE standard.

As introduced in Chapter 2, the current definition of NZE housing in China is still very vague. It neither defines the boundaries of building systems nor clarifies the scales of energy balance. Therefore, before conceptualising ‘affordable NZE townhouse’, in section 4.2, the fundamental definition of NZE building is explored in more details. Firstly, it analyses the descriptions in other countries and China. Then, the boundaries of building systems and scales of energy balance in this research are clarified. Finally, it defines the terminology of ‘affordable NZE townhouse’.

In section 4.3, the prototype studies of other countries’ NZE houses are reviewed, to understand the role and approaches of such research. The prototype of affordable NZE townhouse in China is then developed, based on other countries’ experiences and China’s context.

In section 4.4, firstly the existing conceptual design frameworks of designing NZE housing are reviewed. Based on the review results, this research formulated a conceptual design framework to assist the design development of the affordable NZE townhouse prototype.

4.2 Affordable NZE townhouse: a new terminology of low-carbon housing in China

4.2.1 Overview of NZE building definitions around the world and in China

As shown in Chapter 2, NZE house plays the leading role in the practice to promote low-carbon building. However, in the research field, the definition of NZE or above building is not sophisticated until the recent years and is still under development in many countries’ policy makings. As reviewed by D'Agostino (D’Agostino 2015), only four countries among the 27 studied European Member States (MS) developed a full definition of NZE building (Figure 4.1 a). Moreover, only ten counties managed to apply such a definition in practice through demonstration and pilot projects (Figure 4.1 b). Therefore, this is a very new area for every country to explore.

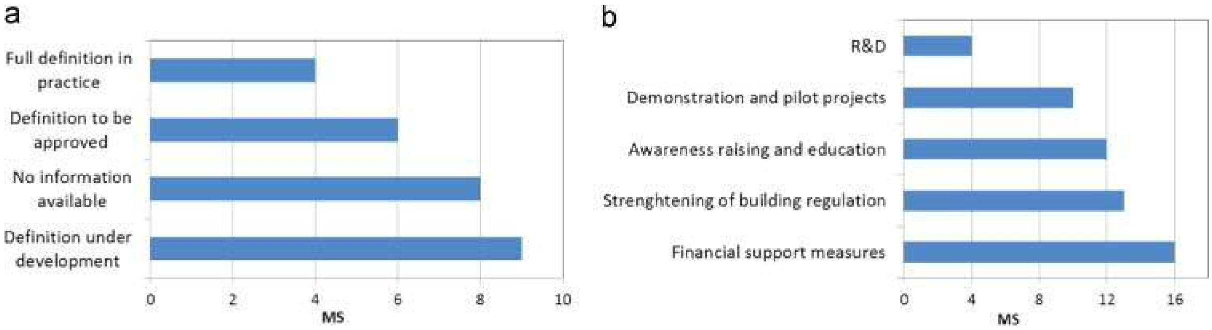


Figure 4.1 Overview of the status of NZE building definitions and implementation in MS
(D’Agostino 2015)

In terms of the contents of NZE building definitions, D'Agostino and Mazzarella (D’Agostino and Mazzarella 2019) summarised the ones formulated in the MS (Table 4.1). Table 4.1 shows that the terms developed around NZE buildings are formulated around certain low-carbon technologies, and discussed at different boundaries of building systems. These terms answered the main arguments (Figure 4.2) around NZE Buildings (nZEB as in the reference) in either generic or specific way. Similar arguments were also once summarised by (Bourrelle et al. 2013), in a more generic but energy-focused way (Figure 4.3).

Table 4.1 Main terms launched around NZE buildings in MS
(D'Agostino and Mazzarella 2019)

Acronym	**Meaning**	**Characteristics**
NZEB	Nearly Zero Energy Building	Very high energy performance building with a very low amount of energy required covered to a very significant extent by energy from on-site or nearby renewable sources
Net ZEB	Net Zero Energy Building	A yearly energy-neutral building that delivers as much energy to the grid as it draws back
ZEB	Zero Energy Building	Zero energy consumed by a building in its day-to-day operation
ZEB	Zero Emission Building	Zero carbon emissions released into the environment
NZSoEB	Net Zero Source Energy Building	A building that produces at its location as much energy as it uses in a year when accounted for at the source
NZSiEB	Net Zero Site Energy Building	A building that produces at its location as much energy as it uses in a year when accounted for at the building
NZEC	Net Zero Energy Cost Building	The amount of money the owner pays for the energy consumed is equal to the money the owner receives for the energy delivered to the grid over a year
nNZEB	Nearly Net Zero Energy Building	A building with a national cost-optimal energy use higher than zero primary energy
Autonomous ZEB	Autonomous Zero Energy Building	A stand-alone building that supplies its own energy needs
+ZEB	Energy Plus Building	A building that produces more energy from renewables than it imports over a year
PV-ZEB	Photovoltaic Zero Energy Building	A building with a low electricity energy demand and a photovoltaic system (PV)
Wind-ZEB	Wind Zero Energy Building	A building with a low electricity energy demand an on-site wind turbine
PV-Solar thermal-heat pump ZEB	Photovoltaic Solar thermal heat pump Zero Energy Building	A building with a low heat and electricity demand, a PV system in combination with solar thermal collectors, heat pumps and heat storage
Wind-Solar thermal-heat pump ZEB	Wind Solar thermal heat pump Zero Energy Building	A building with a low heat and electricity demand and a wind turbine in combination with a solar thermal collector, a heat pump and heat storage

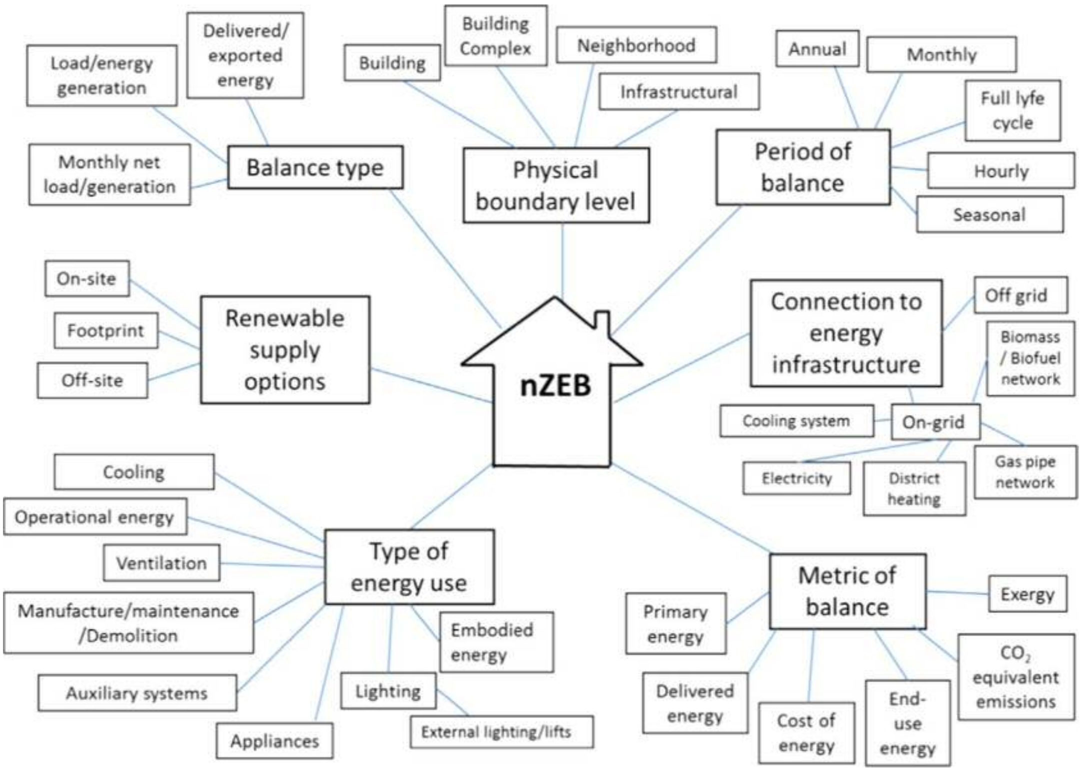
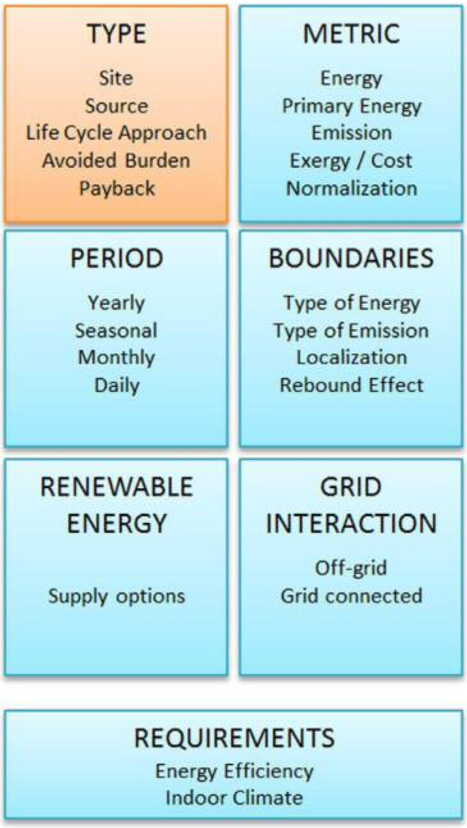


Figure 4.2 Main arguments around NZE buildings for formulating the definitions (D'Agostino 2015)


TYPE
Site
Source
Life Cycle Approach
Avoided Burden
Payback

METRIC
Energy
Primary Energy
Emission
Exergy / Cost
Normalization

PERIOD
Yearly
Seasonal
Monthly
Daily

BOUNDARIES
Type of Energy
Type of Emission
Localization
Rebound Effect

RENEWABLE ENERGY
Supply options

GRID INTERACTION
Off-grid
Grid connected

REQUIREMENTS
Energy Efficiency
Indoor Climate

Figure 4.3 Characteristics of NZE buildings energy balance (Bourrelle et al. 2013)

Comparing with China's definitions around ZE buildings, which are launched in 2018 by *Technical Standard for Nearly Zero Energy Building:*

> ***Ultra-low energy building***
>
> *Adapt to climate characteristics and natural conditions. Significantly reduce the heating and cooling demand of buildings through passive technical means, and provide a comfortable indoor environment with less energy consumption through improving the efficiency of energy equipment and system. The energy consumptions of heating, air conditioning and lighting should be more than 50% lower than the Building Energy Saving Design standards in 2016.*
>
> ***Nearly zero energy building***
>
> *Adapt to climate characteristics and natural conditions. Significantly reduce the heating and cooling demand of buildings through passive technical means, and provide a comfortable indoor environment with less energy consumption through improving the efficiency of energy equipment and system. Make use of renewable energies and optimise the operation of energy systems, in order to provide a comfortable indoor environment with minimal energy consumption. The indoor environmental parameters and energy consumption parameters must achieve the requirements of this standard.*
>
> ***Zero energy building***
>
> *Adapt to climate characteristics and natural conditions. Significantly reduce the heating and cooling demand of buildings through passive technical means, and provide a comfortable indoor environment with less energy consumption through improving the efficiency of energy equipment and system. Sufficiently make use of renewable energies generated from building itself and nearby, as well as purchased from external sources, in order to make the annual renewable energy supply more than or equal to the annual energy use of the building.*

The above contents show that China has formed its basic definitions around ZE buildings. However, these three definitions are more useful for policymaking rather than for design practices - they neither give a clear description of building system boundaries nor specify the type of energy use and scale of energy balance in details. Moreover, in the following technical contents about building characters, the Standard only mentioned about using '*a high-rise slab-type apartment*' as a prototype. It does not provide any further descriptive information for it either. Such a prototype is not sufficient to guide the designers in their works, especially when the concepts are fresh new to them. It also excludes the low and multi-story residential buildings, which have a more significant potential to be NZE or above housing.

Therefore, more research works are needed to clarify the definitions technically and enrich the prototype to cover a broader range of building forms.

4.2.2 Building system boundaries and energy balance scales to clarify the NZE building definition in China

As pointed out in section 4.2.1, before defining NZE housing, it is necessary to clarify the system boundaries of the NZE building, so that different designers have the same ground for discussions. Also, it is critical to declare at which scale to achieve the ZE balance so that the NZE standard has a stable benchmark to compare.

The boundary study has been extensive in developed countries in the past eight years. For example, Zero Carbon Hub (Zero Carbon Hub 2014) in the UK formulated a user side focused boundary (Figure 4.4).

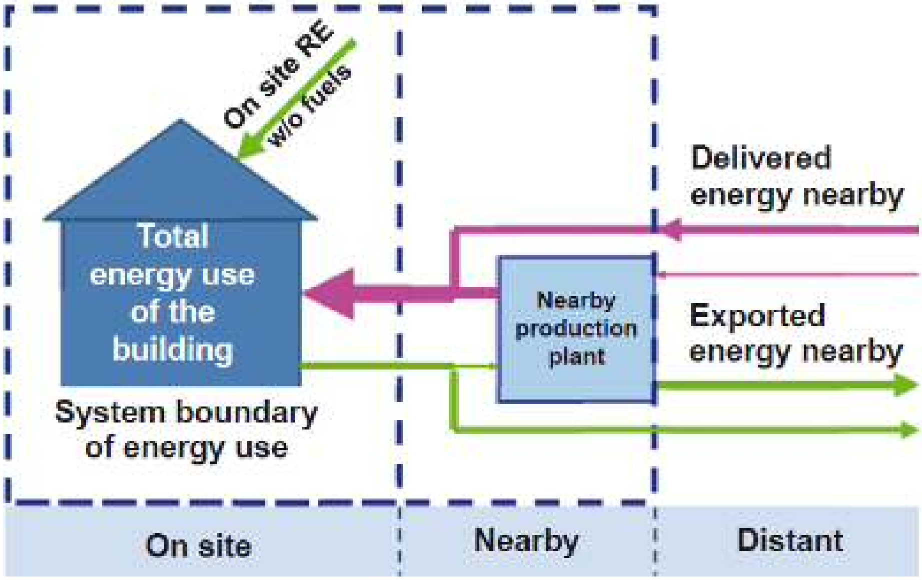


Figure 4.4 NZE Building System Schematic (Zero Carbon Hub 2014)

The advantage of this schematic is that it gives the designers elementary and clear boundaries to link the physical scales of building systems to the ones of energy balance. The disadvantage, however, is that this schematic does not have visual highlights of passive energy losses and gains. Such missing information could mislead the designers who are newly coming to this area. They might not understand the comprehensive calculations of '*total energy use of buildings*', which includes both passive and active energy losses and gains.

D'Agostino's boundary explanation (D'Agostino 2015) better presents the involved energy transformations within and between the boundaries (Figure 4.5). Such a schematic is straightforward for the designer to check the comprehensiveness of their calculations. However, comparing with the Zero Carbon Hub's schematic (Figure 4.4), the D'Agostino's schematic has its disadvantage as well. It is weak in showing the energy flow and route when across boundaries. Such discrete energy flow could lead to careless consideration of losses or gains.

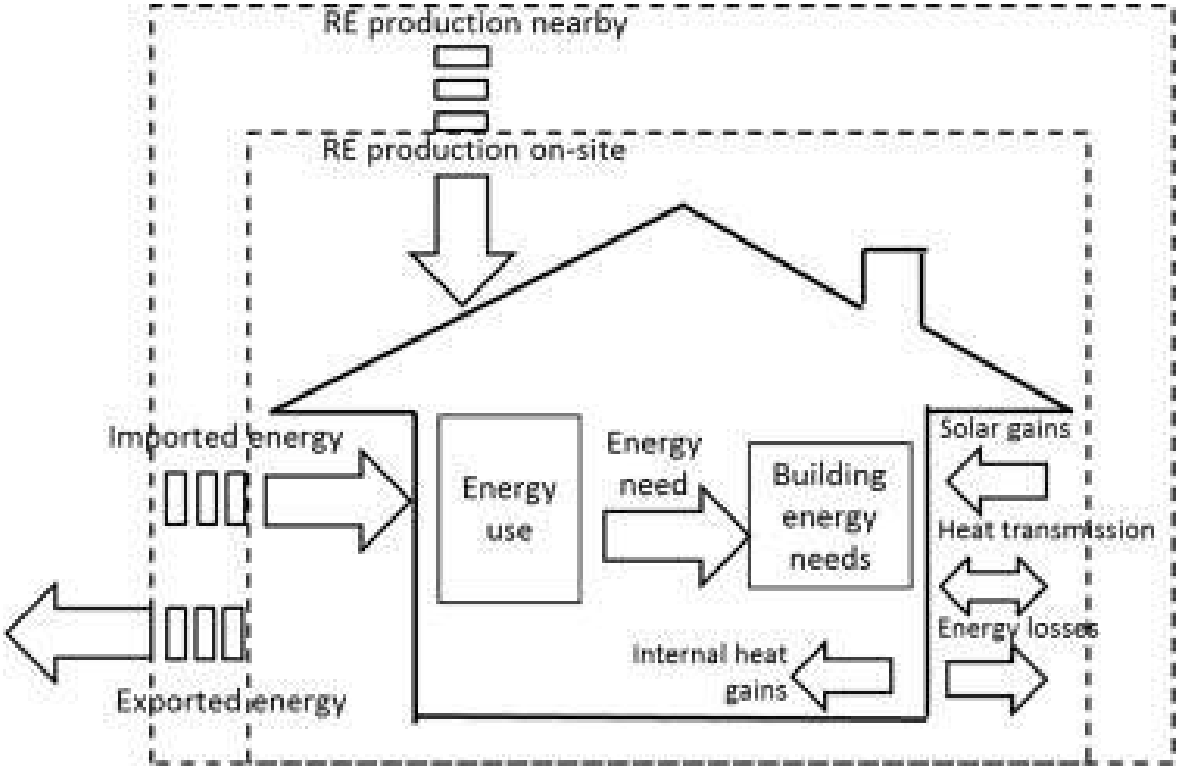


Figure 4.5 A schematic NZE building with possible system boundaries (D'Agostino 2015)

Kurnitski et al. (2011) formulated such a schematic from another point of view (Figure 4.6). They focused on the relationships between services and energy. They set up boundaries around services systems rather than the building. This approach is more engineering focussed, therefore benefits the engineering designers in finding their boundaries of work in the building design. However, comparing with the above two approaches, it loses the sense of physical scale boundaries and the building's relationship with both internal and external environment.

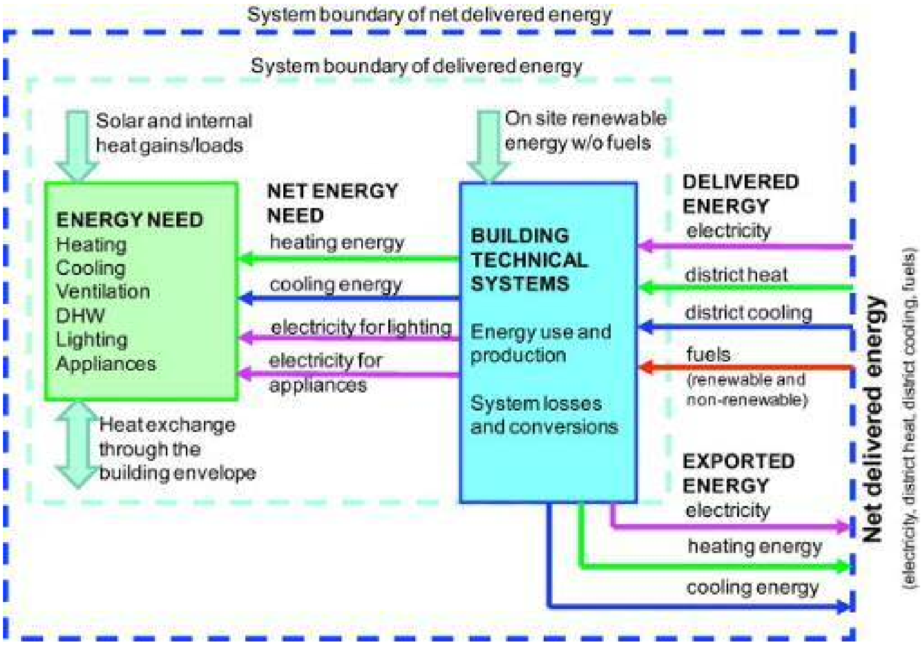


Figure 4.6 System boundary of net delivered energy (Kurnitski et al. 2011)

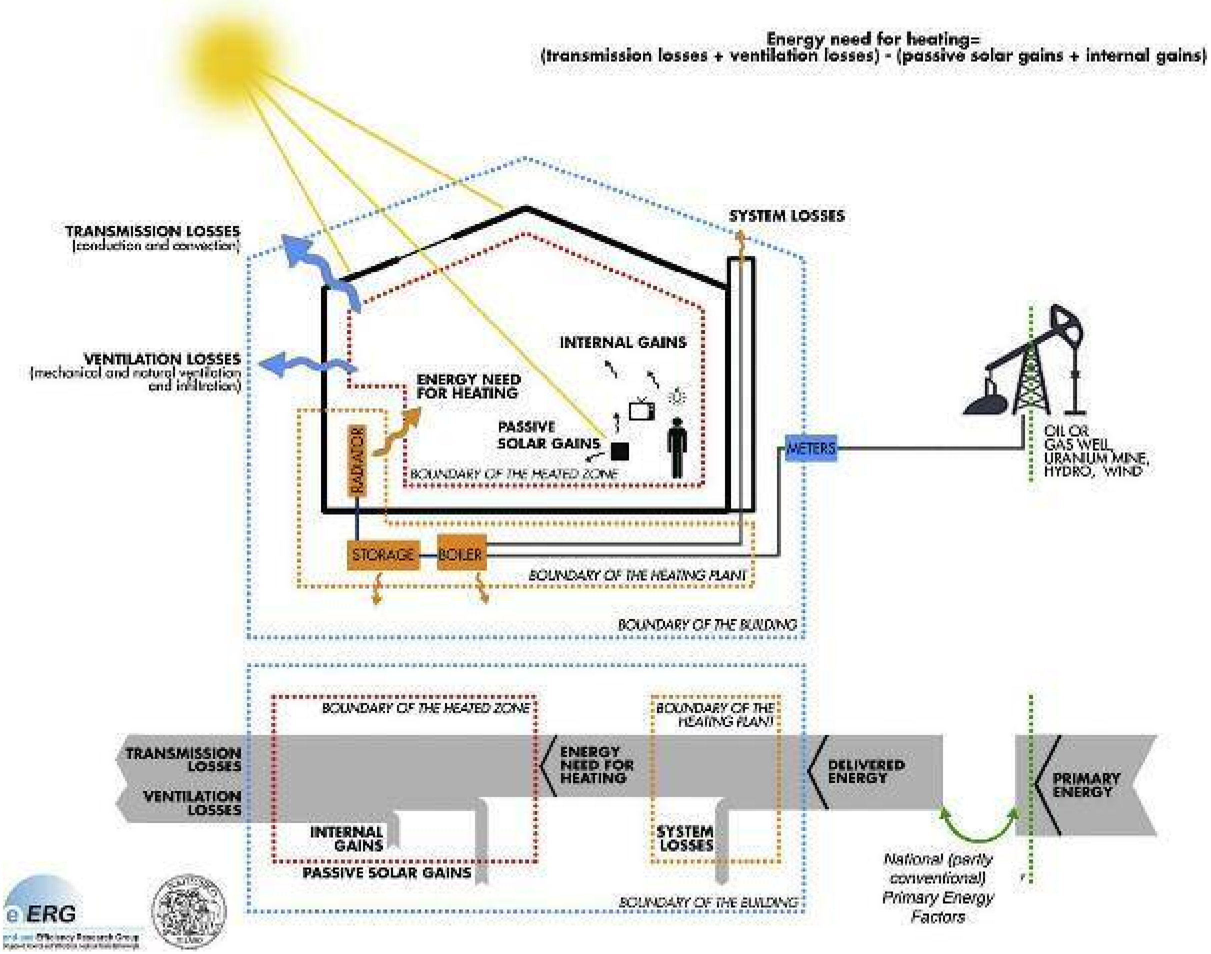
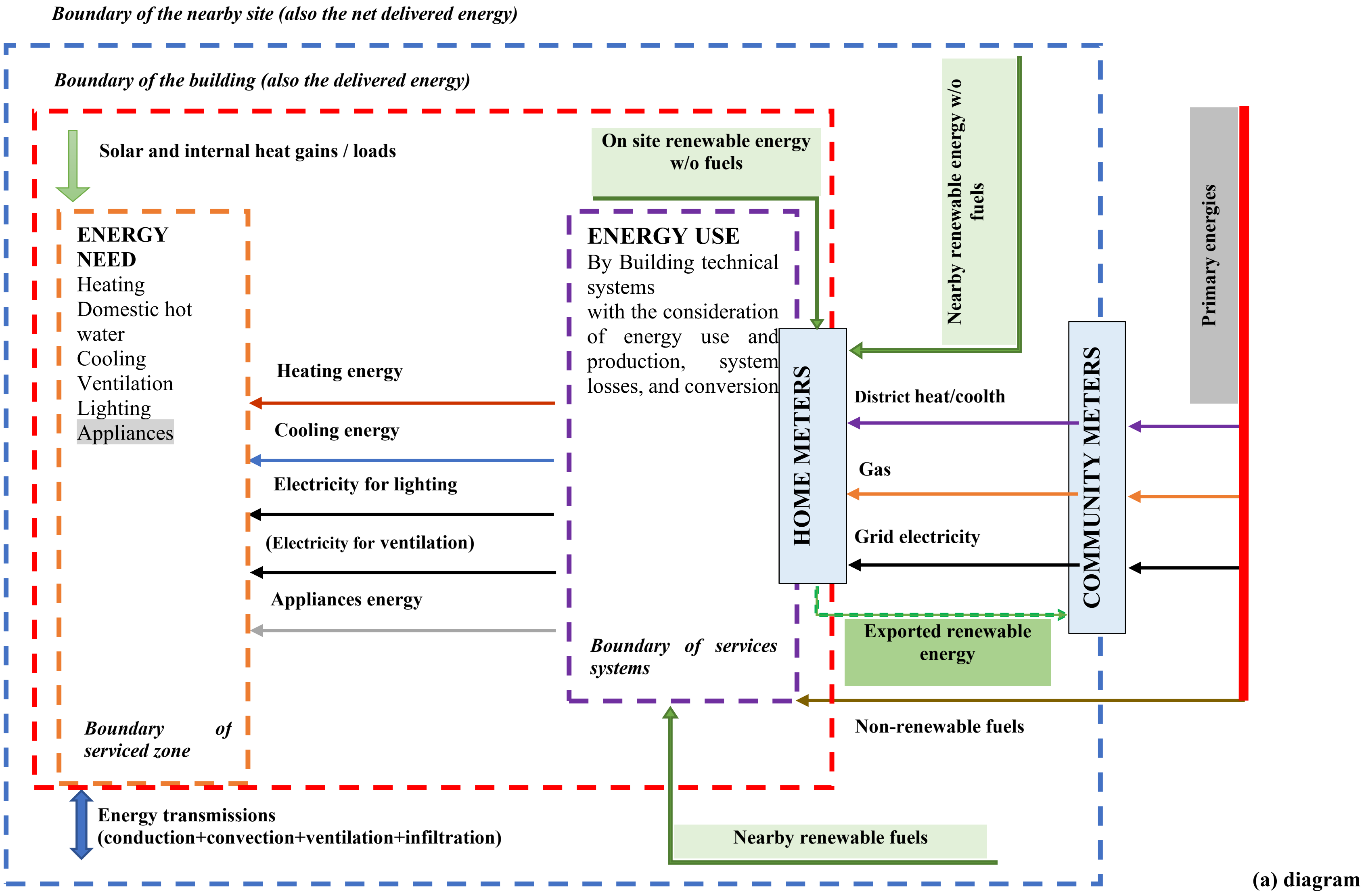


Figure 4.7 Representations of energy levels according to European Union standards, limited to the case of heating for the sake of clarity (Attia et al. 2017)

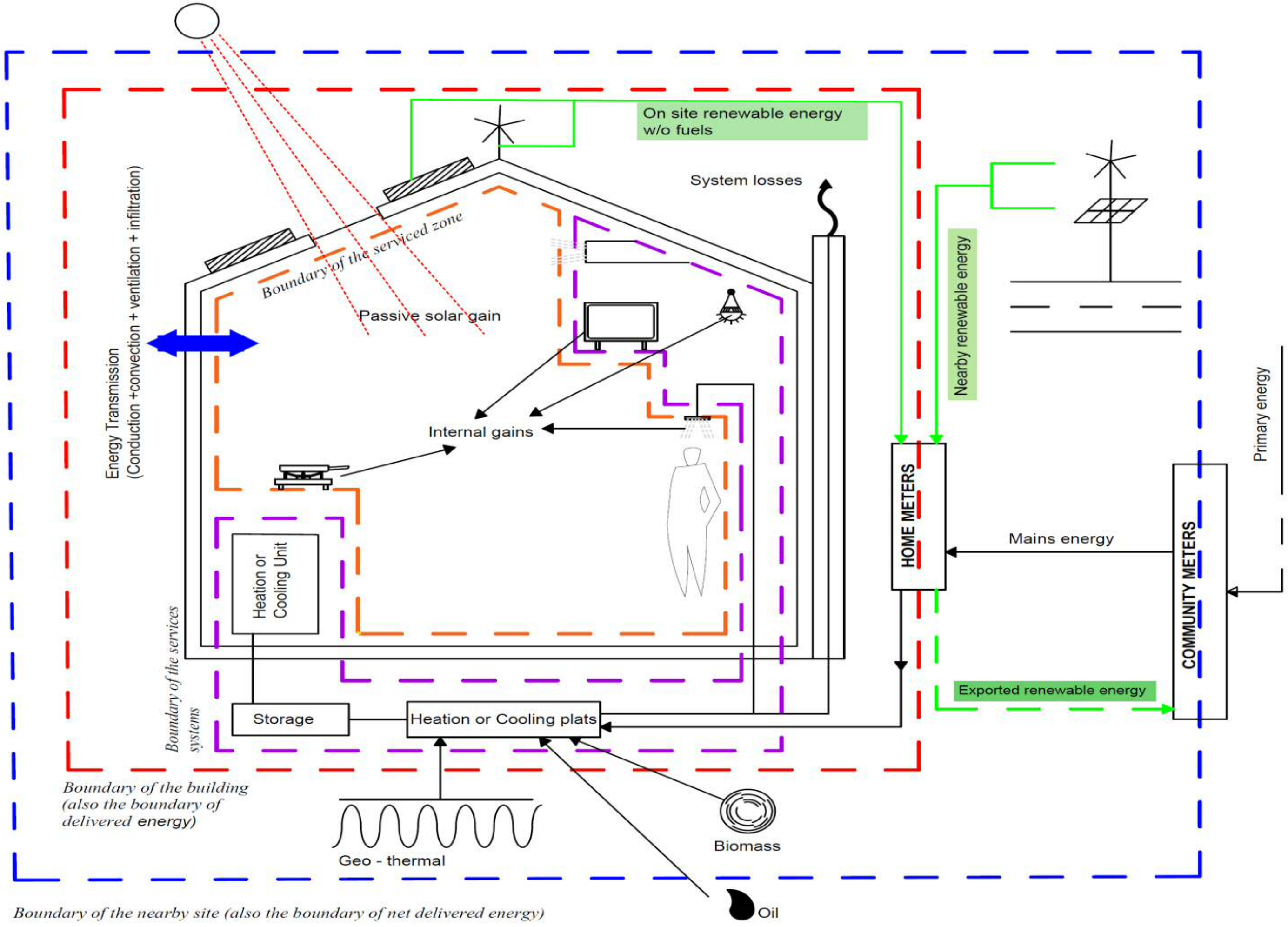
Attia et al. (2017) made progress of such schematic in terms of presenting both the building and the services system's boundaries with clear energy flow (Figure 4.7). However, their work simplifies the whole model to focus on heating only. Such simplification cannot fully interpret the general energy use in and out of the building. Also, comparing the work with Kurnitski et al.'s (2011), such simplification could miss the possible integration strategies of energy use. For example, when only looking at heating, heat pumps may not be as competitive as boilers. However, if providing both heating and cooling, the heat pump would play a more critical role.

Therefore, in this research, a schematic of NZE building systems and energy balance boundaries is developed (Figure 4.8 a & b). It develops from the review of the above research work, and it reflects China's definitions around ZE buildings. Comparing with existing work, improvements of the schematic in this research include:

- It links the building's physical boundaries to its energy balance boundaries so that the ZE balance point can be defined clearly by the terms in either type of boundaries. Such dual-boundary schematic helps to increase communication between architects and engineers.
- It specifies the energy types and flows across the boundaries so that trade-off calculations of in/out energy can be comprehensive and thorough
- It clarifies the metering point so that the monitoring can reflect the theoretically calculated energy balance in the real world
- It divides energy and fuels so that the possibly hidden energy consumptions (such as biomass for heating, or oil for heating) could be easily spotted
- It highlights the renewable energy sources (shaded in green in Figure 4.8 (a)) and organises the renewable energy flow, so the NZE or above strategies could be formulated quickly around these sources in the early design stage
- It addresses appliances' energy consumption (shaded in grey in Figure 4.8 (a)) and points out that it is part of the building energy demand but not included in the regulated energy for the definition of NZE building
- It treats all the possible energies (power, heat or coolth) from the building to its nearby site as one renewable energy, which simplifies the calculations and avoids confusions


Boundary of the nearby site (also the net delivered energy)
Boundary of the building (also the delivered energy)
Solar and internal heat gains / loads
On site renewable energy w/o fuels
Nearby renewable energy w/o fuels
Primary energies
ENERGY NEED
Heating
Domestic hot water
Cooling
Ventilation
Lighting
Appliances
ENERGY USE
By Building technical systems with the consideration of energy use and production, system losses, and conversion
Heating energy
Cooling energy
Electricity for lighting
(Electricity for ventilation)
Appliances energy
HOME METERS
COMMUNITY METERS
District heat/coolth
Gas
Grid electricity
Exported renewable energy
Boundary of services systems
Boundary of serviced zone
Non-renewable fuels
Energy transmissions (conduction+convection+ventilation+infiltration)
Nearby renewable fuels

(a) diagram



(b) visualisation

Figure 4.8 Schematic of NZE building boundaries and energy flow – visualisation

Hence, to make the definition of NZE building in China more specific based on the schematic developed in this research (Figure 4.8), it could be clarified as:

The annual regulated energy use (heating, domestic hot water, cooling, ventilation, and lighting energy demand converted by services systems' efficiencies) of the building can be covered by energy from on-site or nearby renewable resources. In the meantime, the indoor environmental parameters and energy consumption parameters must achieve the requirements of the *Technical Standard for Nearly Zero Energy Building* in China.

4.2.3 The measurement of housing affordability in China

According to the review in Chapter 2, China's affordable housing policies mainly address the quantity and unit price, which causes 'cheap and quick' practices. Even low-income occupants do not prefer such cheap but low-quality affordable housing. Therefore, they are left empty or abandoned after a short period of living. This empty or abandoned housing is a massive waste of resources and public funds. That is why this research emphasised that future housing should put affordability, liveability and livelihood under one umbrella, and aims for long term sustainability and resilience (Figure 4.9).

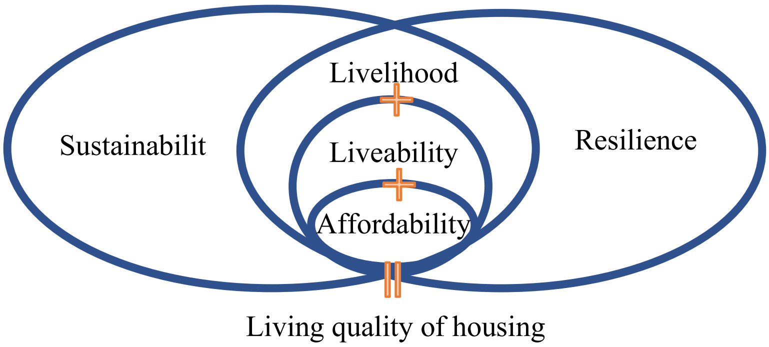


Figure 4.9 Hierarchy and relationships among sustainability, resilience, and living quality of housing

The existing research done in other countries illustrates the perspective of this research. For example, Tapsuwan et al. (2018) explored people's preferences for characteristics of neighbourhoods and homes through questionnaire study. Based on their literature review results, they summarised 67 neighbourhood features and 38 home features in the questionnaire, and they surveyed 300 residents in Australia. In this research, affordability is classified as a home feature and interpreted as the capital cost of buying a house. The research does show that affordability is always the prioritised home feature to individuals (Table 4.2). Moreover, the result does not vary much with the social classifications of the surveyed people (buying intension, gender, income and age).

Table 4.2 Perceived top 3 features of the home (summarised from (Tapsuwan et al. 2018)**)**

Social classification	**Group**	**Top 1 feature**			**Top 2 feature**			**Top 3 feature**		
		Feature	**M**	**SD**	**Feature**	**M**	**SD**	**Feature**	**M**	**SD**
Ratings of house features by buying intention	Investor	It is resilient to severe storms	5.95	1.2	It is affordable	5.9	1.01	stays warm in the winter without heating	5.9	1.1
	Owner-occupier	It is affordable	6.14	1	stays warm in the winter without heating	6	1.02	It is resilient to severe storms	5.9	1.1
Ratings of house features by gender	Male	stays cool in the summer without the use of air conditioning	5.89	0.9	stays warm in the winter without heating	5.9	0.99	It is affordable	5.8	1.2
	Female	It is affordable	6.35	0.9	stays warm in the winter without heating	6.1	1.04	stays cool in the summer without air conditioner	6.1	1.1
Ratings of house features by income	Lower half	It is affordable	6.03	1	will increase in value	6	1.01	stays warm in the winter without heating	5.9	1.1
	Upper half	It is affordable	6.31	1	stays warm in the winter without heating	6.2	0.95	will increase in value	5.6	1.3
Ratings of house features by age	<45	It is affordable	6.26	0.9	It is resilient to severe storms	6.2	0.91	stays warm in the winter without heating	6.2	0.9
	≥45	It is affordable	5.96	1.1	stays cool in the summer without the use of air conditioner	5.8	1.06	stays warm in the winter without heating	5.8	1.1

Note: M – Mean, SD – Standard Deviation, scale (1 = not at all important; 7= extremely important)

Indeed, people will generally have a budget that they cannot afford to exceed, but within this budget, there will be critical aspects that they prioritise above others.

As shown in Table 4.2, although the desire for comfort was beaten by affordability in respondents' choices for priority, their scores are close to each other. Still, in Tapsuwan et al.'s research (2018), energy/water bills and maintenance cost also scored high in preferred economic features of the home (Figure 4.10).

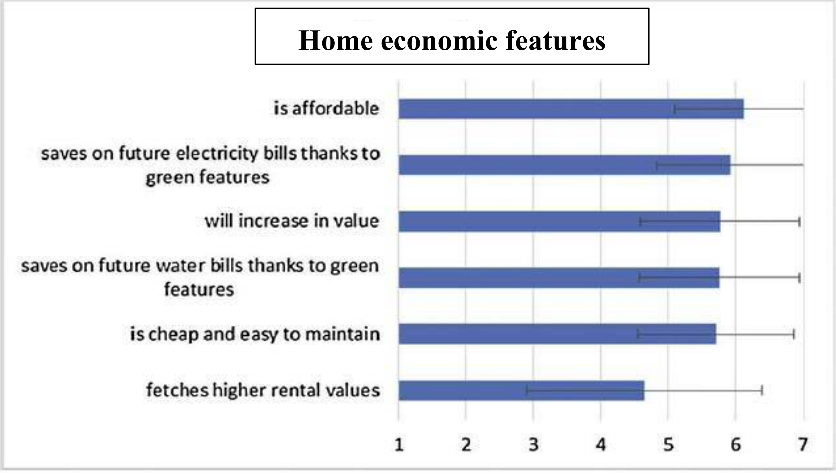


Figure 4.10 Mean rating (and standard deviation) of preferred home economic features (Tapsuwan et al. 2018)

Note: 1 =Not at all important; 7= Extremely important

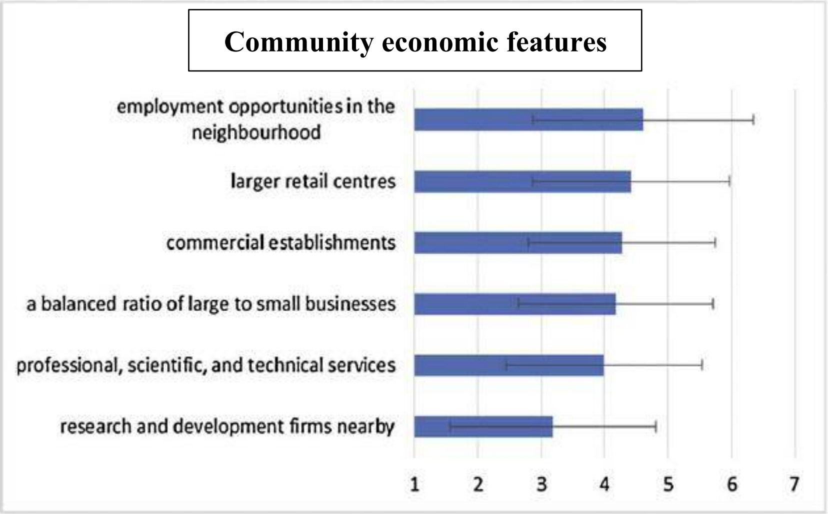


Figure 4.11 Mean rating (and standard deviation) of preferred community economic features (Tapsuwan et al. 2018)

Note: 1 =Not at all important; 7= Extremely important

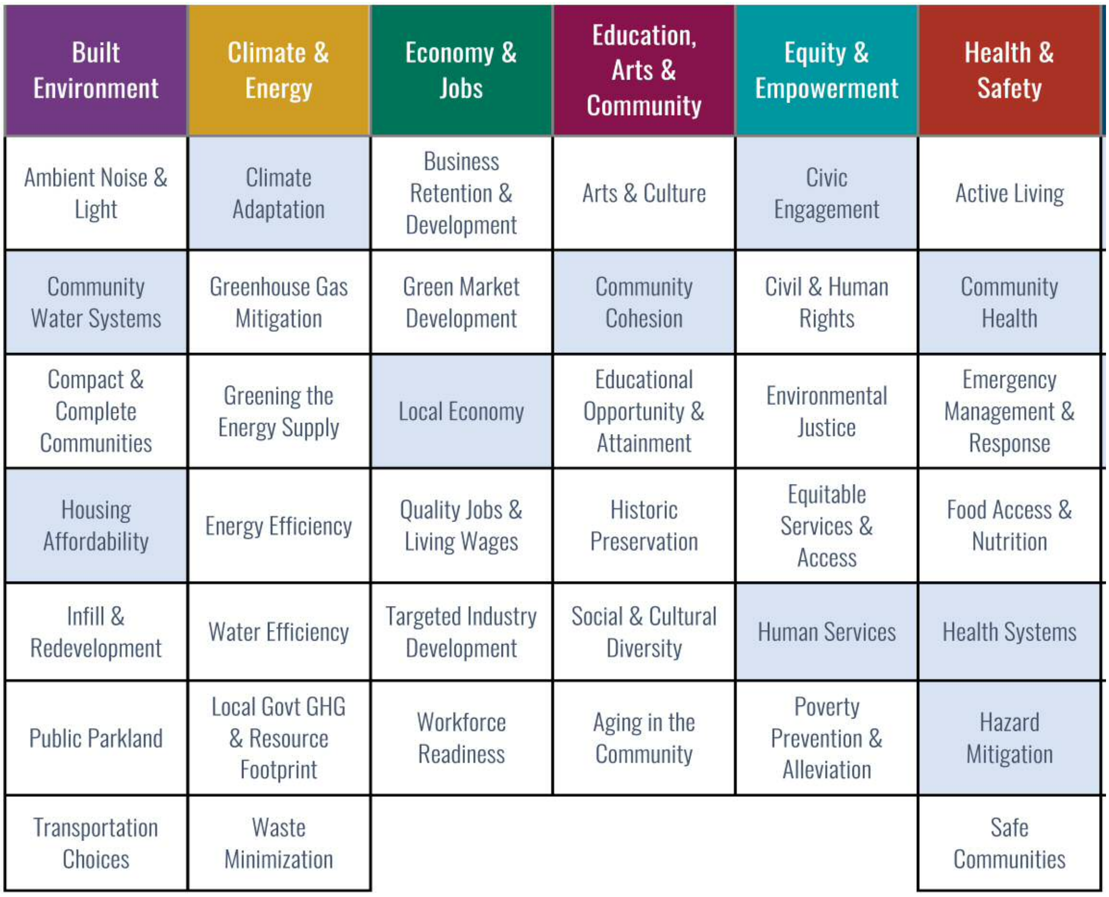
This result means people can hardly buy a cheap home without considering the costs of using and maintaining it. Also, value creation and resilience to natural hazards are listed on the top 3 priorities. Thus, Tapsuwan et al.'s research show that affordability does not have significant more weights in people's housing preferences.

Again, when voting for the preferred economic features of the community, '*employment opportunities in the neighbourhood*' ranks the first, and the accesses to other services and facilities also scores high (Figure 4.11). Such results demonstrate that one would not buy or live in a cheap home without a job to do nearby or convenient life to live day by day.

Hence, it is objective to say that affordability issues (to build, buy/rent, operate, maintain and live) strongly link to 'liveability' and 'livelihood'. Only tackling one of the issues cannot achieve the overall affordability of living quality.

Liveability is '*the degree to which a place supports quality of life, health and well-being*'. '*Hence, a liveable neighbourhood or city should be peaceful, safe, socially cohesive and inclusive, harmonious, attractive, affordable, high in amenity, environmentally sustainable, and easily accessible*' (Lowe et al., 2015 and Major Cities Unit, 2012; cited by (Tapsuwan et al. 2018)). Livelihood, according to DFID (2001), '*compromises the capabilities, assets and activities required for a means of living*'. Therefore, before making a dwelling's capital cost (buy/rent) and energy consumptions (operate) very low, it is more important to make sure that the settlement and building form can enable sustainable livelihood (to settle in) and endurable liveability (build to good quality and then maintain it).

Other research also addressed such a conclusion about the integrity of affordability, liveability and livelihood. The STAR Community explored such integrity in its most recent document *Measuring Community Resilience with the STAR Community Rating System* (Helling and Shaver 2018). It addressed that '*Housing Affordability is one of the most challenging objectives in the STAR rating system*'. However, it also points out that housing affordability is only one of the twelve identified overlapped objectives (grey blocks in Figure 4.12) between the sustainability rating system and the FEMA's resilience categories. The other 11 overlapped objectives are more relevant to liveability and livelihood issues. Also, within the 'housing affordability' feature, '*affordable transportation costs*' is listed as a target to be achieved. Such a criterion setting again suggests that designers and policymakers should consider housing affordability issues beyond the residential buildings' capital cost.



Built Environment	Climate & Energy	Economy & Jobs	Education, Arts & Community	Equity & Empowerment	Health & Safety
Ambient Noise & Light	Climate Adaptation	Business Retention & Development	Arts & Culture	Civic Engagement	Active Living
Community Water Systems	Greenhouse Gas Mitigation	Green Market Development	Community Cohesion	Civil & Human Rights	Community Health
Compact & Complete Communities	Greening the Energy Supply	Local Economy	Educational Opportunity & Attainment	Environmental Justice	Emergency Management & Response
Housing Affordability	Energy Efficiency	Quality Jobs & Living Wages	Historic Preservation	Equitable Services & Access	Food Access & Nutrition
Infill & Redevelopment	Water Efficiency	Targeted Industry Development	Social & Cultural Diversity	Human Services	Health Systems
Public Parkland	Local Govt GHG & Resource Footprint	Workforce Readiness	Aging in the Community	Poverty Prevention & Alleviation	Hazard Mitigation
Transportation Choices	Waste Minimization				Safe Communities

Figure 4.12 twelve priority objectives of the STAR rating system aligning with the Federal Emergency Management Agency resilience categories (Helling and Shaver 2018)

The reason behind such criteria setting of this USA's rating system can be well explained by Litman's research (Litman 2018). He pointed out that '*households often make trade-offs between housing and transport costs, for example, between cheaper urban-fringe housing or more expensive central-area housing*'. Therefore, based on BLS's research (2016, referenced by (Litman 2018)) on '*Household Expenditures by Income Quintile*' in the USA (Figure 4.13), Litman (2018) concluded that the housing affordability (to buy or rent) in the USA should define as '*households spending no more than 45% of their budgets on housing and transport* *combined*'. The reason is that the middle and upper class in the USA spend about 45% of their income on housing (total housing expenses) and transportation (Figure 4.13). These people are the ones who can afford to buy their houses. For the lower classes, the proportion of their income will be even higher, although renting houses is the majority of the cases for them. Such expenditure percentage is also very common in the main cities of the USA (Figure 4.14).

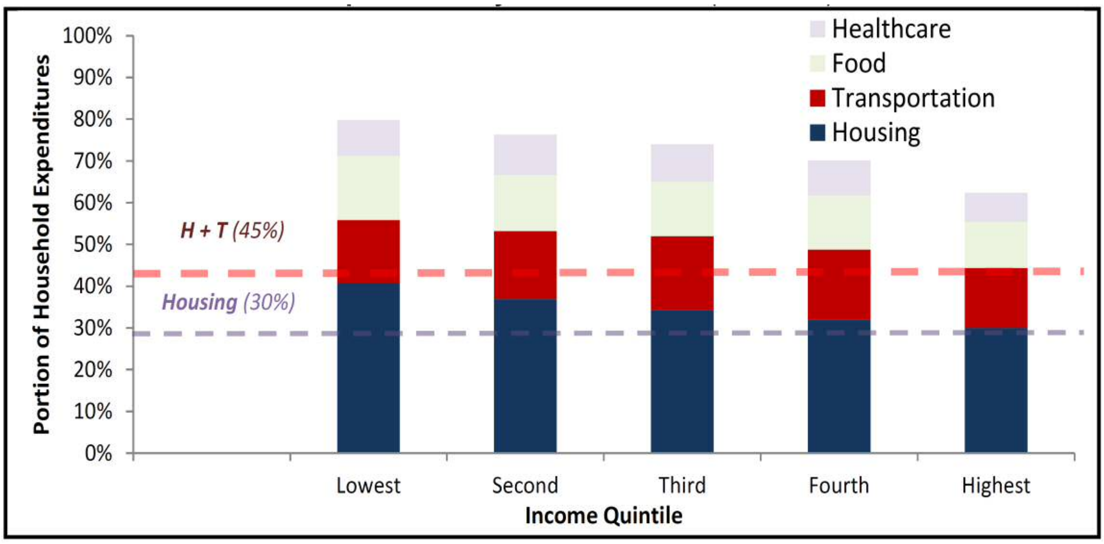


Figure 4.13 Household Expenditures by Income Quintile (BLS, 2016, referenced by (Litman 2018)

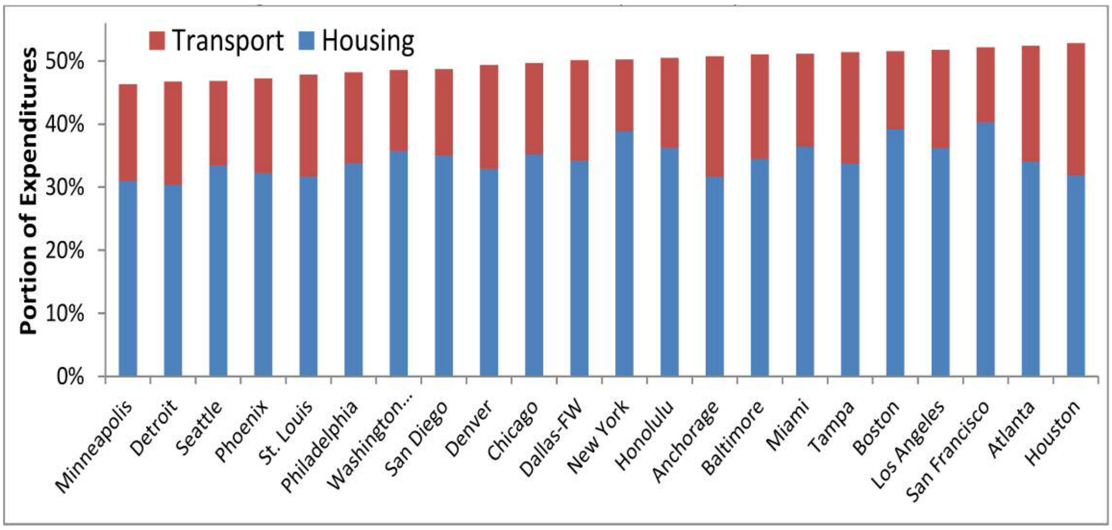


Figure 4.14 Housing and Transport Expenditures in different cities of the USA (BLS, 2016, referenced by (Litman 2018)

In China, there has not been any similar research found in the available literature. However, according to China's National Bureau of Statistics (National Bureau of Statistics of China

2018), the national average household expenditure in 2017 on housing is 36% of their income (residence 22% + Transport and Communications 14%) (Figure 4.15). This figure is close to but less than the USA's proportion (45% to 51%, as shown in Figure 4.14).

The trade-off phenomenon between housing and transportation costs is widespread around the world and particular in China. Thus, the method to define housing affordability in the USA can apply in China. However, due to the different statistic calibres between the USA and China, the percentage of expenditure used in the USA's definition cannot be directly adopted by China. Moreover, as a developing country, Chinese people's expenditure on food is much higher than the American people's. Therefore, even though Chinese people spend a high proportion of income on housing and transportation, so far, they cannot afford to spend 45% on them yet.

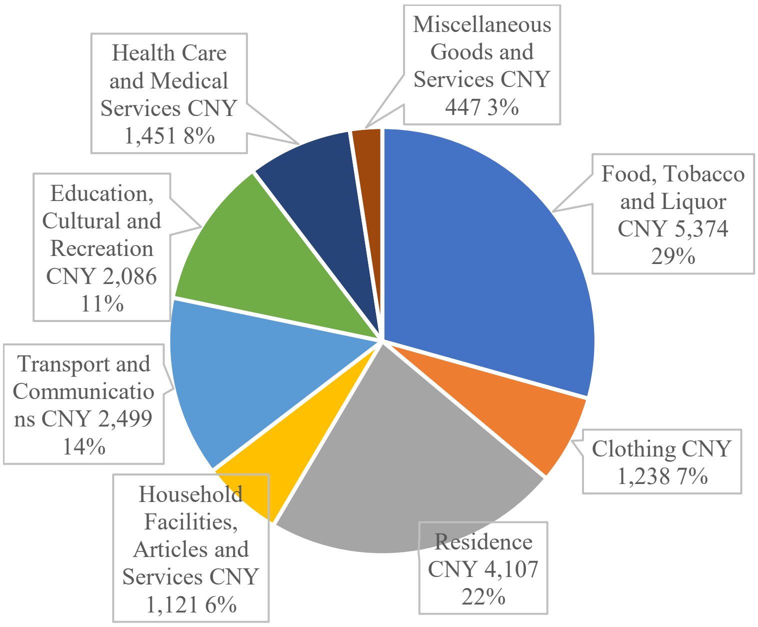


Figure 4.15 The national average household expenditure composition of China in 2017
(National Bureau of Statistics of China 2018)

Hence, based on the current expenditure level in China and the national average portable income besides food, the measurement of housing affordability in China (to buy or rent) is defined as:

Households spend no more than 40% of their budgets on the residence, and transportation & communication.

Such calibration is also to unify with China's statistic calibres of expenditure data (Figure 4.15).

4.2.4 Summary: the terminology of affordable NZE townhouse in China

In chapter 1 (Figure 1.4), it demonstrates that court form townhouse could achieve plot ratio over 1.0, which does not over-consume land. In chapter 2, it found the evidence that the medium density (plot ratio 1.0 – 1.5) provided by townhouses is reasonable to China's future population trend. Therefore, in this research, the townhouse is defined as 'medium-density (plot ratio 1.0 – 1.5) single-family suburban houses'. Such a definition is to avoid misleading the interpretation of 'townhouse' as 'terraced house', which easily confuses people between court formed terraced houses and row terraced houses. Also, it addresses the suburban nature of such housing in China.

For the rural areas, even though rural terrain in China is more abundant in renewable energy resources, the needed labour skills and supply chain for NZE building are not available there.

For the central urban areas, because the gradient of population density is much more uneven in China than in other countries, it makes the central urban areas extremely crowded. According to Zhuo and Zhang (2019), the central population density (10 km radius from the Central Business District centre) is 21,000 people/km^2 in Beijing and 26,000 people/km^2 in Shanghai. They are both far more than Tokyo, which is 13,000 people/km^2. Such a density level makes China's big cities over-crowded with high-rise high-density buildings. The overshadowing effect makes the needed onsite renewable generations of townhouses not possible in such central urban areas.

For the suburban areas, such type of housing could be affordable if locating in locations with good public transports. According to (Yu 2017), the land cost takes about 50% of the buildings' capital costs in central urban China, while it is only about 13% in developed countries. That is why in Chapter 2, the review points out that the affordable housing projects in China mainly locate in remote urban areas, which creates a lot of infrastructure and livelihood problems. However, in the suburban areas, the land cost is higher than remote urban fringe but considerably lower than the central urban areas. Now that the townhouse form can significantly reduce the construction and maintenance costs, and the NZE standard will minimise the general infrastructure and operation costs. With these two advantages, the general living and transportation costs can reduce to an affordable level.

Indeed, urban expansion is not beneficial for reducing transportation costs and carbon emissions. However, in China, the urbanisation is only halfway to its peak in many cities. Therefore, the expected future urban population increase will occupy the current suburban areas quickly and make them urban shortly. Also, the major cities in China are developing public rail transportation and other public transports to reduce the commuting time, costs and CO_{2e} emissions for suburban residents.

Thus, put all the above together, this research defines the terminology of ***affordable NZE townhouse*** in China as:

Medium-density (plot ratio 1.0 – 1.5) single-family suburban houses, which meet their regulated energy uses (heating, domestic hot water, cooling, ventilation and lighting converted by system efficiencies) by a significant amount of renewable energies generated on-site and within the community. Households spend no more than 40% of their budgets to live in (to buy or rent) and transport to them.

4.3 The prototype of affordable NZE townhouse

In section 4.2, this research forms a definition of affordable NZE townhouse. However, it only draws the borderlines for identifying such building. The definition hs not yet specified the conditions of living in such buildings (e.g. indoor and outdoor environmental standards, and issues relevant to livelihood). Therefore, to designers, the information provided is not enough to guide them for their design works. Consequently, whether such a concept is liveable and feasible in practice is not convinced.

As Elliott (2016) commented, '*Today prototyping can be used throughout the design process: to generate ideas, validate concepts, or explore technologies*'. That is why this section is going to develop a prototype to provide comprehensive information to specify the concept of affordable NZE townhouse in more details.

4.3.1 Types of prototype and its relationship with reference buildings

Before developing a prototype for the affordable NZE townhouse in China, the use and content of the prototype have to be clarified. Therefore, in this section, the types of prototype and its relationship with reference building are investigated in detail.

According to Borysowich (2007), there are five main types of prototype, and each serves a different purpose, has different characters, and use at the different design stage (Table 4.3).

Table 4.3 Typical prototypes, their characters and design stage to use (Borysowich 2007)

Type of Prototype	Typical Purpose	General Characteristics	When to Use
Concept Prototype	Analyse system approaches	The high-level and overall vision	Concept Definition Stage
Feasibility Prototype	Determine the feasibility of various solutions	Proof of concept for specific issues	Concept Definition Stage
Horizontal Prototype	Clarify scope and requirements	Demonstrates outer layer of the human interface only, such as windows, menus, and screens	Function Definition Stage
Vertical Prototype	Refine database design, test key components early	Demonstrates a working, though the incomplete, system for critical functions	A later portion of the Function Definition Stage
Functional Storyboarding	Determine useable sequences for presenting information	Demonstrates the typical order in presenting information	Function Definition Stage

The prototype to be formed in this section is '*feasibility prototype*'. It is to provide more details for the definition of affordable NZE townhouse in China and enrich contents of the critical design features, in order to make it liveable and feasible in practice.

Also, as Borysowich (2007) explained that:

> *'To establish the feasibility of a solution, all of the pieces must fit together properly. The Feasibility, or Technical, Prototype proves out some technical assertion that is key to the feasibility of the preferred alternative. It verifies that critical components of the technical architecture integrate properly and are capable of meeting the business needs.'*

To the policy-making and design in the construction industry, such a feasibility prototype usually means a reference building (RB).

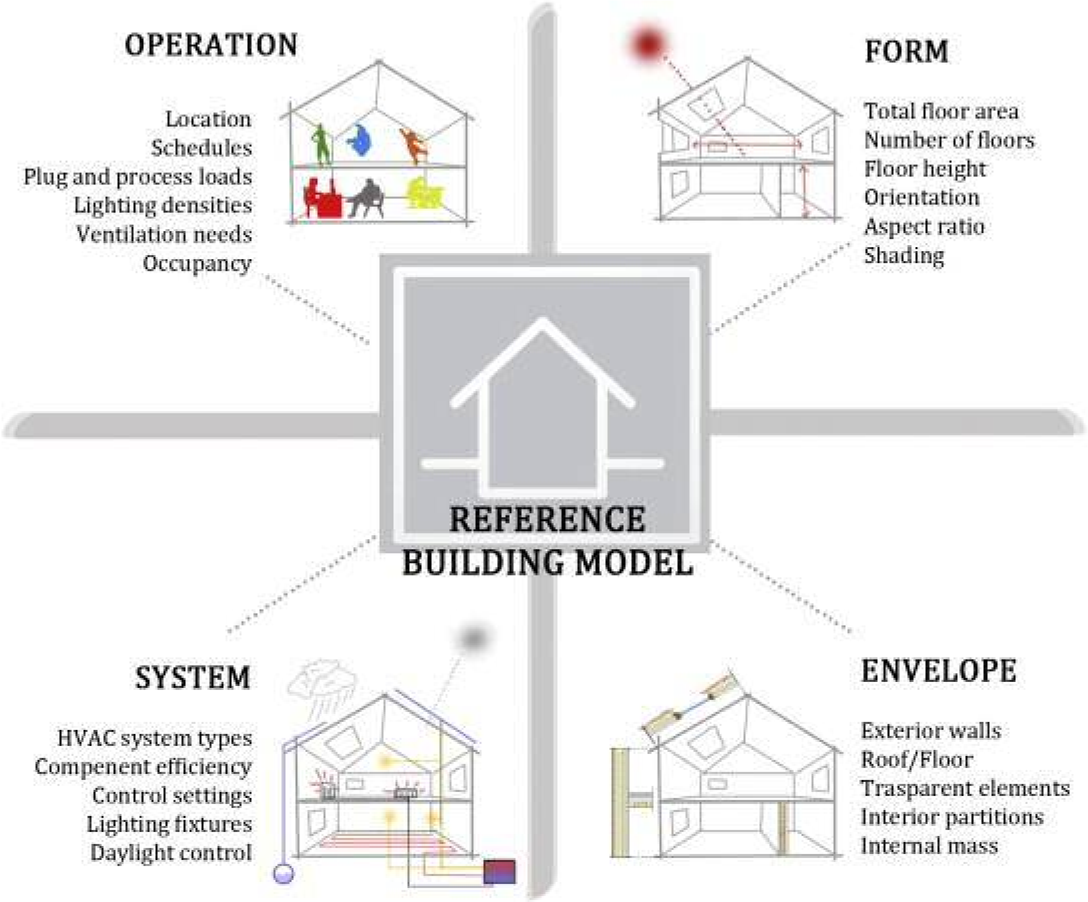


Figure 4.16 Four sub-sets of features for defining reference building models according to the Department of Energy (DOE) of United States methodology (Corgnati et al. 2013)

Corgnati et al. (2013) referenced Energy Performance of Buildings Directive (EPBD) of EU to define RBs as '*buildings characterised by and representative of their functionality and geographic location, including indoor and outdoor climate conditions*'. Corgnati et al. (2013)

also summarised four sub-set of features to gather the data for establishing RBs (Figure 4.16), taking inspiration from the methodology used by the Department of Energy (DOE) of United States.

Moreover, Corgnati et al. (2013) collected data within the four sub-sets to further compare the DOE's and EPBD's methodologies for establishing reference buildings. They concluded three general methodologies for formulating the models (as illustrated in Figure 4.17).

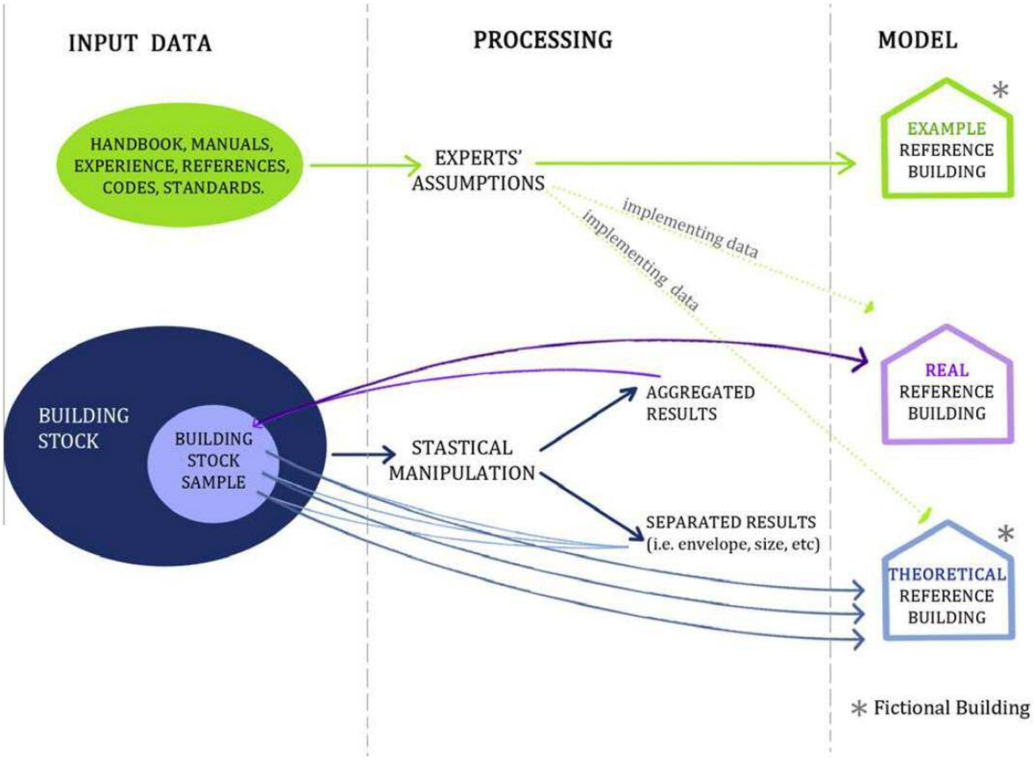


Figure 4.17 General methodology for establishing reference building models (Corgnati et al. 2013)

The three methodologies to classify RBs are defined by Corgnati et al. (2013) as:

> *'Creation of an* ***<u>"Example (Reference) Building"</u>****. This methodology is used when no statistical data are available, and it thus relies on the basis of experts' assumption and studies. Information from different sources but all based on experience and experts' inquiries are properly combined to*

> *provide a building that is the most probable of a group of buildings, within a selected location and age.*
>
> *Selection of a **“Real (Reference) Building”**. RB is the most typical building in a certain category. It is a real existing building, with typical characteristics based on statistical analysis. To define a Real Building, it is therefore necessary to have a large amount of information on the building stock.*
>
> *Creation of a **“Theoretical (Reference) Building”**. This method processes statistical data in order to define an RB as a statistical composite of the features found within a category of buildings in the stock. The building is therefore made of the most commonly used materials and systems.’*

The prototype (reference building) to be formulated in this research is an ‘*example*’ model, which belongs to the fictional building. The reason is that there has not been such a building in real practice in China, which means no statistic data available for analysis. However, on the four sub-sets (form, envelope, system and operation), there has been sufficient research in China to design an NZE residential building. There are also many ‘*experts’ assumptions*’ about affordable housing in China. Therefore, the main work of the prototype in this research is to review, extract, and integrate these pieces of information.

Corgnati et al. (2013) pointed out in their research that Denmark is a typical country in the EU which uses example buildings to guide the designs. By reviewing China’s *Technical Standard for Nearly Zero Energy Building*, this research found that China also adopts such methodology in this design code. Therefore, the prototype formulated in this research can fit in China’s design code appropriately and helps to fill the blank areas of low-rise NZE housing in China.

In terms of the prototype’s generality level, the classification of Schaefer & Ghisi’s research (2016) can be referenced. They formed a dendrogram to represent the generality for obtaining reference buildings (Figure 4.18). For such a bottom-up method, there are three steps to obtain the needed data and extract the similarities at different level (Figure 4.19).

Schaefer & Ghisi's research (2016) is inspirational for this research to formulate the prototype (example reference building) in a reversed way. Rather than collecting '*objects*' (A to E in Figure 4.18) through field study or statistic data, this research starts from the top (ABCDE in Figure 4.18). Because affordable NZE townhouses have not yet appeared in the practices, the formulation of the concept and prototype is purely from the top-down point of view.

Thus, the prototype (example reference building) in this research aims to provide a structure at the national level to the designers as the start points to develop more detailed designs. In the meantime, for some key parameters, this prototype (example reference building) also can be used as a baseline to be compared with, in order to narrow the range of design thinking for quicker delivery.

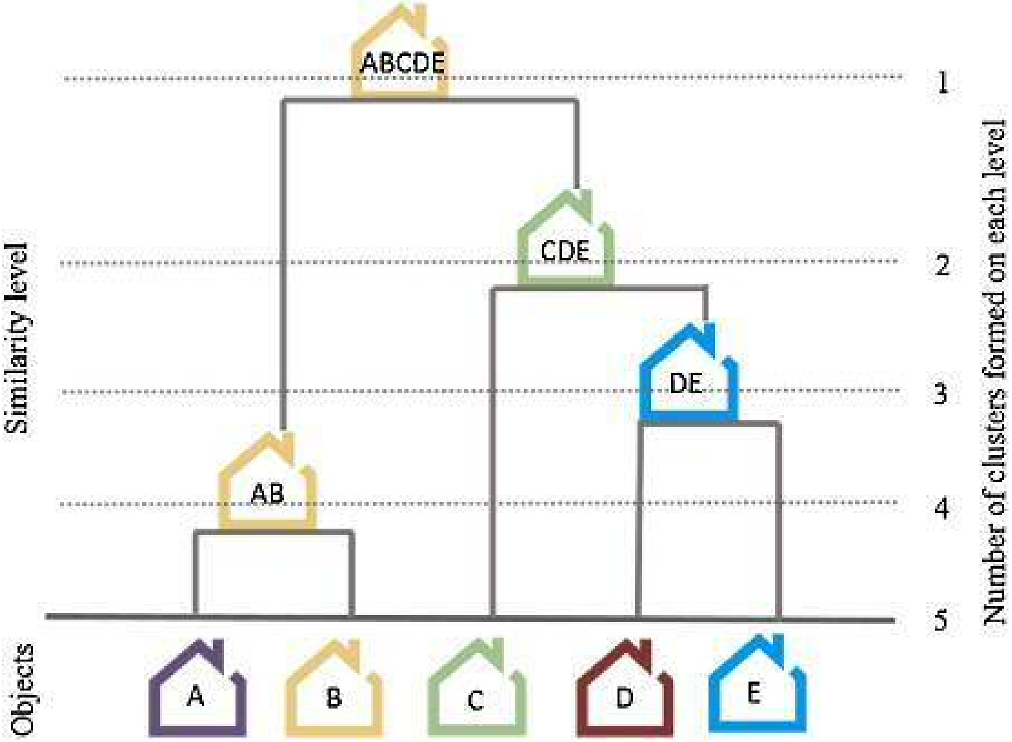


Figure 4.18 Process of a dendrogram construction (Schaefer and Ghisi 2016)

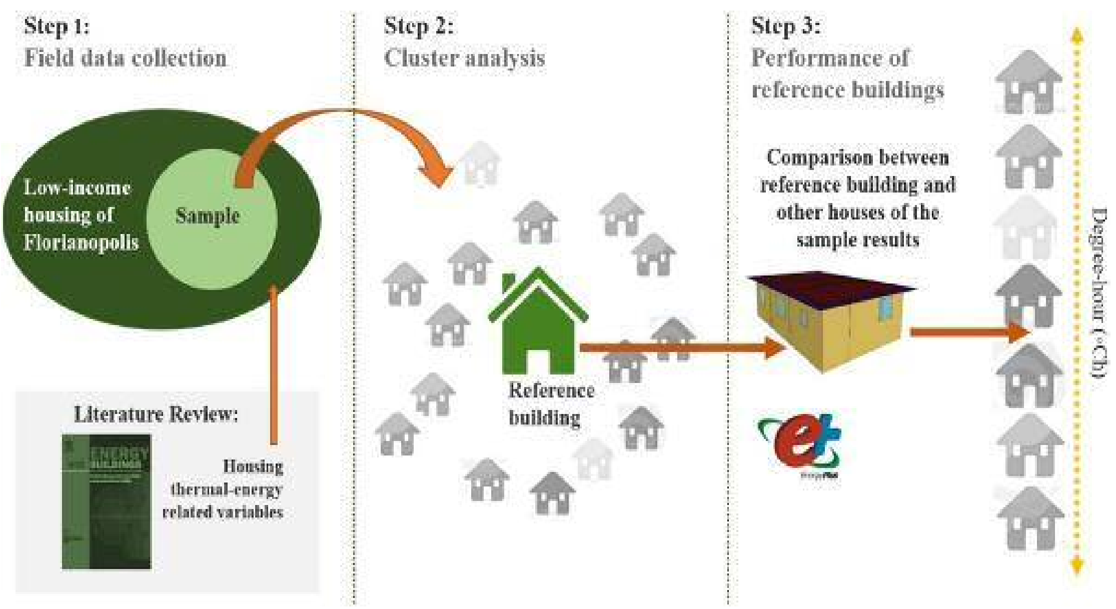


Figure 4.19 Summary of the bottom-up method for obtaining reference buildings
(Schaefer & Ghisi, 2016)

4.3.2 The key features to make the reference building of townhouse affordable and Nearly-Zero-Energy

House Size	120 m^2 over 2.5 m cellar containing heating equipment	
Neighbors	Similar neighboring buildings on the two sides of the house	
Envelope		
Windows	23 m^2 with double clear glass (~2.2 W/m^2K)	
Walls	R 1.3 Insulated perlite filled masonry walls (~0.8 W/m^2K)	
Attic	R-5.3 insulation (~0.18 W/m^2K)	
Doors	Insulated wood entry door (~0.8 W/m^2K)	
Air Leakage	Standard construction (4 ACH at 50Pa blower door pressure)	
System		
Heating	Hydronic natural gas heating system, 82% efficiency	
Cooling	COP 4.1 mini-split cooling system	
T Set point	20°C for heating, cooling 23°C	
Hot Water	155 l insulated boiler in cellar providing 120 l per day at 55°C	
Mechanical Ventilation	20.3 1/s continuous with 72% efficient ERV	
Appliances	A+	Option A+++
Refrigerator	340 kWh/yr.	201
Cooking	334 kWh/yr.	302 (Induction)
Dishwasher	319 kWh/yr.	258
Clothes dryer	0.98 kWh/kg	0.59 kWh/kg
Clothes washer	183 KWh/yr	150 kWh
Lighting	80%incandescent: 600 kWh/yr	100% CFL/LED: 175 kWh/yr
Renewables		
PV System	None	4.0 kWp with 95% efficient inverter
Solar Hot Water	None	6m^2 closed-loop system

Figure 4.20 Characteristics of the baseline building used in the Optimisation to reach NZE buildings for new housing in Europe (D'Agostino and Parker 2016)

As explained above, the methodologies of obtaining reference buildings have been well established in developed countries. For example, D'Agostino and Parker (2016) formulated a reference house in order to find the optimal paths to reach NZE housing for new constructions in Europe (Figure 4.20).

The advantage of this prototype is that it indicates the baselines under each sub-set so that the designers can have a clear target to aim. The disadvantage, however, is that it does not look at the features influencing affordability, and it gives specific figures rather than a range for some parameters. Such a reference building is useful for testing strategies at a later design stage for ensuring NZE or above performances. However, it is not generic enough as an example reference building at the national level. Especially for a country as large as China, economic and climate status varies hugely among regions. Therefore, in this research, the formulation of the prototype as an example building at the national level will extend the contents furthermore as six sub-sets: location, density, form, envelope, system, operation. The first two sub-sets set up boundaries to identify affordable livelihood for the residents, while the latter sub-sets look at the critical elements for ensuring NZE performances and decent liveability.

4.3.2.1 Location

As introduced in Chapter 1, apart from tier 1 cities in China, all other tier cities have different levels of over-supplied private housing. In Chapter 2's review, it clarified that not all the cities in China have rapid population growth. Some of them even struggle to keep their current citizens, which means less demand for new housing in the future. Therefore, in terms of regional-scale location, the affordable NZE townhouse would only be suitable for some tier 2 to 4 cities. Moreover, section 4.2.3 explained the reason for the suburban nature of such townhouse. However, how such a suburban nature fits in the affordability measurement needs to be further clarified here.

Pan's research (2019) studied the relationship between commuting distance and metropolitan area. He summarised that '*for the relatively stable metropolitan areas in the world (such as Tokyo or New York), the farthest distance from the city centre is roughly stable at 50 km.*' He pointed out that ‘*the generally bearable commuting time of the public (in China) is no more than 1 hour*’. Moreover, he addressed that the one-hour commuting time should not include the distance running by high-speed train, because ‘*it is not economical for citizens as daily commuting*’.

He also emphasised that the commuting situation in China is different from the metropolitan area as in Tokyo or New York. His study shows that Chinese cities rarely have the metropolitan areas as large as 50 km in radius (e.g. Beijing and Shanghai only have a metropolitan radius of 30 km), and is unlikely to develop to such scale. Pan (2019) gave the relationship between Beijing and the three northern counties of Hebei Province as an example – these three counties are only 30 to 40 km from Beijing’s city centre, and people commuting daily from these three counties to Beijing for work. However, the administrative border line between Beijing and Hebei sits in the middle, which creates burdens to connect infrastructures and share public services. This situation makes the livelihood of the residents living in the three Hebei counties far worse than the citizens in Beijing. Pan’s research (2019) indicates that new housing development in China is better not to target the livelihood beyond a city’s borderline. In China, the administrative division is a significant burden for the big cities to integrate the infrastructures and public services in more extensive metropolitan areas. Living in one city and working in another is practically doable, but such housing development does not seem beneficial to residents for their livelihood and liveability.

Pan’s opinion has been well illustrated by Wang et al.‘s research (2018b), which studied the data records of those Beijing citizens who commuted by underground in the past consecutive seven years. It found out that 45 minutes in the underground is the time most bearable in the average – if it is shorter than 45mins, people tend to move further for better job opportunities or residential conditions; if it is longer than 45 minutes, people tend to move closer to keep the commuting time bearable. This research also commented that if adding up the time between the underground station and the residence or working area, the actual commuting time is about one hour on a daily one-way pass.

Moreover, besides the commuting time and costs, another essential condition to locate the affordable NZE townhouse is the access to renewable energy resources. The reason is that only abundant renewable energy resources can guarantee the payback of renewable energy supply technologies. Given the urban environment generally lacks access to wind, hydronic or biomass resources, this research uses solar access as the crucial criterion.

As shown in Figure 4.21, not all the regions in China are rich with direct solar radiation. Therefore, in order to promote on-site and building integrated renewable generations, the suitable regions would only be those with over 400 kWh/m^{2}yr mean distribution of direct solar radiation. This figure is concluded through the comparison with the EU countries, which promoted the NZE or above houses well (such as Germany, Denmark, Switzerland and the UK, as shown in Figure 4.22).

Thus, to summarise the above contents, the suitable location for the prototype formulated in this research is:

- within 30 km in the radius of tier 2 to 4 cities' centres in China
- costs people no more than 1 hour private or public one-way pass commuting time daily
- in the 400 kWh / (m^2·year) or above mean distribution of direct solar radiation zones

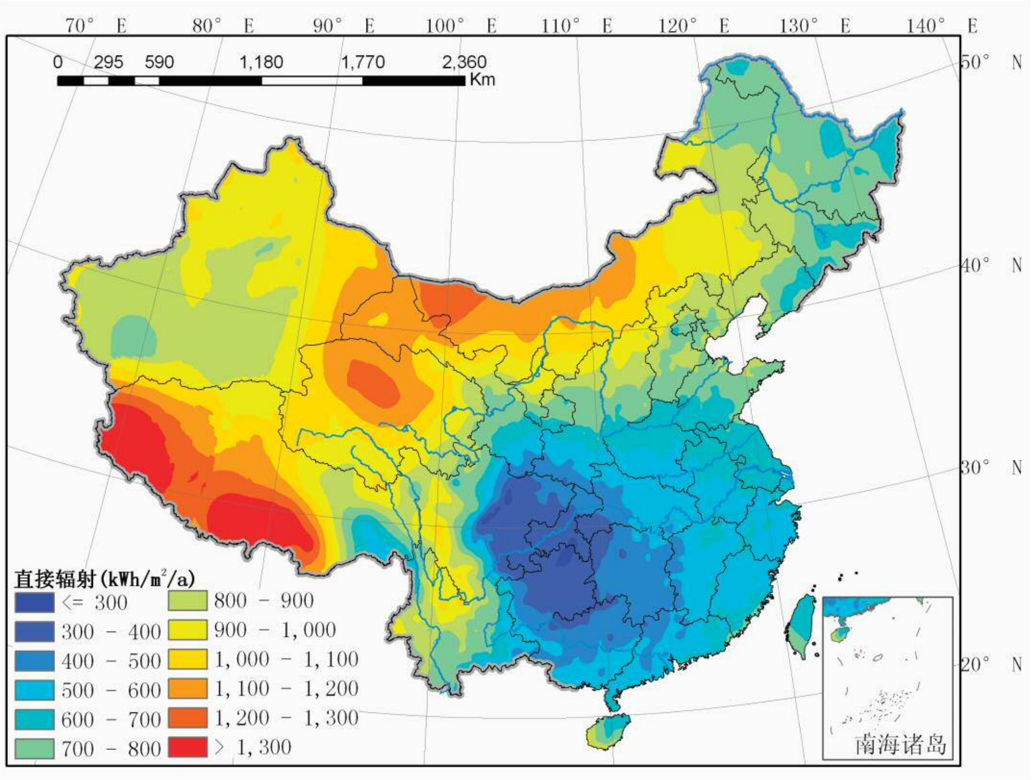


Figure 4.21 Annual mean distribution of direct radiation (National Academy of Engineering and National Research Council 2010)

Source: China Meteorological Administration.

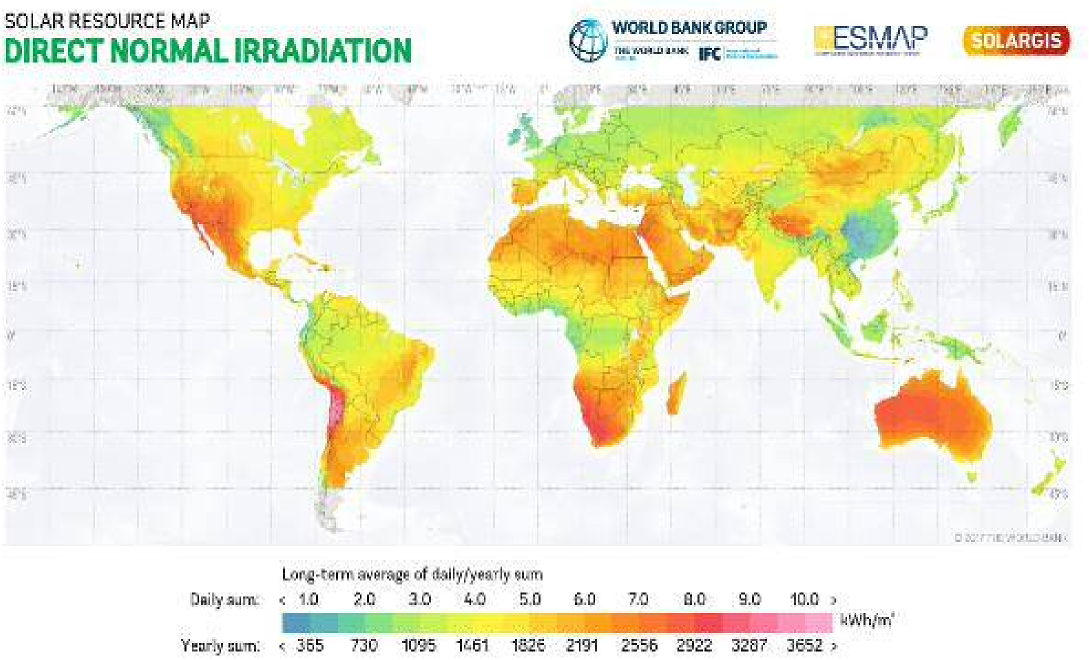


Figure 4.22 Global Map of Direct Normal Radiation (The World Bank Group 2019)

Source: https://globalsolaratlas.info

4.3.2.2 Density

As presented in Chapter 1 (Figure 1.4) that the plot ratio varies between 0.7 and 1.59 for one-hectare square if occupied by different court form townhouses. Within this plot ratio range, there could be 24 to 96 units per hectare. According to Figure 1.4, such form can provide each house at least one parking place at the courtyard, which solves the parking land use at the same time.

Based on the above figures, the actual occupancy would determine the population density. As found out in the review of Chapter 2, the average household numbers in China currently is 2.9. Therefore, the most direct results of density would be 70 to 279 people per hectare (7000 to 27900 people / km^2). However, such calculation does not take the needed surrounding transport and services land use into account. Hence, 7000 to 27900 people/km^2 is not reasonable in the real townhouse residence area.

This research reviewed some well-established megacities' figures to find out the reasonable population density for China's future townhouse residence area. Table 4.4 presents the original figures of the megacities in the world, and China's tier 1 and top twelve tier 2 cities. There are ranges of 1484 to 21370 people/km^2 in the cities' centre and 705 to 3753 people/km^2 of the metropolitan areas in Table 4.4. Table 4.5 further distilled the figures for the suburban areas only.

The calculated average suburban density of the developed countries' megacities (Tokyo, Seoul, Paris, London and New York) is 1048 people/km^2. The figure for top Chinese cities is 775 people/km^2. Therefore, it is reasonable to assume that these top Chinese cities' suburban density could keep on growing to the average developed counties' megacity level. Moreover, because of the similar living style between China and its neighbour Japan and South Korea, the suburban density could be even higher than developed counties. However, to make a conservative assumption, in this research, the minimal density expected to be achieved by the townhouse communities is set as 1000 people/km^2. In the meantime, the land use of housing construction should comply with China's planning regulations.

Table 4.4 Comparison of population density among cities (urban and metropolitan areas)

		Metropolitan Area (km²)	Metropolitan Population	Metropolitan Density (persons /km²)	Central City Area (km²)	Central City Population	Central City Density (persons /km²)
Asian countries	Singapore[1,2]	719	5607283	7799	---	---	---
	Tokyo[1,3]	13558	35618564	2627	622	8945895	14382
	Seoul[1,4]	11819	23836272	2017	605	9741871	16102
China's tier 1 cities[8]	Hong Kong[1,5]	1106	7336600	6633	---	---	---
	Beijing[6,7]	16410	21729000	1324	---	---	---
	Shanghai[6,7]	6341	24197000	3816	---	---	---
	Guangzhou[6,7]	7434	17595000	2367	2099	13341400	6356
	Shenzhen[6,7]	1997	11908400	5963	---	---	---
China's current tier 2 and future tier 1 cities[8]	Tianjin[6,7]	11917	15621200	1311	2583	9400900	3640
	Nanjing[6,7]	6587	8270000	1256	4226	6272000	1484
	Chongqing[6,7]	43263	30484300	705	7438	14530000	1953
	Chengdu[6,7]	4242	15920000	3753	1194	6903500	5782
	Wuhan[6,7]	8569	10766200	1256	1452	7057500	4861
	Hangzhou[6,7]	16596	9188000	554	1485	5629100	3791
	Qingdao[6,7]	11282	9204000	816	2294	4416200	1925
	Suzhou[6,7]	8657	10647400	1230	1524	3122300	2049
China's current tier 2 and future tier 1 cities[8]	Xi'an[6,7]	10097	8832100	875	542	4360300	8045
	Shenyang[6,7]	12860	8292000	645	3572	5362100	1501
	Zhengzhou[6,7]	6066	9724000	1603	424	5964500	14067
	Ningbo[6,7]	9817	7850000	800	1097	2845700	2594
European countries	Paris[1]	12012	11786234	981	105	2243833	21370
	London[1]	27189	20264764	745	1572	8173941	5200
USA	New York[1]	17319	18897109	1091	784	8175133	10427

Source of figures:

1. Jin and Zhang, 2018. *Seoul and the metropolitan cities in the world – Comparison of these cities' development after the millennium*
2. Department of Statistic, Singapore. 2018. https://www.singstat.gov.sg/find-data/search-by-theme/economy/national-accounts/latest-data [accessed on 2nd Oct 2018]
3. Tokyo Metropolitan Government. 2018. TOKYO'S HISTORY, GEOGRAPHY, AND POPULATION. http://www.metro.tokyo.jp/ENGLISH/ABOUT/HISTORY/history03.htm [accessed on 2nd Oct 2018]
4. Korean Statistic Information Service. 2018. Statistical Database. http://kosis.kr/eng/statisticsList/statisticsList_01List.jsp?vwcd=MT_ETITLE&parmTabId=M_01_01 https://en.wikipedia.org/wiki/List_of_urban_areas_by_population [accessed on 2nd Oct 2018]
5. The social and economic developments of Hong Kong. 2017. Hong Kong Annual Digest of Statistics. https://www.censtatd.gov.hk/hkstat/sub/sp50.jsp?productCode=B1010003 [accessed on 2nd Oct 2018]
6. Bureau of Statistic of each city in China. 2017. Statistic yearbook.
7. Ministry of Housing and Urban-Rural Development of the People's Republic of China. 2017. Statistical yearbook of China's urban construction

8. The rank of China’s tier 2 cities based on Sohu Online. 2018. The latest 2018 ranking of Chinese cities, 108 cities compete for their places in tier 1 to 3 category http://www.sohu.com/a/217314861_100028279 [accessed on 2nd Oct 2018]

Table 4.5 Comparison of population density among cities (suburban areas)

		Suburban Area (km^2)	**Suburban Population**	**Suburban Density (persons /km^2)**
Asian countries	**Singapore**[1,2]	---	---	---
	Tokyo[1,3]	12936	26672669	2062
	Seoul[1,4]	11214	14094401	1257
China's tier 1 cities[8]	**Hong Kong**[1,5]	---	---	---
	Beijing[6,7]	---	---	---
	Shanghai[6,7]	---	---	---
	Guangzhou[6,7]	5335	4253600	797
	Shenzhen[6,7]	---	---	---
China's current tier 2 and future tier 1 cities[8]	**Tianjin**[6,7]	9334	6220300	666
	Nanjing[6,7]	2361	1998000	846
	Chongqing[6,7]	35825	15954300	445
	Chengdu[6,7]	3048	9016500	2958
	Wuhan[6,7]	7117	3708700	521
	Hangzhou[6,7]	15111	3558900	236
	Qingdao[6,7]	8988	4787800	533
	Suzhou[6,7]	7133	7525100	1055
	Xi'an[6,7]	9555	4471800	468
	Shenyang[6,7]	9288	2929900	315
	Zhengzhou[6,7]	5642	3759500	666
	Ningbo[6,7]	8720	5004300	574
European countries	**Paris**[1]	11907	9542401	801
	London[1]	25617	12090823	472
USA	**New York**[1]	16535	10721976	648

Note: 1. Suburban Area = Metropolitan area – Central city area in Table 4.4
2. Suburban Population = Metropolitan Population – Central city Population in Table 4.4
3. Suburban Density = Suburban Population / Suburban Area

To sum up, the density of the prototype in this research has two criteria:

- The plot ratio of townhouses should achieve 1.0 or higher within the community to save the land
- The townhouses formed community needs to aim for more than 1000 people/km^2 residential density. In the meantime, the land use of housing construction should comply with China’s planning regulations.

4.3.2.3 Form

Under '*Form*' sub-set of the DOE's reference building methodology (as shown in Figure 4.16), only '*Total floor area*', '*Number of floors*' and '*Floor height*' are the relevant features at the national level. All the other three features need a project's specific conditions to clarify.

In terms of '*Total floor area*', the review in Chapter 2 shows that the highest demand for housing is 90-120 m^2. However, as China cancelled its single child policy and needs room for more children, the needed accommodation area is expected to grow for future households. Moreover, China is quickly ageing, but the public old care facilities are not building at the same rate. Such mismatch increases the possibility of multi-generation living in a single-family for elderly care. With the expected population structure of China, in this research, the targeted household number per family is set as 3 to 6. A three-person family is seen as a newly married couple with one kid, while a six-person family is seen as the three generations living together with two kids. These families are more likely to be the main occupants for the suburban townhouses in China. Therefore, the floor areas aiming for such families expect to be larger than 90-120 m^2.

According to the recently launched *Urban Residential District Planning and Design Standards* in China (GB50180-2018), the maximal allowable floor area per person for low-rise (1-3 floors) housing is 36 m^2. Hence, 3 – 6 person family could occupy 108 – 216 m^2 floor areas. It also required that site coverage of low-rise residential area must be no more than 35%, with a plot ratio over 1.0. In such a case, bungalows are not suitable for the townhouse form, while 2 – 3 floors terraced or court form houses would be better for the 108 – 216 m^2 floor areas.

The given '*18 m*' height limitation of low-rise housing in this Standard gives plenty of space for the building height, which can be directly referenced.

To sum up, the three criteria of the prototype's form in this research are:

- Total floor area: 108 – 216 m^2
- Number of floors: 2 – 3
- Roof height: not exceed 18m in total

4.3.2.4 Envelope

The features of '*Envelope*' sub-set closely link to the local climate and comfort level required. In China, there have been codes at the regional level to regulate the design parameters. Moreover, the *Technical Standard for Nearly Zero Energy Building* in China summarises the relevant design parameters based on existing design codes. Therefore, for this research, China's existing technical standard can be directly referenced.

4.3.2.5 System

The features of '*System*' sub-set has been thoroughly explained in the *Technical Standard for Nearly Zero Energy Building* in China too. However, there is one disagreement between this research and the suggested system composition of this Standard (Table 4.6), which is that the Severe Cold and Cold regions only apply Coal-fired boiler as the heat source.

The system design suggested by China's NZE building standard based on the default reference building for housing, which is a high-rise slab-type apartment. For such type of residential buildings in the Severe cold and Cold region of China, district or community central heating is the primary service system for heating and domestic hot water. In such a case, coal-fired boilers is most affordable and technically viable in China to be used as the heat resource.

Table 4.6 The reference building's heating and cooling system composition of China's NZE building standard

Building type		**Severe cold region**	**Cold region**	**Hot summer and cold winter region**	**Hot summer and warm winter region**	**Temperate region**
Residential buildings	**End plant**	Radiators for heating, Air conditioning for cooling	Radiators for heating, Air conditioning for cooling	Air conditioning for both	Air conditioning for both	Air conditioning for both
	Cool resource	Split air-conditioner	Split air-conditioner	Split air-conditioner	Split air-conditioner	Split air-conditioner
	Heat resource	Coal-fired boiler	Coal-fired boiler	Air-source heat pump	Air-source heat pump	Air-source heat pump

Note: translated by the author from *Technical Standard for Nearly Zero Energy Building's Table* A.3.1-2

However, even though townhouse communities can follow the same route of heating and hot water services as slab-type apartments, they have much more choices of localised heat resources. When the NZE townhouse brings heating and hot water demand to a minimal level, heat pumps become a feasible solution in the Severe cold and Cold regions. The research done in Denmark demonstrated the case (Häkämies et al. 2015). Denmark has the winter outdoor temperature of -10 C° or even lower, and long heating season (September to April). Even under such conditions, ground- and air-source heat pump proved to be economically sound for the NZE residential buildings (house or apartment) (Häkämies et al. 2015). Among all the heat pump system concepts, ground-source heat pump (GSHP) integrating with on-site renewable energy generations calculated as the most cost-effective solution for all the studied buildings (Häkämies et al. 2015). For the air-source heat pump systems, the air-to-water system performed better than air-to-air and then exhaust air system (Häkämies et al. 2015).

Therefore, based on the above facts and existing research results, this research re-defines the prototype's heating and cooling system components. It integrated heating, cooling and domestic hot water within one heat pump system for the townhouse form. It also extends the application of heat pump system concept from air-to-air heating or cooling to other possible composition (e.g. air-to-water systems, ventilation integrated exhaust air system, renewable energy integrated multi-services system).

Table 4.7 The suggested heating, cooling and domestic hot water system composition of the prototype in this research

Building type		**Severe cold region**	**Cold region**	**Hot summer and cold winter region**	**Hot summer and warm winter region**	**Temperate region**
Affordable NZE townhouse	**End plant**	Radiant and/or convective exchanger	Radiant and/or convective exchanger	Radiant and/or convective exchanger	Radiant and/or convective exchanger	Radiant and/or convective exchanger
	Domestic hot water	Heat pump integrated or separately heated	Heat pump integrated or separately heated	Heat pump integrated or separately heated	Heat pump integrated	Heat pump integrated
	Cool and Heat resource	Ground- or air-source heat pump	Ground- or air-source heat pump	Air-source heat pump	Air-source heat pump	Air-source heat pump

4.3.2.6 Operation

Among the six features of DOE's '*Operation*' sub-set (see Figure 4.16), only '*Ventilation needs*' is necessary to be specified at the national level. All the other five features have significant variations due to local climates and specific project conditions. In the *Technical Standard for Nearly Zero Energy Building*, the requirement of air change rate at 50Pa is ≤0.6 change/hour for Severe cold and Cold regions and ≤1.0 change/ hour for other three climate regions. In such a case, it needs mechanical ventilation with heat recovery for the Severe cold and Cold regions. The reason is that such an airtightness level makes the infiltration not sufficient to satisfy the indoor air quality requirements. For other regions, mechanical ventilation is not a 'must-have' feature if only considering the oxygen level. However, as pointed out by the Standard, both indoor and outdoor air pollutions are prevalent in China. Especially in recent years, smog pollution is a big problem all over China and last for a long time during a year. The chemical pollution coming from interior furnishing is also worrying. Therefore, in order to promote a high quality of living in the future, the ventilation needs of the prototype in this research is concluded as in Table 4.8.

Table 4.8 Ventilation requirement of the prototype

	Severe cold region	**Cold region**	**Hot summer and cold winter region**	**Hot summer and warm winter region**	**Temperate region**
Air change rate at 50Pa	≤0.6 air change per hour		≤1.0 air change per hour		
Ventilation to satisfy the needs	Mechanical ventilation with heat recovery in the heating and cooling season, as well as smoggy days. Natural ventilation in other situations			Mainly natural ventilation. Mechanical ventilation for air purification.	

4.3.3 Summary: the prototype developed in this research

In section 4.3, this research thoroughly discussed the types of prototype, the relationship between prototype and reference building, as well as the features to formulate the national level reference building. Based on the above contents, Table 4.9 summarises the prototype for the affordable NZE townhouse concept at the national level.

Table 4.9 The sub-sets and critical features of the prototype (example reference building) for the affordable NZE townhouse concept

Sub-sets and key features		Severe cold region	Cold region	Hot summer and cold winter region	Hot summer and warm winter region	Temperate region
Location		within 30 km in the radius of tier 2 to 4 cities' centres in China costs people no more than 1 hour private or public one-way pass commuting time daily in the 400 kWh/m^{2}yr or above mean distribution of direct solar radiation zones				
Density		The plot ratio of townhouses should achieve 1.0 or higher within the community to save the land The townhouses formed community needs to aim for more than 1000 people/km^2 residential density. And the land use of housing construction should comply with China's planning regulations				
Form		Total floor area: 108 – 216 m^2 Number of floors: 2 – 3 Floor height: not exceed 18m in total				
Envelope		Directly reference the *Technical Standard for Nearly Zero Energy Building*. For other design parameters not mentioned in this standard, it follows the design codes for residential buildings in each region.				
System	**End plant**	Radiant and/or convected exchanger	Radiant and/or convected exchanger	Radiant and/or convected exchanger	Radiant and/or convected exchanger	Radiant and/or convected exchanger
	Domestic hot water	Heat pump integrated or separately heated	Heat pump integrated or separately heated	Heat pump integrated or separately heated	Heat pump integrated	Heat pump integrated
System	**Cool and Heat resource**	Ground- or air-source heat pump	Ground- or air-source heat pump	Air-source heat pump	Air-source heat pump	Air-source heat pump
	Others	Comply with the *Technical Standard for Nearly Zero Energy Building*				
Operation	**Air change rate at 50Pa**	≤0.6 air change per hour		≤1.0 air change per hour		
	Ventilation mode	Mechanical ventilation with heat recovery in the heating and cooling season, as well as smoggy days. Natural ventilation in other situations			Mainly natural ventilation. Mechanical ventilation for air purification.	
	Others	Comply with the *Technical Standard for Nearly Zero Energy Building*				
Overall energy and environmental performances		1. Comply with the *Technical Standard for Nearly Zero Energy Building* 2. Meet the regulated energy uses (heating, domestic hot water, cooling, ventilation and lighting converted by system efficiencies) all by renewable energies generated on-site and within the community. The utilisable renewable energies comply with the definitions given in the *Technical Standard for Nearly Zero Energy Building*				

4.4 The conceptual design framework of affordable NZE townhouse

The existing research shows that in order to achieve NZE performance cost-effectively, the design needs to follow specific procedures. Moreover, a conceptual design framework would be helpful to enable the integration of design features and enhance coordination among designers from different disciplines. Therefore, besides defining the affordable NZE townhouse concept and establishing its prototype at the national level, this research also draws a conceptual design framework to help guide the design.

4.4.1 The design process

In China's *Technical Standard for Nearly Zero Energy Building*, the design process to achieve NZE performances summarises as:

1. Maximise the demand reduction through passive methods
2. Maximise the efficiency of energy transfer plants and system
3. Utilise renewable energies
4. Optimise the operation of the whole energy system

Such a process is classic in developed countries at their early development stage of NZE buildings (as shown in Figure 4.23).

Figure 4.23 Hierarchical design strategy for NZE buildings(Wells et al. 2018)

However, after practising for more than a decade in developed countries, the design of NZE buildings has been evolved to the '*4G generation*' (as shown in Figure 4.24).

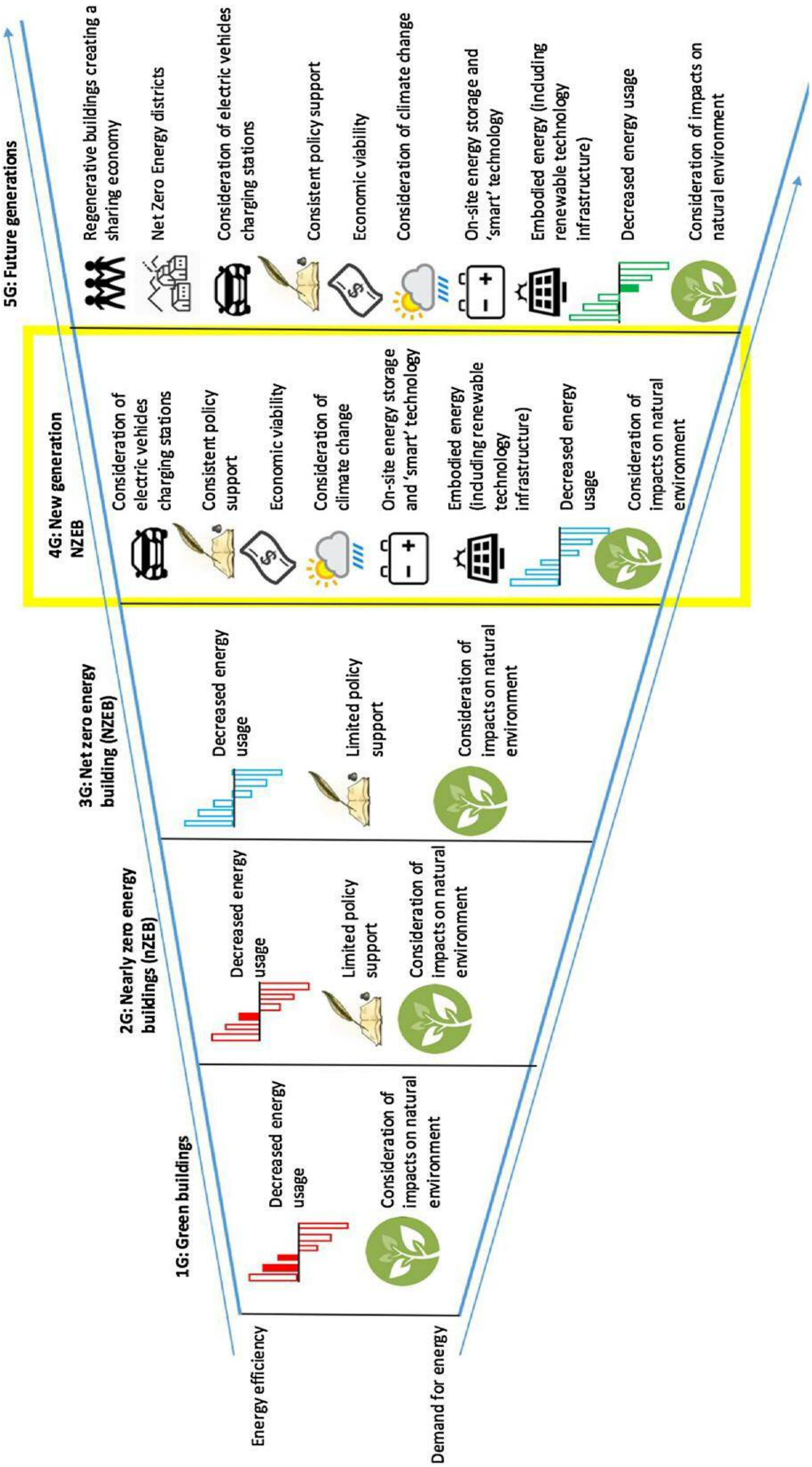


Figure 4.24 One interpretation of NZE buildings generations (Wells et al. 2018)

Note: The figure was designed by the first author using open source clipart

Comparing China's design approach with the '*4G generation*' design features, some key elements are missing:

- Energy storage (both electric and thermal)
- System flexibility for possible future climate change
- Interactions between buildings and transport (electric vehicle charging)
- System-envelope integration to further reduce costs and embedded energy

In the most recent work, (D'Agostino and Parker 2018)**04-028** drew a framework for the cost-optimal design of NZE buildings in representative climates across Europe (Figure 4.25).

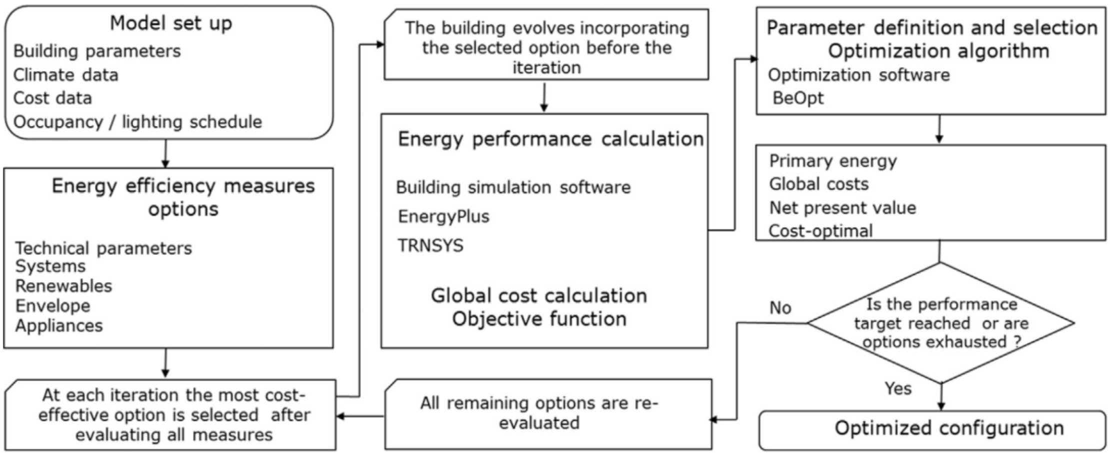


Figure 4.25 The methodological approach of designing cost-optimal NZE buildings
(D'Agostino and Parker 2018)

The advantage of this framework is that it takes the building, climate, costs, and occupancy issues into consideration at the model set up (conceptual design) stage. Then, all the energy efficiency measure options are specified immediately. Therefore, after setting up such a model, designers could concentrate on iterating the specific alternatives until the performance target achieved within the available budget. Alternatively, if all the options are exhausted, the designers can be assured that the proposed strategy would not work, so that they can come back to the beginning for a new strategy. Moreover, because of the previous tests results, the designer can quickly identify the problematic areas and concentrate on solving these problems in the new strategy. Therefore, this research adopts such a methodological approach for the multi-benefits.

The disadvantage of (D’Agostino and Parker 2018) approach, however, is that it does not visualise the systematic links among the design features of such a model. For example, it does not show the energy flow between systems and physical elements (e.g. spaces and envelopes). Also, through this schematic, designers cannot quickly identify the integrating points between buildings’ envelopes and systems. On this aspect, Ascione et al.’s schematic formed in their research (Ascione et al. 2016) on designing a net-zero-energy building in Germany has its advantage (Figure 4.26).

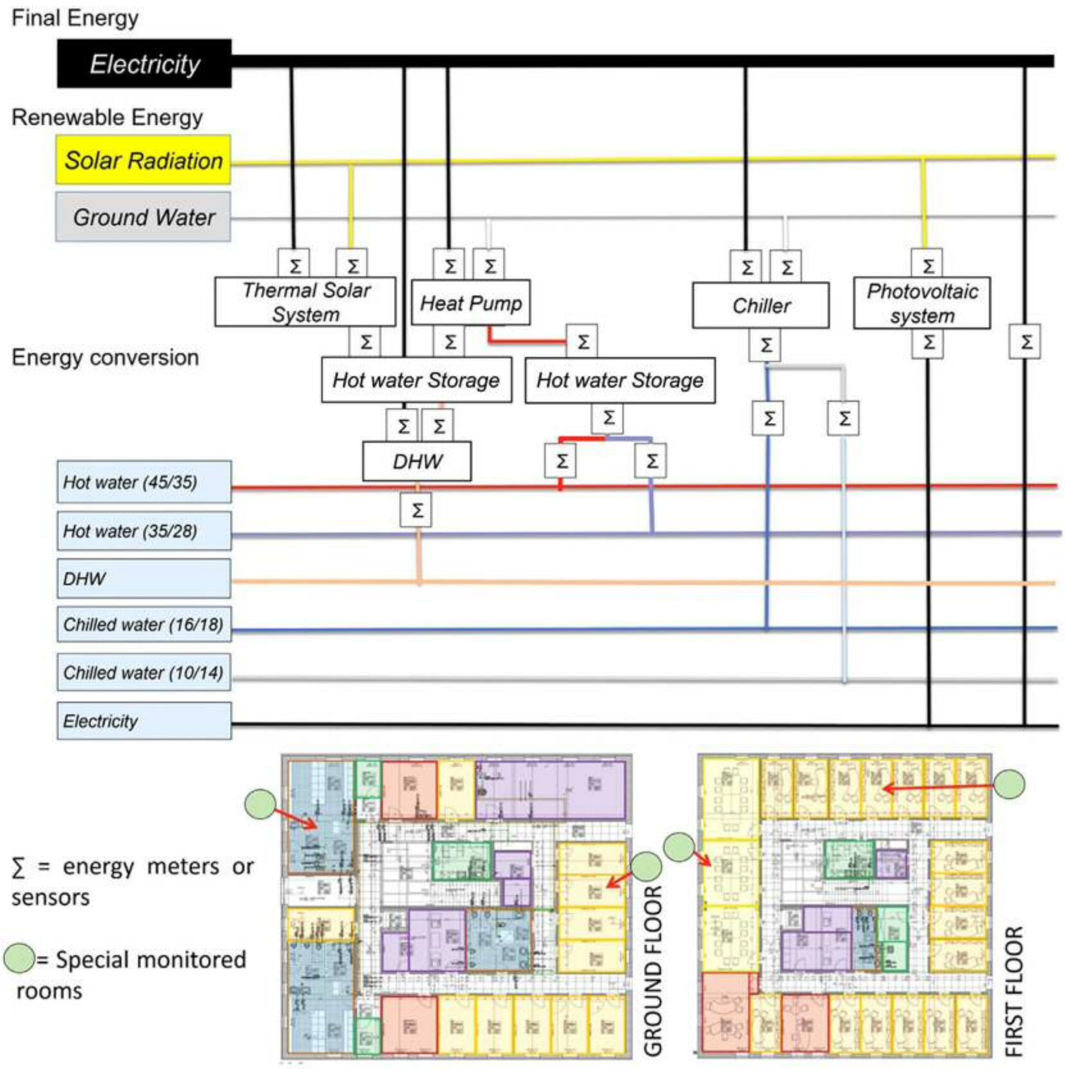


Figure 4.26 Schematic diagram of energy systems and monitoring apparatus for a design of Net zero-energy buildings in Germany (Ascione et al. 2016)

In the schematic drawn by Ascione et al. (2016), the types of energy and their transferring routes are laid out in layers. The relationship between distributed energies and the building's physical spaces are easily spotted out. Such schematic can make the monitoring work for post-occupancy evaluation much more manageable. Through such a schematic, even if the initial designers do not carry out post-occupancy evaluation, people who come later to check the performances can still understand the design strategy and integration easily.

The problem of Ascione et al.'s (2016) schematic, though, is that it needs very much detailed information for the building and its system. Unfortunately, the majority of them are not yet available in the conceptual design stage. For instance, at the conceptual design stage, the internal partitions of a building might not even be considered. Again, the appropriate system can only be roughly proposed based on the local climate and building form, and designers would not decide its specific locations and relationships with the building until the design development stage.

Therefore, learning from the above research, in this research, the conceptual design framework is formulated as in Figure 4.27. The design features and energy flow are further generalised and distilled to avoid the demand for information in much detail. The sub-sets also laid out in an order which designers can follow for the logic tests of performances.

If the designers follow the guidance of such a schematic in Figure 4.27, it expects that they can design a '*4G generation*' NZE housing. The 'design conditions' feature highlights the costs and climate issues, which can be thoroughly discussed by the stakeholders from the beginning. Then, a supply, storage and demand balance would be set up at the conceptual design stage when energy storage embeds in the 'technologies' feature. Also, the electric car is included in the 'integrated components' rather than 'technologies' features, because it does not belong to any particular building services system but can function as electricity storage. When all the physical elements of the house are listed, it is easy to identify their links with building services systems.

Furthermore, even though performances would drive the majority design of NZE housing (top-down process), there are exceptional cases in which the design should guarantee occupants' special needs first. For example, care homes for elderly or disabled people have many special needs in the space to ensure safety and wellbeing. In these cases, a bottom-up process of design might need to be followed, which can be enabled by this schematic as well.

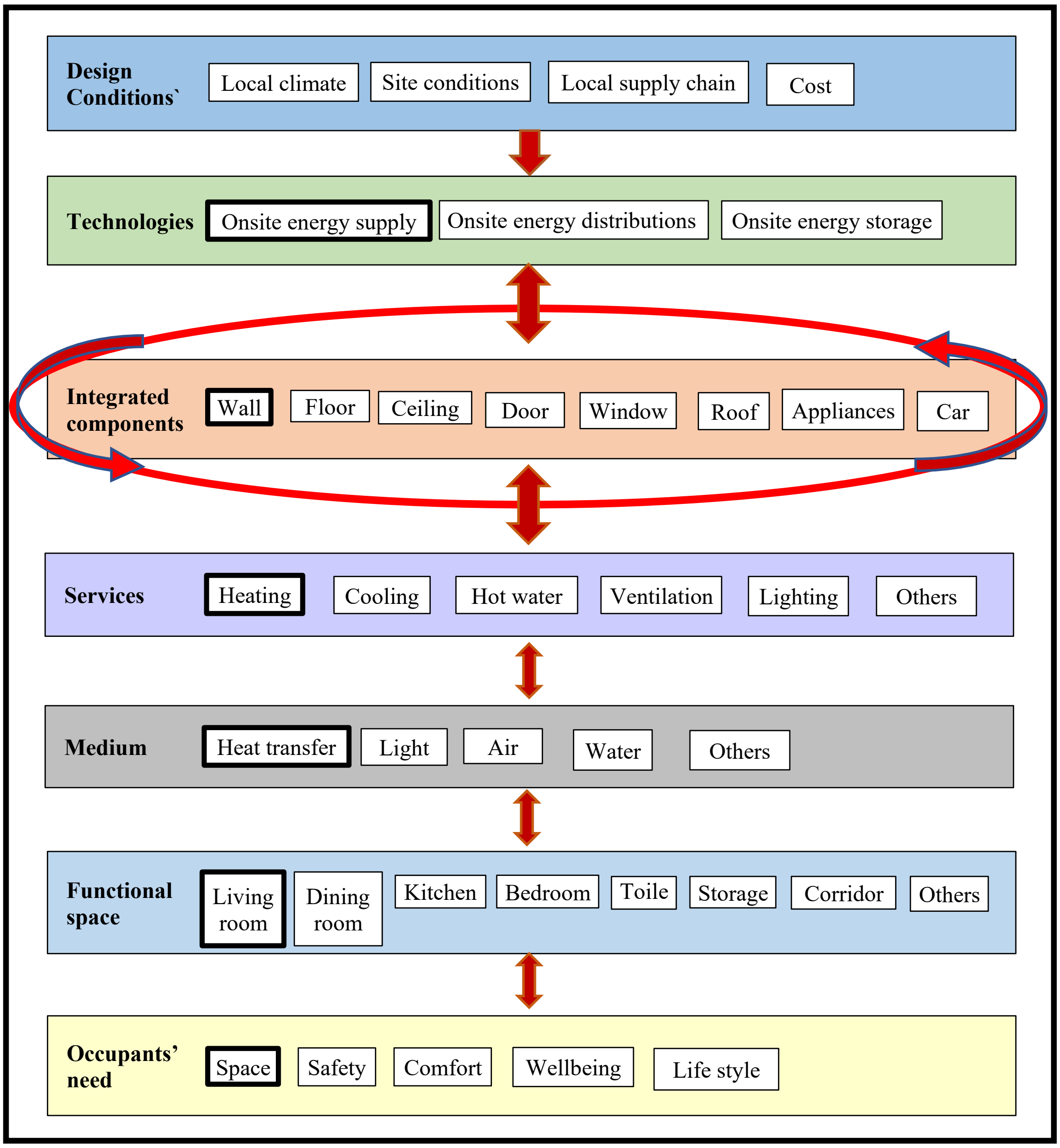


Figure 4.27 The basic schematic of designing the affordable NZE townhouses

Last but not least, this schematic highlights the trade-off among integrated components to address the critical areas of integrating design. For the majority of cases, the adjustments of these components could achieve the final optimisation of performance, costs and fabric-systems integration.

4.4.2 The strategy of integrating low-carbon technologies for the affordable NZE townhouse

The conceptual design framework developed in this research does not just stop at the level of Figure 4.26. It also pre-set some features based on the prototype formulated in this research, which will further help the designers to avoid additional considerations of irrelevant strategies.

Domestic heating, cooling and hot water take about 65% of total energy consumption in residential buildings in China (NHBC Foundation 2011). The proportion will be higher in the future, due to the comfort requirements have been increasing quickly in China. This part of energy consumption contributes significantly to greenhouse gas emissions because the energy used is mainly from fossil fuels. Electrification of these three systems through a heat pump multi-services system, and then decarbonisation of the electricity by building integrated renewable power generation, will help to reduce CO2e emissions significantly.

In the past five years, utilising the renewable electricity generated on-site and shifting electric load from on-peak to off-peak hours by local storage has become a multi-benefit strategy (Arteconi et al. 2013; Liu et al. 2017a; Zhang et al. 2017). It reduces CO_{2e} emissions, enhances grid safety, and brings economic gains to residents. HP air-to-water system has an advantage over the air-to-air system to implement such a strategy. Its heat media – water – has a higher thermal capacity. Therefore, it can store more heat in the media and hold it for more prolonged use in the end plant.

Moreover, they can embed with building envelopes to extend the storage capacity, which makes the building fabrics thermally active. Such Thermally Activated Building Systems (TABS) have proved to be energy efficient (Park et al. 2014; Schmelas et al. 2017; Shen and Li 2017), environmentally friendly (Xu et al. 2017), cost-effective (Schmelas et al. 2017) and thermally comfortable (Park et al. 2014; Shen and Li 2016). Thus, in this research, battery storage for electricity is excluded, given its cost, end of life environment impacts, and the fact that electric car has been on board in the integration strategy.

However, the previous studies on the TABS were more from the heat transfer and envelope's heat storage capability point of view (Ma et al. 2015; Navarro et al. 2016). There are rare cases on investigating the applications of 'HPs + TABS + Renewable Energy' in residential buildings. The few existing research either do not see onsite renewable electricity generation as a cost-effective way of CO_{2e} emissions reduction (Xu et al. 2010), or they do not investigate the capital cost-saving potential as thoroughly as operational cost savings (Rodrígueza et al. 2018; Romaní et al. 2018). As Navarro et al. stated (2016) *'Although current TES (Thermal Energy Storage) technologies developed by researchers demonstrate significant potential, there is a lack of knowledge concerning their functional and architectural building integration.'*

Despite the limited existing research on the 'HP multi-services system + TABS + onsite renewable electricity' integration, the existing research shows the immense potential of such system to play an essential role in the future housing sector. Especially for the townhouses, its building form has significant advantages to deploy such an integration strategy.

Therefore, in the prototype developed in the research, heat pumps are assigned as both the heat and coolth resource for the services system. The conceptual design framework pre-sets the relevant technology features accordingly to focus on developing a detailed strategy based on such integration concept.

4.4.3 Summary: the conceptual design framework formulated in this research

This section distilled the conventional design process for affordable NZE buildings by reviewing the existing literature of both China and other countries. It discussed the advantages and disadvantages of existing schematics for conceptual design. Based on these contents, it structured the basic schematic for the conceptual design of the affordable NZE townhouses. However, the basic schematic has not yet taken the integration of low-carbon housing technologies into account. Therefore, this section carried on to analyse the appropriate technologies integration strategy for the prototype of this research. Based on the proposed design process, as well as the integration strategy of building services systems, the final conceptual design framework is presented as in Figure 4.28.

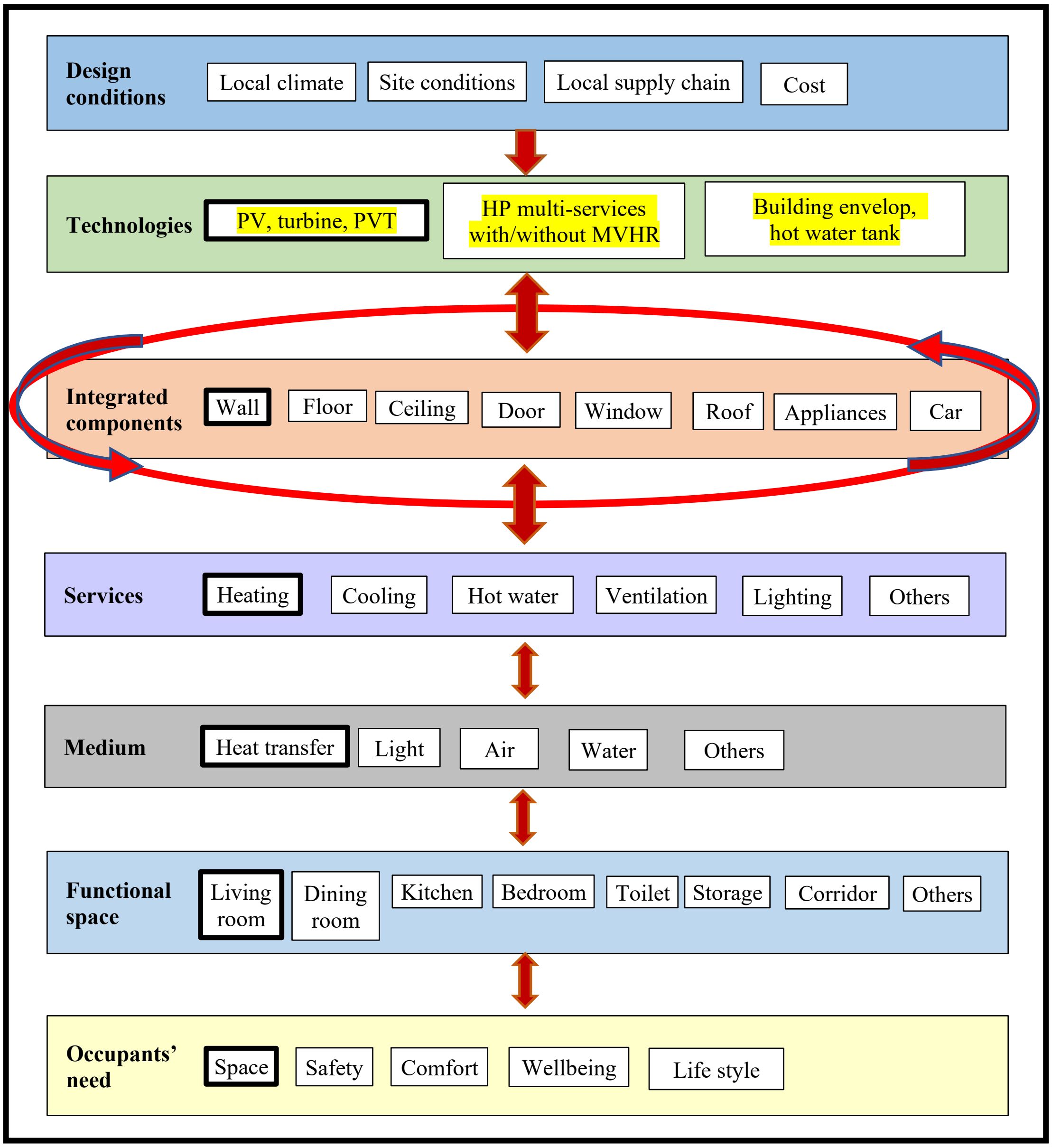


Figure 4.28 The developed schematic of designing the affordable NZE townhouses

Chapter 5

Applicability validation – using the prototype to formulate a reference (baseline) building for a real project

5.1 Introduction

The focus of this chapter is to identify a suitable case study project to implement the prototype of this research. Through the case study project, the prototype's applicability is validated, in terms of whether or not it could help to formulate a detailed reference (baseline) building for a specific project.

Section 5.2 explains the process of identifying suitable cities for the affordable NZE townhouses concept. Such a filtering process can find out whether the prototype would only apply in a particular area, or it has a wide range of applications in China.

Section 5.3 presents the case study project in sub-urban area of Xi'an. It not only explains the suitability of such a case but also provides the background information for the formulation of the specific reference (baseline) building.

Section 5.4 illustrates how to add detailed information on top of the notional prototype at the national level and how to formulate the real-case reference (baseline) building.

Section 5.5 explains how to integrate the detailed design of specific building components into one holistic strategy and how the conceptual design framework helps to guide the detail design process.

Section 5.6 concludes in what range and under what conditions the prototype can apply in a specific project.

5.2 The suitable cities for the affordable NZE townhouse in China

Based on reviewing and analysing the existing standards and literature of both in China and other countries, this research established the prototype at the national level. Therefore, it needs to validate whether such a hypothetic example building can develop to a real-case reference building in practice. The following criteria further define the conditions under the 'location' and 'density' sub-sets.

- **Within 30 km in a radius of tier 2 to 4 cities' centres in China (Condition 1 under the 'location' sub-set of the prototype)**

  Comparing with the major metropolitan areas in the world (such as Tokyo, Seoul, Paris, London and New York, as analysed in 4.3.2), 30 km radius is not a significant dimension for sub-urban housing. However, section 4.3.2 explained that so far China's tier 1 cities only developed sub-urban housing to 30 km radius for the daily commuting. Moreover, in section 4.3.2, it also explained that the administrative borderline is a unique situation in China, which largely restrains the land supply and infrastructure constructions to a distance within 30 km. Furthermore, in Chapter 2, the literature reviews show that some already established big cities in China have experienced a net population decrease in the past five years. China's demographic data and population projection also show quicker and more profound population reduction in the coming 50 years. Therefore, this condition has three hidden criteria:

  - The suitable city should expect a considerable population increase in the future, or else they would not need to stretch new housing to its sub-urban area
  - The suitable city should have sufficient sub-urban land for new housing construction within its administrative borderline
  - The suitable city should have an established and active metropolitan area, in order to provide enough jobs and business opportunities for decent livelihoods to the current and future population

It is important to note here the tier 1 cities, which are all municipalities, are compared to other provinces rather than cities. There are three reasons for such ‘inconsistency’ of scale:

1) China’s municipalities have equal executive power as provinces, so it is fairer to compare the municipalities with other provinces
2) In China, the cities’ borderlines within a province changed now and then by the central government. Therefore, even in the future, some of the cities change their borderlines, as long as they are still in the same province, the filtering results would not be changed fundamentally.
3) China is still in the middle stage of urbanisation, and many of its tier 2 to 4 cities are still very young. Applying these criteria on the unmatured cities at this stage would underestimate their full potential in the future.

- **Costs people no more than 1 hour private or public one-way pass commuting time daily (Condition 2 under the ‘location’ sub-set of the prototype)**

For the famous metropolitan areas in the world, underground commuting plays the critical role of low-carbon sub-urban transport. Such a phenomenon also exists in China. Moreover, as analysed in section 4.3.2, the most frequent underground commuting time in Beijing is 45 minutes of one-way pass. If adding up the commuting time between home and station, 1-hour commuting distance between accommodation and work perceived as convenient to the majority of people in Beijing. This commuting distance also helps to stretch Beijing’s residential areas even further to its nearby province Hebei for a larger metropolitan area.

In China, so far only tier 1 and some of the tier 2 cities have underground transport. Other smaller cities even have not yet developed a convenient public bus system. Foreseeably, the proposed affordable NZE townhouse would not be cheap enough at the beginning to compete with currently affordable housing. Existing experiences gained in developed countries show that it takes a while for the new low-carbon technologies to get their costs competitive to the traditional ones. In such a case, the existing public transport system needs to be convenient and cheap enough for the residents to make a trade-off for the affordability to live in suburban areas. It is good to have an underground or light railway transport system. However, the cost of building up such infrastructure is enormous. Therefore, there is also a hidden criterion for this condition:

- The suitable city is better to have an established (including under construction) underground or light railway transport system. Otherwise, it should have established renewable energy sourced public transport system

It is also important to acknowledge that renewable energy sourced public transport system is also forward-looking for future cities. Currently, even the five major cities in the world (Tokyo, Seoul, Paris, London and New York) have not yet established such systems in their metropolitan transportation. Therefore, in this research, only underground or light railway transport system is set up as the filtering rules to identify the suitable cities in China.

- **The townhouses formed community needs to aim for more than 1000 people/km^2 residential density (Condition under the 'density' sub-sets of the prototype)**

For all the analysed major metropolitan areas in the world, they not only achieved high density in the suburban area but more importantly, a very high density in the city centre. As shown in Table 4.4, in the five major cities (Tokyo, Seoul, Paris, London, and New York), there is a range of 5200 to 21370 people/km^2 in the city centres and 745 to 7799 people/km^2 in the metropolitan areas. China's cities have not yet urbanised to such level. Therefore, before targeting more than 1000 people/km^2 residential density in the suburban area, it is more critical to achieve high density in its city centre. Only with this condition, the cities can guarantee the efficiency of infrastructure and livelihood. Therefore, the criterion for this condition is:

- The suitable provinces and cities should already have had a density of more than 1000 people/km^2 in its city centre, and its existing central density needs to be at least 3.6 times higher than its metropolitan density (see Appendix 2 for detailed calculations).

The rule for filtering out the suitable provinces and cities under this criterion is slightly different. For the provinces, the rule for its metropolitan density is set as 350-1000 people/km^2. This range is to find out those metropolitan areas which have passed their primary urbanisation stage but still have plenty of space for future townhouse development in the suburban areas. For the cities, there is no such rule applied, because not applying such a rule when choosing cities will allow flexibility for their future development - A province's current capital city is more likely to be the future metropolitan centre. Its surrounding smaller cities and towns might merge into the capital cities in the future as the suburban areas. Such a phenomenon has happened in China in many provinces.

When applying the above conditions to identify the suitable cities, this research intensively reviewed China's statistic data at the national and the province level. Appendix 2 explains specific filtering rules and results of suitable cities.

Among the 31 listed provinces and municipalities in China's Urban Construction Statistic Yearbook, there are 12 provinces identified as suitable. However, all the cities in Sichuan province are rejected by rules at the city scale, due to their availability of solar resources. Therefore, 11 provinces are currently suitable for the conditions set up in this research, which is 35.5% of the administrative regions in China (Table A1-1).

Among 11 selected provinces, there are 34 cities identified as satisfied for the majority of the criteria (Table A1-2), except the one '1-hour commuting time by convenient public transport'. Table A1-2 shows that public transportation is the main obstacle for the development of affordable NZE townhouse in the sub-urban areas. However, there are still four other cities identified fully ready to implement the affordable NZE townhouse concept now.

The four cities identified fully ready are: Xi'an from Shaanxi Province, Wuhan from Hubei Province, Nanchang from Jiangxi Province, and Nanning from Guangxi Province. It seems a coincidence that all these four cities are tier 2 cities and they are all capital city for its province. However, it reflects China's urbanisation and economic status at the moment. The data summarised in Table A1-2 show that many municipalities and economically active provinces have either experienced population reduction or have insufficient suburban land for future suburban housing development. On the contrary, all the tier 3 and 4 cities either have not fully urbanised to a dense city centre yet or are stuck by the public transport system to support convenient daily sub-urban commuting.

However, China is constructing the most substantial amount of underground or light rail infrastructure in the world and is still planning more shortly. Therefore, it is confident that there will be more cities suitable for the affordable NZE townhouse soon. Moreover, affordable NZE townhouse is not just a dwelling; it is also part of the low-carbon energy infrastructure. Thus, they can be developed together with the renewable electricity-powered bus system. Such an advantage will benefit more cities which cannot afford to construct the underground transport system. Especially, those tier 3 and 4 cities within or near the 1-hour commuting distance from the tier 1 and 2 cities have an enormous potential to promote such integrated low-carbon housing-transport system.

The 38 cities are all distributed on the right side of the Population Density Demarcation Line (Hu Huanyong-Line), which reflects China's urbanisation and geographic status (Figure A1-1). Among these 38 cities, 20 are within the 400-500 kWh/m^2 annual mean distribution of direct solar radiation zone, and others are in the 500-800 kWh/m^2 zones (Figure A1-1). Therefore, there has been a reasonable solar resource for these cities to develop on-site renewable generations. In terms of climate zones, 5 of them are in Cold climate zone, 3 of them are in the Temperate climate zone, 7 of them are in the Hot Summer and Warm Winter climate zone, and 23 of them are in the Hot Summer and Cold Winter climate zone (Figure A1-2). All these climate zones can apply air-source heat pump systems, which has fewer concerns for the HP systems' capital cost.

5.3 The project identified in the suburban area of Xi'an

Among the four fully ready cities, the developers who have projects in Wuhan and Xi'an were contacted, in order to find the opportunity for the real project case study. These developers are either Welsh School of Architecture's previous project partners or contacted through the school's alumni. Among all the feedbacks, there was one project identified as suitable. It had obtained its planning permit then, which means many sites and form conditions can not be changed. However, after reviewing the documents provided by the developer, it is believed that there is still a significant potential for this project to implement the affordable NZE townhouse concept. Therefore, Xi'an is chosen as the demonstrating city in this research for validating the applicability of the prototype and conceptual design framework.

The data in Table A2-1 and Table A2-2 of Appendix 2 have explained why Xi’an is suitable as a city to implement the prototype. Therefore, the following contents explain the local conditions for the formulation of a real-case reference (baseline) building on top of the national level hypothetic prototype.

5.3.1 Location

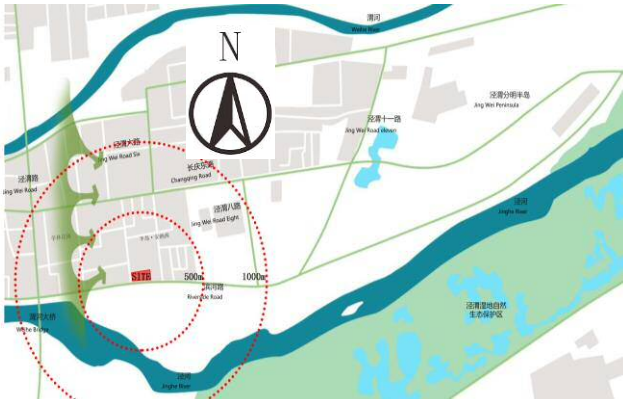
The project locates within Gaoling District, which is the north sub-urban area of Xi’an (Figure A2 - 1). Currently, there has been no underground or light rail near the site, but in the already released plan, there will be line 10 (underground) and line 22 (light rail) nearby (Figure A2 - 2). There are currently four bus lines running on 20 mins intervals between 6:30 – 19:30, which have bus stops being very close to the site. However, it takes more than an hour to travel on bus if someone wants to go to either the centre of Xi’an city or Gaoling district centre. Therefore, the occupants living in this community would have to rely on the private car in the short term. It would take the car journey 55 mins to go to Xi’an city centre and 35 mins to Gaoling district centre. Appendix 3 summarises the detailed information against the criteria and rules for each condition under ‘location’ sub-set (Table A3-1).

The site is near to the Chanba National Wetland Park, therefore, benefits from the beneficial local microclimate and is suitable for many passive design strategies. It has convenient access to wind and solar resources, and on the south of the site, there is considerable open space towards the main road near a riverbank (Figure 5.1).

The mid-terraced house in the most southerly row (highlighted in the red rectangle in Figure 5.1) adopted the prototype formulated in this research. Before the project was chosen as the studied case, its planning permit has been issued based on the local team’s conceptual design. The planning permit prohibits any alteration to the house’s orientation, form, shape, height, and external layout.

The weather data analysis shows that the local site is suitable for PV and solar thermal installation. The wind resource is not ideal in general, so whether or not to install a micro wind turbine has to be decided when finalising the demand-side data. Table 5.1 summarises the local feed-in-tariff rate. Based on the local policy and site conditions, it was decided that the strategy for renewable energy generation system is ‘self-use mainly + export to the grid if leftover’.

(a) Location of Xi'an city



(b) Surrounding environment of the site

(c) Location of the house (red dot) in the project

Figure 5.1 Brief information about the completed house

Note: 1. The image of (a) is from https://www.chinadiscovery.com/xian-tours/maps.html#lg=1&slide=0

2. The images of (b) and (c) are from Xiaoyuan Technology

Table 5.1. Feed-in-tariff of renewable electricity in Xi'an (Unit: Yuan RMB)

Feed-in-tariff policy	Self-use	Export to the grid if leftover	Wholly export
Basic cost saving	0.4983 for the first 180 kWh per month, 0.5483 for the 181 – 350 kWh per month, and 0.7483 for 351 and above	0.3346	0
Feed-in-tariff	0.42	0.42	0.85
Total cost benefit	0.9183 – 1.1683	0.7546	0.85

Source: the Xi'an Development and Reform Commission (2015)

Note: This was the tariff when the project was at the design development stage in 2017. It has changed since August 2018. The new policy makes self-use even more beneficial, so the strategy used in the case study is still suitable after the policy change.

5.3.2 Density

As explained in Chapter 4, residential density is not just about the total occupants and the land used for their housing. The land used for infrastructure and public facilities (such as road, utility hub, greenfield, wetland, school, hospital, community centre) has to consider holistically. Given this project as an example, if calculating (see Table 5.2) the general sub-urban density purely based on the site's housing density, the figure would be 38,353 to 43,243 people/km^2, achieved just by the townhouse area's density only. If looking at the combined high-rise buildings and townhouses, the density would be 113,385 to 137,728 people/km^2. Such figures are not realistic, because as shown in Table 4.4, the densest city Paris so far only achieves 21,370 people/km^2 in its city centre.

Therefore, the general residential density (people/km^2) has to be considered by the government's planning department at the planning stage. The developers do not have sufficient information about the city and nearby sites. For this reason, the developer's responsibility is mainly to comply with the plot ratio and floor area per person, which are regulated by the local standards and the obtained planning permit.

Table 5.2 The background information of the case study project’s density

Plot ratio and land use			
High-rise buildings	two 18 floors, two 26 floors and two 33 floors		
Townhouses	4-10 three floors terrace houses in a block, and five blocks in total on-site		
The plot ratio of the high-rise areas	4.5	**Land use of the high-rise areas**	20082m^2
The plot ratio of the townhouse areas	1	**Land use of the townhouse areas**	7770m^2
The average plot ratio of the whole site	3.44	**Total land use of the site**	27852m^2
Green land ratio	35%	**The total units of the site**	568
Car park places	784	**The total occupants expected**	2860 – 3500 for high-rise area, 298 – 336 for townhouse area
Townhouse area’s density	38,353 to 43,243 people/km^2	**Whole site’s density**	113,385 to 137,728 people / km^2

For this case study, as shown in Table 5.3, both the high-rise and the townhouse area achieved a plot ratio of 1.0 or above, and floor area per person less than 36 m^2/person.

Table 5.3 The background information of the case study project’s units

High-rise Layout	**Bedrooms**	**No. of units**	**Floor areas (construction) m^2**	**Expected occupants per unit**	**Total expected occupants**
1	4	132	166	5 - 6	660 - 792
2	3	132	125	4 - 5	528 - 660
3	2	104	84	3 - 4	312 - 416
4	3	104	116	3 - 4	312 - 416
5	3	104	112	3 - 4	312 - 416
6	1	72	52	2	144 - 0
7	1	72	40	2	144 - 0
8	1	72	38	2	144 - 0
9	1	72	40	2	144 - 0
10	2	32	86	3-4	96 - 128
11	1	32	64	2	64 - 0
Townhouse Layout	**Bedrooms**	**No. of units**	**Floor areas (construction) m^2**	**Expected occupants per unit**	**Total expected occupants**
1	4	4	184	6 - 8	24 - 32
2	3	4	186	6	24 - 0
3	4	4	190	6 - 8	24 - 32
4	3	4	193	6	24 - 0
5	4	4	278	8	32 - 0
6	4	4	278	8	32 - 0
7	5	5	256	7 - 8	35 - 40
8	5	5	258	7 - 8	35 - 40
9	5	4	248	7 - 8	28 - 32
10	5	4	249	7 - 8	28 - 32
11	4	1	178	6 - 8	6 - 8
12	4	1	178	6 - 8	6 - 8

5.3.3 Summary of the identified case study

The background conditions of ‘location’ and ‘density’ introduced in section 5.3 have set up the necessary boundaries for many passive and active NZE strategies to the studied project. After reviewing the documents provided by the developer, it is convincing that the local team’s original design has satisfied the principles of the national level prototype developed in this research. Therefore, this research took the project as a case study.

5.4 The reference (baseline) building’s concept design

Based on the design conditions summarised in section 5.2 and 5.3, this section illustrates how a detailed reference (baseline) building developed from the national scale prototype. Rather than being a hypothetic building as the prototype presents at the national level, this baseline building will be a real reference building for the specific case study project. It adds more detailed data of local conditions on top of the prototype at the national level. It also guides the local stakeholders to achieve integrated design across the design development stage.

As Ascione et al. (2016) explained in a case study of a net-zero-energy house in Berlin, a clear definition of the ‘zero-energy line’ (see Figure 5.2) is essential to guide the design targets. Against this line, the reference building’s performance will mostly help to secure the energy efficiency, and consequently, the affordability of the needed on-site renewable energy.

Stene et al. (2018) also summarise a similar path towards net-zero-energy buildings (nZEB), with the nearly and the plus variants. They highlight the zero-energy line, as well as the start point of the reference building’s performance level. The difference comparing with Ascione et al.’s (2016) model is that it allows more weighted factors (e.g. kWh, CO_2) to be involved in the balance calculation.

In this thesis, chapter 4 thoroughly analysed the definition of the net-zero-energy line and the performance level of the affordable NZE townhouse prototype at the national level. However, it has not yet validated whether such prototype can implement in real practice. Therefore, in this section, each of the following sub-sets is specified, in order to see whether they can practically formulate a baseline building.

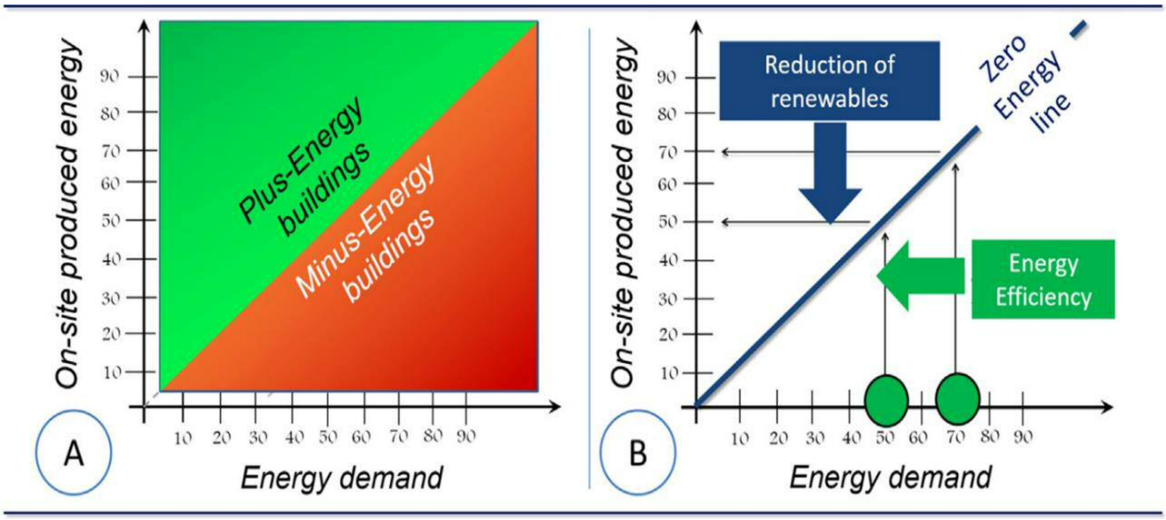


Figure 5.2 Concept and strategies for achieving net-zero-energy buildings: a) definition, b) relation between the energy efficiency of the envelope/active systems and need of on-site energy conversion (Ascione et al. 2016)

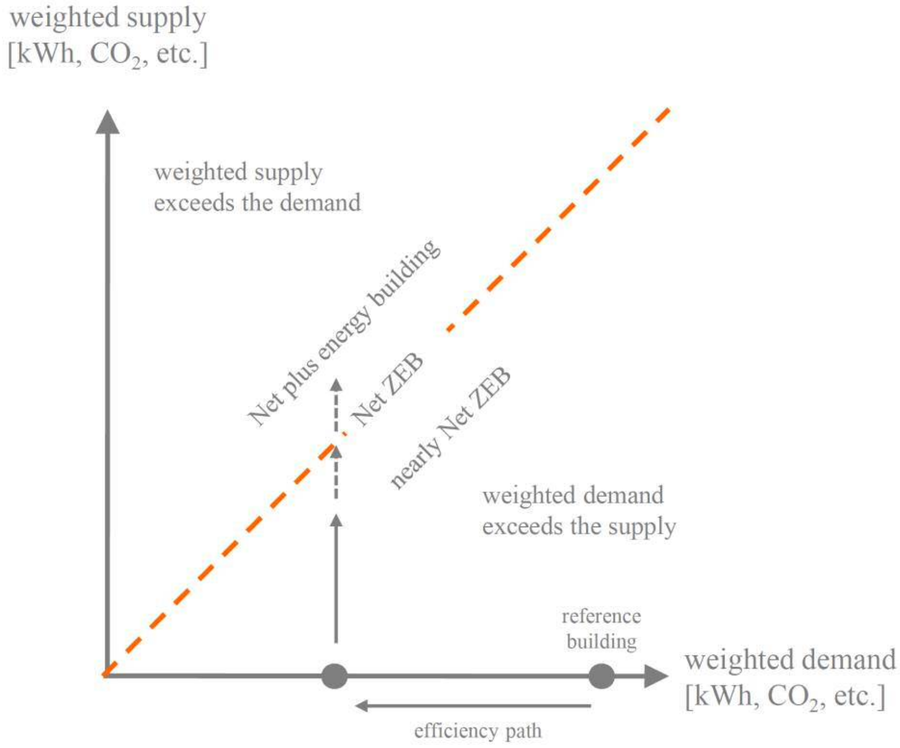


Figure 5.3 Graph representing the path towards a Net Zero Energy Building (Net ZEB), with the nearly and the plus variants (Stene et al. 2018)

5.4.1 Form

The planning permit fixed the following conditions, which influence the building form:

- The orientation of the studied mid-terraced house is 15 degrees to the southeast
- The house has to be no more than 5m at the width and 12 m at depth (including balcony)
- The roof height should not exceed 12 m
- Building Shape Coefficient (the surface area to volume ratio) should not exceed 0.52, which is the Shaanxi' province's local standard
- Each house has one parking place
- Floor area per person less than 36 m^2/person
- 'Minimal 2 hours' insolation duration in the habitable rooms' has to be satisfied

Based on the above conditions and the developer's original design, this research proposed the following features of the 'form' sub-set:

- Orientation: 15 degrees to the southeast (within the reasonable range)
- Shape: 5m at the width and 11.4 m at depth (including balcony), 3m height for each floor, with flat roof surface not higher than 9.5m and solar panel installation not higher than 12m from the ground surface
- Building Shape Coefficient 0.287, which complies with the higher standard of 0.3 required by the regional standard for the Cold climate zone
- Car park place: integrated into the garden area, in order to save land for road
- Total floor area: 178 m^2 (including the priced area of the balcony) with 3 or 4 bedrooms for 5 – 6 occupants
- Living room and main bedroom(s) are located on the south side of the building to achieve the maximal insolation duration

There are two reasons for not proposing a pitched roof to integrate the solar panel:

1) The planning permit has restrained any change about the elevation of the ground plane. Therefore, the adjustment of each building's height is limited. The original design assigned flat

roof for the most southerly row of the terraced house on the site, in order to give the second row a view of the riverbank. If changing the flat roof to a pitched one, this view will be blocked, which influences the second row's selling price.

2) The local supply chain has not dealt with a pitched roof-integrated solar PV before. Therefore, they are not confident to deliver such a PV-roof integrated design.

5.4.2 Envelope

The planning permit fixed the following conditions, which influence the envelope:

- The window-to-wall ratios and heat transfer coefficient of all the envelope have to achieve the minimum standards of local energy-saving design codes for residential buildings

When the design of the case study started in 2017, the NZE standard had not formally launched. Even being launched now, the *Technical Standard for Nearly Zero Energy Building* (GB/T51350-2019) is still recommendary rather than compulsory. Therefore, the reference building was mainly formulated based on local building regulations. For those features which can save the developer's capital cost (such as smaller windows), the values of the reference building tend to be better than the requirements (Table 5.4). Otherwise, it complies with the necessary standards to get the most cost benefits (Table 5.5).

Table 5.4 The window-to-wall ratios

Orientation		**North**	**East / West**	**South**
Window-to-wall ratio	Local standard	≤0.3	≤0.35	≤0.5
	NZE standard	Follows the local standard		
	Reference building	≤0.2	0	≤0.4

Note: the window-to-wall ratio is the average ratio of the whole façade, rather than of a specific room or floor
Source: 1. Design standard for energy efficiency of residential buildings (Shaanxi Province) DBJ 61-65-2011; 2. Technical Standard for Nearly Zero Energy Building (GB/T51350-2019)

Table 5.5 The heat transfer coefficient K (W/m^2K)

Envelope		**Heat transfer coefficient K (W/m^2K)**		
		Local standard	**NZE standard**	**Reference building**
Roof		0.35	0.10-0.20	Follow the local standard
External wall		0.45	0.15-0.20	
Overhead or overhang floor		0.45	0.20-0.40	
The floor between heated and unheated space		0.5	0.20-0.40	
The partition wall between heated and unheated space		1.5	1.00-1.20	
The door between heated and unheated space		2.0	1.6	
The board of the door to the balcony		1.7	1.5	
The door between unheated and external space		4.0	1.5	
External window	Window-to-wall ratio ≤0.2	2.8	≤1.2	
	0.2 <Window-to-wall ratio ≤0.3	2.5		
	0.3 <Window-to-wall ratio ≤0.4	2.0		
	0.4 <Window-to-wall ratio ≤0.5	1.8		

Source: 1. Design standard for energy efficiency of residential buildings (Shaanxi Province) DBJ 61-65-2011;
2. Technical Standard for Nearly Zero Energy Building (GB/T51350-2019)

Note: The heat transfer coefficient K is a design parameter to describe a material's thermal transmittance. It has the same unit and meaning as the U-value but tested under different conditions. The following table summarises the difference between the U-value used in the EU and the K used in China.

Symbol	Standard	Test conditions				
		Outdoor temperature (°C)	Indoor temperature (°C)	Outdoor wind speed (m/s)	Indoor ventilation mode	Solar radiation (W/m^2)
K	China's GB10294 standard	-20	18	3.0	Natural ventilation	0
U-value	EU's BS EN673 standard	2.5	17.5	4.5	Natural ventilation	0

Therefore, for the same thermal transmittance of a material, the value of K and U-value will be slightly different. The following table gives an example of different types of window's valued under these two parameters.

Window type	U-value	K-value
Normal plain single glazing 6e	5.00	5.44
Normal plain double glazing 6e+12A+6e	2.58	2.58
Heat-reflecting single glazing 6 CTS140	4.58	5.03
Heat-reflecting double glazing 6 CTS140+12A+6e	2.42	2.41
Low-e double glazing 6 CEB12+12A+6e	1.5	1.57

As can be seen above, the difference is small enough that they could be treated as the same parameter when simulating the performance. Thus, in this research, the U-value used in the simulation tool HTB2 can represent the parameter regulated in China's standard.

The full summary is available at http://www.haomaohm.com/baike/show.php?itemid=41216

5.4.3 System

As shown in Figure A1-2, Xi’an locates in the south edge of the Cold climate zone. Therefore, it rarely experiences freezing winter, in which external temperature drops below -10 °C. However, in winter, the external temperature still drops below 0 °C frequently. Besides cold winter, Xi’an also has a hot summer. In fact, due to the unique terrain, Xi’an has been on ‘China’s top ten furnace cities list’ for a long time (Yi 2012). In 2018, Xi’an hit its second-high summer temperature in its 50 years’ meteorological record, which had 14 days over 40 °C (Ji 2018). For such a climate, the heat pump is ideal to act as both the cool and the heat resource. The air-source heat pump (ASHP) is less restrained by the available site and is also more economically sound. Therefore, this research proposed an air-source heat pump system to deal with heating and cooling.

Domestic heating, cooling and hot water take a large proportion of total energy consumption in residential buildings. They also contribute significantly to greenhouse gas emissions because the energy used is mainly from fossil fuels. Electrification of these three systems combined through ASHP, and then decarbonisation the electricity by building integrated renewable power generation, will help to reduce CO2e emissions significantly. Therefore, for this case study, the building’s heating, cooling and domestic hot water are proposed to be supplied by one ASHP system.

Moreover, the water loops of ASHP air-to-water system can be embedded in the building envelopes to make the whole building as the active thermal storage. Comparing with the battery storage for electricity, the Thermally Active Building Storage (TABS) is much more cost-effective and environmentally friendly. Therefore, rather than involving a battery to increase the self-use of renewable energy on-site, large capacity of thermal storage through building fabric for heating and cooling plus a water tank for domestic hot water is proposed.

Furthermore, such a system can shift domestic energy consumption from peak usage period to local renewable generation’s peak output period, while still providing the needed comfort in time. In that case, the grid is less interrupted, and the occupants can have better financial benefits without compromising comfort needs. Thus, this research targeted to reduce the demand side heating and cooling load to the level which could be met by the local renewable power generation.

For the above reasons, this research formulated an 'ASHP multi-supply system for minimal load + TABS & Hot water tank heat storage + onsite renewable power generation' system. It has not been seen in China's housing practice, neither is it mentioned in China's newly launched *Technical Standard for Nearly Zero Energy Building*. Also, it has not been seen in the literature review of other countries' publications either. Therefore, this is new knowledge added by this research to the proposed affordable NZE townhouse prototype.

5.4.4 Operation

As pointed out by the *Technical Standard for Nearly Zero Energy Building* (GB/T51350-2019), so far, China's existing building regulations have not yet set up any criteria for the whole house airtightness. Even though China's building regulations have set up requirements of the airtightness level of windows, doors or glass curtain wall, there are still many other leakage points not being mentioned. For the radiant heating and cooling system, the indoor air temperature is more sensitive to the heat loss/gain through ventilation and infiltration. For the winter mode, the low radiant heating temperature will not be able to provide enough comfort if a house is full of cold air. For the summer mode, when the external air is warm and humid, the air leakage can easily cause a condensation problem. Therefore, in this research, the air permeability of 0.8 air change per hour at 50 Pa was proposed for the baseline building. This criterion does not achieve the requirement by the *Technical Standard for Nearly Zero Energy Building* (GB/T51350-2019) for the Cold climate zone (see Table 4.8). However, this criterion reflects the current building regulations, which has not yet put enough emphasises on whole house airtightness.

When a building becomes very tight, mechanical ventilation (MV) is needed to ensure adequate indoor air quality (IAQ). For Xi'an's situation, both the outdoor PM2.5 pollution and indoor chemical pollution (caused by indoor decoration materials) are conventional and high. In such a case, MV with air purification becomes a 'must-have' service. Because Xi'an locates in the Cold climate zone, mechanical ventilation with heat recovery (MVHR) is more suitable than simple MV. It would be ideal if the MVHR could be integrated into the ASHP multi-supply system and dehumidify the intake of fresh air in summer. The EU has invented such a system in the early 2010s (Figure 5.4), but the feedback from the local team is that there has not been such a system in China. Therefore, the ventilation system and HP heating-cooling-hot-water system operated separately.

Moreover, indoor temperature and relative humidity (RH) not only impact on people's comfort level directly but also influence a building's energy performance significantly. Therefore, in building regulations, they are recommended for the designers. In Shaanxi's local design code (DBJ 61-65-2011), it recommends an indoor air temperature of 18 °C for heating and 26 °C for cooling. However, China's *Technical specification for radiant heating and cooling* (JGJ142-2012) has different guidelines for the whole house radiant heating and cooling system. An indoor air temperature of 16 °C for heating and 27.5 °C for cooling is considered reasonable in this national standard for such whole-house radiant heat transfer system. Thus, this research adopted the national standard for the reference building, because it is more beneficial for achieving better energy performance.

Figure 5.4 Components for Clivet´s ELFOSystem GAIA for 'Class A' single-family houses
(Clivet 2011)

Note: ELFOControl² - the central comfort control unit that allows controlling the complete system for power generation, distribution, indoor comfort and rational use of the renewable sources

ELFOFresh² – the unit for air exchange and purification with thermodynamic recovery and electronic filters (H10) can cool and heat the fresh air with minimum energy consumption

ELFOFresh Air - the complete air distribution system easy to install and configurable on the web, which enhances efficiency with its low noise mechanical ventilation system

Radiant panels or radiators - Distribution of hot and cold temperatures through radiant panels to each room

ELFORoom - the hydronic terminals with temperature control room by room, minimal design and small dimensions, variable fan speed, homogeneous temperature and low consumption

GAIA - the heat pump with DC inverter technology which transfers heating and cooling energy, integrating all the components of a heating plant (including the production of hot water with a 186 litre storage tanks and circulating pumps). GAIA derives 75% of its energy from the sun through heat pump technology which captures the energy contained in air, ground or water with just 25% from electricity.

Connection to the solar panel - The unit is suitable for connection to solar panels so that the system can produce the domestic hot water with significant savings. If used in combination with photovoltaic panels, GAIA can become 100% renewable energy.

Source: REHVA Journal – October 2012, page 58

5.4.5 Overall energy performances

Table 5.6 Energy requirements defined by the EU Member States for NZEB levels

Country	Residential Buildings (kWh/m^{2}yr or Energy Class)	
	New	Existing
Austria	160	200
Belgium	45 (Brussels region)	~54
	30 (Flemish region)	
	60 (Walloon region)	
Bulgaria	~30–50	~40–60
Cyprus	100	100
Czech Republic	75–80% PE	75–80% PE
Germany	40% PE	55% PE
Denmark	20	20
Estonia	50 (detached house)	n/a
	100 (apartment blocks)	n/a
France	40–65	80
Croatia	33–41	n/a
Hungary	50–72	n/a
Ireland	45 (Energy load)	75–150
Italy	Class A1	Class A1
Latvia	95	95
Lithuania	Class A++	Class A++
Luxemburg	Class AAA	n/a
Malta	40	n/a
Netherlands	0	n/a
Poland	60–75	n/a
Romania	93–217	n/a
Spain	Class A	n/a
Sweden	30–75	n/a
Slovenia	45–50	70–90
Slovakia	32 (apartment buildings)	n/a
	54 (family houses)	n/a
UK	~44	n/a

Note: PE in this table means primary energy, which includes all the energy consumptions within the building. n/a: not available.
Source: (D'Agostino and Mazzarella 2019)

NZE housing aims to achieve extremely low energy consumptions so that the final CO_{2e} emissions to the atmosphere could be minimised. However, there are different interpretations in each country about what level of energy consumption is 'low'. For example, Table 5.6 presents the current energy requirements defined by EU member states for NZE residential buildings.

In order to standardise the energy performance for better coordination, the EU has set up a climate-based standard for its member states to achieve by 2020 (Table 5.7).

Table 5.7 NZE performance (kWh/m^{2}yr) of the new single-family house according to the European climate

	Climate			
	Mediterranean	**Oceanic**	**Continental**	**Nordic**
	Catania (others: Athens, Larnaca, Luga, Seville, Palermo)	**Paris (others: Amsterdam, Berlin, Brussels, Copenhagen, Dublin, London, Macon, Nancy, Prague, Warszawa)**	**Budapest (others: Bratislava, Ljubljana, Milan, Vienna)**	**Stockholm (others: Helsinki, Riga, Stockholm, Gdansk, Tovarene)**
net primary energy	0–15	15–30	20–40	40–65
primary energy use	50–65	50–65	50–70	65–90
on-site renewable energy generation	50	35	30	25

Note: the 'net primary energy' in the table corresponds to energy use for heating, cooling, ventilation, hot water and lighting.

Source: (D'Agostino and Mazzarella 2019)

China also sets its national NZE standard for housing in its *Technical Standard for Nearly Zero Energy Building* (GB/T51350-2019) as follows:

- **Heating:** ≤15 kWh/m^{2}yr
- **Cooling:** ≤ = 9.97 kWh/m^{2}yr

  (**:** Wet-bulb degree hours 20, is the cumulative difference between the external temperature and Wet-bulb air temperature of 20°C over a year, Unit: kKh; **:** Dry-bulb degree hours 28, is the cumulative difference between the external temperature and Dry-bulb air temperature of 28°C over a year, Unit: kKh). See Table A4-1 in Appendix 4 for detailed calculations.

- **Net primary energy:** ≤55 kWh/m^{2}yr (The total primary energy consumption deduces the onsite and nearby renewable energy utilisations)
- **Renewable energy utilisation rate:** ≥10% of the overall primary energy use. For the system proposed in this research, renewable energy utilisation calculated as follows. The detailed calculations will carry on in Chapter 6.
    - Air source heat pump for heating
    - Air source heat pump for cooling
    - Air source heat pump for domestic hot water
    - Solar PV
    - Micro wind-turbine

Comparing the EU standard with China's standard, it can conclude that China has reached a competitive NZE performance level (the climate of Xi'an is similar to the Nordic area of EU), even though the calculation might be different in some specific areas. Therefore, in this research, the baseline building's energy performance fully complies with China's standard.

As explained in section 2.4.2 (Table 2.9), the energy performance of China's national NZE standard is generally 60% better than the Cold zone's energy-saving regulations. For the baseline building, it is mainly based on local and regional building regulations. Moreover, it is hard to predict the energy consumptions of hot water, ventilation and lighting through modelling, because it is very much down to personal living style. Therefore, its energy performance baselines are set as follows based on the concept design:

- **Heating:** ≤ 25 (=15/0.6, based on the fact that China's national NZE standard is generally 60% better than the Cold zone's energy-saving regulations. The same rule applies to the following figures) kWh/m^{2}yr
- **Cooling:** ≤16.6 (=9.97/0.6) kWh/m^{2}yr

- **Net primary energy:** ≤92 (=55/0.6) kWh/m^{2}yr (The total primary energy consumption deduces the onsite and nearby renewable energy utilisations)
- **Renewable energy utilisation rate:** ≥10.2 kWh/m^{2}yr ((=92/0.9)*0.1, 10% of the projected total primary energy, as required by China's national NZE standard)

5.4.6 Summary of the baseline building concept

In section 5.4, under the six sub-sets of the prototype, the case study project's specific conditions are analysed, in order to form a baseline building as a real reference. It took existing conditions (restraints) from already done planning concept on board. It also distilled more detailed design features for the architectural concept design from regulations and design codes. Furthermore, it concluded the performance baseline by comparing the developed countries' requirements and China's standards. With the summarised baseline building in Table 5.8, it provided clearer design strategy options and targets to help the project team to approach detailed design effectively.

Table 5.8 The sub-sets and critical features of the baseline (real reference) building for the case study project

Sub-sets and key features	Contents
Location	• 25.9 km from Xi'an city centre • 55 mins car trip to Xi'an city centre and 35 mins car trip to Gaoling district centre • In the 500-600 kWh/m^{2}yr or above mean distribution of direct solar radiation zone
Density	• The plot ratio of townhouses area only is 1.0, and the whole project's average plot ratio is 3.44 • Floor area per person less than 36 m^2/person

Sub-sets and key features	Contents	
Form	• **Orientation:** 15 degrees to the southeast • **Shape:** 5m at the width and 11.4 m at depth (including balcony), 3m height for each floor, with flat roof surface no more than 9.5m and solar panel installation not higher than 12m from the ground surface • **Building Shape Coefficient:** 0.287, which achieved a higher standard of 0.3 required by the national standard for the Cold climate zone • **Parking:** One car park place integrate into the garden area, in order to save land for road • **Total floor area:** 178.4 m^2 (including the priced area of the balcony) 3 or 4 bedrooms for 6-8 occupants, among which 150.8 m^2 is the net heated/cooled floor area. • **Layout:** Living room and main bedroom(s) are located on the south side of the building to achieve the maximal insolation duration	
Envelope	As shown in Table 5.4 and Table 5.5	
System	**End plant**	Floor and ceiling integrated water loops for radiant heating and cooling
	Domestic hot water	Heat pump integrated. Stored in the hot-water tank.
	Cool and Heat resource	Air-source heat pump
	Others	A dehumidifier might need in summer
Operation	**Air change rate at 50Pa**	≤0.8 air change per hour
	Ventilation mode	Mechanical ventilation with heat recovery in the heating and cooling season, as well as smoggy days. Natural ventilation in other situations
	Others	• Indoor air temperature setpoints of 16 °C for heating and 27.5 °C for cooling • Air purification for PM2.5 is needed
Overall energy and environmental performances	**Heating:** ≤ 25 kWh/m^{2}yr **Cooling:** ≤16.6 kWh/m^{2}yr **Net primary energy:** ≤92 kWh/m^{2}yr **Renewable energy utilisation rate:** ≥10.2 kWh/m^{2}yr	

5.5 The reference building's detailed integrating design

This section presents the whole design development process in detail. It made an in-depth analysis of local climate to help integrate the design strategies. With these work, the baseline building prototype further develops to the detailed design for constructions and system installations.

Ideally, the weather data analysis should be carried out before applying for the planning permission because it can identify the suitable strategies from the very beginning and maximise the benefits of effective strategies. For this case study, many conditions had been fixed when the planning permit was issued. Therefore, the weather data analysis in this research will focus on the conditions influencing the detailed design features.

5.5.1 Weather data analysis and the comfort standard

As (Janda 2011) stated, 'Buildings do not use energy: people do'. With the same design, higher comfort requirements will lead to higher energy consumptions. Therefore, before assessing a house's energy performance, it is always important to specify what level of comfort the design aims to achieve. For the NZE housing, it always aims to satisfy the reasonable comfort needs with minimal energy consumption.

It has to address here that in order to achieve better energy-saving results, the indoor dry-bulb design temperature (T) of the baseline building sets as 16 °C for heating and 27.5 °C for cooling. In the meantime, there is no criterion set up for its relative humidity (RH). These settings based on the guidance of China's design code (JGJ142-2012) for whole-house radiant heating and cooling system. This code stated that maximally '2°C less than the standard heating temperature of 18°C' and '1.5 °C higher than the standard cooling temperature of 26°C' can be adopted for such system.

However, China's newly launched *Technical Standard for Nearly Zero Energy Building* sets up higher requirements than the existing standards. In this standard, T≥20°C (RH ≥ 30%) for heating and T≤26°C (RH ≤ 60%) for cooling set to be mandatory parameters. Therefore, China's new NZE standard not only raises the bar of energy performance, but its requirement for comfort is also higher as well.

In this research, the used weather data analysis tool is Climate Consultant 6.0. There are four default comfort models in this tool, which sets up the background standard for indoor thermal comfort. Different models have diverse emphasises on the key design parameters of the indoor thermal environment. Choosing a different model would influence the design strategies recommended by Climate Consultant 6.0. By these different comfort models, this tool allows the user to include energy-saving potentials by occupants' adaptations.

After choosing the thermal model, Climate Consultant 6.0 could generate 14 types of charts to visualise the distribution of the essential design parameters throughout the year. Such a function can help users to understand the local climate from different aspects. By exploring these charts, the designers can either quickly analyse a more specific parameter for detailed design analysis, or bring all the design strategies together for comprehensive decision makings. Therefore, Climate Consultant 6.0 is exceptionally suitable for early design analysis.

In the end, Climate Consultant 6.0 provides a list of the top 20 guidelines most appropriate for the analysed climate and the chosen comfort level. Moreover, Climate Consultant 6.0 also displays sketches or graphic images to help illustrate the application of these guidelines and explain how it might influence building design. Such a function benefits the interdisciplinary design team by enabling the analysis of design strategies from both visual and numerical aspects.

For this research, 'ASHRAE Standard 55 and Current Handbook of Fundamentals Model' is chosen as the background standard for weather data analysis. Choosing this standard is because it shares the same method as China's NZE standard by using the PMV (Predicted Mean Vote) model to define the internal comfort zone.

The comfort band is compared in this research from the beginning, in order to see whether it fundamentally influences design strategies. In Climate Consultant 6.0's comfort criteria settings, it is calculated out that the Comfort Lowest Winter Temperature is 16.8 °C with Winter Clothing 1.5 Clo (Figure A4-1 a, Appendix 4). If changing the Winter Clothing to 1.0 Clo (fewer layers or less insulation level), the Comfort Lowest Winter Temperature raises to 20.3°C (Figure A4-1 b, Appendix 4). For the cooling season, Summer Clothing 0.5 Clo would lead to 26.7 °C Comfort Highest Summer

Temperature. For the fan-forced ventilation cooling zone, under 0.8 m/s mechanical ventilation velocity, it could achieve 3°C maximal Perceived Temperature Reduction. This phenomenon means that 29.7 °C Comfort Highest Summer Temperature can be adopted with fan-aid high-speed mechanical ventilation. Such variation well reflects the range of the baseline building setting (T=16 °C for heating and 27.5°C for cooling). Therefore, for this case study, the minimal comfort standard has been well defined by the baseline building.

Moreover, the recommended design strategies for two Winter Clothing levels are very similar. Among the 20 recommendations, only three strategies are different, and the top 4 strategies are precisely the same (Figure A4-2, Appendix 4). Therefore, the design development of the baseline building organises around the weather data analysis of the Winter Clothing 1.5 Clo scenario.

5.5.2 Design strategies generated by weather data analysis and the relevant integration of building components

Following the conceptual design framework (Figure 4.28), each design feature group's contents are filled with the case study project's specific conditions. Then, the most critical work is to integrate the relevant strategies of different features into specific building components. For this case study, through weather data analysis, the following design strategies are organised under each principal component.

5.5.2.1 Floorplan

The recommended strategies in Climate Consultant 6.0 about floorplan are as follows:

- *Keep the building small (right-sized) because excessive floor area wastes heating and cooling energy*
- *Organise floorplan, so winter sun penetrates in spaces used in the daytime with specific functions that coincide with solar orientation*
- *Extended narrow building floorplan can help maximise cross-ventilation in climates with high temperature and hot humid*

Comparing the above suggestions with the baseline building concept, the principles of these strategies have embedded into the prototype. For the detailed design, the following specific strategies developed in this research reflected the above recommendations:

- Keep the corridor and balcony to the minimal size for its function, and not to heat or cool these areas to save energy
- Locate kitchen and toilets on the north side of the building, while main bedrooms and living room on the south side of the building, to maximise the passive solar gain and daylight in winter
- Add glazing area on the internal partition walls of the south bedrooms towards the corridor, in order to enhance daylighting in the core area of the building
- The internal openings of doors not only satisfy their circulation needs but enable rectilinear cross ventilation at the same time

The final design of the baseline building's floor plan is as Figure 5.5:

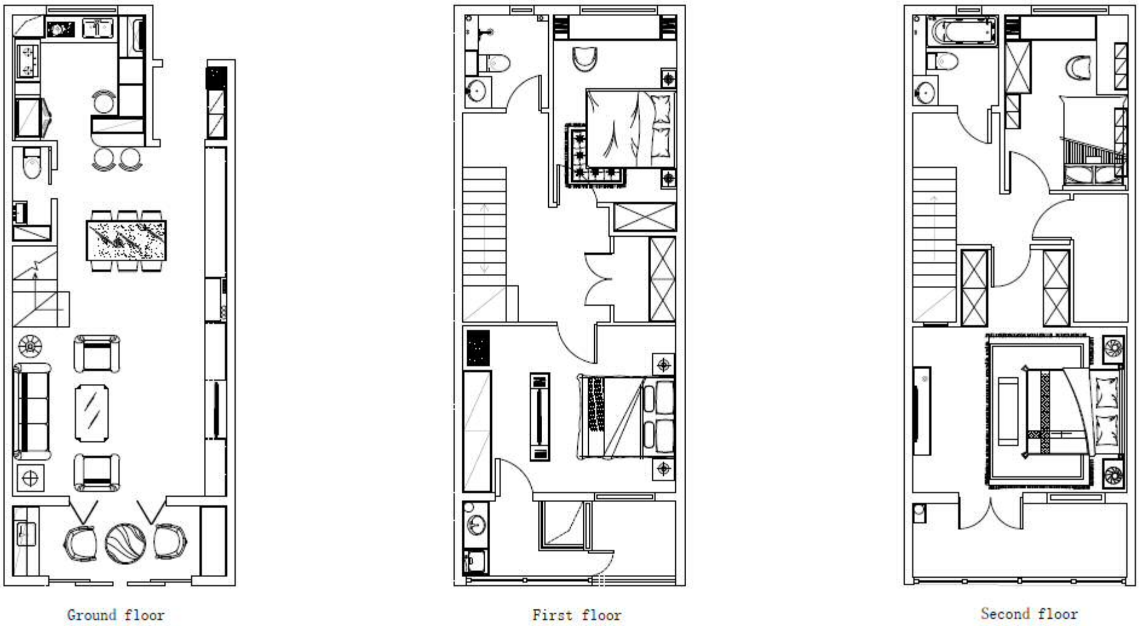


Figure 5.5 The floor plan of the baseline building

Source: Xiaoyuan Technology (the developer of the case study)

5.5.2.2 Windows

The recommended strategies in Climate Consultant 6.0 about windows are as follows:

- *Provide double pane high-performance glazing (low-E) on west, north, and east, but clear on south for maximum passive solar gain*
- *Face most of the glass area south to maximise winter sun exposure, but design overhangs to fully shade in summer*
- *Proper natural ventilation can reduce or eliminate air conditioning in warm weather if windows are well shaded and oriented to prevailing breezes*
- *Traditional passive homes in warm, humid climate used to high ceilings and tall operable (French) windows protected by deep overhangs and verandahs*
- *Window overhangs (designed for this latitude) or operable sunshade (awning that extends in summer) can reduce or eliminate air conditioning*

With the form fixed in planning permit, the following strategies are developed in this research to integrate the above strategies to the details of windows:

- The windows designed as two parts: opaque part for ventilation only, and transparent double pane part for daylight and sunlight (shown in Figure 5.6).
- The sizes of windows designing to be smaller than the requirements of building regulations for the north façade, but complying with the building regulations for the south façade. This design enables sufficient sunlight in winter as well as an excellent view of the riverbank.
- It is using the depth of the balcony on the south façade as the overhang of windows to block all the sunlight in summer while allowing deep penetration of sunlight in winter. This design saves the cost of overhang while providing more useful space.
- The windows and internal doors are located in a line to enhance cross-ventilation.
- The French windows of the ground and first floor are covered by the conservatory, in order to reduce their heat loss in winter. Such design also encourages more comfortable natural ventilation in the early spring and late autumn, when the local climate becomes mildly cold.

Figure 5.6 The detailed design of windows – an example of existing projects

Source: Xiaoyuan Technology (the developer of the case study)

5.5.2.3 North and South façade

The relevant envelope strategies, which influence the design of the facade, are recommended in Climate Consultant 6.0 as follows:

- *Extra insulation (super insulation) might prove cost-effective and will increase occupant comfort by keeping the indoor temperature more uniform*
- *Carefully seal the building to minimise infiltration and eliminate drafts, especially in the windy site (house wrap, weather stripping, tight windows)*
- *No trees (neither conifer nor deciduous) should be planted in front of passive solar windows, but are ok beyond 45 degrees from each corner*
- *Insulating blinds, heavy draperies, or operable window shutters will help reduce winter night-time heat losses*

There is a cost concern of increasing the insulation level at the north and south façade. Because this case study is a mid-terraced house, while all other houses in the row are not to build to the same level. Increasing this house's façade insulation level will cause a significantly overall raise of capital cost in this row. Because it means other houses need to increase the same level of insulation to match the external wall. Alternatively, else, keeping two different insulation levels will create difficulties for the construction, which is not a preferred strategy from the developer and construction company's point of view.

Moreover, the extra insulation will increase the thickness of the external wall. As the planning permit has fixed the borderline between the house and its garden, increasing the thickness of the external wall will make the internal usable area shrink. In China, the purchased area do not calculate by useable but construction areas. Moreover, the high property cost makes customers more sensitive to the usable area rather than energy performance issues. Therefore, extra insulation can only put on the ground floor and roof.

However, there are still methods identified to enhance the insulation level of the two external facades. For the north façade, windows are as small as possible to reduce the weak insulation areas. For the south façade, this research also suggested an integrated balcony conservatory. It covers the whole ground floor and half of the first-floor's south façade. A hole is opened on the first-floor verandahs' slab to enable heat transfer from ground verandahs' thermal mass to the first-floor conservatory through ventilation. The laundry machine and cabinets are located in the first-floor conservatory too, in order to make use of the accumulated passive heat in the conservatory for drying clothes. Such design not only further saves operational energy caused by tumble dryer, but also enable communication between the ground and the first floor. Furthermore, it gives the kitchen or bathroom (the familiar places for washing machine) more usable areas, while causing less noise disturbance to the occupants. Figure 5.7 presents the construction result of the two facades.

South North

Figure 5.7 The constructed façades of the case study

Source: Xiaoyuan Technology (the developer of the case study)

5.5.2.4 System and operations

The relevant system strategies, which influence the HVAC system design, are recommended in Climate Consultant 6.0 as follows:

- *In this climate air conditioning will always be needed, but can be greatly reduced if building design minimises overheating*
- *High-efficiency furnace at least energy star should prove cost-effective*
- *Heat gains from lights, people and equipment greatly reduces heating needs so keep home tight, well-insulated (to lower Balance Point temperature)*
- *Lower the indoor comfort temperature at night to reduce heating energy consumption (lower thermostat heating setback)*

At the architecture concept development stage, the research has drawn a major decision that walls are not to embed the water loops of ASHP air-to-water multi-supply system. With the help of the conceptual design framework, it identified from the beginning that embedding water loops on the wall would occupy much usable space. If saving the space by using capillary radiation, the cost will be unacceptably high. Therefore, it proposed in this research that water loops are to embed with the three floors and the top ceiling (Figure 5.8).

In such a case, the internal spaces will be heated and cooled by both their ceilings and floors. Such way of installation would have minimal influence on the internal space use and costs much less than the capillary radiation from the wall as well. It proposed in this research that the system design should aim to meet the heating and cooling load only by the radiant heat transfer, in order to save the capital cost of fan coil units.

It highlighted in the weather data analysis that the dew point temperature in summer would raise to be within the comfort zone (Figure 5.9). This condition means the fresh air is warm and wet, which has already got risks of condensation when coming to the internal cooled spaces. If topping up with internal moisture gains from human bodies and other open water usage points, the indoor dew point temperature will be even higher.

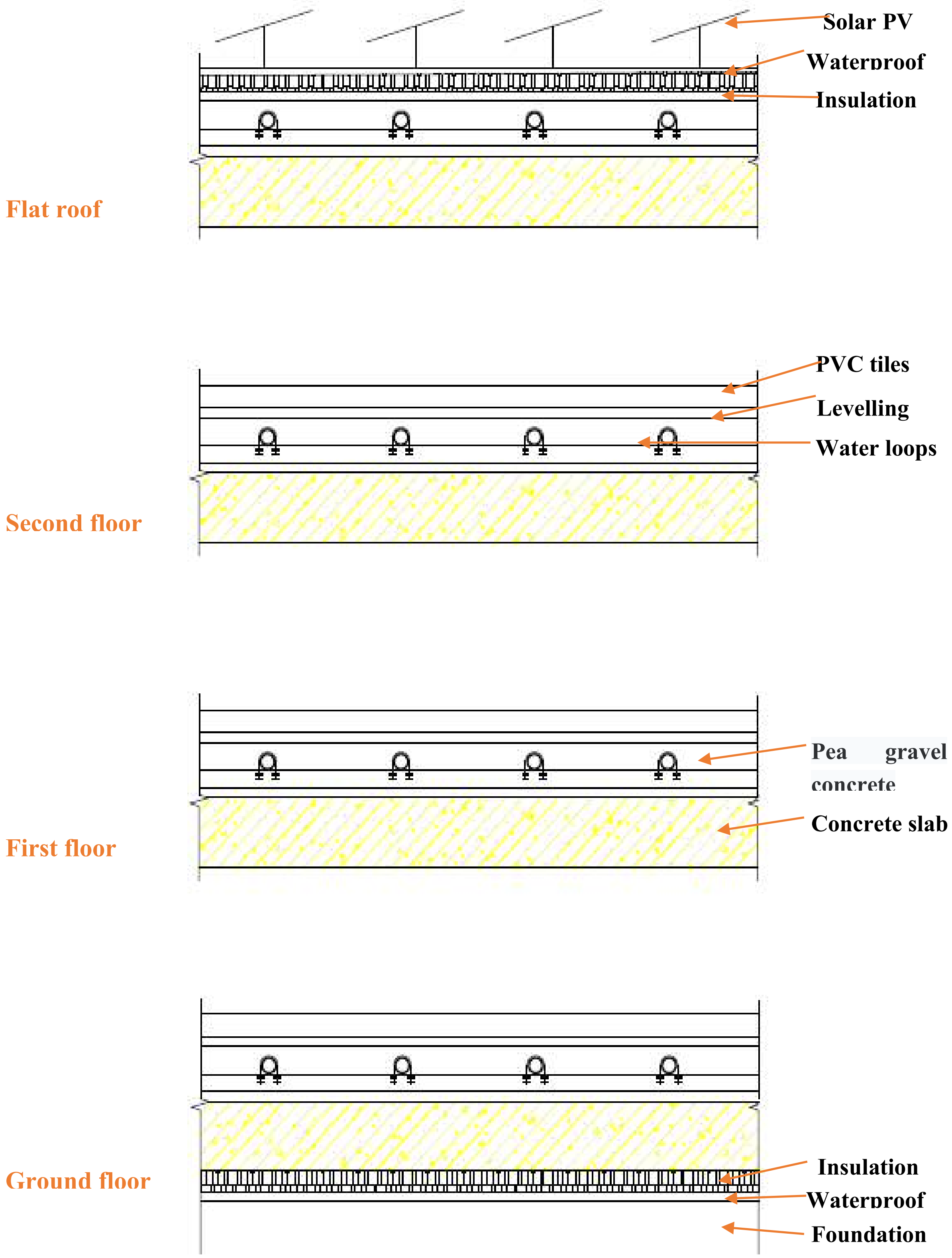


Figure 5.8 The illustration of the embedded water loops in the floors and the flat roof

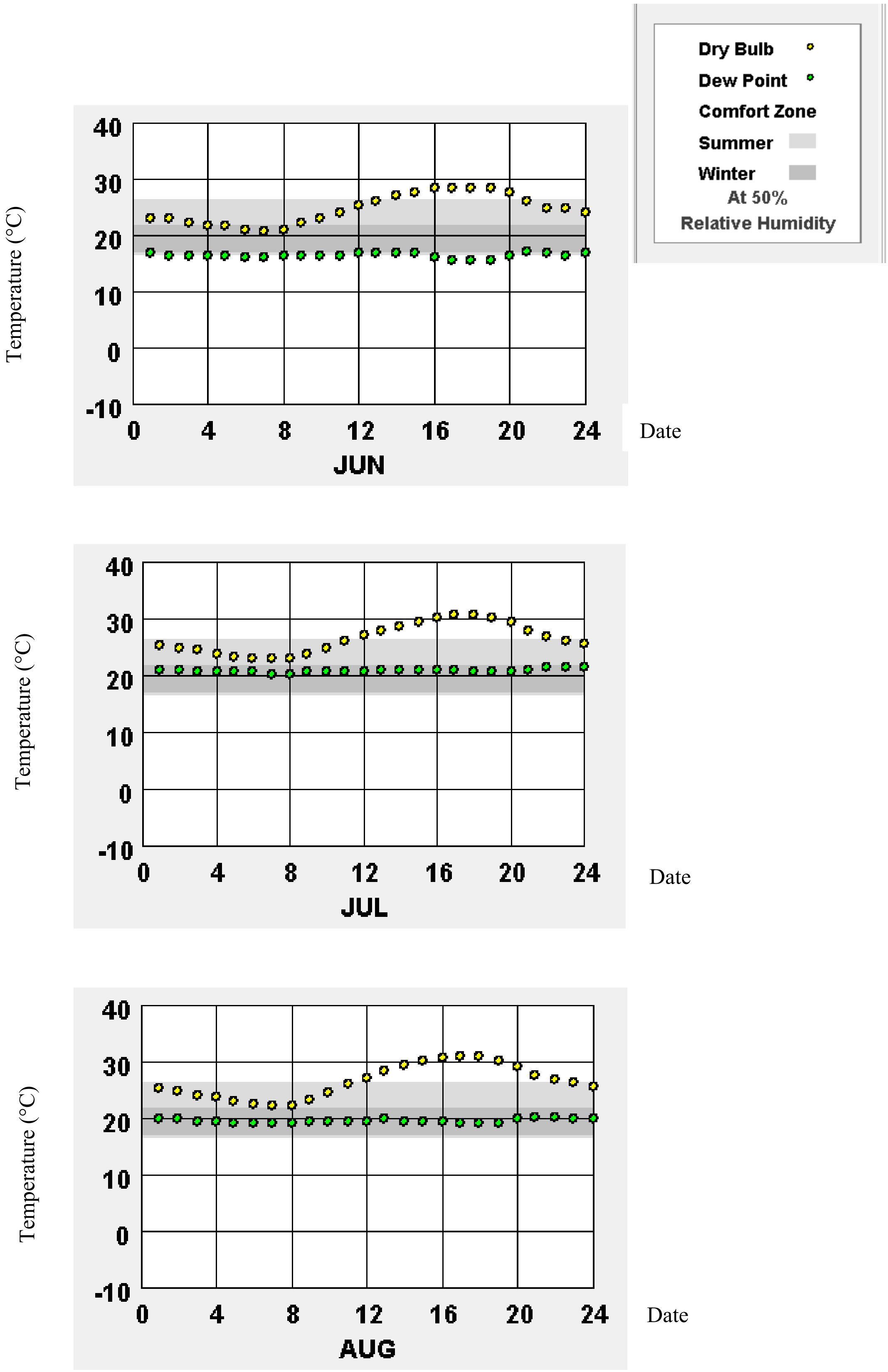


Figure 5.9 Dry-bulb and dewpoint temperature in the summer season of Xi'an city

Note: yellow dots line – dry bulb temperature, green dots line – dew point temperature, light grey band –summer comfort zone, dark grey band – the winter comfort zone

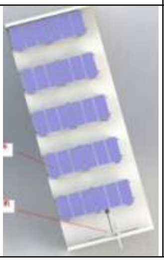
As explained above, the designed internal dry-bulb air temperature is 27.5 °C in summer, and the project aims to achieve radiant cooling without dehumidification to save the system's capital cost. With the external background RH of 60%, the dew point temperature is 19.0 °C against dry-bulb air temperature 27.5 °C. If internal RH rises to 70%, the dew point temperature will be 21.5 °C. This situation largely restrains the cooling surface's temperature, because it has to be higher than the dew point temperature in order to avoid condensation. This condition means that the building's cooling load has to be very low so that the needed cooling capacity could achieve by the limited radiant cooling surface temperature. Such a challenge has been made clear to the local design team at the beginning. Therefore, the architect was well informed to create more effective radiant surface areas in the floor plan design in order to create a bigger cooling capacity. The HVAC engineer started to calculate the needed and available capacity as early as the architectural conceptual design stage. This action is much earlier than the traditional design procedure in China, in which HVAC design would not start until the floor plan and elevation fixes.

Moreover, the above recommendations indicate that there is a conflicting requirement about internal heat gain due to the local climate (freezing winter and scorching & wet summer). Therefore, there must be a balanced consideration for the internal heat gain. It is not possible to change the heat emitted from the equipment once they are installed. However, it is possible to organise the ventilation in a different way to vary the internal heat distribution. For this case, all the lighting bubs and appliances are proposed to be high efficiency. In such a case, they will not only consume less energy but also emit less energy to internal spaces. This design is beneficial to the summer season. Then, the MVHR system's air outlets are all assigned to the kitchen and two bathrooms, while all the air inlets located in the living room and bedrooms. This design will bring the air from cool to hot space in summer while collecting as much heat as possible for heat recovery in winter.

5.5.2.5 Renewable energy generation

With the given roof area and installation specifications, the supplier of PV-wind turbine hybrid generation system proposed two strategies (Table 5.9).

Table 5.9 Comparison of the two strategies of generation *

Strategy	Way of installation	Capacity	Annual predicted power generation	Payback period
A South orientation, 26° tilted		3.84KWp PV + 1.5KWp Turbine	PV: 4673 kWh Turbine: 112.9 kWh	Capital cost would be paid back in 9 years (maintenance cost and tax for generating income included, but not PV supporting frame and installation labour) Capital cost would be paid back in 15 years (all included)
B orientation 15° degrees towards the southeast, 20 ° tilted		4.86KWp PV + 1.5KWp Turbine	PV: 5490.8 kWh Turbine: 112.9 kWh	Capital cost would be paid back in 10 years (maintenance cost and tax for generating income included, but not PV supporting frame and installation labour) Capital cost would be paid back in 18 years (all included)

* Data provided by the system supplier – Guangzhou HY Energy Technology Limited Corp.

Strategy A is more economical than B from the installation point of view, because of less capital cost and a shorter payback period. However, strategy B is chosen by this research because it has a higher peak power generation capacity. This advantage makes it potentially possible to drive the heat pump system in off-peak usage time (peak generation time); therefore, it significantly increases the self-used electricity percentage.

One issue identified when matching the brief calculation of demand-side load to the generation capacity of strategy B - the kitchen should not be heated or cooled by the ASHP multi-supply system, because:

1) In winter, the kitchen could maintain its comfort level for a short period of cooking activities without extra heating. Because the overlapped area between the kitchen ceiling and the above

bedroom’s floor provides constant background heating. Moreover, the kitchen equipment provides significant episodic internal heat gains too

2) In summer, the maximal available floor and ceiling area in the kitchen cannot provide enough cooling capacity to ensure the comfort level during the short cooking period
3) Such ‘not useful’ episodic cooling load pushes the ASHP multi-supply system’s peak electricity consumption far beyond the average monthly onsite generation capacity. As a result, the autonomous energy ratio would be significantly lower down, which largely influences the occupants’ renewable energy income
4) The ‘not sufficient’ water loops in the kitchen area will also push up the ASHP multi-supply system’s pump energy consumption

As a result, a detachable air conditioner is proposed in this research to solve the comfort problem of the kitchen, as it can better deal with this space’s peak load.

5.5.3 Summary of the reference building’s detailed design after integrating the strategies in the building components and systems

As illustrated above, many key strategies implemented in the detailed design already embedded in the reference building prototype. Meanwhile, the conceptual design framework helps to integrate these strategies into the detail design of building components and HVAC system (Figure 5.10).

The conceptual design framework identifies the specific building components for integrating design strategies: if a building component has more links with other features in the framework, the more important role it would play for the integration (see Figure 5.10).

With the guidance of such a conceptual design framework, this research identified two building components for the integrating design.

The first one is a holistic two-parts window. The opaque and insulated part enables natural ventilation without compromising the fabric’s insulation level too much, while the transparent part provides accesses to sufficient daylight and sunlight (see Figure 5.6). The grills on the outside layer of the opaque part take care of the security issues for opened windows while being useful external shading devices to prevent overheating. The middle layer is a screen window which can filter the particle pollutions while allowing natural ventilation. The internal layer is an insulated timber board, which prevents the heat or coolth from emitting to outdoor space.

The second one is the floors and roof embedded ASHP air-to-water multi-supply system. Such design of the heating and cooling system has the following advantages:

- It provides better comfort than the air-conditioning system through whole-house ambient radiant heating or cooling
- It saves capital cost by using the building’s main structure as holistic heat storage with massive capacity
- It makes the thermal storage of the building active because the heat put in and taken out can be well calculated and controlled by the operation of the ASHP system
- It saves the usable spaces which could otherwise have been occupied by the wall-mounted water loops
- It has the potential to achieve radiant cooling without dehumidification to save the system’s capital cost

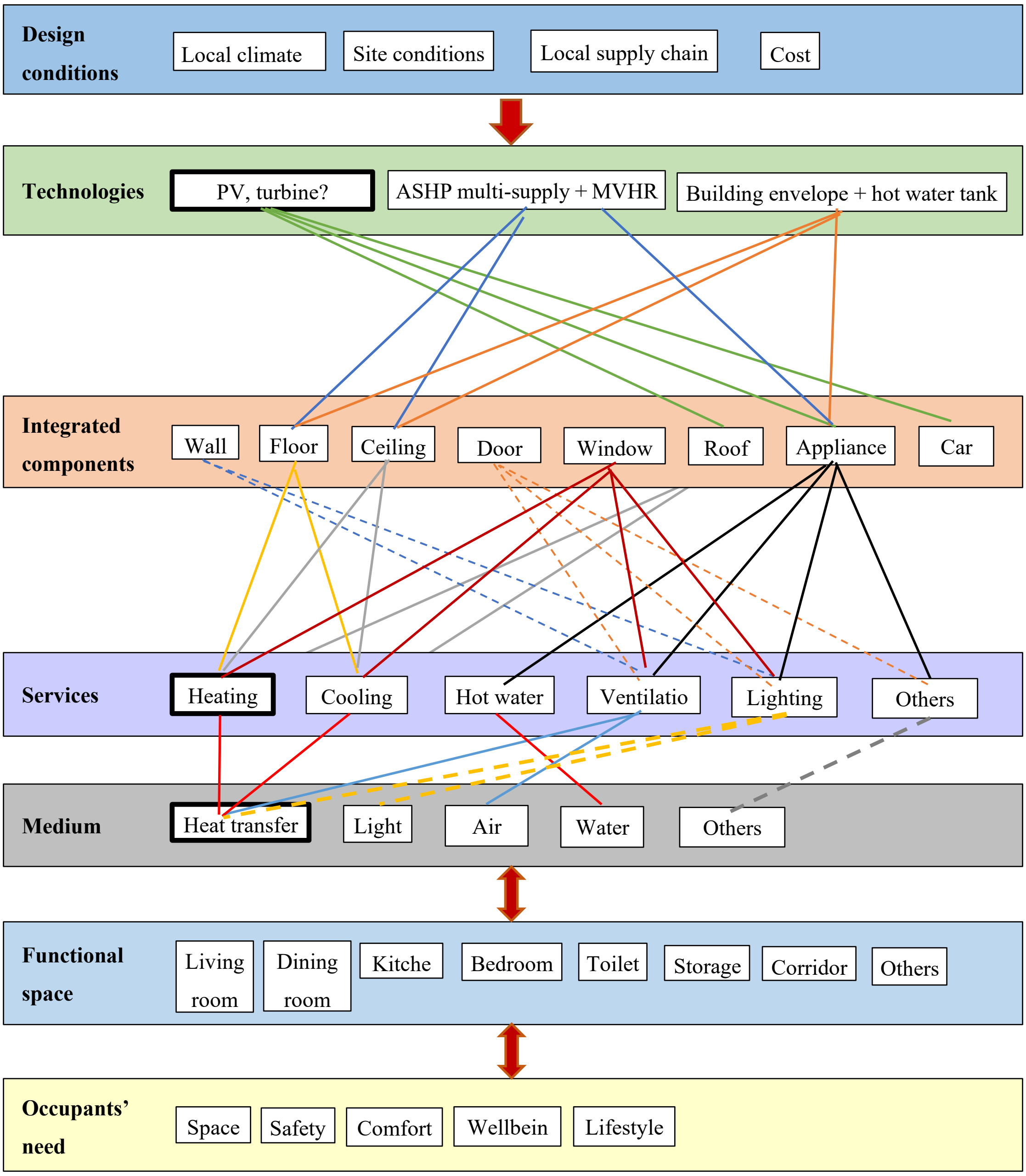


Figure 5.10 Occupied design framework for the baseline building

Chapter 6

Performance validation – modelling and monitoring study on the energy and indoor thermal performance of the case study project

6.1 Introduction

6.1.1 Brief of the performance validation background

In chapter 5, a ‘rooftop PV + TABS & Hot water tank storage + ASHP multi-supply’ system is designed as a holistic package to deliver the prototype in real practice. However, it has not confirmed yet whether the designed baseline building can lead to the targeted NZE performance. Neither is the indoor thermal environment validated against the requirements of China’s regulations and design codes.

Therefore, in this chapter, the energy and indoor thermal performances of the baseline building are evaluated through modelling at the design stage. It acknowledged that modelling study could only predict the performances. However, the existing research in this field has well demonstrated that modelling is an effective method to identify performance gaps and the reasons behind at the early design stage (Nimlyat 2014; D’Agostino and Parker 2018).

Then, this research simulated the final design’s energy and indoor thermal performances. Comparing the simulation results with the baseline building’s ones, it can identify the performance gap from theory to design.

Furthermore, this research monitored the constructed building in the cooling season. These monitoring data are to compare with the simulation results of the final design, in order to find the drawback or improvement of performance in actual operation.

The involved costs analysis is to evaluate whether such a case is economically sound to promote in future practice. Further cost reduction areas and methods are also discussed.

With the above work, this research thoroughly validated the prototype's effectiveness of enabling good performances at low cost.

The case study project is in China, while the author is in the UK; therefore, the monitoring was designed to carry out remotely from the beginning. The author initiated the comprehensive monitoring plan with specifications of needed equipment. This information was handed over to the local project management team for procurement and installations. Then through video conferences, the author oversaw the installation process and made adjustments wherever necessary. In the commissioning stage, real-time monitoring was followed daily through remote data collection and display system. The problems occurring on site were dealt with in real-time by the author's analysis and the local team's operation adjustments.

6.1.2 Content of this chapter

There are five parts of investigations in this chapter.

The first part, section 6.2, is the modelling assessment of the baseline building. There are three aspects evaluated in this section:

- Whether the heating and cooling energy demand can achieve the prototype's theoretical benchmark based on regulations
- Whether the onsite renewable generation can meet the regulated proportion of energy consumptions
- Whether the indoor thermal parameters can meet the requirement of China's standards

The second part, section 6.3, is the prediction of energy and indoor thermal performances through simulating the final design. There are three aspects investigated in this section:

- Whether the constructed building achieves the baseline building’s predicted energy performance
- Whether the onsite renewable generation can meet the regulated proportion of the constructed building’s predicted energy consumptions
- Whether or not the constructed building could achieve the indoor thermal performance predicted by the baseline building

The third part, section 6.4, is the monitoring study of the commissioning process in the cooling season. There are three groups of data collected:

- External weather data
- Supply & return water temperature plus flow rate of the heat pump system, as well as its electricity consumption
- Indoor dry-bulb temperature and RH of the main occupiable rooms.

Based on the above monitoring data, the constructed building’s cooling energy consumptions and indoor thermal performance during the cooling season can be validated.

Table 6.1 Contents of the validation study

Method	**Simulation**		**Monitoring**	**Analysis**	
Section	**6.2**	**6.3**	**6.4**	**6.5**	**6.6**
Case	**Baseline building**	**As constructed**	**As operated**	**Performance gaps**	**Cost**
Energy demand	• Heating • Cooling • Net primary energy	• Heating • Cooling • Net primary energy	• Average energy efficiency ratio (EER) • Cooling	• Energy • Indoor thermal conditions	• Capital • Installation • Operation • Maintenance and management
Renewable energy	• MVHR heat recovery rate • Renewable energy generation • Renewable energy rate	• MVHR heat recovery rate • Renewable energy generation • Renewable energy rate	• Renewable energy generation		
Indoor thermal comfort	• Dry-bulb temperature • RH	• Dry-bulb temperature • RH	• Dry-bulb temperature • RH		

The fourth part, section 6.5, is a comparative analysis of the results generated from section 6.2, 6.3 and 6.4 (as shown in Table 6.1). Not only highlighting the different results of the three studies but more importantly, it analyses the reasons behind these differences and explores the possible solutions for the improvements.

The fifth part, section 6.6, is the cost analysis of the achieved performance in this case study. The specific prices of the construction and installations cannot obtain due to the case's commercial nature. However, this research analysed the level of cost increases or savings in a percentage scale, in order to understand the general cost level to deliver such a prototype in real practice.

6.2 Simulated energy and indoor thermal performance of the baseline building

6.2.1 The simulation settings of the baseline building

In order to simulate the energy and indoor thermal performance of the baseline building, this research assigned the following settings in HTB2 (Table 6.2).

Table 6.2 Settings of the baseline building's parameters in HTB2

Sub-sets and key features	Contents
Location	**HTB2 format weather data** - converted from the EnergyPlus website's '.EPW' format data for Xi'an city, which is generated by the Chinese Standard Weather Data (CSWD) method
Density	Not relevant to simulation
Form	**Orientation:** 15 degrees to the southeast, as shown in Figure 5.1 **Shape and Layout:** See Figure 5.5 and Figure 5.7 **Building Shape Coefficient:** 0.287 **Net floor area (calculated according to China's NZE standard for energy simulation, not the priced area for selling):** 150.8 m^2

Sub-sets and key features		**Contents**
Envelope		**The window-to-wall ratio (average ratio of the whole facade):** North:0.11 South:0.28 **The components U-values (W/m^{2}K):** Roof – 0.3488; External wall – 0.4536; Overhead floor – 0.4463 External door – 1.9586; Windows – 2.0349; Ground – 0.5049; Ventilation windows – 0.6748
System	**Internal gains from equipment (W/m^2)**	All are running for 24 hours. Living and dining room – 5, usage proportion 39.4%; Bedroom room – 6, usage proportion 19.6%; Kitchen – 24, usage proportion 16.7%
	Internal gains from occupants	Four adults and one kid with regular occupancy schedule
	Internal heat gains from lighting	6 W/m^2 (based on China's NZE standard)
	The radiant surface capacity of each room	Calculated from available radiant areas and the temperature difference between settings and assumed room temperature
	Airtightness level	0.8 air change per hour (based on the prototype at the national level)
Operation	**Ventilation mode**	Mechanical ventilation with heat recovery in the heating and cooling season, as well as early spring and late autumn. Natural ventilation is in the majority time of spring and autumn, which is to comply with the local building regulation's health and well-being standard.
Operation	**HVAC system**	24hrs running for the heat pump system, and episodically for the detachable air-conditioner in the kitchen
	Room Temperature	Not assigned in HTB2, but calculated according to the above settings, as well as the assumed supply water temperature
Performance (based on the prototype at the national level)		**Heating:** ≤ 25 kWh/m^{2}yr **Cooling:** ≤ 16.6 kWh/m^{2}yr **Net primary energy:** ≤ 92 kWh/m^{2}yr **Renewable energy utilisation rate:** ≥10.2 kWh/m^{2}yr

Note: Within the research's time scale, no occupants could be involved in the commissioning stage for monitoring validation. However, occupants were still defined in the modelling settings of this research. There are two reasons behind:

1. China's NZE building standard (GB/T51350-2019) regulates the occupancy schedule and rate for system operation and internal gains calculations. Therefore, the simulation conditions need to comply with it, so that the predicted performance could be compared with the benchmarks.
2. The hydronic heat pump system is susceptible to the internal moisture level. Therefore, involving occupants' moistures gains is beneficial to predict the system's performance under more stringent conditions in the cooling season.

The detailed modelling validation is explained in Appendix 6.

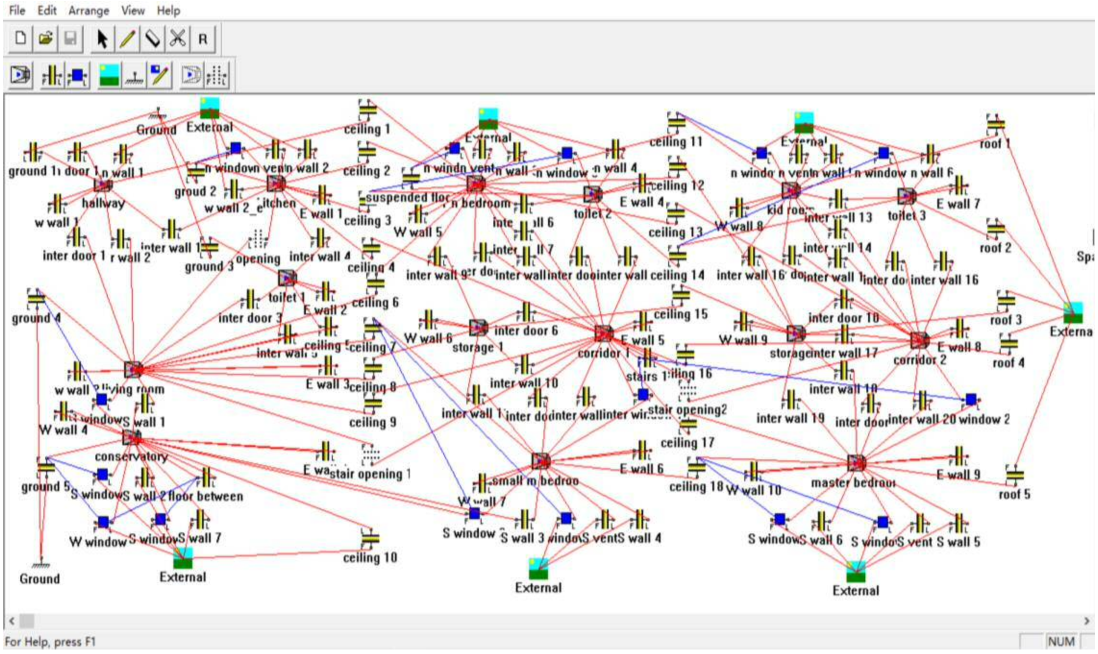


Figure 6.1 The baseline building's schematic layout in HTB2

6.2.2 The predicted energy performance of the baseline building

Based on the above parameter settings, the heating and cooling load of the theoretical baseline building are simulated out and presented in Table 6.3.

Table 6.3 shows that the predicted heating, cooling and net primary energy of the baseline building is well within the relevant energy benchmarks set by China's NZE standard. This result proves that the baseline building for this case study, which developed from the national level prototype formulated in this research, can set up a solid energy performance ground for the final design.

Table 6.3 The predicted heating and cooling energy consumptions of the baseline building

Validated parameters	China's NZE standard	The prototype's theoretical performance	The prototype's simulated performance *
Heating energy	≤ 15 kWh/m^{2}yr	≤ 25 kWh/m^{2}yr	16.7 kWh/m^{2}yr
Cooling energy	≤ 9.97 kWh/m^{2}yr	≤ 16.6 kWh/m^{2}yr	5.5 kWh/m^{2}yr
Net primary energy	≤ 55 kWh/m^{2}yr	≤ 92 kWh/m^{2}yr	49.1 kWh/m^{2}yr **

Note:

* To convert the predicted demand into actual electricity consumption, the COP (Coefficient of Performance) for heating is 4.09 and the EER (Energy Efficiency Ratio) for cooling is 5.07. These figures are calculated based on the heat pump manufacturer's information about heat pump efficiency (see Appendix 5 TableA5-1)

**The regulated heating and cooling energy take about (25+16.6)/92=45.2% of the regulated net primary energy. Therefore, it is calculated in the same proportion as (16.7 +5.5)/ 45.2% =49.1 kWh/m^{2}yr for the simulation result.

Then, based on the standard weather data and theoretical equation, the heat recovery rate of MVHR and renewable power generations from PV and wind-turbine can be calculated. Table 6.4 shows that the predicted renewable energy generation is 58.0% of the predicted net primary energy consumption. This figure is far beyond the requirement of China's NZE standard, which reflects the fact that low-rise building has more potential to utilise local renewable energy generations.

As can be seen in Table 6.4, the subcontractors' prediction of renewable energy generation is 7.6% higher than the simulated results. This outcome is mainly due to different calculation method and tools. Through checking the subcontractors' documents, this research found that they use monthly average weather data rather than hourly average weather data in this research for the calculation. Therefore, in terms of accuracy, it is believed that the predictions in this research would be closer to the actual performance.

Table 6.4 The predicted other energy-related figures of the baseline building

Tested parameters		The required performance of China's NZE standard	The theoretical performance of the baseline building	The sub-contractors' reference figures*	The predictions from the simulation**
Energy recovery (%)	MVHR	≥75 % in the heating season for sensible heat exchange only	≥75 % in the heating season for sensible heat exchange only	79 % for sensible heat exchange only	78.4 % for sensible heat exchange only
Renewable energy rate (%)	PV+ Wind-turbine	≥10% of the overall primary energy use	≥10% of the overall primary energy use	N/A	58.0% ((27.8+0.68) /49.1=58.0%)
Renewable energy generation (kWh)	PV	≥6.1 kWh/m^{2}yr (55/0.9*0.1=6.1)	≥10.2 kWh/m^{2}yr (92/0.9*0.1=10.2)	36.4 kWh/m^{2}yr	27.8 kWh/m^{2}yr
	Wind-turbine			0.75 kWh/m^{2}yr	0.68 kWh/m^{2}yr

Note: * the developer of the case study provides the sub-contractors' figures.

** The detailed calculation of the MVHR energy recovery rate is shown in Table A5-2 of Appendix 5. The detailed calculation of renewable energy generation is in Table A5-3 and A5-4 in Appendix 5. The 48.9 kWh/m^{2}yr figure in this table is the predicted net primary energy consumption summarised in Table 6.3

Notably, the simulation results are significantly better than the theoretical benchmarks concluded by the baseline building. Notably, the predicted cooling load is much better than China's NZE standard.

Through analysis, this is due to the different indoor thermal comfort standards between the baseline building and China's NZE standard. The next section presented a detailed analysis.

6.2.3 The predicted indoor thermal performance of the baseline building

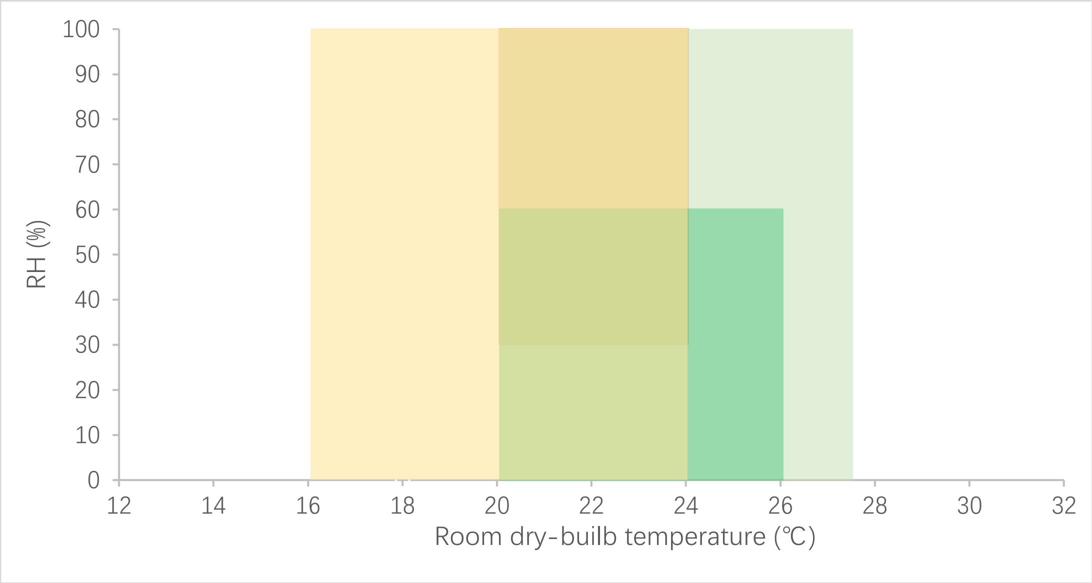
Being a start point to guide the design towards NZE performance, the baseline building's parameter settings based on current national and local building regulations. However, China's NZE standard is not only stricter on the energy side, but also higher on the indoor thermal comfort level. Table 6.5 summarises the individual differences.

Table 6.5 The difference of indoor thermal comfort level between China's NZE standard and the current mandatory building regulations or design standards

	Heating comfort band		**Cooling comfort band**	
	Indoor dry-bulb temperature (℃)	**RH %**	**Indoor dry-bulb temperature (℃)**	**RH %**
China's NZE building standard (GB/T51350-2019)	≥20	≥30	≤26	≤60
Design code for energy efficiency of residential buildings in severe cold and cold (JGJ 26-2018)	≥18	not required	≤26	not required
Design standard for energy efficiency of residential buildings (Shaanxi Province, DBJ 61-65-2011)	≥18	not required	≤26	not required
The technical specification for radiant heating and cooling (JGJ 142 - 2012)	2 degrees lower than the national code if whole-house radiant heating	not required	0.5-1.5 degrees higher than the national code if whole-house radiant cooling	not required
Adopted by the baseline building	≥16	not required	≤27.5	not required

As shown in Table 6.5, not only the temperature benchmark is set with higher standards in the NZE standard, but more importantly, the RH standard is much stricter for both heating and cooling. Such a situation means that more energy would be needed in winter for humidification and in summer for dehumidification. Nevertheless, China's NZE standard requires such higher comfort to be achieved by extremely low energy consumptions, while the current building regulations and design codes have much lower requirements on both energy and comfort. For the baseline building in this research, because it is based on current building regulations and adopts China's NZE standard wherever possible, it does not set up the comfort level as high as in the NZE standard. The intention is to save energy through occupants' further adaptation. If the occupants could cope with lower comfort standard, the design should not restrain them from saving energy by their proactive compromise of comfort.

The differences between China's NZE standard and the adopted standard of the baseline building, as well as their overlapped comfort zones, are summarised in Figure 6.2.



Note:		℃	%
🟨	The heating comfort zone of the baseline building	16-24	0-100
🟨	The heating comfort zone of China's NZE standard	20-24	30-100
🟩	The cooling comfort zone of China's NZE standard	20-26	0-60
🟩	The cooling comfort zone of the baseline building	20-27.5	0-100

Figure 6.2 Comparison of the thermal comfort zone between China's NZE standard and the baseline building in this research

The HTB2's simulation results of indoor dry-bulb temperature and RH reflects the settings of the baseline building. As can be seen from Figure 6.3 to 6.7, the distributions of dry-bulb temperature and RH in kitchen, living room, bathroom, main bedroom and kids' bedroom are commonly out of the NZE comfort standard but within the baseline building's comfort zones.

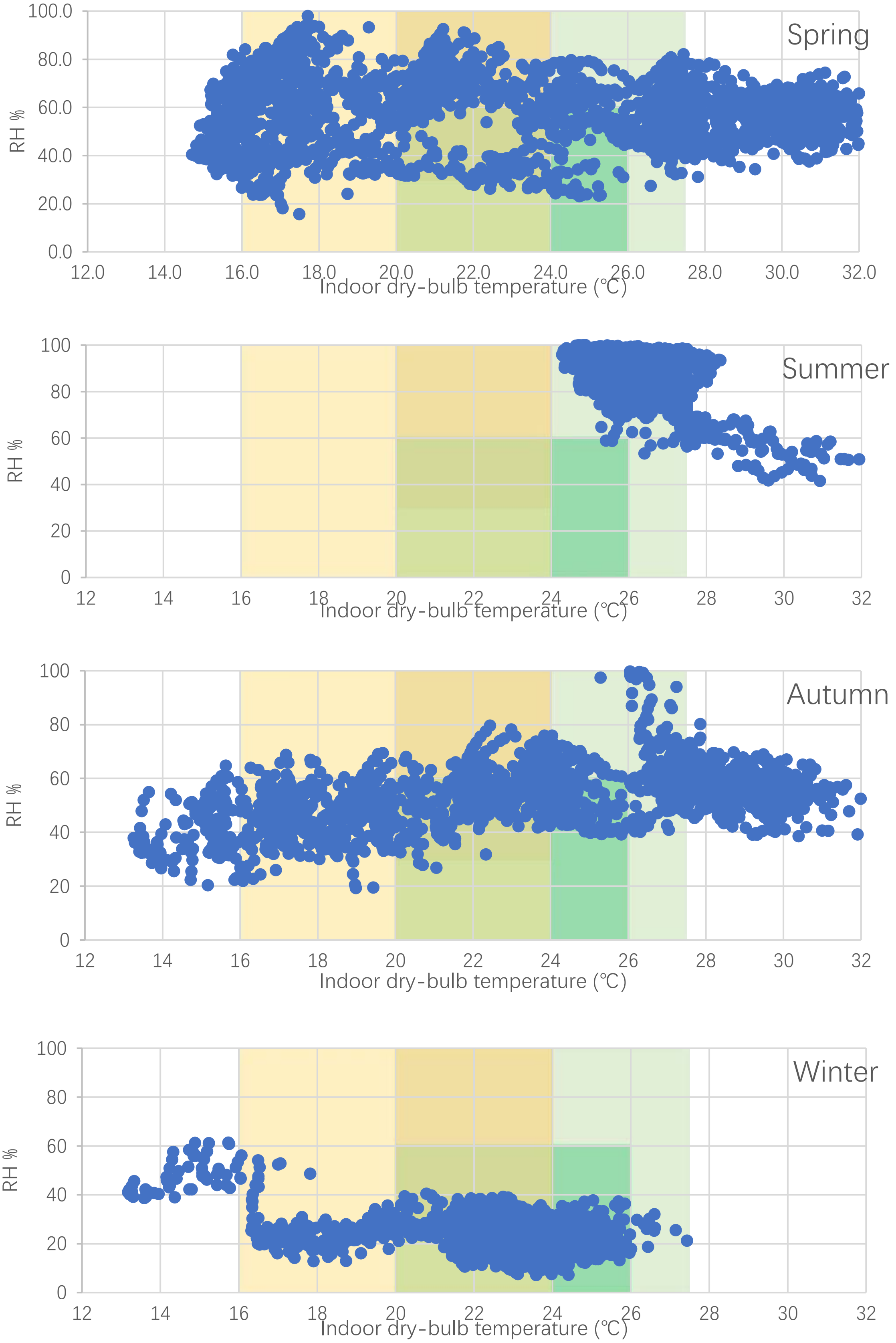


Figure 6.3 The simulated four seasons' dry-bulb temperature and RH distributions of the kitchen

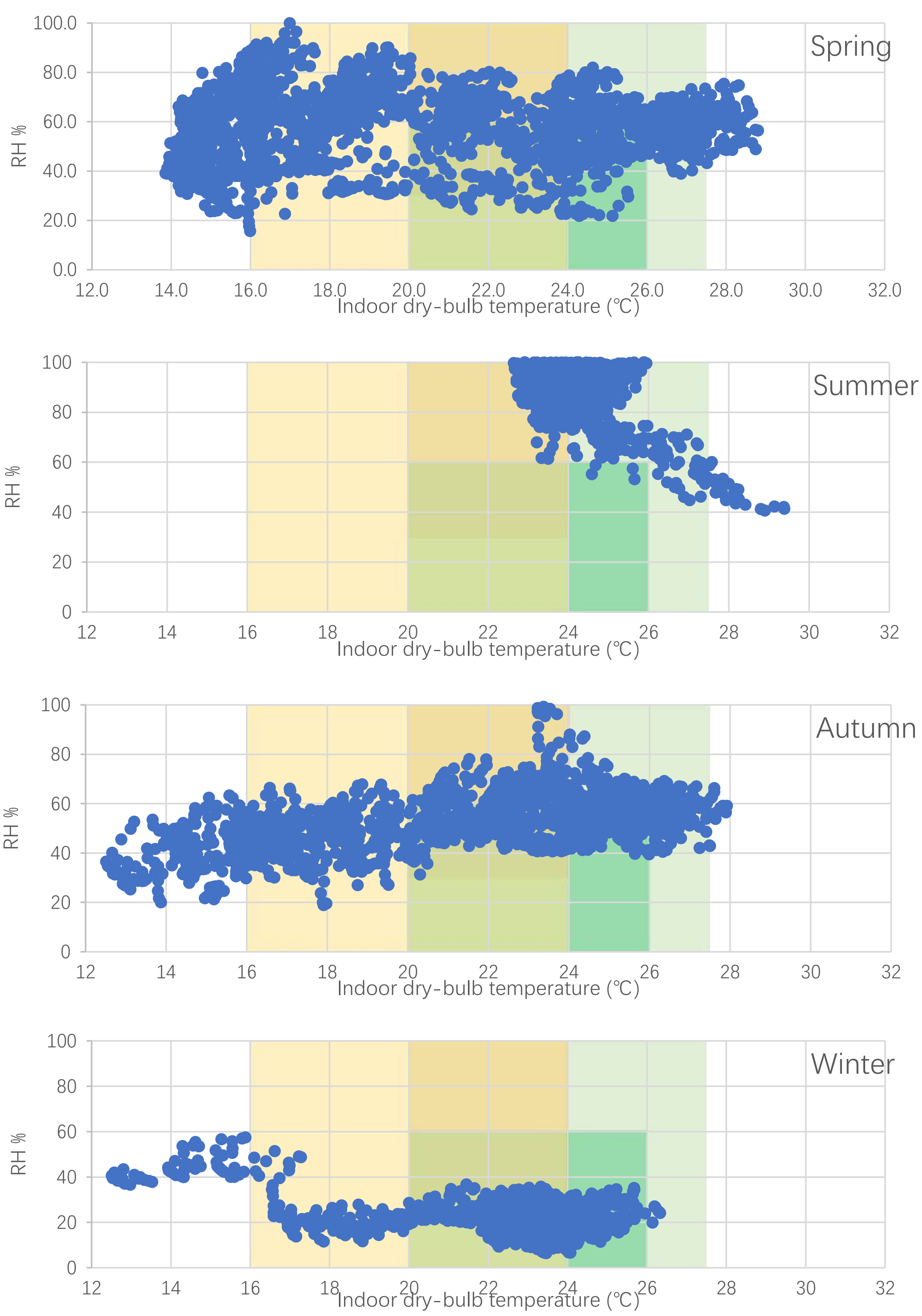


Figure 6.4 The simulated four seasons' dry-bulb temperature and RH distributions of the living room

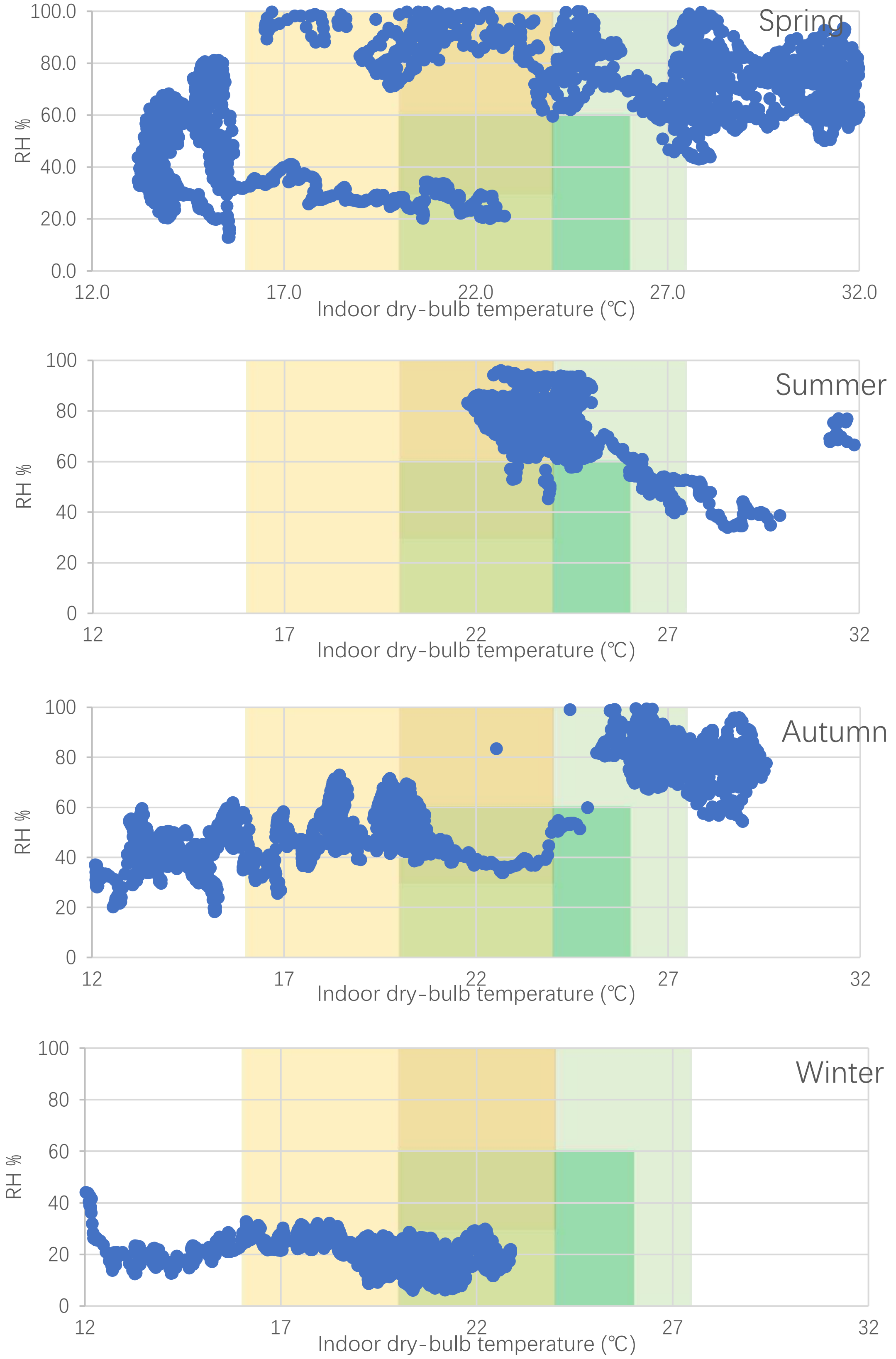


Figure 6.5 The simulated four seasons' dry-bulb temperature and RH distributions of the second-floor bathroom

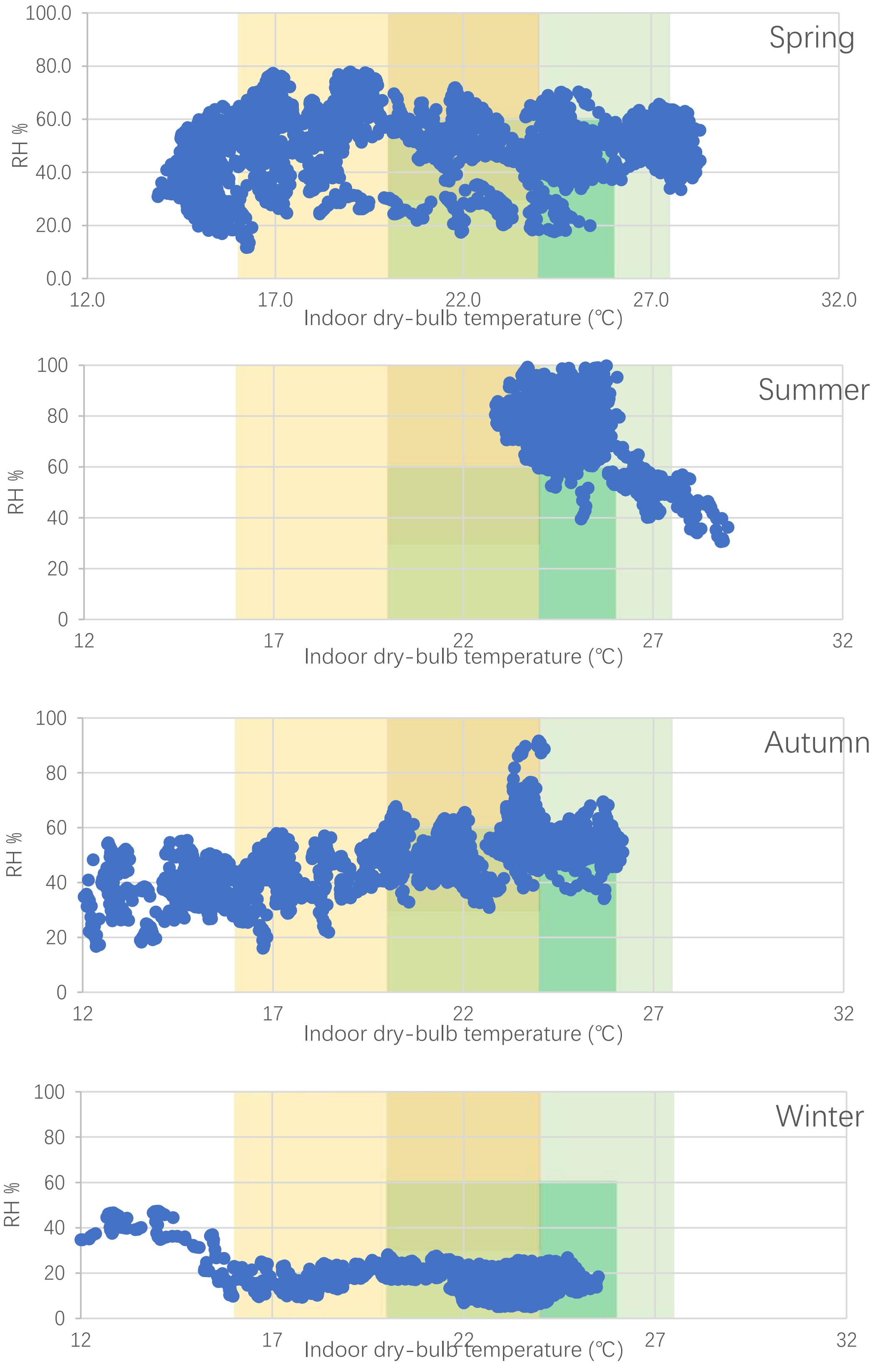


Figure 6.6 The simulated four seasons' dry-bulb temperature and RH distributions of the second-floor main bedroom (south-facing)

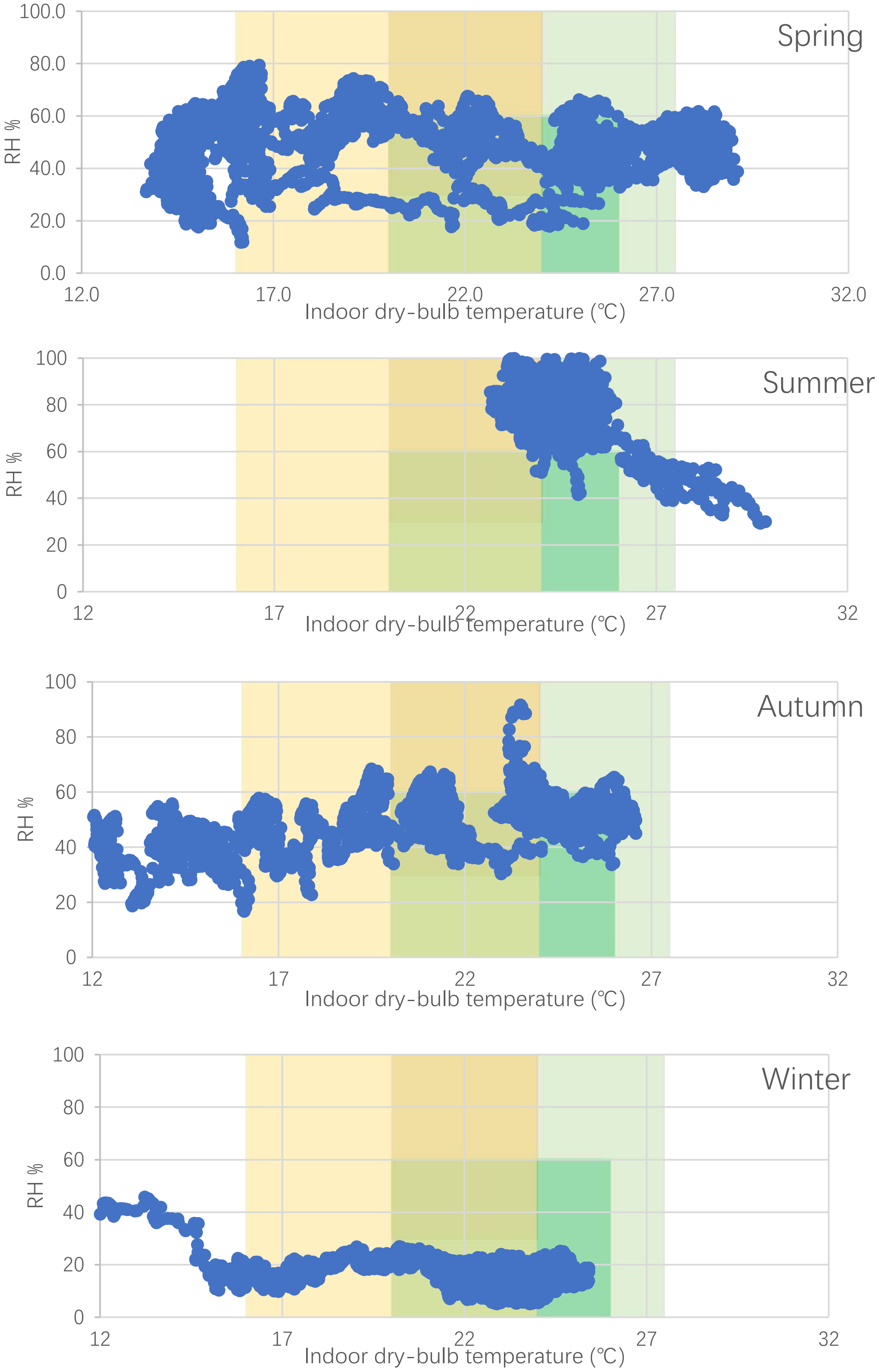


Figure 6.7 The simulated four seasons' dry-bulb temperature and RH distributions of the second-floor kids' bedroom (north facing)

The prevailing situation shown in Figure 6.3 to 6.7 are:

- **In summer, indoor dry-bulb temperature and RH of the four rooms commonly distributed outside the comfort zone defined by China's NZE standard, not because of temperature but the high RH.**

Such a situation explains why the simulated cooling energy consumption is significantly lower than China's NZE standard. In order to reduce the RH from higher to 60%, considerable energy has to be consumed by dehumidification. The current building regulations and design codes do not regulate this part of energy. Therefore, it is not required by the prototype in this research. This simulation result reminds that the prototype can only achieve the proposed thermal comfort standard with very low energy consumptions. If the design targets higher thermal comfort standard, dehumidification has to be involved in the system design, which causes higher capital cost and cooling energy consumption.

- **All four rooms show RH 100% period, which warns of condensation risk**

As explained in Chapter 5, the main disadvantage of the radiant cooling system is its condensation risk. When the surface temperature is lower than the air's dewpoint temperature, condensation will appear in larger areas, which causes damage to the interior decorations as well as harms occupants' health. The simulation result shows that the assumed 20 ℃ supply and 24℃ return water temperature cannot avoid the condensation problem. This water temperature setting has approached to the heat pump's limit for cooling and appropriate in terms of bringing the indoor dry-bulb temperature down to the comfort level. Therefore, the detailed design needs to reduce the cooling load further. In that case, with the same cooling capacity, the lower indoor dry-bulb temperature can be achieved to bring the dewpoint temperature down for lower risk of condensation.

- **All four rooms have underheated period in early spring and late autumn, as well as overheat period in late spring and early autumn**

As explained in Chapter 5, the prototype adopts the minimal insulation level required by the building regulations to save the capital cost. Meanwhile, its window-to-wall ratio is smaller than the basic level required by the building regulations, which is supposed to save both energy and window cost. Therefore, the essential improvement needed in the detailed design is to increase the insulation level.

- **There have been considerable over-heating periods (over 24℃) in winter in both the living room and the main bedroom**

The water temperature is assumed to be 30 ℃ supply and 26 ℃ return in simulation, which has been the lowest temperature the heat pump can provide. The insulation level has not been excellent. Therefore, it is unlikely to cause overheating. In such a case, the reason can only be that the heat pump system does not need to be run for 24 hours as required in China’s NZE standard. When the whole house’s fabric is sufficiently heated up and stores the right amount of heat, it will release the heat to both indoor and outdoor space gradually. These thermal masses created a passive heating effect, which further reduces the energy consumption of the heat pump system.

The passive cooling effect also works in the summer. The simulation results show that the cooling load do not appear 24 hours to maintain the indoor dry-bulb temperature, as shown in Figure 6.3 to 6.6.

6.3 Simulated energy and indoor thermal performance of the final design

6.3.1 The simulation settings of the final design

Based on the simulation results of the baseline building, as well as the available components and equipment from the local supply chain, the final design has made the following changes of the envelope:

- Upgrade the insulation level of the external envelope to the level which the developer accepts the capital cost increase for both the case study house and other houses in the terrace row
- Replace the ventilation window by standard double-glazing window, due to the unavailability of products from the local supply chain

The different settings in HTB2 comparing with the baseline building are as follows: (Table 6.6).

Table 6.6 Settings of the constructed building's parameters in HTB2

Sub-sets and key features	Contents
Envelope	**The window-to-wall ratio (average ratio of the whole facade):** North: 0.142 (29% larger than the baseline building) South: 0.306 (9.3% larger than the baseline building) Still complies with the local building regulations (≤0.3 for the north and ≤0.5 for the south) **The components U-values (W/m^{2}K):** Roof – 0.3191 (8.5% better) External wall – 0.3951 (12.9% better) Overhead floor – 0.4441(almost the same) External door – 1.5953 (18.5% better) Windows – 2.0349 (the same) Ground – 0.2977(41% better) Ventilation windows – replaced by normal double-glazing window

6.3.2 The predicted energy performance of the final design

Based on the parameter changes of the final design for construction, Table 6.7 summarises the predicted heating and cooling load.

Table 6.7 The predicted heating and cooling energy consumptions of the final design

Validated parameters	China's NZE standard	The prototype's simulated performance	The final design's simulated performance
Heating energy	≤ 15 kWh/m^{2}yr	16.7 kWh/m^{2}yr	15.2 kWh/m^{2}yr
Cooling energy	≤ 9.97 kWh/m^{2}yr	5.4 kWh/m^{2}yr	5.4 kWh/m^{2}yr
Net primary energy	≤ 55 kWh/m^{2}yr	48.9 kWh/m^{2}yr	45.6 kWh/m^{2}yr

Note: The assumptions of COP, EER and net primary energy based on the same methods as explained in Table 6.3.

Table 6.7 shows that the predicted energy performance of the final design is 8.4% better in winter and almost the same in summer. If looking at the capital cost increased due to added insulation and larger windows, such improvement is not as economical as hoped. The reason behind is that larger glazing area makes the fabric's general insulation level weaker, even though the design added more insulation to the other opaque area.

For this studied case, an important lesson to be learnt is that the change of critical building components should not happen in the last minute. If the subcontractor could inform the design team from the beginning that for sure they are not able to deliver the ventilation window, the design of façade would have been different. Unfortunately, it was not until the main structure of the building had done that the sub-contractor informed unavailability of the ventilation window. By then, it had been too late to comply with the baseline building's window-to-wall ratio, because it would influence the whole façade's aesthetics as well as create structural problems. Therefore, filling the ventilation window's places with glazing is the only option by then.

For the renewable utilisation, based on the standard weather data and theoretical equation, the heat recovery rate of MVHR and renewable power generations from PV and wind-turbine are calculated (Table 6.8). The renewable generation stayed the same while there was a slight reduction in energy requirement, so the renewable energy rate increases from 58.0% of the baseline building to 62.5% of the final design. The MVHR energy recovery rate stays the same as 78.4% of the baseline building.

Table 6.8 The predicted other energy-related figures of the baseline building

Tested parameters		**The required performance of China's NZE standard**	**The sub-contractors' reference figures**	**The baseline building's predicted performance**	**The final design's predicted performance**
Energy recovery (%)	MVHR	≥75 % in the heating season for sensible heat exchange only	79 % for sensible heat exchange only	78.4 % for sensible heat exchange only	78.4% for sensible heat exchange only
Renewable energy rate (%)	PV+ Wind-turbine	≥10% of the overall primary energy use	N/A	58.0% ((27.8+0.68)/49.1=58.0%)	62.5% ((27.8+0.68)/45.6=62.5%)
Renewable energy generation (kWh)	PV	≥6.1 kWh/m^2yr (55/0.9*0.1=6.1)	36.4 kWh/m^2yr	27.8 kWh/m^2yr	27.8 kWh/m^2yr
	Wind-turbine		0.75 kWh/m^2yr	0.68 kWh/m^2yr	0.68 kWh/m^2yr

6.3.3 The predicted indoor thermal performance of the final design

As in section 6.2.3, this research analysed four seasons' indoor dry-bulb temperature and RH distribution of the main rooms (kitchen, living room, bathroom, main bedroom and kids' bedroom). Figure 6.8 to 6.12 present the results.

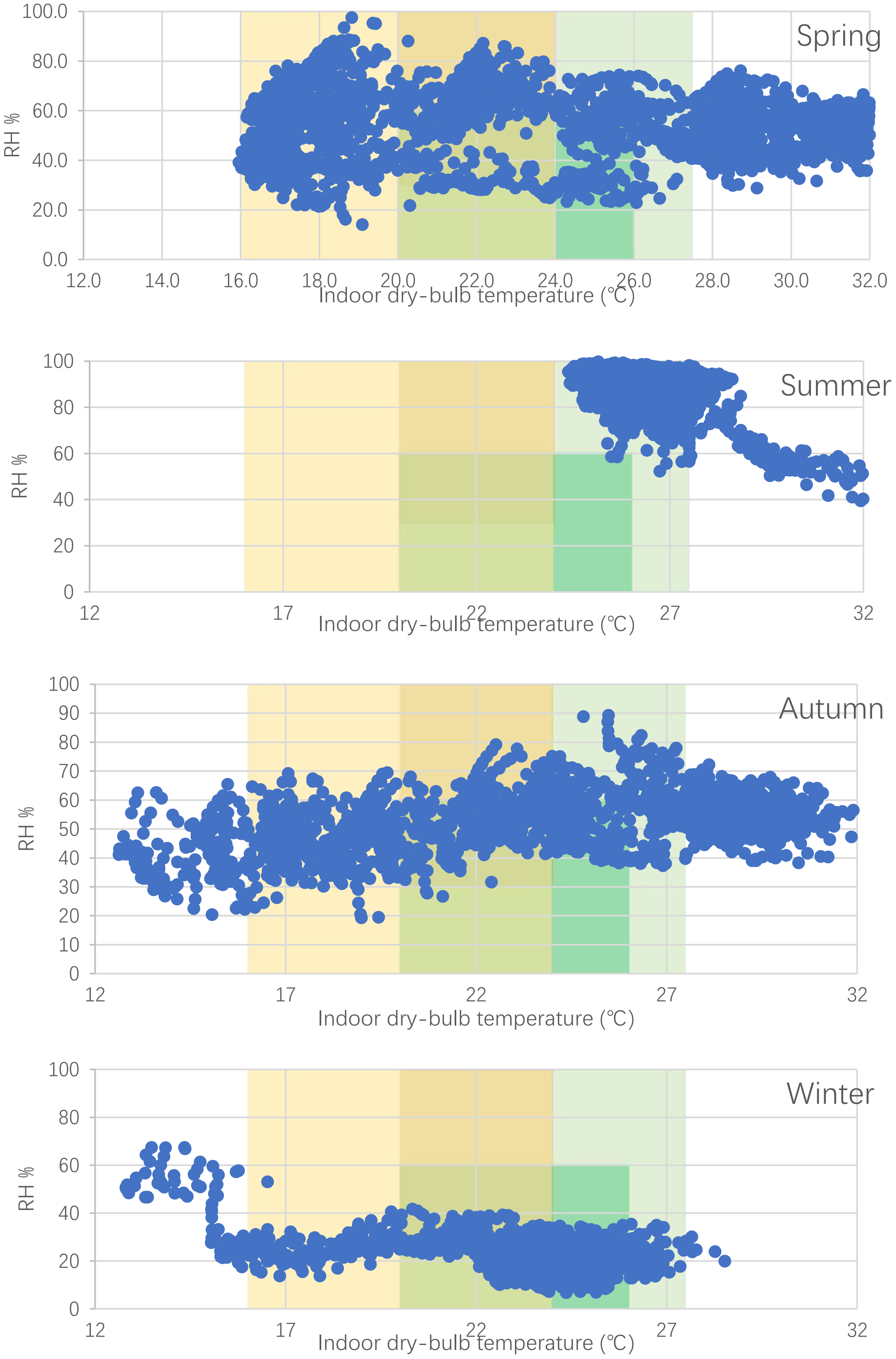


Figure 6.8 The simulated four seasons' dry-bulb temperature and RH distributions of the kitchen

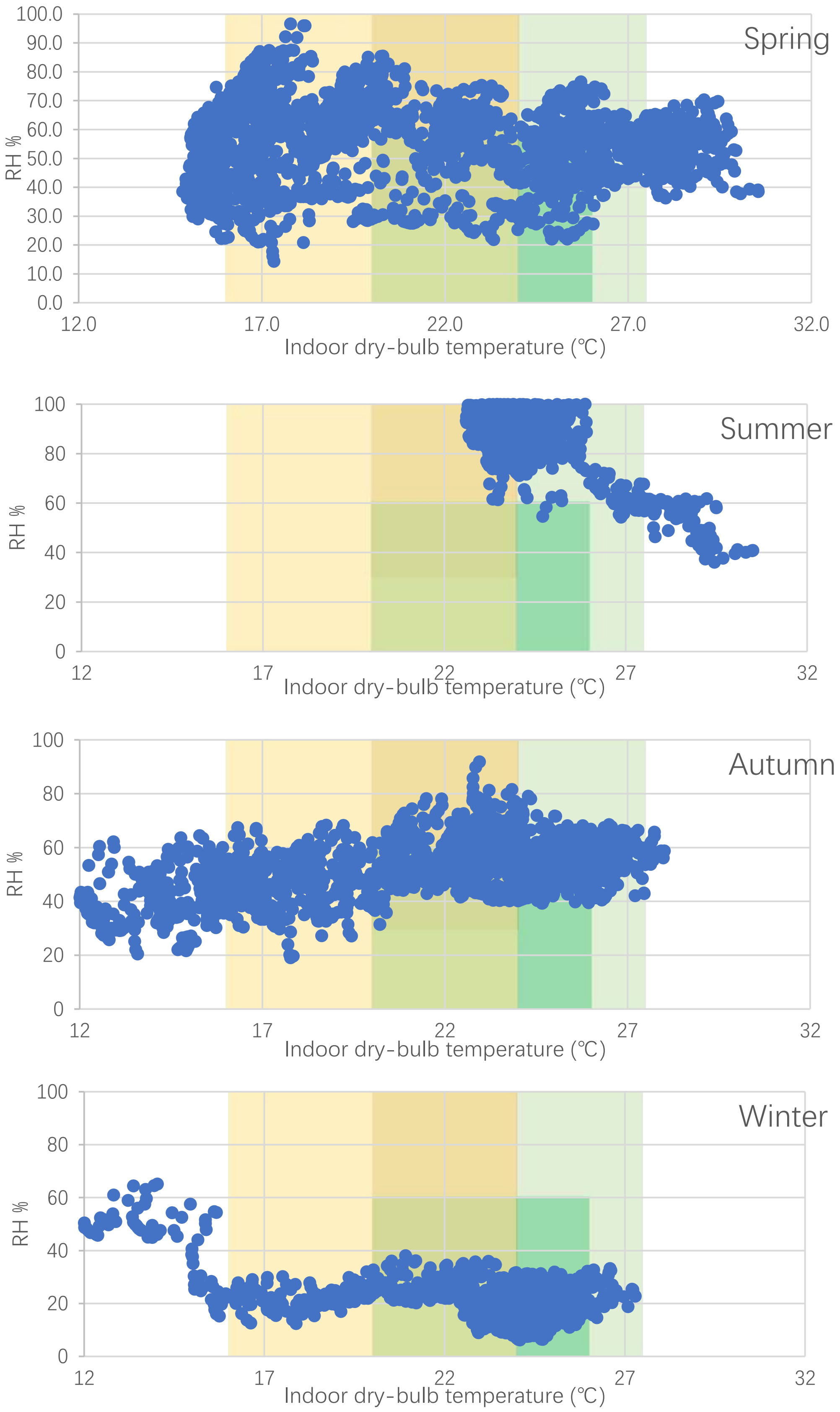


Figure 6.9 The simulated four seasons' dry-bulb temperature and RH distributions of the living room

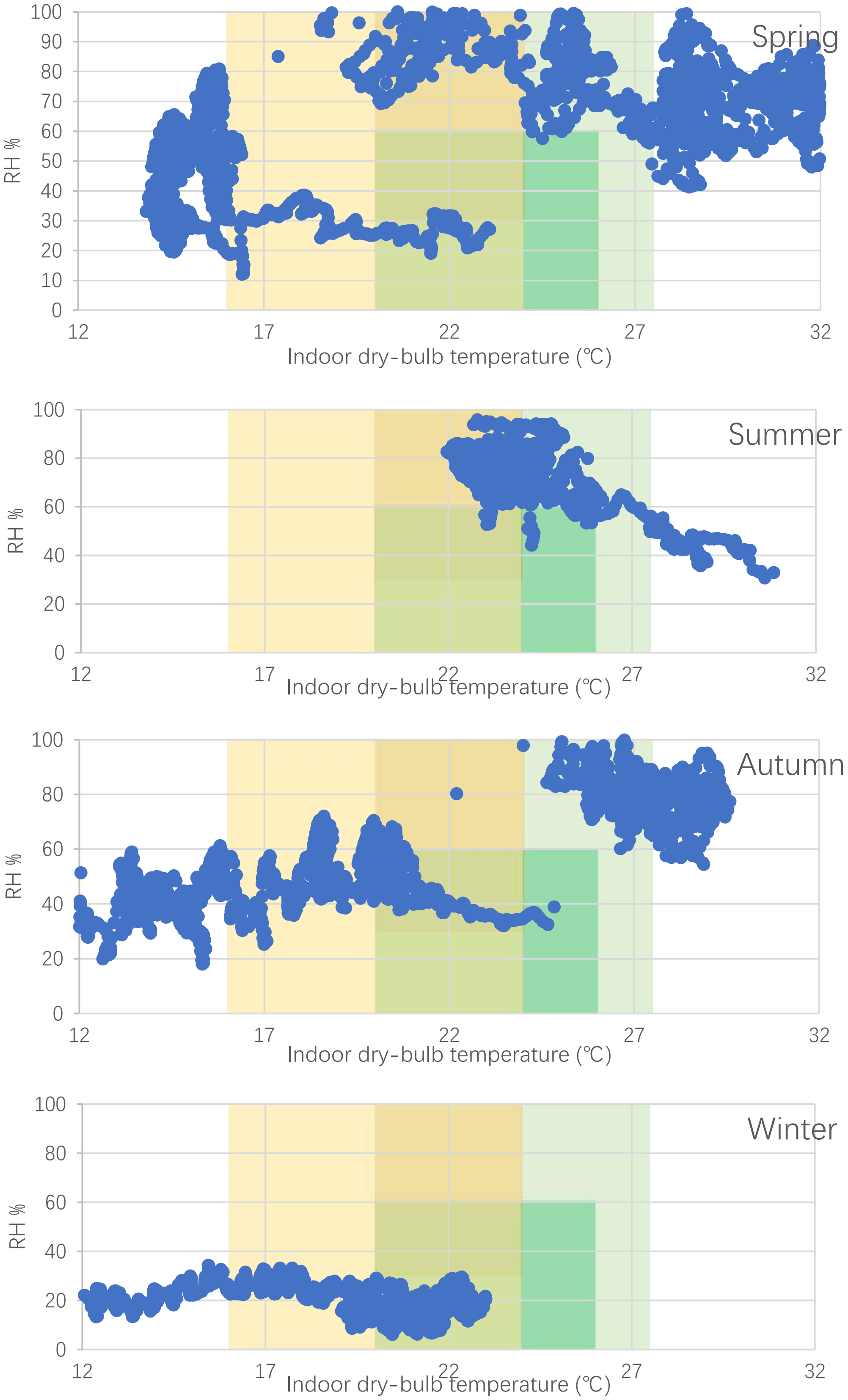


Figure 6.10 The simulated four seasons' dry-bulb temperature and RH distributions of the second-floor bathroom

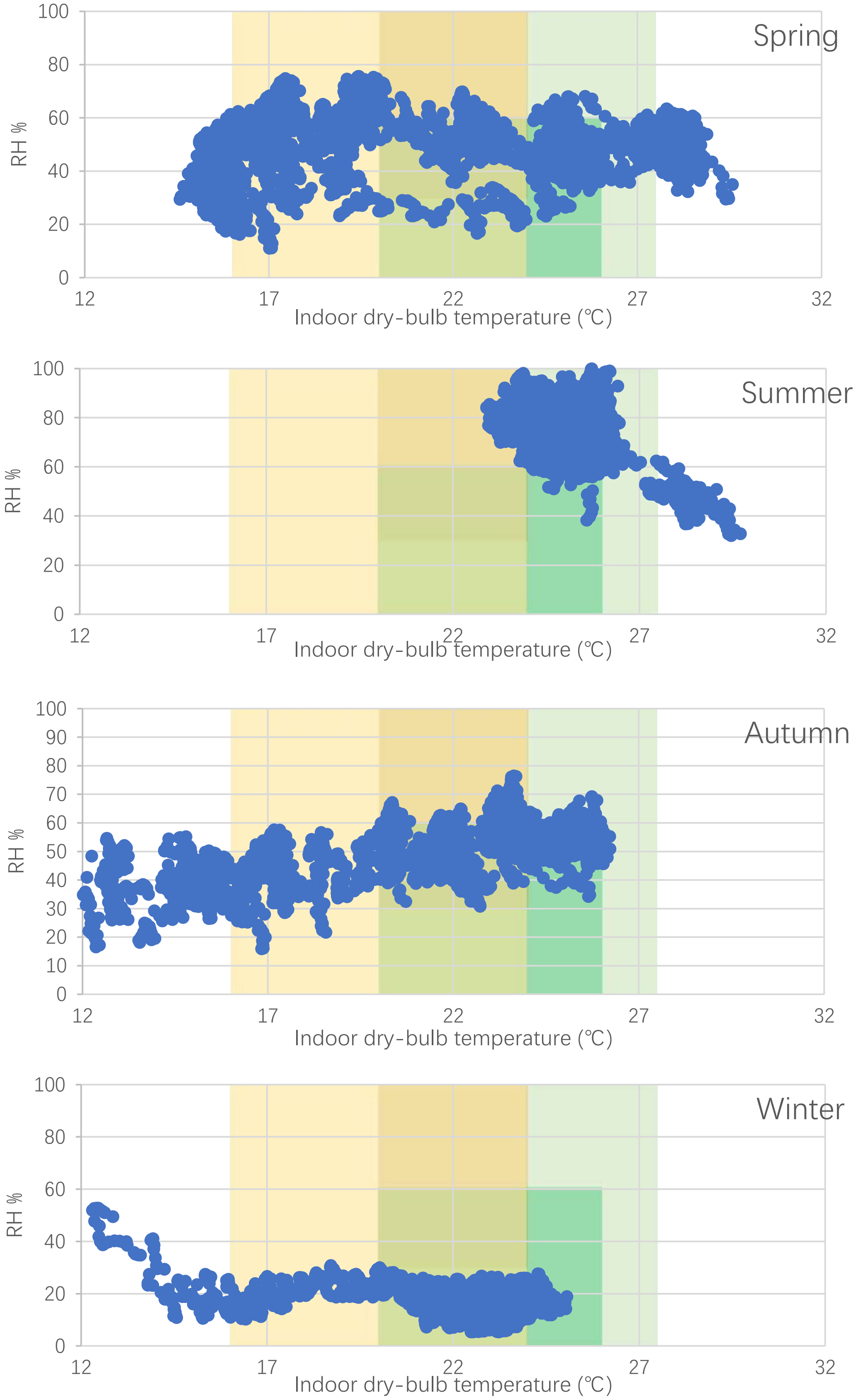


Figure 6.11 The simulated four seasons' dry-bulb temperature and RH distributions of the second-floor main bedroom (south-facing)

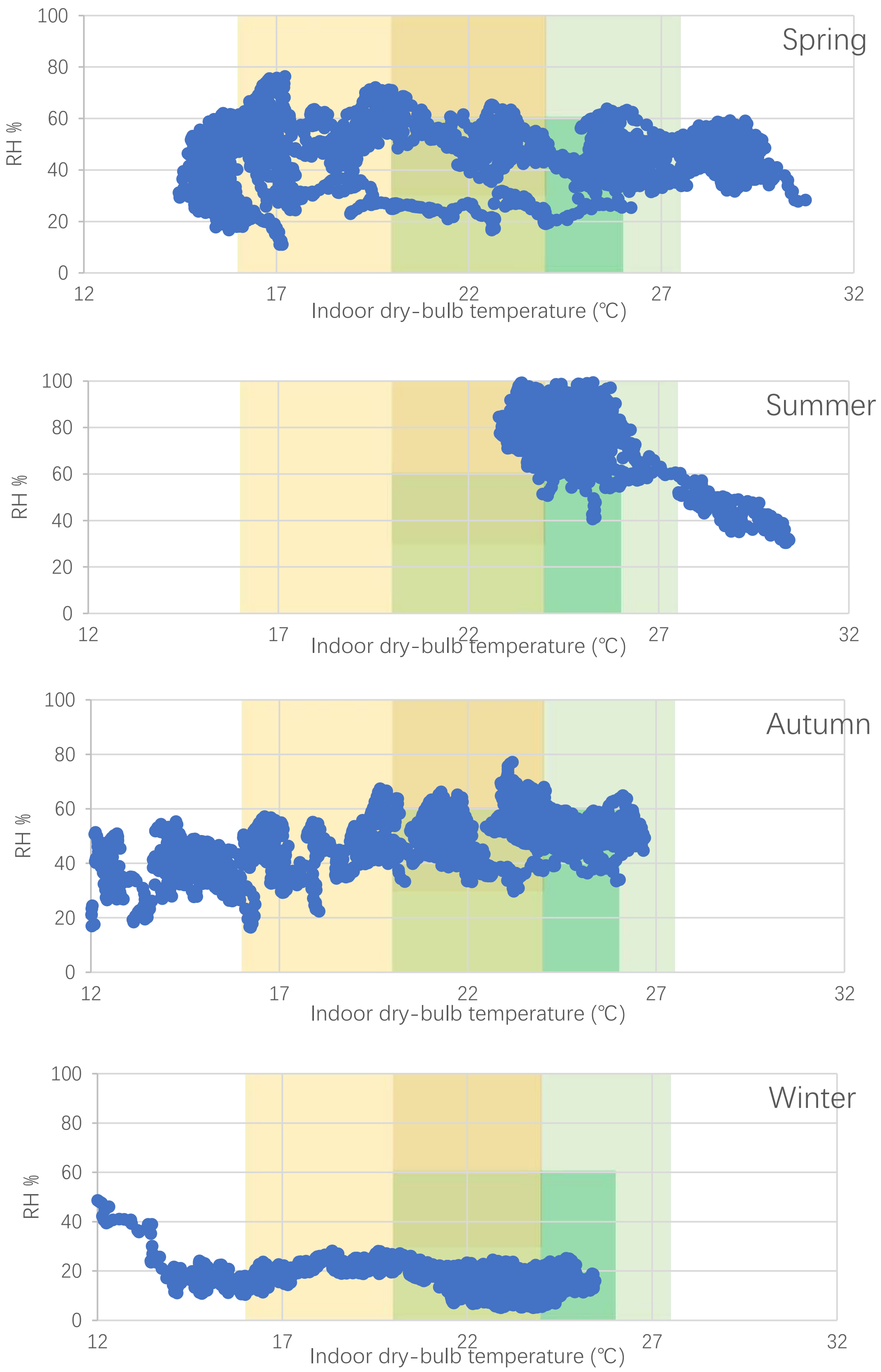


Figure 6.12 The simulated four seasons' dry-bulb temperature and RH distributions of the second-floor kids' bedroom (north facing)

As shown in Figure 6.8 to 6.12, the final design's simulated indoor dry-bulb temperature and RH distributions are very similar to the baseline building. The only difference is that it has slightly more underheat and overheat conditions in all these rooms in all four seasons than the baseline building. This result means that the final design's indoor thermal performance is worse than the baseline building, even though it achieves slightly improvement in energy performance.

6.4 Monitored energy and indoor thermal performance of the constructed building

6.4.1 The data collected and their eligibility

Restrained by the progress of onsite construction, the data collection for the cooling season can only kick off from 20th July 2019, and it ended on 15th Sep 2019. In such a case, it missed the early part of the cooling season. However, it covers the worst cooling condition (hot and wet) for the commissioning of the radiant cooling system, therefore is reliable for the validation purpose. Table 6.9 summarised the commission activities during this period.

Among the above days, some of them are to test the systems' working conditions rather than providing the indoor comfort, and others experienced data losses due to power cut or data collecting signal problems. Therefore, not all of them are eligible for the analysis of the energy and indoor thermal performance. With the available data, the following days shown in Table 6.10 are suitable for the validation of the prototype.

Table 6.9 Journal of the commissioning period

Trial operation	Period	20 Jul	21 Jul	22 Jul	23 Jul	24 Jul	25 Jul				
	Purpose	To be familiar with the system: 1. Test the lowest water supply temperature which causes condensation 2. Understand the fabric's coolth charging process 3. Test the EER of the heat pump under different operations (water supply/return temperature, and different schedules)									
Gap days for switching testing conditions	Period	26 Jul									
	Purpose	Turn off the cooling and conduct whole-house ventilation to heat the building up									
Commissioning	Period	27 Jul	28 Jul	29 Jul	30 Jul	31 Jul					
	Purpose	Commissioning of the data collection sensors and recording/real-time display system									
Commissioning (manual control)	Period	1 Aug	2 Aug	3 Aug	4 Aug	5 Aug	6 Aug	7 Aug	8 Aug		
	Purpose	24hrs running of cooling, occasionally stop for whole-house ventilation when the indoor pollution level was too high, or when the surface temperature approached the rooms' dewpoint which may cause condensation									
Commissioning (manual control)	Period	9 Aug	10 Aug	11 Aug	12 Aug	13 Aug	14 Aug	15 Aug	16 Aug		
	Purpose	whole house ventilation for half-day to reduce the indoor air pollution level	24hrs running of cooling, occasionally stop for whole-house ventilation when the indoor pollution level is too high					Turn off the cooling since 14:00 and conduct whole-house ventilation to heat the building up			
Gap days for switching testing conditions	Period	17 Aug	18 Aug								
	Purpose	Turn off the cooling and conduct whole-house ventilation to heat the building up									
Commissioning (auto control)	Period	19 Aug	20 Aug	21 Aug	22 Aug	23 Aug	24 Aug	25 Aug			
	Purpose	Constant cooling until the monitored parameters achieve the setting point		Two shifts, mid-night + daytime, automatic control to maintain the setpoint							
Commissioning (auto control)	Period	26 Aug	27 Aug	28 Aug	29 Aug	30 Aug	31 Aug	1 Sep	2 Sep	3 Sep	4 Sep
	Purpose	Two shifts, mid-night + daytime, 10 hours in the total operation of the cooling system									
Commissioning (auto control)	Period	5 Sep	6 Sep	7 Sep	8 Sep	9 Sep					
	Purpose	Two shifts, mid-night + daytime, 10 hours in the total operation of the cooling system									
Commissioning (auto control)	Period	10 Sep	11 Sep	12 Sep	13 Sep	14 Sep	15 Sep				
	Purpose	Two shifts, mid-night + daytime, 10 hours in the total operation of the cooling system									

Table 6.10 Suitable days for the validation of energy and indoor thermal performance

Trial operation (not eligible)	Period	20 Jul	21 Jul	22 Jul	23 Jul	24 Jul	25 Jul				
	Reason	The indoor thermal environment did not maintain the requirements of the prototype									
Gap day (not eligible)	Period	26 Jul									
	Reason	The cooling system was off									
Commissioning (data collecting issues, not eligible)	Period	27 Jul	28 Jul	29 Jul	30 Jul	31 Jul					
	Reason	Data lost due to errors of the data collecting system									
Commissioning (manual control)	Period	1 Aug	2 Aug	3 Aug	4 Aug	5 Aug	6 Aug	7 Aug	8 Aug		
	Reason	Apart from 7 Aug, which lost a few hours' data due to onsite power cut, other days are eligible for validation									
Commissioning (manual control)	Period	9 Aug	10 Aug	11 Aug	12 Aug	13 Aug	14 Aug	15 Aug	16 Aug		
	Reason	Only 11 and 14 Aug are eligible for validation. Other days were interrupted by an onsite power cut or window opening to improve indoor air quality									
Gap days	Period	17 Aug	18 Aug								
	Reason	The cooling system was off									
Commissioning (auto control)	Period	19 Aug	20 Aug	21 Aug	22 Aug	23 Aug	24 Aug	25 Aug			
	Reason	Eligible									
Commissioning (auto control)	Period	26 Aug	27 Aug	28 Aug	29 Aug	30 Aug	31 Aug	1 Sep	2 Sep	3 Sep	4 Sep
	Reason	Eligible									
Commissioning (auto control)	Period	5 Sep	6 Sep	7 Sep	8 Sep	9 Sep					
	Reason	Eligible									
Commissioning (auto control)	Period	10 Sep	11 Sep	12 Sep	13 Sep	14 Sep	15 Sep				
	Reason	The outside weather conditions do not satisfy the cooling criteria of the regulation									

This research compared the standard weather data used for simulation with the monitored weather data used for the commissioning of HVAC systems. As shown in Figure 6.13, the monitored outdoor dry-bulb temperature has a satisfying general consistency with the standard weather data in July and August, but a significant fluctuation in September. In total, the average outdoor dry-bulb temperature of the standard weather between 20th July and 9th September is 25.8°C, while the monitored average is 27.8°C over the same period. Therefore, it would be reasonable if the monitored energy performance is slightly higher than the simulated result.

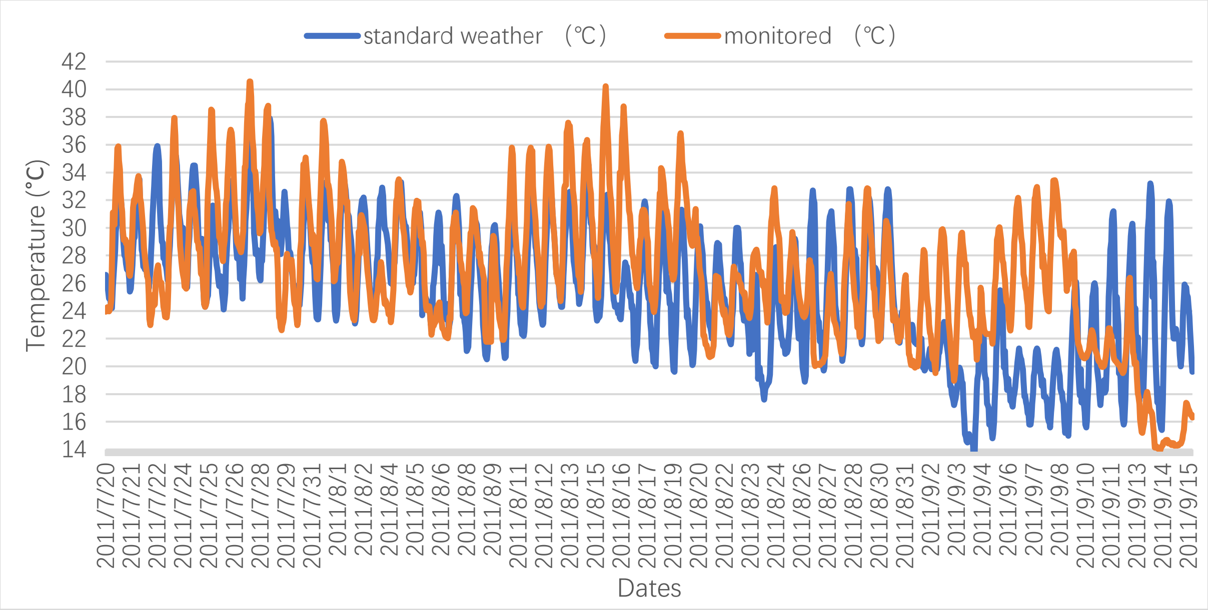


Figure 6.13 Comparison of outdoor dry-bulb temperature between the standard weather and the monitored real weather

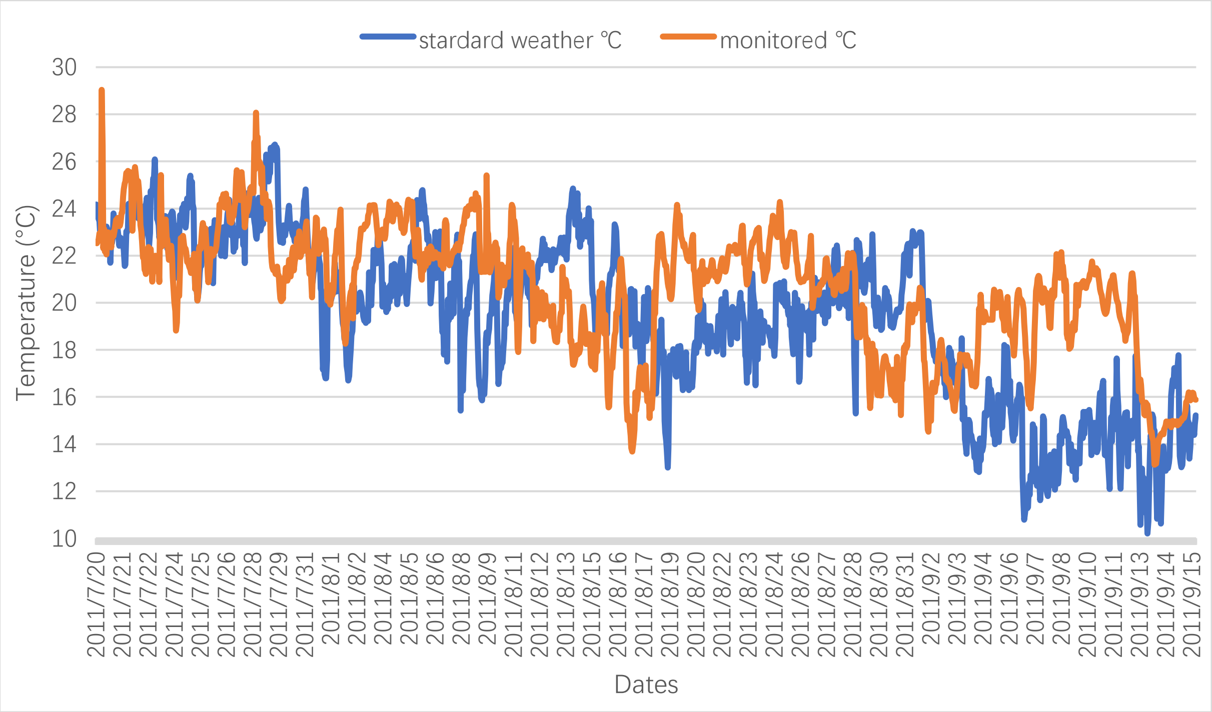


Figure 6.14 Comparison of outdoor dewpoint temperature between the standard weather and the monitored real weather

Note: the dewpoint temperature calculated from the dry-bulb temperature and the RH for the same period. The calculation equation is as follows:

$$Td = RH * (A+B*T) + C + C*T - 19.2$$

Ａ = 0.1980;　Ｂ = 0.0017;　Ｃ = 0.8400

Td: dewpoint temperature, ℃；T: dry-bulb temperature, ℃；RH: relative humidity, ％

Also, Figure 6.14 shows that even with some fluctuations of the dewpoint temperature, the general monitored outdoor dewpoint temperature is higher than the standard weather. The average of the former is 21.0°C, and the latter is 20.0°C. Because the HVAC system of this study case does not deal with dehumidification, such difference will not influence the cooling energy consumption. However, such outdoor condition does mean it is wetter in the hot days, and this will make the indoor condensation risk higher than the simulated situation. Therefore, if the house can manage to avoid condensation in the commissioning, it is for sure able to cope with the standard weather conditions.

Putting Figure 6.13 and 6.14 together, it is clear that the monitored weather condition is generally hotter and wetter than the standard weather. This situation means that this research tested the case study project under tougher conditions than the standard weather. Therefore, if the monitored energy and indoor thermal performance are slightly worse or achieve the simulated performance of the final design, it can be seen as that the prototype successfully guides the project to achieve the required performances.

There is also a necessary clarification to make here that during the commissioning period, there were no occupants in the monitored house. Therefore, the internal gains of heat and moisture are less than the simulated final design. However, given the heat and moisture from occupants are only a small proportion of the total internal gains, the monitored situation is still eligible.

6.4.2 The monitored energy performance of the constructed building

As explained above, there are two main stages of commissioning of the eligible monitored period. The first stage is between 1st August and 16th August, which is to understand the systems' behaviours by the designed schedule and identify the potential of further energy savings. The second stage is between 19th August and 9th September, which is to observe and validate the achievable performance after adjusting the operation of the systems.

With all the monitored weather conditions and commissioning activities, there are 31 days in Table 6.10 (not shaded ones) eligible for the validation of the energy and indoor thermal performance. Among these 31 days, the validation analysis used 15 days divided by three typical operations (Table 6.11).

Table 6.11 The chosen days for performances validation

<table>
<tr><td rowspan="2">Commissioning (manual control)</td><td>Period</td><td>1 Aug</td><td>2 Aug</td><td>3 Aug</td><td>4 Aug</td><td>5 Aug</td><td colspan="2">6 Aug</td></tr>
<tr><td>Reason</td><td colspan="7">Similar outdoor conditions as the simulated final design, and with the same 24 hours cooling schedule</td></tr>
<tr><td rowspan="2">Commissioning (auto control)</td><td>Period</td><td>19 Aug</td><td>20 Aug</td><td>21 Aug</td><td>22 Aug</td><td>23 Aug</td><td>24 Aug</td><td>25 Aug</td></tr>
<tr><td>Reason</td><td colspan="7">Hotter and wetter outdoor conditions than the standard weather, with 24 hours cooling scheduled on 19 and 20 Aug to charge the fabric, and then two shifts schedule to run the systems appropriately. A typical kicking-off process in real operation.</td></tr>
<tr><td rowspan="2">Commissioning (auto control)</td><td>Period</td><td colspan="3">28 Aug</td><td colspan="4">29 Aug</td></tr>
<tr><td>Reason</td><td colspan="7">Very similar outdoor dry-bulb temperature condition, so very suitable to compare the commissioned two shifts schedule operation outcomes with the simulated final design 24 hours schedule's performance.</td></tr>
</table>

With the collected data, this research found the following results.

Table 6.12 The energy status of the analysed days

Time	**Daily average renewable generation**	**Daily average cooling load**	**Daily average heat pump energy consumption**	**Daily average EER**
	(kWh)	**(kWh)**	**(kWh)**	
1 – 6 Aug	14.1	67.7	25.0	2.7
19 – 25 Aug	10.8	69.4	20.6	3.4
28-29 Aug	18.6	65.1	17.7	3.7

The summarised results in Table 6.12 shows that the actual monitored EER varies under different operation methods. There is a significant gap of EER between the manufacturer's reference number (5.07), which the simulation used for the baseline building and the final design, and the monitored results (2.7 to 3.7). There is an even more significant gap of cooling energy consumption between the simulated results of the final design and the monitored results of the constructed building. However, before drawing any conclusion on whether the prototype failed to guide the studied project to achieve high energy performance, the monitored indoor thermal performance has to be clarified.

6.4.3 Monitored indoor thermal performance of the constructed building

Figure 6.15 shows the indoor dry-bulb temperature, and the RH distributions of the analysed 31 days. Comparing with the summer conditions in Figure 6.8 to Figure 6.12, the identified similarities and differences are:

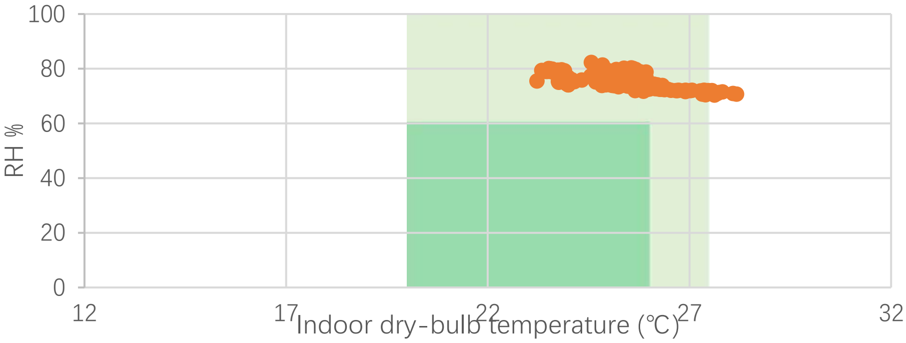
Similarities

- The indoor distributions of RH are significantly higher than China's NZE standard (60% maximum). Even without any internal moisture source during the commission period, the internal RH of the bedrooms are commonly above 70%, and even approaching 90% in the kids' bedroom on the second floor with north facing.
- The character of the fabric heat storage's charging period is the same. When cooling the house from external temperature to the required comfort zone, shows a linear relationship between the indoor dry-bulb and RH distribution.
- In general, the data dots located in the light green area (regulated comfort zone), but there are a few dots points outside it.

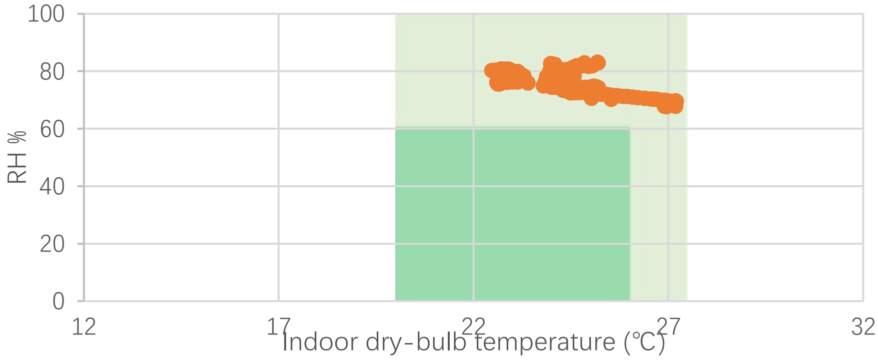
Differences

- The start point of cooling is lower and wetter than the simulated results in all the rooms. This condition is mainly due to the lack of internal heat sources and wetter outside condition in the commissioning period.

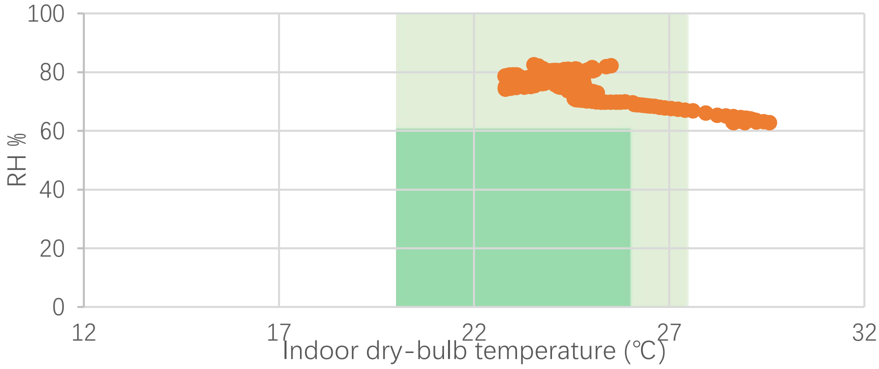
These monitoring results show that even though the simulated and monitored conditions are different, both indoor and outdoor, the prototype at the project level (baseline building) can well guide the final design and construction to achieve its required indoor thermal comfort level.



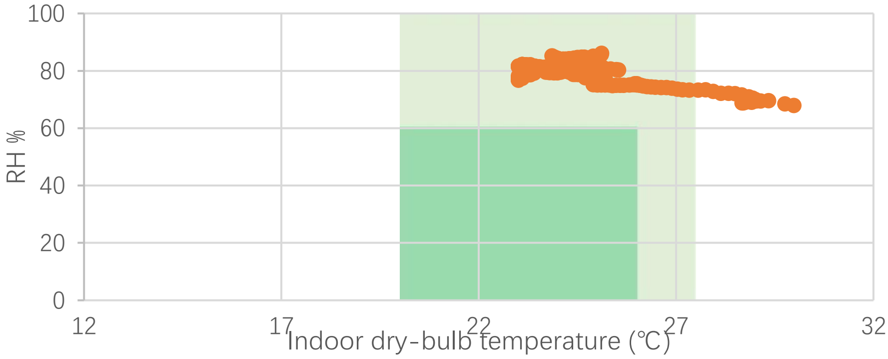
(a) Kitchen



(b) Living room



(c) Second-floor Main bedroom (South-facing)



(d) Second-floor Kids' bedroom (North-facing)

Figure 6.15 The indoor dry-bulb temperature and RH distributions of the three analysed periods

6.5 Analysis of the reasons for performance gaps among baseline building, final design, commissioning and China's NZE standard

From section 6.2 to section 6.4, it can conclude that the prototype can set up a good start point for the final design and construction to achieve the required indoor thermal performance. However, there is no considerable improvement from the prototype to the final design in terms of energy performance. The monitored energy performance did not achieve the predicted level of the final design either. Therefore, this research made the following analysis to identify the reasons and discuss possible improvements in the future.

It must be noted here that the simulated performance and the monitored performance are not directly comparable. In the simulation at the design stage, internal gains must be involved so that the prediction can get closer to the occupied situation. For the monitoring in this research, because it conducted at the commissioning stage, no occupants or indoor activities could be involved. However, the research can still compare the general level of performance, because the design set the whole cooling season for mechanical ventilation, which is the case in commissioning as well. In such a case, the occupants' interruption to the indoor environment narrows to the internal heat and moisture gain. Therefore, it is easy to foresee the situation when occupants are involved.

6.5.1 The gaps of indoor thermal performance among the baseline building, final design and commissioning

In order to discuss indoor thermal performance, outdoor conditions need to clarify at the same time. As explained above, the proposed HVAC systems of this case study do not deal with dehumidification. In that case, the indoor dry-bulb temperature could be controlled by the radiant cooling system to the wanted point, but the indoor RH will fluctuate with the outdoor condition (no internal sources at the commissioning stage). Table 6.13 is a summary of the indoor and outdoor conditions of the prototype (simulated), final design (simulated) and the commissioning (monitored) of the three analysed periods.

Table 6.13 Thermal conditions comparison of the monitored cooling period

Compared features	Simulated		Monitored
	Baseline building	Final design	Commissioning
1-6 Aug			
Outdoor average dry-bulb temperature (°C)	28.3		27.3
Indoor average dry-bulb temperature (°C)	24.3	24.4	24.1
Outdoor average dewpoint temperature (°C)	20.8		22.4
Indoor average dewpoint temperature (°C)	21.8	21.9	20.8
Condensation risks (hours)	188	191	10
19-25 Aug			
Outdoor average dry-bulb temperature (°C)	24.4		26.9
Indoor average dry-bulb temperature (°C)	23.5	23.5	24.4
Outdoor average dewpoint temperature (°C)	18.6		22.0
Indoor average dewpoint temperature (°C)	19.4	19.8	20.4
Condensation risks (hours)	55	69	16
28-29 Aug			
Outdoor average dry-bulb temperature (°C)	26.6		26.5
Indoor average dry-bulb temperature (°C)	23.5	23.7	23.1
Outdoor average dewpoint temperature (°C)	20.8		19.9
Indoor average dewpoint temperature (°C)	21.8	21.4	19.6
Condensation risks (hours)	67	56	5

Note:

1. **Outdoor average dry-bulb temperature (°C):**
The hourly average outdoor dry-bulb temperature of the standard or monitored weather
2. **Indoor average dry-bulb temperature (°C):**
The hourly average indoor dry-bulb temperature of the simulated or monitored indoor conditions
3. **Outdoor average dewpoint temperature (°C):**
The calculated hourly average outdoor dewpoint temperature (see Figure 6.14's equation) of the standard or monitored weather
4. **Indoor average dewpoint temperature (°C):**
The calculated hourly average outdoor dewpoint temperature (see Figure 6.14's equation) of the standard or monitored weather
5. **Condensation risks (hours):**
The total hours in which the indoor simulated or monitored average RH is more than 90%
6. **The indoor average dry-bulb temperatures do not include kitchen, toilet and storages**

Without indoor heat and moisture sources during the commission stage, it is hard to conclude whether the house can achieve the predicted thermal performance in the cooling season. However, comparing the three periods' results, it can be seen that the indoor dry-bulb and dewpoint temperature are lower than the predicted level, when the outdoor conditions are better (1-6 Aug) or similar (28-29 Aug). When the outdoor weather is significantly hotter and wetter (19-25 Aug), these two parameters are slightly higher than the prediction of the same period, but still within the prototype's required level. Notably, the monitored condensation risk hours are significantly lower than the prediction. Even though it achieved without internal heat and moisture sources, it is still a piece of substantial evidence to show that the designed HVAC systems have a strong capability to achieve the required indoor thermal performances. It is also able to conclude that there are no apparent gaps in the indoor thermal performance among the baseline building, final design and commissioned operation in the analysed cooling periods.

For other seasons, however, even though they have not yet commissioned by monitoring, the simulation results of the final design have shown some gaps. Table 6.14 and Table 6.15 shows the comparison of the simulated indoor dry-bulb temperature and RH between baseline building and the final design.

Table 6.14 Simulated thermal conditions comparison between the baseline building and the final design in winter (1 Dec to 28 Feb), spring (1 Mar to 14 Jun) and autumn (1 Sep to 30 Nov)

Compared features	Winter		Spring		Autumn	
	Baseline building	Final design	Baseline building	Final design	Baseline building	Final design
Outdoor average dry-bulb temperature (°C)	1.3		16.5		13.3	
Indoor average dry-bulb temperature (°C)	22.6	22.5	20.9	21.7	20.5	20.4
Outdoor average RH (%)	65.9		66.3		72.5	
Indoor average RH (%)	17.0	17.0	51.3	49.2	48.6	48.1

Table 6.14 shows that in all the three seasons, the average indoor conditions are very similar. No matter the average indoor dry-bulb temperature or the RH, the gaps are less than 0.8 °C and 2.1%. Therefore, it can be concluded that in all the three seasons, both the baseline building and the final design can achieve the required comfort level in general.

However, when looking at the uncomfortable hours, the final design performs generally worse than the baseline building (Table 6.15), although the condensation risk improves significantly. The final design has considerably more underheat hours in autumn and winter than the baseline building, while significant more overheat hours in spring and winter. This result points out that changing glazing-to-wall ratio in the last minute makes visible negative impacts on the indoor thermal performance. Moreover, underheat and overheat in spring and autumn will make the occupants operate the HVAC system longer to cope with the discomfort, which leads to worse energy performance in real operation as well.

Table 6.15 Comparison of simulated uncomfortable hours between the baseline building and the final design in winter (1 Dec to 28 Feb), spring (1 Mar to 14 Jun) and autumn (1 Sep to 30 Nov)

(a) Winter

Compared features		Winter					
		Living room	Guest room	Second main bedroom	Kids' room	Main bedroom	Total
Baseline	Underheat period (hours)	61	109	52	132	101	455
	Overheat period (hours)	382	287	1667	256	193	2785
	Condensation risks (hours)	0	0	0	0	0	0
Final design	Underheat period (hours)	79	129	61	150	132	551
	Overheat period (hours)	1057	325	1517	262	90	3251
	Condensation risks (hours)	0	0	0	0	0	0

(b) Spring

Compared features		Spring					
		Living room	Guest room	Second main bedroom	Kids' room	Main bedroom	Total
Baseline	Underheat period (hours)	482	636	373	508	407	2406
	Overheat period (hours)	775	893	885	960	909	4422
	Condensation risks (hours)	15	0	0	0	0	15
Final design	Underheat period (hours)	245	427	194	376	282	1524
	Overheat period (hours)	1013	971	965	994	974	4917
	Condensation risks (hours)	5	0	0	0	0	5

(c) Autumn

Compared features		Autumn					
		Living room	Guest room	Second main bedroom	Kids' room	Main bedroom	Total
Baseline	Underheat period (hours)	256	477	332	501	436	2002
	Overheat period (hours)	700	447	534	475	364	2520
	Condensation risks (hours)	16	15	14	3	4	52
Final design	Underheat period (hours)	314	497	369	507	454	2141
	Overheat period (hours)	645	473	491	496	373	2478
	Condensation risks (hours)	1	0	0	0	0	1

Note:

1. **Underheat period (hours):** Whenever the hourly average indoor temperature is lower than 16 °C

2. **Overheat period (hours):** Whenever the hourly average indoor temperature is higher than 24 °C
3. **Condensation risks (hours):** The total hours in which the simulated indoor hourly average RH is more than 90%

6.5.2 The gaps of energy performance among the baseline building, final design and commissioning

In order to make the monitored data comparable to the simulated results of the base building and final design, it needs to calculate the cooling energy consumptions of the same period. Table 6.16 summarises the results of the three situations.

Table 6.16 Comparison of cooling energy consumptions of the same period for the baseline building, final design and commissioning

Compared features	Simulated		Monitored
	Baseline building	Final design	Commissioning
1-6 Aug (monitored outside condition is cooler but wetter than standard weather data)			
Average daily cooling load (kWh)	63.7	63.7	67.7
EER for converting to the energy consumption	5.07	5.07	2.7
Heat pump energy consumption (kWh)	12.6	12.6	25.0
19-25 Aug (monitored outside condition is hotter and wetter than standard weather data)			
Average daily cooling load kWh)	45.9	45.9	69.4
EER for converting to the energy consumption	5.07	5.07	3.4
Heat pump energy consumption (kWh)	9.1	9.1	20.6
28-29 Aug (monitored outside condition is similar standard weather data)			
Average daily cooling load (kWh)	47.7	47.7	65.1
EER for converting to the energy consumption	5.07	5.07	3.7
Heat pump energy consumption (kWh)	9.4	9.4	17.7

Table 6.16 shows that there is no energy performance gap between the baseline building and the Final design in the three cooling periods. However, there is a significant gap between the final design and the monitored operation. Through analysis, the gap comes from two aspects: 1) The higher average daily cooling load shows that the completed envelope of the building is weaker than the design specifications. 2) The significant higher heat pump energy consumption is a result of much lower EER of the heat pump, which indicates a much lower system efficiency than the manufacturer's lab test results for the standard conditions.

In terms of the envelope, two possible reasons could cause worse energy performance: airtightness and thermal bridge. There is no blower door test to confirm the actual infiltration rate of the house, but one test in the commissioning can give a brief sense of infiltration level.

Figure 6.16 shows the changing of the indoor dry-bulb temperature and dewpoint temperature in the kitchen on 16 August 2019. On that day, all the windows and doors opened between 7:00 and 9:00 for whole-house ventilation. This operation would get rid of all the previous indoor moistures and keep the absolute humidity similar between indoor and outdoor condition. Then all the windows and doors were shut between 9:01 to 11:00, and re-opened between 11:01 and 12:00, in order to check whether the dewpoint temperature trends of indoor and outdoor are the same. As can be seen in Figure 6.16, the two dewpoint temperature lines did fluctuate correspondently. This phenomenon means that there were no apparent indoor moisture sources to change the indoor dewpoint temperature’s changing trend.

In the meantime, the radiant cooling system was off between 7:00-9:00 in order to avoid condensation when windows and doors were open. Then it was turned on with 18℃ supply water temperature between 9:01 and 11:00. Figure 6.16 presents that the kitchen’s dry-bulb temperature reduces about 1℃ during this time, but the indoor dewpoint temperature did not change much. This result confirms that the radiant cooling system did not cause an increase or decrease of moisture level in the kitchen. Then the radiant cooling system was turned off again between 11:01 and 12:00 when the windows and doors were re-opened. In Figure 6.16, the kitchen’s indoor dewpoint temperature fluctuated as the same trend as the outdoor one during this period. It was turned on again between 12:01and 14:00 to keep the fabric cool for the testing of heat transfer through infiltration.

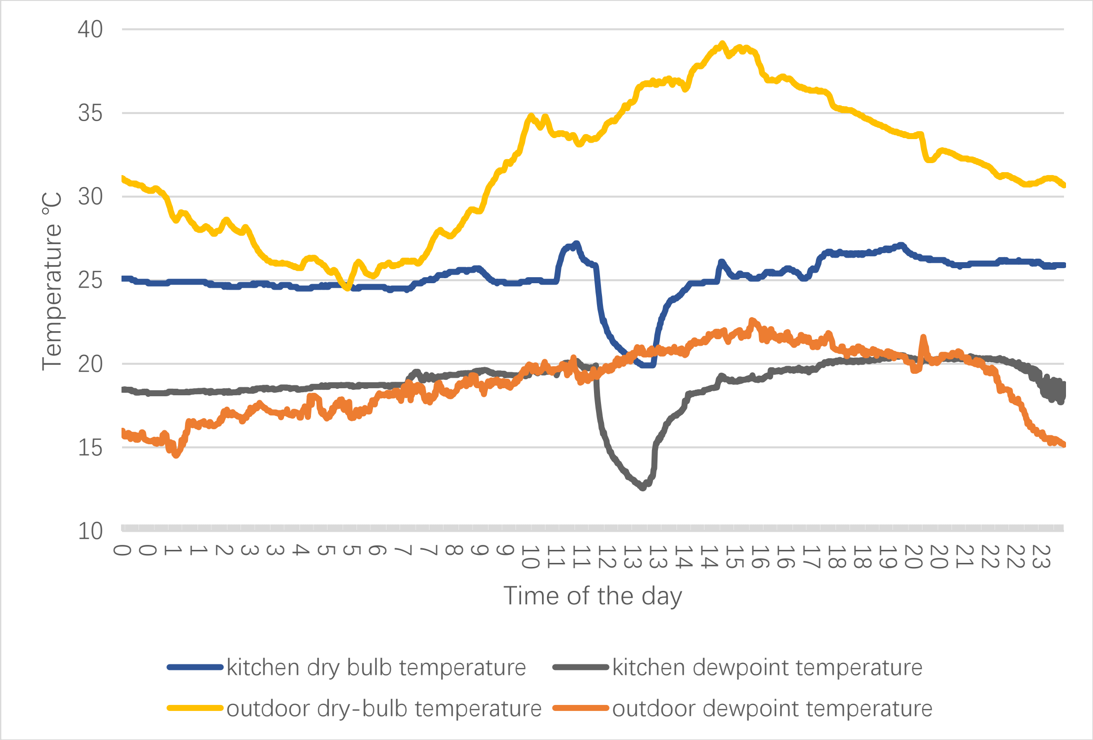


Figure 6.16 The testing process of indoor moisture level change in the kitchen to reflect the airtightness level

Until this point, the indoor environment established a stable moisture transfer between indoor and outdoor. The above procedure demonstrated that the indoor dewpoint temperature would only be influenced by infiltration when no internal moisture sources were involved. It also changed with the same trend as the outdoor dewpoint temperature.

Then, all the windows and doors shut off again, and the detached air-conditioner turned on at 20℃ on 12:01. The detached air-conditioner was off on 13:14℃ when the kitchen’s indoor dry-bulb temperature reached 20℃ and stabilised for 18 minutes. This operation extracted moisture from the air in the kitchen because it reached the dewpoint temperature of the previously established stable condition. As shown in Figure 6.16, the kitchen’s dewpoint temperature reduced from 19.8℃ on 12:01 to 12.5℃ on 13:14. This result means a significant amount of moisture was taken out of the air in the kitchen during that time.

From 13:15 on the detached air-conditioner was kept shut, and the kitchen's indoor dry-bulb temperature and dewpoint temperature rose quickly in the same trend. Then, it re-established the slow-changing trend from 14:26.

This testing shows good coordination that it took 73 minutes to reduce the kitchen's indoor moisture from stably high to stably low by air-conditioned dehumidification. Then without any interruptions of an indoor moisture source, the infiltration took 72 minutes to raise the dewpoint temperature level from stably low to stably high again.

When infiltration is the only interruptive factor of the moisture level, one air change per hour level means that within 60mins the whole indoor air will be replaced by the outdoor air. Therefore, after turning off the detached air-conditioner, the indoor dewpoint temperature would come back to a stable high level in 60 minutes. In the test, it took 72 minutes, which equals 0.83 air change per hour.

The infiltration rate refers to air change per hour under 50 Pa air pressure, which is much higher than the pressure of standard natural ventilation mode. Therefore, it evidences that the completed house did not achieve the assumed airtightness level at the design stage. Without a blower door test, it is not possible to know the actual infiltration rate. However, the simulation test shows that the cooling load of 28-29 August would be averagely 50.0 kWh per day if changing the infiltration rate from 0.8 to 1.2 change per hour under 50 Pa. This outcome is only a 4.8% increase in the final design's simulated cooling load (47.7 kWh). Consequently, airtightness is unlikely to be the principal reason for the vast energy performance gap between monitored energy performance (averagely 65.1kWh per day) and the predicted value (47.7 kWh) during this period.

In terms of the thermal bridge, there was no test carried out in the commissioning, so it is hard to conclude the extent of its impact on energy performance. However, the images of the completed construction do show a lot of thermal bridge points. According to BRE's research (2019) that 'thermal bridging can be responsible for up to 30% of a dwelling's heat loss'. For the proposed thermally activated fabric radiant cooling, the influence could be even more significant than the traditional air-conditioning system. The air-conditioning mode mainly loses heat through convection, but the activated fabric loses heat by both conduction and convection. That is why the latter will be more sensitive to the thermal bridge.

Through comparing the cooling load of the baseline building, final design and commissioned operation during 28 – 29 August (similar outdoor conditions), it found that the monitored average daily cooling load is about 1.36 times more than the simulated figures (Table 6.16). If taking away the 4.8% cooling load increase due to poorer airtightness, there would be a 31.2% increase in cooling load. If further taking away the heat transfer between the cooled and uncooled houses, the unidentified cooling load increase is about 12.4%. Such a portion of heat loss reflects BRE’s (2019) research of thermal bridge’s impact on a dwelling, as well as the problems identified in the completed house. The content in Appendix 6 explains the modelling validation results after the commissioning to reach such a conclusion. Such a situation reflects BRE’s (2019) research of thermal bridge’s impact on the heat loss of a dwelling, as well as the system’s specific character.

Thus, it might be concluded that both the more inferior air-tightness level and thermal bridge status lower down the energy performance, with thermal bridge takes a larger share of the negative impact.

For the actual heat pump energy consumption, with the similar outdoor conditions during 28-29 August 2019, the monitored figure is 1.88 times higher than the prediction. Despite the 36% increase of the cooling load, the monitored EER (3.7) during this period is significantly lower than the assumed EER (5.07). If running the heat pump as simulated 24 hours, even though the outdoor condition is cooler (1-6 August 2019), the cooling energy consumption is worse (1.98 times higher than the simulation).

It is not an unusual situation that the actual system efficiency is lower than the assumed figure in design. Therefore, the proposed monitoring is to identify the possible reasons, and it found the following three reasons:

1) **When the pump was running without cooling effect, it wasted energy, and even worse, sometimes the stored coolth was extracted from the fabric to outside**

In Figure 6.17, there were many occasions that the heat pump still consumed energy when no cooling load was involved. The reason is that when the heat pump runs in 24 hours, the return water temperature will get closer and closer to the supply temperature until they are the same (Figure 6.18). It means that the fabric is ‘fully charged’ and does not need any more coolth for a while. Therefore, the compressor will not work because the return water’s temperature is equal to the supply water. In such a case, the heap pump only consumed energy for circulating the water without providing any cooling, and the EER turns to 0.

Sometimes the EER is even less than 0, which means the system extracted coolth out of the fabric when the compressor was not on. This outcome is due to the heat pump’s location, which is on the top of the roof and exposed to the sun (Figure 2.19). When the compressor did not turn on, the sun heated the plant and main pipes on the roof. In the meantime, the quickly returned water still kept the temperature as the chilled fabric; therefore, slightly lower than the supply temperature (Figure 6.20). Then the heated water was pumped backed to the fabric immediately, which was cooled by the fabric rather than the heat pump. These part of coolth was emitted to the air on the roof and wasted.

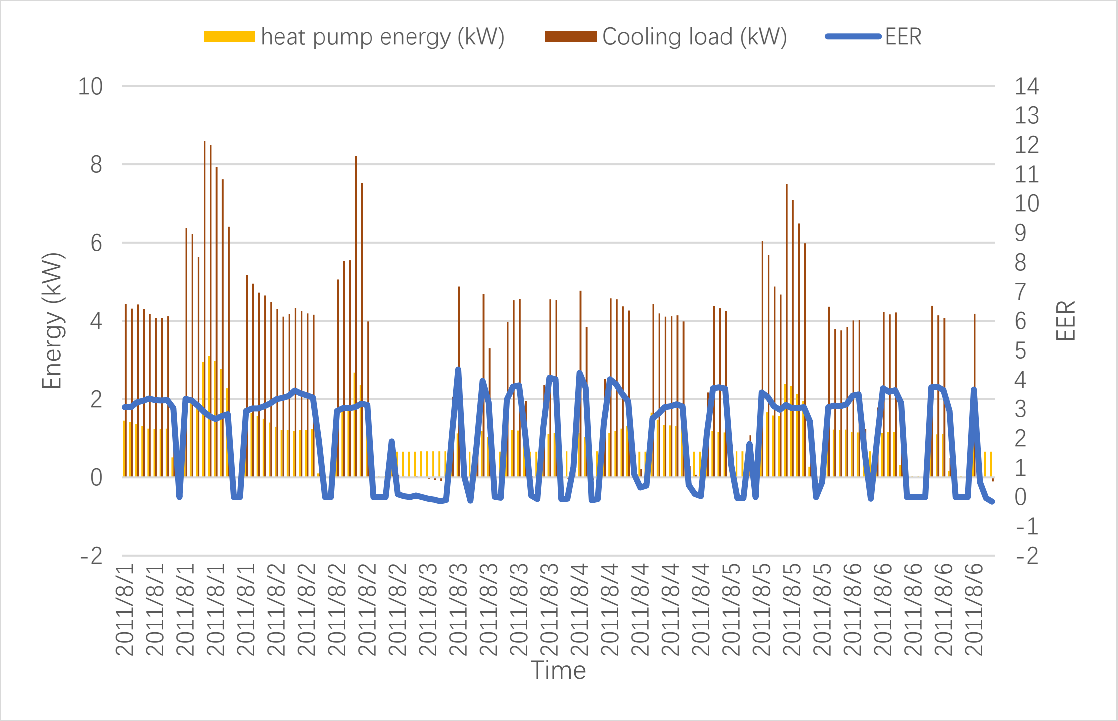


Figure 6.17 Monitored cooling load, heat pump energy consumptions and EER (1 – 6 August 2019)

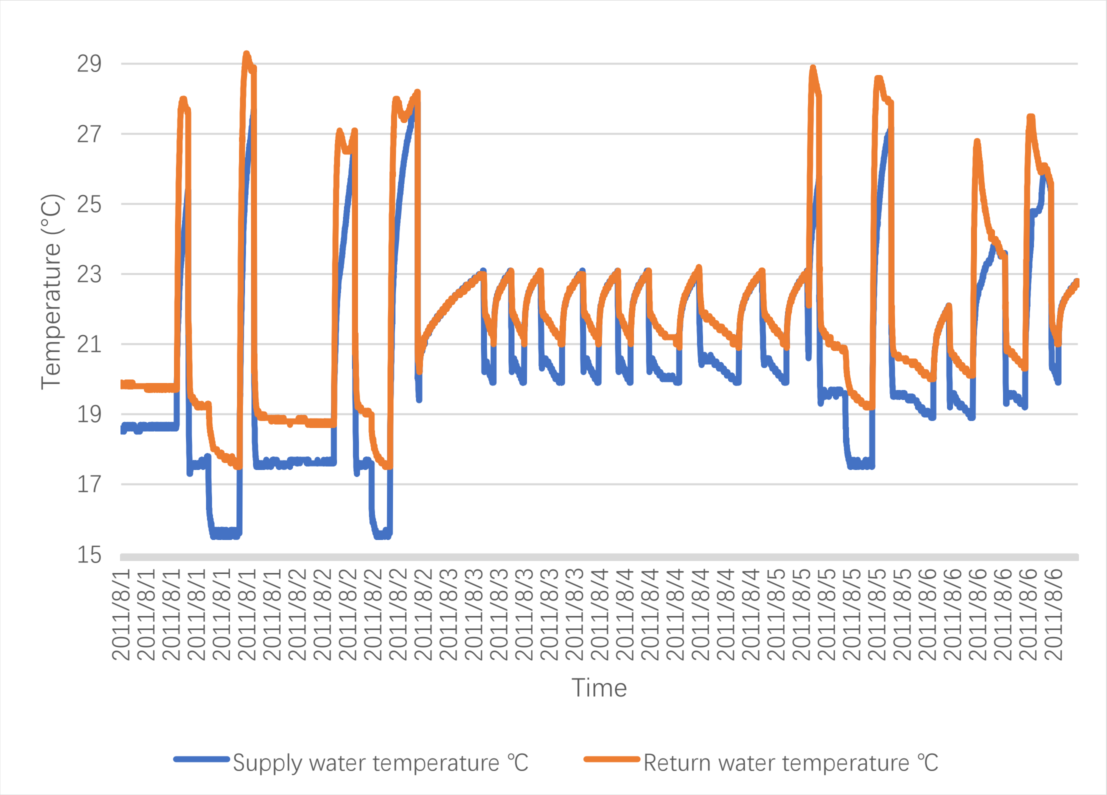


Figure 6.18 Monitored supply and return temperature of the heat pump (1 – 6 August 2019)

Figure 6.19 Heat pump system outdoor unit on the roof

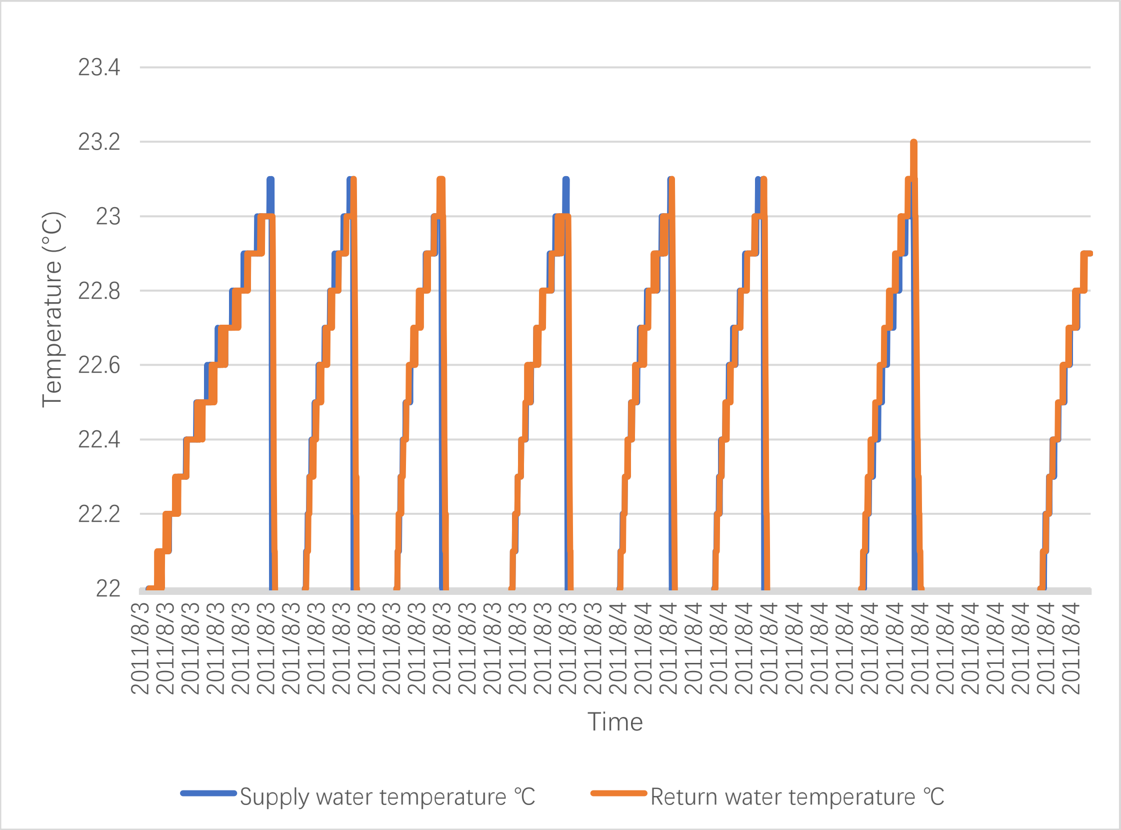
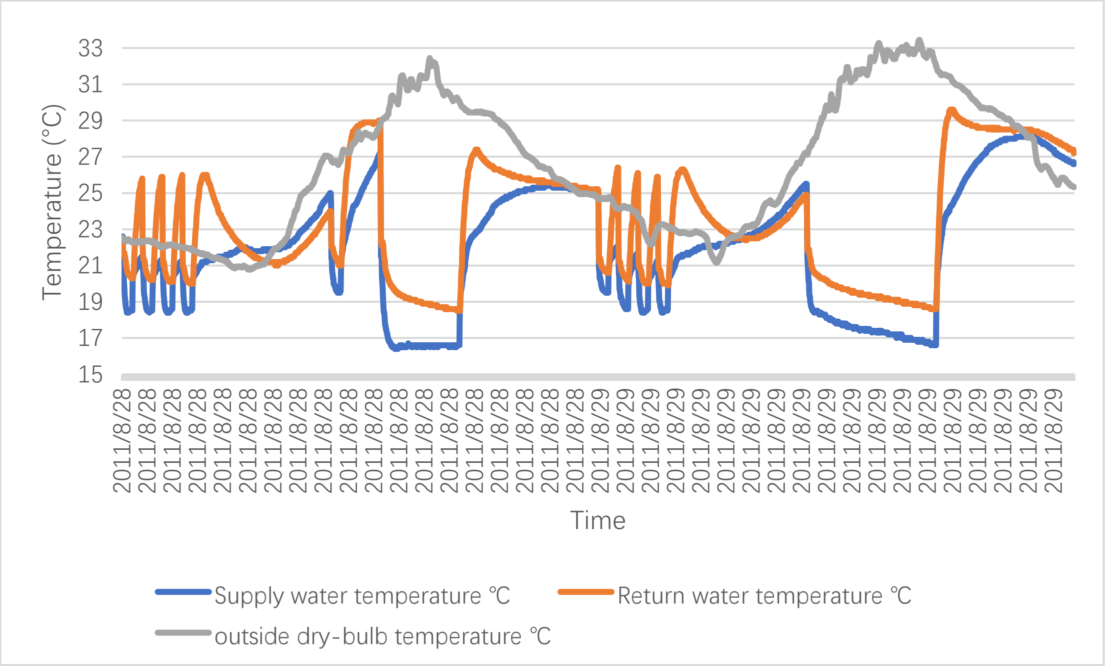


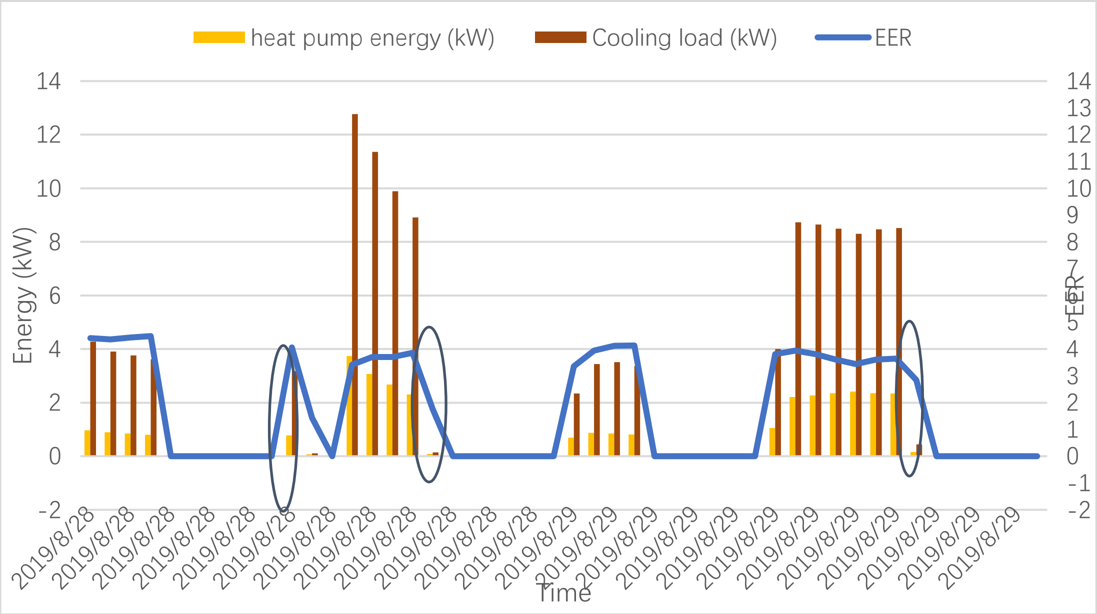
Figure 6.20 Monitored supply and return temperature of the heat pump (3-4August 2019)

2) Inaccurate control caused by the location of sensors

As explained above, the sensors of supply and return water temperature of the heat pump are pre-embedded with the external plant. The plant locates on the flat roof and directly exposes to the sun (Figure 6.19). As a result, the monitored supply and return water temperature are primarily interrupted by the heat gain from solar radiation and external temperature. Figure 6.21 (a) shows that when the heat pump is not on, and the sun shines, the measurement of return temperature went anamorphic. It immediately jumped up from the original return water temperature to close to or even higher than the outdoor dry-bulb temperature. This phenomenon shows that the sensor exposed to the external environment. Therefore, the measured temperature will always be higher during the daytime than the actual situation. As a result, the plant would not be able to stop at the point when the actual return water temperature reaches the set point. This outcome will waste the pump and the compressor's energy consumption because they cannot be off at the time when cooling is no longer needed (highlighted in grey ovals in Figure 6.21 (b)). Even though this part of the energy is not major when looking at them individually, it will be a considerable waste when accumulating them together throughout the whole cooling season.



(a) Supply and return water temperature of the heat pump



(b) Cooling load, heat pump energy consumptions and EER

Figure 6.21 Monitored energy consumption and water temperature of the heat pump (3-4August 2019)

3) The difference between supply and return water temperature is too small

As can be seen from Figure 6.18 that the difference between supply and return water temperature of the radiant cooling system is generally less than 1.5°C when running 24 hours. After commissioning and running for only 10 hours a day, it improves to 1.5-2°C, but such difference is still too small (Figure 6.21(a)). This temperature difference is not economical, because it means the pump consumed the majority of the energy for water circulation.

The fundamental reason is the oversised pump for the proposed system. The standard pump for the heat pump used in this project consumes 550W electricity per hour, while the used one was oversised on purpose and used 750W electricity per hour. The designer chose a bigger pump for two reasons:

- To overcome the extra resistance caused by denser water loops
- To meet the peak cooling load quicker by circulating the water in higher speed, therefore, the system will have larger volume chilled water to take away the heat

The monitoring result shows that these two purposes were successfully served by the oversised pump, because:

- The return water temperature can quickly catch up with the supply water temperature, and distributed evenly in the house.
- The monitored charging time of the fabric when kicking off the system is about 33 - 42 hours depends on the external dry-bulb temperature, which is quicker than the simulated 54 hours

However, the less than 2°C temperature difference between supply and return temperature shows it is too much oversised, which harms the system efficiency.

In a word, the weakened fabric and reduced efficiency system together cause worse performance than the prediction at the design stage.

Finally, for the renewable energy generation, there are no directly monitored figures because the system has not got grid licence yet. However, the weather station on the roof monitored the solar radiation on the 1-minute interval and the wind speed on the 1-second interval. Based on the same theoretical calculation as made for the baseline building and the final design, comparison can be made.

Table 6.17 Comparison of the weather status for renewable energy generation calculation

Compared features	Simulated	Monitored
	Baseline building & final design	Commissioning
1-6 Aug (monitored outside condition is cooler but wetter than standard weather data)		
Average daily solar radiation (W/m^{2}day)	4551.7	3640.2
Average wind speed (m/s)	2.6	1.1
Average daily renewable energy generation (kWh)	18.0	14
19-25 Aug (monitored outside condition is hotter and wetter than standard weather data)		
Average daily solar radiation (kWh)	4213.3	3257.6
Average wind speed (m/s)	1.3	1.2
Average daily renewable energy generation (kWh)	16.2	10.8
28-29 Aug (monitored outside condition is similar to the standard weather data)		
Average daily solar radiation (kWh)	4424.0	4853.7
Average wind speed (m/s)	2.3	0.9
Average daily renewable energy generation (kWh)	17.4	18.6

Note: The average daily renewable enegy generation is calculated based on the standard or monitored weather data. Table A5-3 gives an example of PV energy generation calculation on 28th August, based on standard weather data. Table A5-4 gives an example of micro wind-turbine energy generation calculation on 29th August, based on standard weather data.

Table 6.17 shows that the renewable energy generation has a more substantial variation from the predicted figure, comparing with the energy performance predictions (Table 6.16). This result is due to the random nature of solar radiation and wind speed. However, Table 6.17 presents that onsite solar and wind resource are generally less than the standard weather. Apart from the specific weather of the monitored year, it indicates that the surrounding high-rise buildings could have created some shelters to these two natural resources.

6.5.3 The gap of performances among China's NZE standard, prototype and monitored figures

Section 6.5.2 analyses the performance gaps among the simulated baseline building, the final design and the monitored situation during commissioning. Despite not achieving the simulated performances, the results confirm that the completed house still performs better than the prototype's theoretical benchmarks, and not far from China's NZE standard.

Figure 6.22 shows that the average hourly dry-bulb temperature of the six mainly occupied rooms (living room, dining room and four bedrooms) is well maintained under 26 ℃ after the kicking off stage. This condition has achieved both the prototype (based on the current building regulations, light green area in Figure 6.22) and China's NZE standard for indoor dry-bulb temperature (dark green area in Figure 6.22).

The average hourly indoor RH of the six mainly occupied rooms is significantly higher than China's NZE standard because current building regulations (hence the prototype) do not have such requirements. Indeed, the energy consumption will be much higher than the current level if the studied case raises the comfort requirement of RH because dehumidification consumes significant energy. However, it is very arguable that whether for such a whole-house radiant cooling system, dehumidification is a 'must-to-have' thing.

According to Wilson (2016), between 22-24 ℃ people can tolerant the RH of 80%-65%, and if sitting in a breeze or a fan people can still feel comfortable under even higher dry-bulb temperature and RH in the dark yellow zone (see Figure 6.23).

China's design code, *Technical specification for radiant heating and cooling (JGJ 142 - 2012)*, also raises the designed indoor dry-bulb temperature to 27.5 ℃ for a whole-house radiant cooling system.

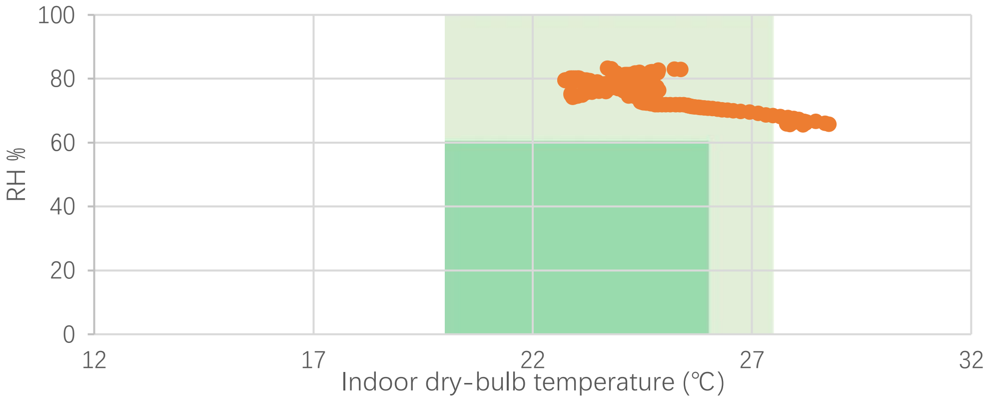
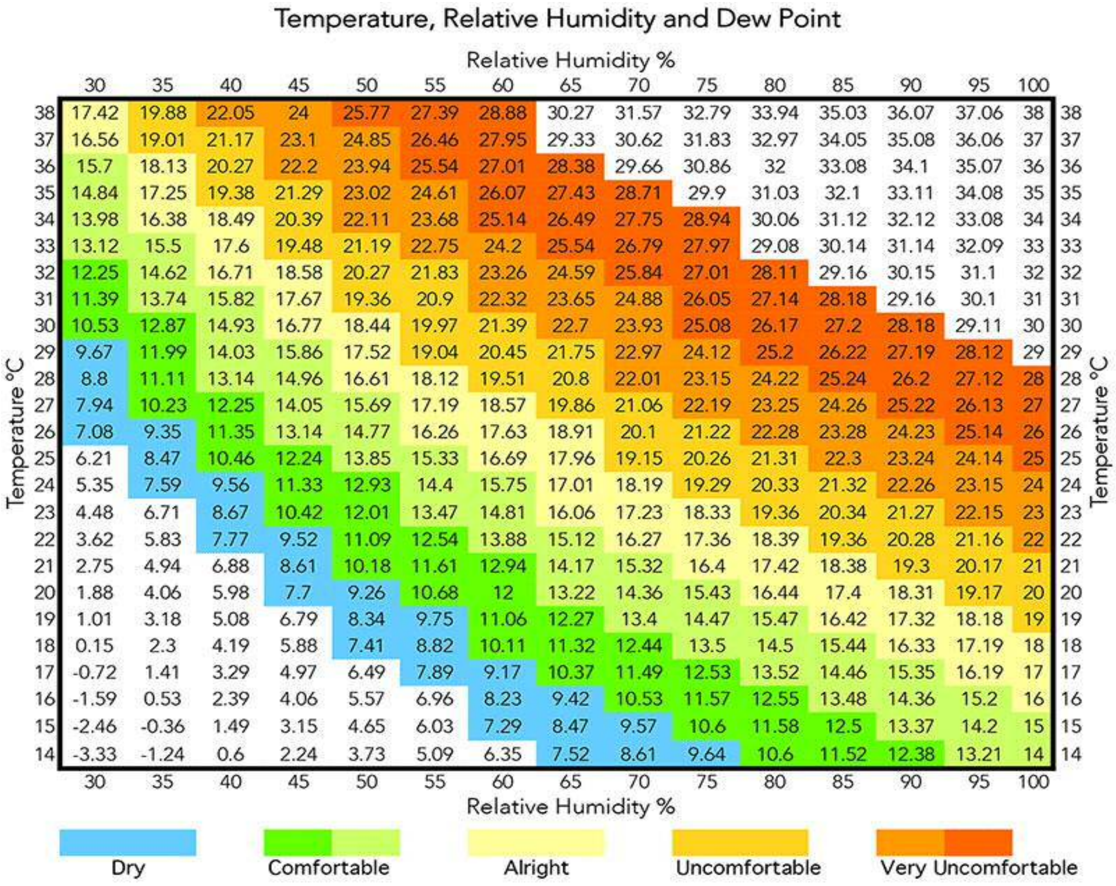


Figure 6.22 The average hourly dry-bulb temperature of the six mainly occupied rooms during the three analysed periods



Temperature, Relative Humidity and Dew Point

Temperature °C \ Relative Humidity %	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
38	17.42	19.88	22.05	24	25.77	27.39	28.88	30.27	31.57	32.79	33.94	35.03	36.07	37.06	38
37	16.56	19.01	21.17	23.1	24.85	26.46	27.95	29.33	30.62	31.83	32.97	34.05	35.08	36.06	37
36	15.7	18.13	20.27	22.2	23.94	25.54	27.01	28.38	29.66	30.86	32	33.08	34.1	35.07	36
35	14.84	17.25	19.38	21.29	23.02	24.61	26.07	27.43	28.71	29.9	31.03	32.1	33.11	34.08	35
34	13.98	16.38	18.49	20.39	22.11	23.68	25.14	26.49	27.75	28.94	30.06	31.12	32.12	33.08	34
33	13.12	15.5	17.6	19.48	21.19	22.75	24.2	25.54	26.79	27.97	29.08	30.14	31.14	32.09	33
32	12.25	14.62	16.71	18.58	20.27	21.83	23.26	24.59	25.84	27.01	28.11	29.16	30.15	31.1	32
31	11.39	13.74	15.82	17.67	19.36	20.9	22.32	23.65	24.88	26.05	27.14	28.18	29.16	30.1	31
30	10.53	12.87	14.93	16.77	18.44	19.97	21.39	22.7	23.93	25.08	26.17	27.2	28.18	29.11	30
29	9.67	11.99	14.03	15.86	17.52	19.04	20.45	21.75	22.97	24.12	25.2	26.22	27.19	28.12	29
28	8.8	11.11	13.14	14.96	16.61	18.12	19.51	20.8	22.01	23.15	24.22	25.24	26.2	27.12	28
27	7.94	10.23	12.25	14.05	15.69	17.19	18.57	19.86	21.06	22.19	23.25	24.26	25.22	26.13	27
26	7.08	9.35	11.35	13.14	14.77	16.26	17.63	18.91	20.1	21.22	22.28	23.28	24.23	25.14	26
25	6.21	8.47	10.46	12.24	13.85	15.33	16.69	17.96	19.15	20.26	21.31	22.3	23.24	24.14	25
24	5.35	7.59	9.56	11.33	12.93	14.4	15.75	17.01	18.19	19.29	20.33	21.32	22.26	23.15	24
23	4.48	6.71	8.67	10.42	12.01	13.47	14.81	16.06	17.23	18.33	19.36	20.34	21.27	22.15	23
22	3.62	5.83	7.77	9.52	11.09	12.54	13.88	15.12	16.27	17.36	18.39	19.36	20.28	21.16	22
21	2.75	4.94	6.88	8.61	10.18	11.61	12.94	14.17	15.32	16.4	17.42	18.38	19.3	20.17	21
20	1.88	4.06	5.98	7.7	9.26	10.68	12	13.22	14.36	15.43	16.44	17.4	18.31	19.17	20
19	1.01	3.18	5.08	6.79	8.34	9.75	11.06	12.27	13.4	14.47	15.47	16.42	17.32	18.18	19
18	0.15	2.3	4.19	5.88	7.41	8.82	10.11	11.32	12.44	13.5	14.5	15.44	16.33	17.19	18
17	-0.72	1.41	3.29	4.97	6.49	7.89	9.17	10.37	11.49	12.53	13.52	14.46	15.35	16.19	17
16	-1.59	0.53	2.39	4.06	5.57	6.96	8.23	9.42	10.53	11.57	12.55	13.48	14.36	15.2	16
15	-2.46	-0.36	1.49	3.15	4.65	6.03	7.29	8.47	9.57	10.6	11.58	12.5	13.37	14.2	15
14	-3.33	-1.24	0.6	2.24	3.73	5.09	6.35	7.52	8.61	9.64	10.6	11.52	12.38	13.21	14

Figure 6.23 Comfort zones in an air-conditioned space (Wilson, 2016)

These literature indicate that the proposed HVAC systems of the studied project have the potential to achieve a high comfort level without dehumidification. If they can manage the indoor dry-bulb temperature to 22-24 ℃ with RH 80%-70%, the ‘alright’ zone in Figure 6.23 can be well maintained. People could still feel ‘alright’ even the RH goes higher up to 90% if pleasant breeze can be created through mechanical ventilation or sometimes top up with electric fans. This situation will save both enormous dehumidification energy as well as the significant capital cost of HVAC systems.

On the energy performance side, despite not achieving the simulated performance of the baseline building and the final design, the achieved performance is not far from China’s NZE standard. It acknowledged that the monitoring study in this research has not yet covered the whole year, and there is no occupancy involved in the tests. However, the monitored period is the most challenging time in a year for the designed system, because condensation risk, indoor thermal comfort and energy consumptions must be taken care of at the same time. If the systems can achieve the monitored performances in the worst working conditions of the year, they can achieve the same level performances easily at other times of the year. Based on this fact, this research made some projections in order to compare the year-round energy performance.

Table 6.18 The comparison of cooling energy consumptions

Validated parameters	**China's NZE standard**	**The prototype's theoretical performance**	**The prototype's simulated performance**	**The final design's simulated performance**	**The monitored performance**
Cooling energy	≤ 9.97 kWh/m^{2}yr	≤ 16.5 kWh/m^{2}yr	5.5 kWh/m^{2}yr	5.4 kWh/m^{2}yr	10.34* kWh/m^{2}yr
Renewable energy	≥6.1 kWh/m^{2}yr	≥10.2 kWh/m^{2}yr	11.5 kWh/m^{2}yr	11.5 kWh/m^{2}yr	9.7** kWh/m^{2}yr

Note:

* This figure is calculated based on the figures of Table 6.16. When the monitored outdoor dry-bulb temperature is similar to the standard weather, the monitored actual energy consumption is 17.7/9.4=1.88 times of the simulated figure for the same period. If applying such proportion on the year-round figure, 5.5*1.88=10.34 kWh/m^{2}yr.

** This figure is calculated based on the figures of Table 6.17. Taking the average monitored generation of these three periods, it would be (14+10.8+18.6)/(18+16.2+17.4)=84.1% of the simulated figure. If applying such proportion on the year-round figure, 11.5*84.1%=9.7 kWh/m^{2}yr.

Table 6.18 shows that the monitored energy performance is far more than the simulated figures, but still obviously better than the baseline building's theoretical performance (based on current building regulations). Moreover, it has been very close to the requirement of China's NZE standard (10.34 against 9.97 kWh/m^{2}yr, only 3.7% more).

On the other hand, even though the monitored renewable energy generation did not achieve the theoretical and simulated figures, it has gone beyond the requirement of China's NZE standard (9.7 against 6.1 kWh/m^{2}yr, 59% more). Putting these two facts together, the actual net primary energy consumptions in the cooling season of this case study would be less than China's NZE standard.

Base on the analysis in section 6.5.2, the performance gaps between the simulated and the monitored performances come from both the completion of fabric and the system operation. Till this stage, there are minimal methods available to improve the fabric, so the 36% increase of cooling load would not be able to improve significantly. However, based on the reasons found for the poorer EER in commissioning (see section 6.5.2), there is still considerable potential to enhance it from monitored 3.7

to higher. There is no need to fundamentally change the current system design to achieve such potential because solving the identified problems mainly down to better sizing of the pump and more accurate control.

Therefore, the monitored performance only has a small gap of performance to China's NZE standard. This outcome proves that the proposed prototype in this research has a reliable capability to guide the final design and construction to achieve China's NZE standard.

6.5.4 Highlights of the achieved performances beyond China's NZE standards and current building regulations in the case study

1) Achieving 24 hours' stable thermal comfort without the need to turn on the cooling system for 24 hours

In China's NZE standard, the systems for heating and cooling must be run for 24 hours to calculate a building's energy consumption. The reason behind is that the common practice of HVAC system - 'boiler + radiator for heating and air-conditioning for cooling' - cannot maintain the indoor thermal comfort if not being turned on for the majority of the day. In real usage, occupants often run the systems in two or three shifts in order to save energy. However, such operation often causes uncomfortable period in between and at the beginning of the turning on period. For the proposed systems in this research, the situation is different - the monitoring shows that the house is stably cool even when the cooling system is off. This situation is because the whole house fabric dense thermal mass provides strong passive cooling capacity at the time when the cooling system is off. As can be seen from Figure 6.24, after kicking off the cooling system on 9:00 am 19 August 2019, the heat pump needs to run continuously for 43 hours to cool the long term occupied rooms to the set 24 °C. However, after that no matter how the external dry-bulb temperature fluctuated, the indoor dry-bulb temperature stably maintained the set 24 °C for 24 hours. During that period, the heat pump was only on for less than 10 hours a day.

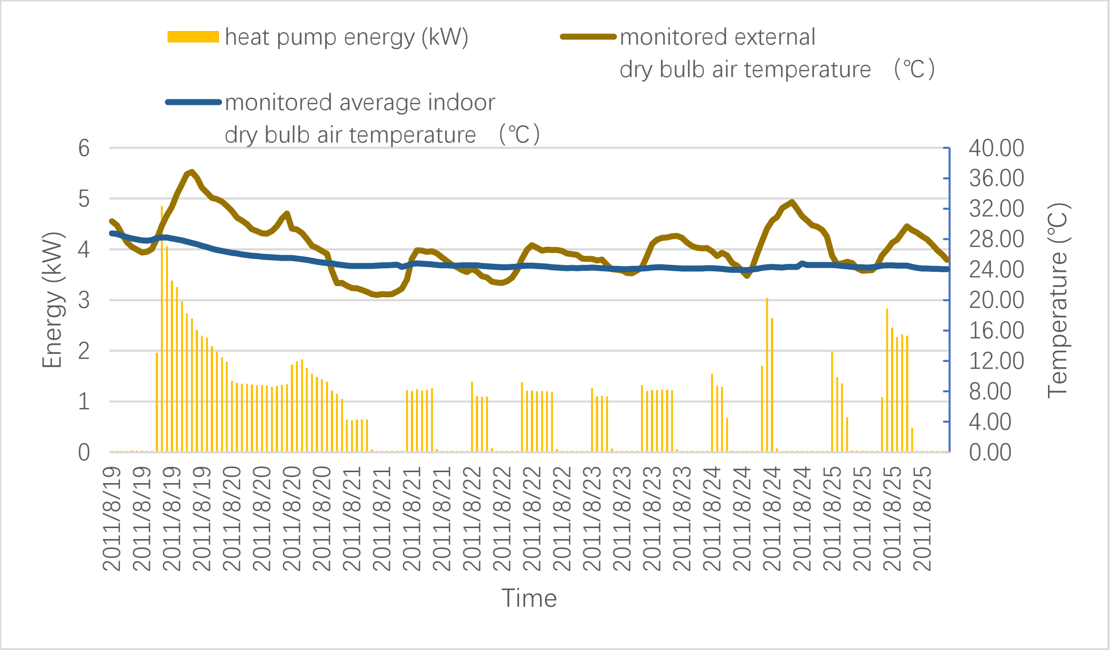


Figure 6.24 Monitored temperature and heat pump energy consumption (19 – 25 Aug 2019)

Note: The average indoor dry bulb temperature is for the long term occupied rooms (living, dining and bedrooms)

The benefit is not just for the long term occupied rooms. For those short term occupied rooms, such as bathroom and corridor, the air-conditioning system does not take them into account for energy-saving purpose. As a result, when people come out from the air-conditioned rooms, they immediately go into a different indoor thermal environment. Such a situation not only creates discomfort but influences people's health and well-being because human bodies are not good at adjusting to the different environment within a short period.

For the systems proposed in this research, they do not cool the bathrooms and corridors on purpose too. However, because the water loops come across the corridors, they get free coolth. For the bathrooms, when the whole house's fabric is cooled down sufficiently, they get passive cooling which makes them comfortable for a short period of occupancy as well.

Although the winter situation has not yet commissioned, it is foreseeable that the same benefits will apply to the winter conditions. Moreover, because there is no condensation risk in the winter to restrain the heating capacity, the thermal storage involved passive heating effect will be even stronger. As a result, the operation time during the winter can further reduce to save more energy.

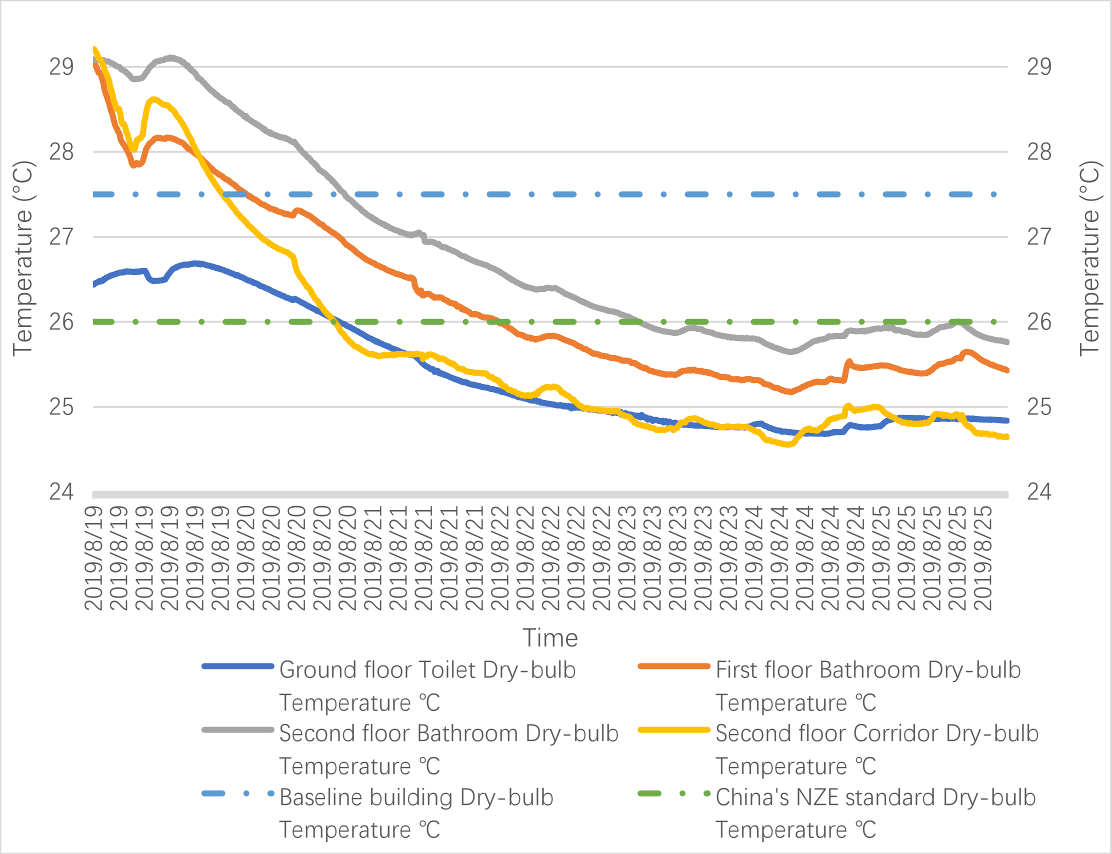


Figure 6.25 Monitored dry-bulb temperature of short term occupied rooms (19 – 25 Aug 2019)

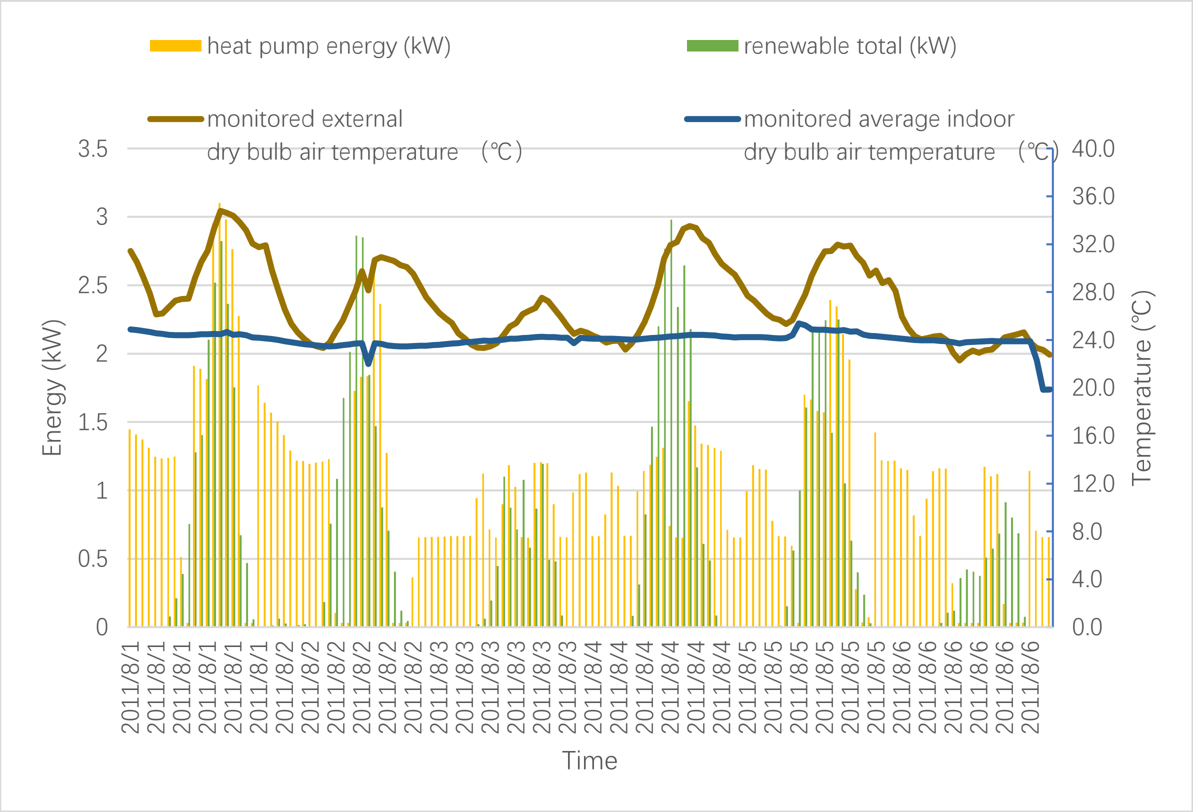
2) Working with the grid's peak-to-valley curve of electricity supply and maximising the use of onsite renewable power to reduce micro-generation interruption to the grid

As early as in the design stage, the simulation results have pointed out that 24 hours operation of the HVAC systems is not necessary. The commissioning of 24 hours operation of the HVAC systems was carried out between 27 July and 16 August 2019 to validate such prediction. The results confirmed that such an operation can achieve the required indoor thermal comfort but has very low efficiency (EER 2.7).

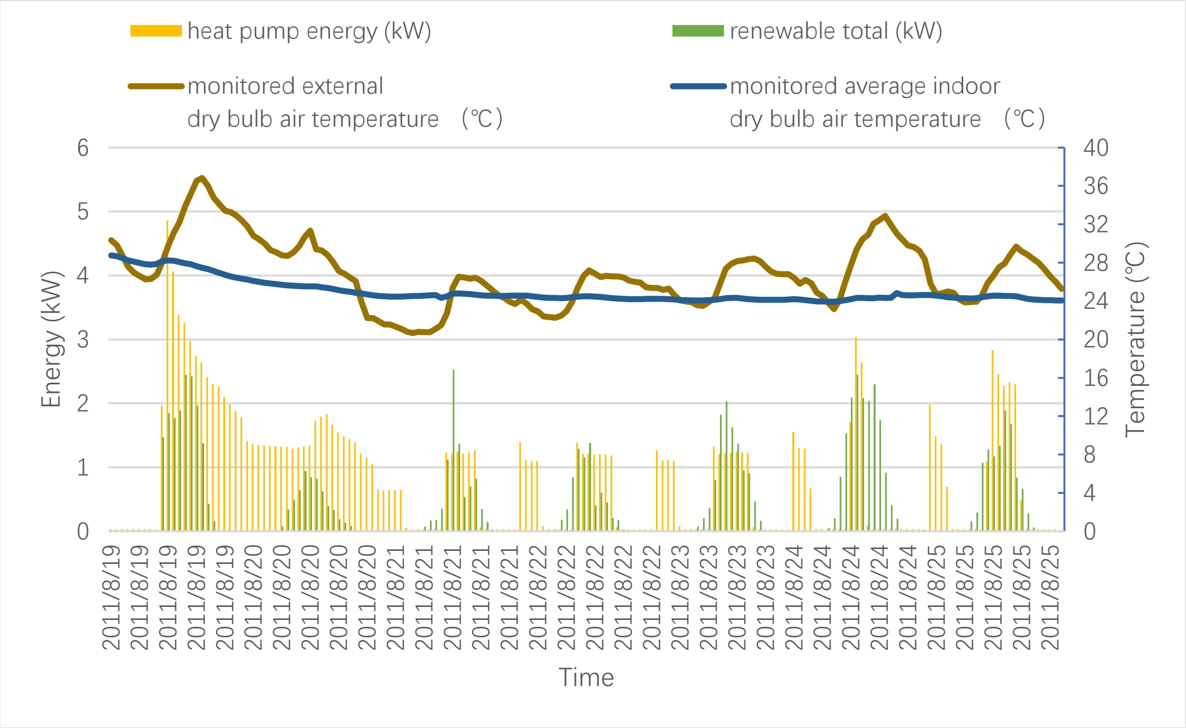
Therefore, based on the analysis of the commissioning data, 10 hours or less operation with two shifts was suggested to the case study. The first shift is during midnight when the grid curve is in its valley, and the second is in the daytime when renewable power generation on the roof reaches its peak. The commissioning results confirm that such operation creates three benefits in one go:

- successfully maintains the required indoor comfort level (see Table 6.13 and Figure 6.24, 6.25)
- significantly increases the system efficiency (from EER 2.7 to EER 3.7)
- increases the energy autonomy rate

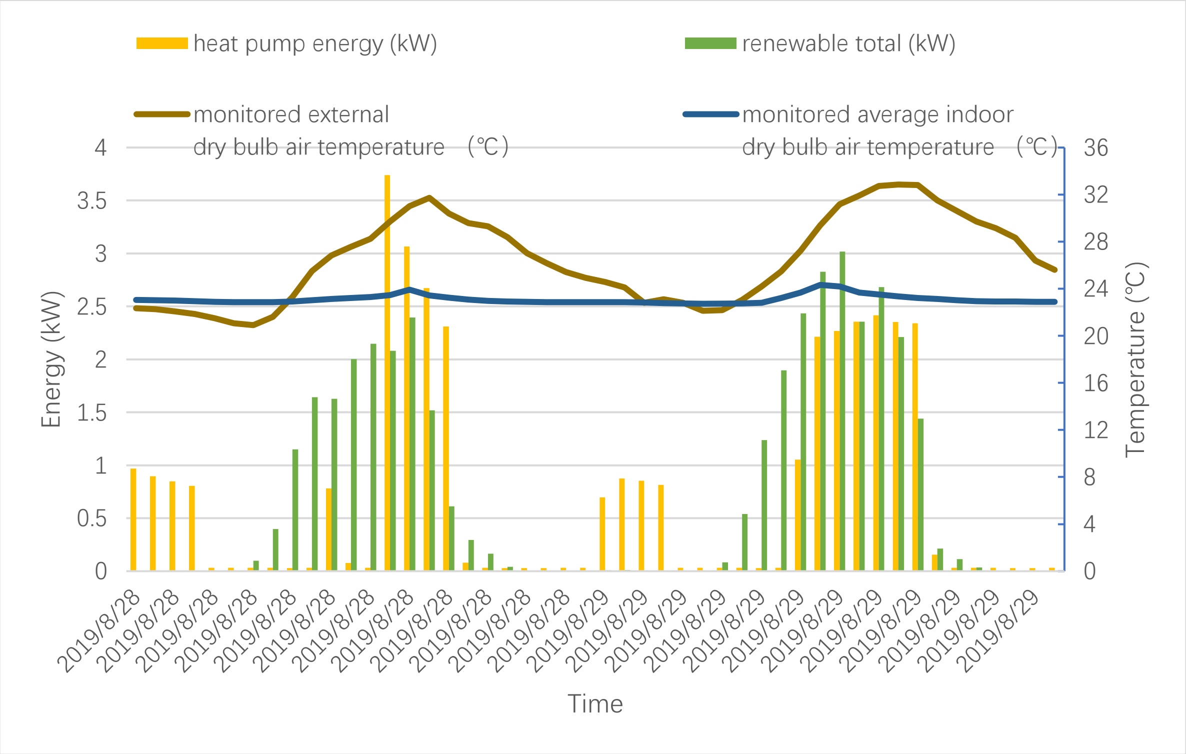
The third benefit was not aware of at the design stage, because China's NZE standard does not mention this figure at all. It only requires the general proportion of the renewable energy used in a project to reach a certain percentage. However, the two-stage commissioning clearly shows the massive difference in energy autonomy rate under different operations (Figure 6.26).



(a) 1 – 6 August 2019 (24 hours operation)



(b) 19 – 25 August 2019 (43 hours kicking off + 10 hours operation per day)



(c) 28 – 29 August 2019 (less than 10 hours of operation per day)

Figure 6.26 Temperature and energy comparison of the three analysed periods

As can be seen from Figure 6.26 that the studied case has much better autonomy rate when running the heat pump for 10 hours or less. For the 144 hours during 1-6 August 2019 (24 hours running), which does not include any charging fabric hours, the local generation covered 35 hours of heat pump energy consumptions. Therefore, the coverage is 24%. For the 168 hours during 19-25 August 2019 (averagely 10 hours running per day), which includes the charging fabric 43 hours, the local renewable coverage rate is 24% (40 hours). For the 48 hours during 28-29 August 2019 (less than 10 hours running per day), the local renewable coverage rate is 21 hours (44%). Because Figure 6.26 only shows the heat pump energy consumption, if topping up with other energy consumptions, the energy autonomy rate will be lower than the coverage rate. However, the monitoring results prove that the proposed HVAC system and thermal storage can work together to tolerate higher cooling load with the same energy autonomy rate (19-25 August 2019). Alternatively, it can almost double the autonomy rate when the cooling load is similar to the design conditions (28-29 August 2019).

Such energy consumption profile and improvement of energy autonomy rate are critical for promoting low carbon housing together with the smart grid. Such electricity use mode not only reduces the peak load of the grid but significantly reduces the micro-generation interruptions to the grid. The house consumes the peak of renewable generations on-site. However, China’s current policy and regulation system have not yet identified these benefits.

3) Recycling waste heat from the heat pump and using it for domestic hot water, which further reduces the domestic energy consumption

The HVAC system proposed in this research not only provides heating and cooling but domestic hot water as well. Moreover, the hot water recycles the waste heat from the heat pump in the cooling cycle, so for the whole cooling season, the heat for hot water is free. In the natural ventilation season, the hot water will be provided by the heat pump by converting electricity to heat. Such a method has much higher efficiency than the gas boiler or electric heater.

Although prepared in monitoring plan and got meters installed, without occupants onboard, the commissioning could not monitor the energy recovery rate of domestic hot water. However, according to the manufacturer's quote, there would be significant savings of energy; therefore, the cost of domestic hot water over a year (Table 6.19).

In China's NZE standard, the default system in Xi'an is 'boiler + air-conditioner'; therefore, there would not be such savings if complying with the standard.

Table 6.19 Comparison of the energy and cost of domestic hot water under different systems (converted from Trine's user brochure)

		The one used in the case study project	Normal electric heater	Standard gas boiler or gas heater
System efficiency		4.16 (yearly average)	0.95	0.90
Summer	Cost (yuan RMB)	Nil	463	203
	Equivalent energy (kWh)	0	771.7	860.7
Spring and autumn	Cost (yuan RMB)	146	639	281
	Equivalent energy (kWh)	243.3	1065	1191.4
Winter	Cost (yuan RMB)	113	496	218
	Equivalent energy (kWh)	188.3	826.7	924.3
Total	Cost (yuan RMB)	259	1597	703
	Equivalent energy (kWh)	431.6	2663.4	2976.4

Note:

1. The calculation based on AquaTrine 16kW plant and the usage of hot water is assumed to be 150L per day per house.
2. In this table, summer is 120 days, spring and autumn is 145 days each, and winter is 100 days
3. The electricity price used for calculation is 0.6 yuan / kWh and does not consider the time-of-use price
4. The gas price used for calculation is 2.5 yuan / m^3, and the converting factor for energy is 1 m^3 = 10.6 kWh
5. The actual values may vary due to local weather and utility prices.

6.6 Cost analysis

Due to the commercial nature of the project, the actual costs of the case study's construction and systems are confidential. Therefore, this research cannot reference the specific cost of each feature. However, it can still use a percentage scale to indicate the cost increase level and make an abstract comparison.

Based on the review of project documents, and comparing this case study with the standard high-rise apartments on the same site (complying with the current 75% energy saving building regulation), this research identified the cost increases in Table 6.20.

Table 6.20 Cost analysis of the case study project

Features	**Sub-features**	**Items**	**Percentage of the increased cost**	**Facts for comparison**
Construction	Structure	Insulation	<1%	Based on actual contract cost
		Windows & doors	0	Based on actual contract cost
		Airtightness	0	This project did not have the extra air-tightness technique or material consumptions
		Thermal bridge	0	This project did not have an extra thermal-bridge technique or material consumptions
Regulated services systems	Heating	Air-source heat pump multi-supply system	<3%	Based on actual contract cost
	Cooling			
	Hot water			
	Installation		<1.5%	The underfloor water loops are denser than the standard project in order to satisfy cooling capacity
	Ventilation	MVHR	<7.5%	Based on actual contract cost and the fact that currently MVHR has not been applied in the housing projects in Xi'an
	Lighting	LED (dimmable)	0.05%	Based on actual contract cost
Monitoring and control	Meters	Room dry-bulb temperature & RH sensors, heat meters, occupancy sensors, electricity meters, air-quality meter, MVHR air temperature & RH meters	<11%	Based on actual contract cost and the fact that there is no monitoring requirement for the typical housing project.
	Weather station	outdoor solar radiation, wind speed and direction, dry-bulb temperature&RH, rain	<10.5%	Based on actual contract cost and the fact that there is no need for real-time weather status for the current housing project.
	Control	Whole house smart control	<18%	Based on actual contract cost and the fact that there is no need for whole-house smart control for the typical housing project.
Renewables (including involved storage)	Power	PV, small wind-turbine, accessories, installation	<37%	Based on actual contract cost and the fact that there is no need for onsite renewable energy generation for the typical housing project.
	Heat	Domestic hot water	0	The cylinder cost for hot water storage has included in the heat pump multi-supply system
The total cost increase			86.7%	

As can be seen in Table 6.20, the total cost increase is as high as 86.7%. This increase seems unacceptable for a standard commercial project to duplicate. However, it is crucial to know where the cost increases come from and whether the cost can further reduce to a more affordable level. Therefore, Table 6.21 presented further discussions for such a project’s cost potential.

Table 6.21 Cost potential analysis of the case study project

Items	Possibility for further cost reduction	Possibility for the further cost increase	Reason for future cost change	Prediction of the future cost range
Insulation	No	No	Base on the case study results, there is no need to further increase the insulation level for the required performance	1%
Windows & doors	No	Yes	The proposed ventilation window will enhance energy performance, as well as the indoor air quality when naturally ventilated. However, it will be slightly more expensive than the glazing cost.	1%
Air-tightness	No	Yes	The case study shows that failing the designed air-tightness level and weak thermal bridge caused a 36% increase in cooling load. Therefore, there need to be more materials and labour costs for the improvement of these two items.	3%
Thermal bridge	No	Yes		
Air-source heat pump multi-supply system	Yes	No	MVHR can significantly reduce energy consumption in winter and enable better indoor air quality for well-sealed buildings. However, it also mainly increases the capital cost of HVAC systems. In this case, because the heat-pump multi-supply system was for a single house project, the extra cost was involved. When scaling up, the 3% cost increase will disappear. Moreover, both the heat pump and the MVHR company charged an extra cost for opening their control to the central control system. The market now has heating, cooling, hot water and ventilation all integrated system. This integration can further reduce the cost of the whole HVAC system to half of the case study level.	6%
MVHR	Yes	No		
The LED (dimmable)	No	No	The case study's application can duplicate in the future	0.05%
Sensors & meters	Yes	No	In this case study, the majority of meters installed are to understand the HVAC system and the whole house energy and indoor thermal performance. In real practice, only 1/3 of the meters needed for control. Therefore, the cost will significantly reduce.	3%

Items	**Possibility for further cost reduction**	**Possibility for the further cost increase**	**Reason for future cost change**	**Prediction of the future cost range**
Weather station	Yes	No	The real-time onsite weather is essential for condensation risk control and dynamic supply water temperature adjustment. Therefore, it is a must-have kit, no matter how many houses are to build. However, one weather station can cover the area of 2 km radius, which is enough for a large-scale residential community. Thus, when scaling up, the cost for each house is negligible.	0
Whole house smart control	Yes	No	In this case study, the majority of control cost is down to design a holistic control system for both the HVAC plants and other smart home features. The real cost increase for equipment is about 5%, which is still necessary when scaling up. However, the knowledge gap involved cost will disappear once the demonstration project has completed.	5%
PV, small wind-turbine, accessories, installation	Yes	No	In this case study, 7% of renewable energy cost is down to the 1.5kW wind turbine, which proved to be not beneficial and economical for local weather. The supporting frames cause another 6% cost for the PV panels, which can be wiped off by PV-roof integrated design and construction. There will be 4% savings of labour and transportation cost when filling the knowledge gap and using the local suppliers. For the leftover 20% cost increase, 4% can be further reduced by less installation when the demand side performance improves to the simulated level, and 4% further saving comes from cheaper PVs when scaling up.	12%
Domestic hot water	No	No	The case study's application can duplicate in the future	0%
The sum of the potential cost increase in future projects				31.1%

Table 6.20 and 6.21 show that only about one third (31.1% vs 86.7%) of the case study’s cost increase is necessary and unavoidable. All other increased costs are either caused by knowledge gap, skill gap or lack of supply chain integration. Once completing the demonstration projects, these costs can be either wiped off or primarily reduced if the future projects can learn the experiences and lessons of these projects.

There have been no comparable benchmark capital and operational costs in China’s housing sector for this case study because there has been no literature about NZE townhouse in China. Nevertheless, there are some indirect figures applicable to the comparison. Green Building Institute (2019) reported that the average increase cost of China's current demonstrating extra-low energy public buildings is between 800 and 1200 Yuan RMB, which is about 20-25% more than the standard practice. There is another case study of multi-story housing (plot ratio 1.2) in Tianjin, which achieved China's extra-low-energy standard with 514 Yuan RMB extra cost per m^2 (WeChat official account – EU and US Green Buildings, 2019). According to the National Statistics Bureau of China (2018b), the average construction cost of high-rise apartments in Xi'an in the first half-year of 2018 is 2316 Yuan RMB. In that case, the expected 31.1% cost increase will be about 720 Yuan RMB.

For this case study's energy performance, the monitoring shows that the completion has a tiny gap to the targeted NZE standard's energy performance. If the 31.1% cost increase could achieve the original prototype's simulated performance, the case study's energy performance would be at least ZE, if not energy positive. Thus, such potential cost increase level is competitive to China's current demonstration projects of extra-low-energy housing.

In terms of the affordability of the 31.1% increased capital cost, the critical thing is whether they can be paid back by the saved energy costs. If the increased cost cannot be paid back within a building's lifespan, it will become a burden on top of the already hard to afford housing in China.

According to the calculations made in section 5.4.5 for the prototype, current housing's heating, cooling and primary energy consumptions (75% energy saving standard) in Xi'an would be:

- **Heating:** ≤ 25 kWh/m^2yr
- **Cooling:** ≤16.6 kWh/m^2yr
- **Net primary energy:** ≤92 kWh/m^2yr (The total primary energy consumption deduces the onsite and nearby renewable energy utilisations)

With a positive projection, the 31.1% cost increase achieves ZE performance, then the savings of energy cost over 50 years' house lifespan would be; 92 kWh/m^2yr * 150.8 m^2 (serviced area) * 50 years * 0.6 Yuan = 416,208 Yuan RMB. The increased capital cost is 720 Yuan/m^2 * 178.3 m^2 (usable area) =

128,376 Yuan RMB. Therefore, the payback year would be 128,376 / 416,208 *50 = 15.4 years. This payback period is a widely accepted economic payback period in the construction industry.

With a conservative projection, the 31.1% cost increase achieves NZE performance (65% of the primary energy consumption on heating, cooling and hot water, see section 2.5.2), then the savings of energy cost over 50 years' house lifespan would be: 92 kWh/m^{2}yr * 65% * 150.8 m^2 (serviced area) * 50 years * 0.6 Yuan = 270535 Yuan RMB. The increased capital cost is the same as above. Therefore, the payback year would be 128,376 / 270535 *50 = 23.7 years. This payback period is still reasonable because a building would not need any major upgrading within 25 years.

The comparison of cost does not just focus on upgrading the building to achieve higher energy performance. This research also compared the land cost because one of the significant arguments for not building townhouse in China is the high land cost. According to Yu (2017), 'For our (China's) urban building, the land cost takes about 50% of the capital cost, while it is only 13% in the developed countries'. Therefore, it is also essential to know the development cost (land + construction) of the proposed townhouse.

Again, without the actual figures of the case study project, it is not possible to compare the development cost of the high-rise apartment and the case study house on the same site. However, literature is available to make a brief comparison.

Early in the 1950s and 1960s, UK was in the situation that high-rise apartments quickly built up to meet the housing need of the rapidly urbanised population. The research was carried out by Stone (1970) about the UK's population trend and housing from 1964 to 2004, and he found that the cost per dwelling goes up with its storeys (Figure 6.27).

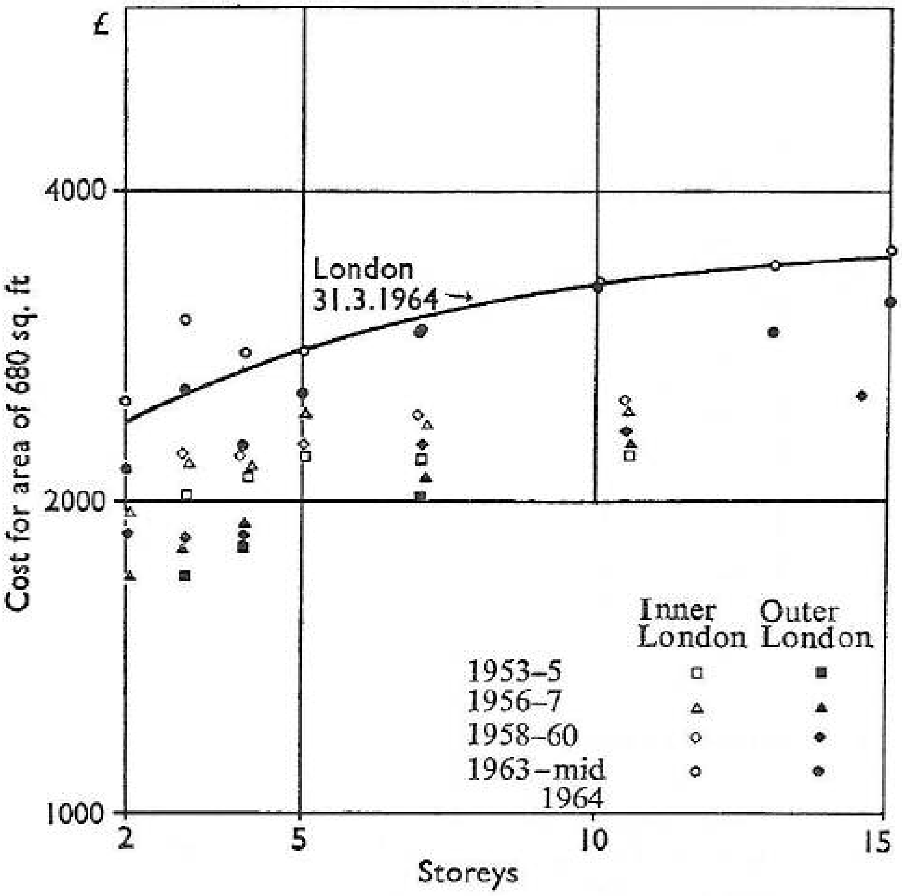
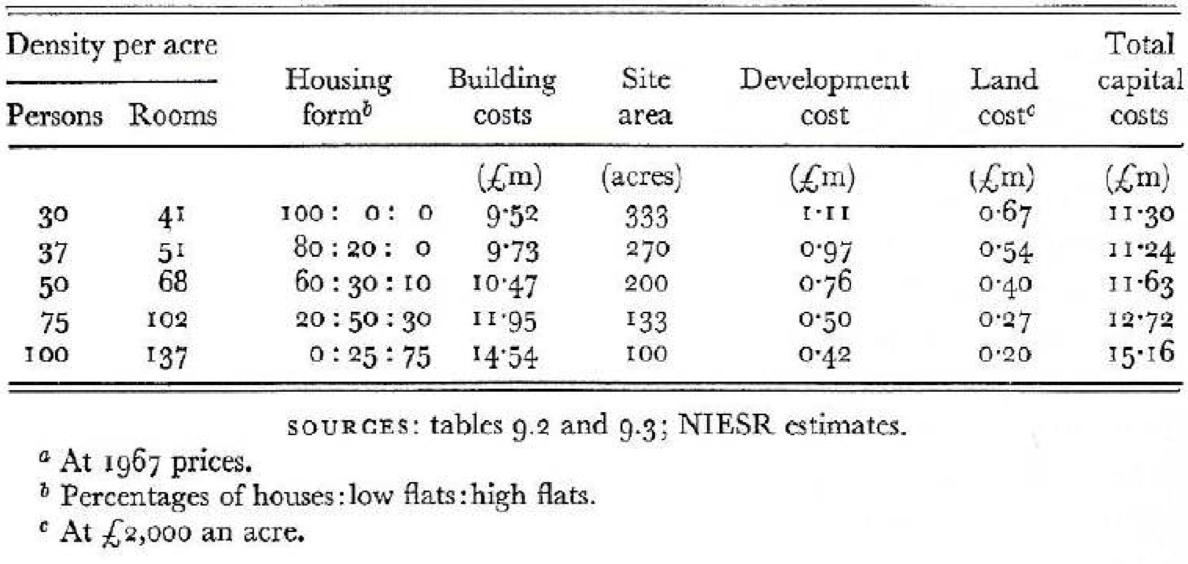


Figure 6.27 Costs per dwelling and number of storeys in flatted blocks, London
(Stone 1970)

Such a conclusion is still applied today in the UK's housing market that the high-rise apartments' per square meter selling price is higher than the one of the houses in the same area. Stone (1973) extended his research to the settlement scale, and again he found that the higher density a settlement wants to build, the more expensive capital cost it will need (Figure 6.28). It is especially worth mentioning that in Stone's research the land + development cost of '100% houses' is 2.87 times more than the cost of '25% low flats + 75% high flats'. This outcome means the flats community is 3.33 times dense (persons/acre) than the houses community (Figure 6.28). However, this does not mean that the houses community is more expensive to build. On the contrary, because the building costs of '100% houses' community is only 65.5% of the '25% low flats + 75% high flats' community, the total capital costs of the former are only 74.5% of the latter (Figure 6.28). Therefore, if without any requirement of density, it is cheaper to build houses than high-rise apartments.



Density per acre		Housing form[b]	Building costs	Site area	Development cost	Land cost[c]	Total capital costs
Persons	Rooms						
			(£m)	(acres)	(£m)	(£m)	(£m)
30	41	100 : 0 : 0	9·52	333	1·11	0·67	11·30
37	51	80 : 20 : 0	9·73	270	0·97	0·54	11·24
50	68	60 : 30 : 10	10·47	200	0·76	0·40	11·63
75	102	20 : 50 : 30	11·95	133	0·50	0·27	12·72
100	137	0 : 25 : 75	14·54	100	0·42	0·20	15·16

SOURCES: tables 9.2 and 9.3; NIESR estimates.

[a] At 1967 prices.

[b] Percentages of houses : low flats : high flats.

[c] At £2,000 an acre.

Figure 6.28 Housing: land and capital costs per 10,000 persons (Stone 1973)

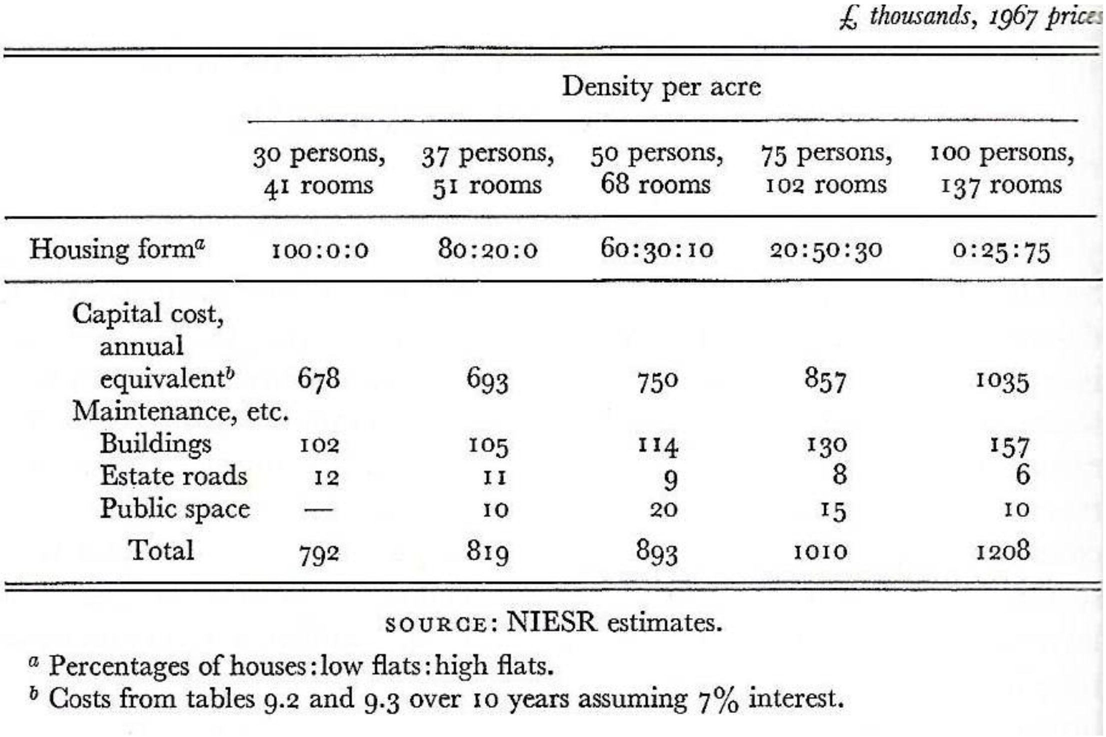
Stone's (1973) research on the differences of density and total capital costs between '100% houses' and the '25% low flats + 75% high flats' community actually can apply to China's situation. The typical plot ratio of an entire townhouse community is 1, while the typical plot ratio of a pure thirty-storeys apartments community is 3.4. If assuming the same floor area would occupy the same amount of people, the density difference in China between apartments and houses community (3.4:1) is very similar to the case presented in Figure 6.28 (3.3:1). Thus, for the case study's situation, the increased 31.1% construction and facility costs can be well absorbed by the 35% lower construction cost of the houses (Figure 6.28, £m 9.52 for '100% houses' vs £m 14.54 for '25% low flats + 75% high flats').

Moreover, the operational and maintenance costs are often neglected in China today when calculating the costs of new housing. Nevertheless, it is essential to compare this part of costs between high-rise apartments and houses, or else this research can not clarify the long-term benefits.

Stone (1963, referenced in Stone 1973) once stated that:

> *'…the larger the complex of facilities under one roof, the greater the proportion of space needed within the building for circulation and storage, and this would be far more expensive than external space to provide and service. Internal transport would have to be electrically powered to overcome the problems of fire, pollution and noise.'*

He also compared the capital and maintenance costs of different housing forms for different density (Figure 6.29), and he found that ‘flatted blocks of five storeys or more have maintenance and management costs about two thirds higher than houses’.



£ thousands, 1967 price

	Density per acre				
	30 persons, 41 rooms	37 persons, 51 rooms	50 persons, 68 rooms	75 persons, 102 rooms	100 persons, 137 rooms
Housing form[a]	100:0:0	80:20:0	60:30:10	20:50:30	0:25:75
Capital cost, annual equivalent[b]	678	693	750	857	1035
Maintenance, etc.					
Buildings	102	105	114	130	157
Estate roads	12	11	9	8	6
Public space	—	10	20	15	10
Total	792	819	893	1010	1208

SOURCE: NIESR estimates.

[a] Percentages of houses: low flats: high flats.

[b] Costs from tables 9.2 and 9.3 over 10 years assuming 7% interest.

Figure 6.29 Annual cost-in-use of dwellings per 10,000 persons by density (Stone 1973)

The above figures are for the prices in the year 1967 in the UK, for today’s situation in China, the cost would be even higher for high-rise apartments. One reason is that the involved ICT facilities and HVAC systems for the modern living standard are far more complicated than the ones of the UK in 1967. This change significantly increases the cost for building maintenance, operation and management. Moreover, the modern living style creates more waste than before (e.g. take away food and internet purchase involved packages). The higher a building is, the more operational energy and administrative cost will be to deal with these wastes. Thus, the cost savings of townhouses communities over high-rise apartments communities will only be larger than the one summarised in Stone’s research (1973).

Based on all the above cost analysis, the proposed NZE townhouse prototype is affordable to building (reasonable capital cost) and live (minimal operational and maintenance cost).

Chapter 7

Conclusions, recommendations, limitations and future works

7.1 Introduction

This research aims ***to formulate a prototype and its conceptual design framework for the low-carbon housing development in China and test their effectiveness of promoting affordable Nearly-Zero-Energy performances in real practice.***

Several objectives are derived as follows to achieve the main aim of this research:

1) To investigate the reasons for NZE housing development in developed countries, and find out what design principles China can adopt

2) To formulate an affordable NZE housing prototype and a conceptual design framework to deliver the summarised design principles

3) To implement the prototype and the conceptual design framework in a real project, to understand how the local conditions are applied

4) To validate the effectiveness of the prototype and the conceptual design framework by simulating and monitoring the energy & indoor thermal performances, so that the costs for achievable performances are clarified

The aim and objectives in this research are achieved by formulating an affordable NZE townhouse prototype and its conceptual design framework at the national scale and using a real project case study to test its applicability and effectiveness.

This chapter concludes all the findings in this research and answers the raised research questions (section 7.2). It then summarises the lessons learnt and makes recommendations for future affordable NZE townhouse development (section 7.3). Finally, it explains the limitations of this study and suggests further research themes to cover them (section 7.4).

7.2 Conclusions

This section presents the essential findings and achievements of this research, which divided into two parts: theoretical explorations and practical implications. These findings answer the research questions by providing facts and solutions.

7.2.1 Theoretical exploration of necessity, definition, and the prototype at the national level

This part of the research is to answer the first two research questions:

1) *Why developed countries promote affordable low-carbon housing with the priority of NZE, ZE or even EP houses, and how that links to China's own needs of future housing development?*

2) *Can China promote affordable low-carbon housing in suburban area by NZE townhouses? If so, what are the main characters of such a residential building?*

It also answers the third research question from a generic theory point of view:

3) *If delivering the affordable NZE townhouse in China via the proposed technical route, what type of conceptual design framework can enable holistic and economical design for local conditions?*

Achievement 1: Filling in the research gap of low-rise building form for China's promotion of low-carbon housing

Chapter 2 carried on this part of the work, and the results answer the first two research questions. This chapter reviewed the evolution of affordable NZE housing concept, theoretical discussions and the current situation in China.

It started by clarifying the three fundamental definitions: sustainability, resilience, and built environment. It then reviewed the affordable NZE housing research and current practices in western countries. Based on this part of the review work (section 2.2), this research summarised the principles of current affordable NZE housing design in western countries and clarified the links to China's needs. This part of work answers the first research question by confirming that western countries' affordable NZE housing principles are applicable and adaptable to China.

Next, China's housing status, strategy and policies are reviewed, and it found the following facts:

- China's current housing sector is struggling with affordability and poor living quality. China's current high-rise high-density affordable housing strategy solved some urgent living problems but is not suitable for promoting low-carbon housing in the future (section 2.3).
- China's policies have started to promote affordable low-carbon housing since 2013. Notably, China established the standard of NZE building to narrow the focus. However, the current policies and regulations in China have not yet merged clearly to promote affordable NZE or above housing (section 2.4).
- China faces the everyday challenges of affordable housing as in other counties, but the driving forces are different from the developed countries when they were at the same urbanisation stage. Hence, China does not need to wait for the same long time to introduce NZE or above housing (section 2.5).

Based on the above facts found in the reviews, the concept of affordable NZE townhouse proposed in this research answered the first half of the second research question. Such concept tackles three identified research gaps in China's future low-carbon housing at the same time:

- settlement and building form
- comprehensive analysis of affordability
- renewable energy generation strategies

The prototype and conceptual design framework of affordable NZE townhouse initiated in this research give a holistic model for China's future affordable low-carbon housing. It also enables the stakeholders to make a comprehensive analysis of their area of work. This type of research has not yet carried out in China's housing or NZE building studies.

Achievement 2: Clarifying the terminology for the affordable NZE townhouse concept

The review results in Chapter 2 show that affordable NZE townhouses have great potential to help China promote low-carbon housing in the future. However, the existing research about such housing is very insufficient. Even the fundamental terminology is missing for such housing. Thus, in Chapter 4, literature is reviewed to form the terminology, so that this research can lay the foundation of discussions.

Section 4.2 reviewed the definitions of NZE building around the world and in China; the system boundaries and energy balance scales in China's definition of NZE building are further clarified. Moreover, it discussed the measurement of housing affordability in China. Based on these works, the terminology of affordable NZE townhouse in China is defined.

This part of the research helps to answer the second half of the second research question. The main contribution of this section is that it clarifies several vital characteristics (density, form, technical route and meaning of affordability) for such housing. This clarification makes the research subject clear to anyone who would like to be involved in the relevant discussions.

Achievement 3: Formulating the prototype and conceptual design framework of affordable NZE townhouse at the national level

In order to link the terminology to the final design features and process, this research formulated the prototype and conceptual design framework of affordable NZE townhouse at the national level.

Section 4.2 thoroughly reviewed the existing research on prototypes and its relationship with reference building. This part of work helps to shape the structure of the prototype and highlight the key features to make the reference building affordable and NZE. As a result, this research formulated the prototype (example reference building) for the affordable NZE townhouse concept at the national level. This prototype can guide the housing project in any climate zone of China by the same platform of critical features, but it does not restrain the detailed designs from being further developed based on the local conditions.

Section 4.3 reviewed the design process of NZE buildings and analysed the strategies to integrate into the prototype. According to the findings in this section, this research proposed a two-dimensional inter-connected framework to help organise the design process (Figure 4.28). On the vertical dimension, there are key design features to highlight the most crucial design topics, which remind the designers about the main design tasks. The horizontal dimension listed specific items under each design topic so that it can provide to the designers a broad view of options for that topic. Then, most importantly, the framework integrates the design outcomes of each feature into building components. This integration makes sure that the stakeholders can identify the cost-saving potential of integrating fabric and equipment at the very early stage of a project. It can also highlight the most critical component(s) for integration so that the designers can give priorities to the component(s). In that case, designers from different disciplines can have a specific subject to work on, and the options from a different point of view can be linked to this specific subject to enable practice solutions.

Till this stage, this research answered the third research question and completed the theoretical part of the study.

7.2.2 The practical implication of the proposed prototype and conceptual design framework at the regional and project level

This part of the work is to answer the fourth research question through a case study:

4) *How do we know whether or not the proposed prototype and conceptual design framework enable affordable NZE performances? If not, what are the problems and reasons?*

Achievement 4: Validating the applicability of the affordable NZE townhouse prototype and its conceptual design framework at the regional and project level

The first part of practical implication is to find out the suitable places and projects for applying the proposed prototype and conceptual design framework, and see whether they are flexible enough to deal with different local conditions.

With the illustration and discussion in chapter 5, this research can draw the following conclusions:

- The affordable NZE townhouse prototype has a wide range of applications in China (as analysed in section 5.2)

  There are 11 provinces currently suitable for the conditions set up in this research, which is 35.5% of the administrative regions in China. Among these provinces, there are four cities fully ready to apply the prototype at the moment; and there are another 34 cities suitable shortly when their public transport infrastructure is ready. These cities spread in 4 out of 5 climate zones in China, and covers from tier 2 to tier 4 cities. Therefore, it convinced that the prototype proposed in this research is suitable to be applied in diverse cities in China.

- There is still an opportunity for townhouse project under current land provision policy (as introduced in section 5.3)

  As explained in the literature review, current land provision policy restrains the development of entire townhouse real estate development project. However, the case study in this chapter demonstrates that combined-form projects could still implement the affordable NZE townhouse prototype.

- The national-level prototype can quickly develope to project level baseline building, just by adopting the local, regional and national regulations and design codes (as explained in section 5.3)

  It is illustrated by the case study project that the concept design of the project scale reference building does not involve many specialities from different disciplines. For any project holder with good knowledge of housing development, the project level baseline building can be formulated just by knowledge acquisition and supply chain consultation.

- The reference (baseline) building prototype can be effectively developed to holistic detail design by following the route pointed out by the conceptual design framework (as illustrated in section 5.4 and 5.5)

The conceptual design framework can help the stakeholders quickly identify the critical integration areas and come to the consensus of the design principles. It also clearly displays the links among different design features, which is helpful for the designers to cooperate to deliver a holistic design. Moreover, because the reference (baseline) building provides detailed design parameters, and the framework clarifies the integrating route, designers can quickly come to the detail design stage.

- The reference (baseline) building prototype and the conceptual design framework are helpful to identify cost-saving strategies at the very early stage of a project (as illustrated in section 5.5). Succeeding or failing these strategies will have fundamental influences on the project's cost and performances level (as illustrated by Chapter 6).

The case study project's design outcomes clearly show that the prototype and conceptual design framework helped to identify two vital cost-saving strategies at the concept design stage.

The first one is the holistic window design, which takes the needs of natural ventilation, daylight, solar gain, fabric insulation level, indoor air quality, and security into account. To satisfy the design, it will be a little cost increase of the window product, but it can be paid back quickly by the saved energy cost due to such design. Moreover, it can help to improve the indoor air quality and daylight environment, which are very beneficial to the occupants' health and well-being.

The second one is the floors and roof embedded ASHP air-to-water multi-supply system. Again, such design will lead to a little cost increase of the fabric construction, but it saves a considerable cost of heat storage and enables much better energy autonomy rate. Therefore, such design significantly reduced the capital cost of equipment and mostly shortened the payback period of renewable energy generation.

However, it highlighted in Chapter 6's analysis of the case study that it is critical to implement these key strategies from the design down to practice. These strategies indeed influence a project's outcome both on cost and performances.

The failure of implementing the window design only lowers a little of the windows' capital cost, but the simulation analysis shows that it almost takes out all the efforts of 8% insulation increase (section 6.3.2). Moreover, it makes the house's indoor thermal performance worse in spring and autumn (section 6.3.3).

On the contrary, successfully implementing the integration of building fabric heat storage and ASHP multi-supply system brings huge cost and performance benefits. Firstly, it provides about 44kWh heat storage capacity for almost free cost (Figure 6.24 - the total charged in energy was 75.5 kWh during 19-20 August 2019, and the total energy used for cooling during 24-25 August 2019 was 31.7 kWh. The indoor and outdoor conditions are similar between these two periods. Therefore, among the 75.5 kWh charged in energy, cooling used 31.7 kWh while 43.8 kWh was stored in the fabric to keep it stably cool). Secondly, it provides 24 hours stable indoor thermal environment to the whole house, rather than only the long term occupied rooms (section 6.5.4).

These findings in this research show that the strategies formulated by the prototype and the conceptual design framework are truly applicable and influential in real projects.

Achievement 5: Validating the effectiveness of the affordable NZE townhouse prototype in terms of enabling NZE performances in real project practice

The second part of practical implication is to design and build up the house according to the guidance of the prototype and the conceptual design framework. Then, this research simulated the indoor thermal and energy performances of the final design. After that, this research monitored the ones of the constructed building. In the end, this research assessed the results against the performance benchmark figures set up in the reference (baseline) building. Such work can validate the prototype and conceptual design framework's effectiveness in enabling good performances.

The reason for setting up such validation is because of the performance gaps between the predictions and the actual operations. They usually occurred in the past projects of NZE buildings, both in China and in other countries. There are two common failures of previous projects: 1) the projects achieved the designed comfort level with much more energy consumptions than the prediction; 2) the energy consumption is low, but the projects cannot achieve the designed comfort level. Thus, in this research, both the indoor thermal and energy performances are validated against the reference (baseline) building and China's NZE standard.

On the indoor thermal performance aspect, it is confirmed by both simulation and monitoring results that current building regulations' standards are well achieved (section 6.2, 6.3, and 6.4). Moreover, the case study project even achieved individual comfort beyond China's current building regulations and NZE standard (section 6.5.4). However, there is an apparent gap between China's NZE standard and the project's result on the indoor RH level, which is also the critical area for energy saving. Existing research is not sufficient to justify whether the thermal environment created in this case study project is comfortable enough or not. Therefore, it needs further research to evaluate occupants' subjective opinions of such whole-house radiant heating and cooling environment, with lower RH in winter and higher RH in summer.

On the energy performance aspect, this research found both expected and unexpected results.

The simulation results show that the baseline building's heating energy consumption is very close to China's NZE standard (section 6.2.2, Table 6.3). With the adjustments in the final design, the predicted heating energy consumption has almost achieved China's NZE standard (section 6.3.2, Table 6.7). Such performance is within expectation because it is what the baseline building designed for: a benchmark close to the target, which can help the final design achieve the targeted performance.

However, the simulated results of the baseline building and final design's cooling energy consumption are only 55% of China's NZE standard (section 6.3.2, Table 6.7). This outcome is out of expectation. Even though it was convincing at the beginning that not involving dehumidification will save cooling energy, it the extent of 45 per cent is not expected. The critical thing for such a vast difference is that if the predicted cooling energy can provide enough comfort to occupants, the all-year-round performance of this prototype will be energy positive rather than NZE. This outcome will fundamentally change the nature of this prototype.

However, the monitoring results show that the predicted energy consumptions do not achieve the predicted indoor thermal performance.

In the commissioning, the general cooling energy consumption is twice more than the predicted values in the same period (section 6.5.2, Table 6.16). According to the analysis in section 6.5.3, the performance gap comes from both fabric quality and system control. For the fabric, once it completed, it is hard to further improve to a better level. For the system, this research has pointed out the improving method, which could further increase its system efficiency in the actual operation.

Despite the monitored cooling energy being worse than the predicted value (the same situation would expect for the heating), the results show that current energy performance has been very close to China’s NZE standard (section 6.5.3, Table 6.18). If applying the improving methods suggested in this research, NZE or even ZE performance could expect in this project. This conclusion based on the fact that this project has a much larger capacity of local renewable generation than China’s NZE standard. The summary of Table 6.18 clearly shows that the gap between energy used and generated in this project is much smaller than the one required by China’s NZE standard.

Achievement 6: Validating the affordability of the NZE townhouse prototype in terms of construction at the project level

The terminology defined and the relevant analysis made in section 4.2 point out that the occupants' affordability of the NZE townhouse prototype comes from three aspects:

- Affordable to buy or rent
- Affordable to live in
- Affordable to travel to

For this research, the travelling cost has been considered in the prototype by the proposed ‘location’ criteria. However, the study of detailed travelling cost is beyond the scale of this research. The ‘live in’ cost, which includes the operation, maintenance and services of the house, is only explored briefly by comparing them generally with current high-rise apartments. The reason is that this part of the cost study needs long term data collection, which is beyond the time limit of this research. However, the most significant chunk of cost (to buy or rent) among these three issues is studied thoroughly by analysing the upfront capital cost of building up the case study house. This research believes that if the market were to price the NZE houses reasonably, the condition would only be to build these houses with competitive costs.

As figured out in section 6.6, the actual capital cost of the case study project is about 86.7% higher than the high-rise apartments on the same site. Such a cost increase is not reasonable for the market to launch affordable housing. However, if breaking the costs down, it is found that 55.6% cost increases are due to knowledge gap, skill gap or lack of supply chain integration. For the rest expected 31.1% necessary cost increases, the payback period is about 15.4 to 23.7 years, depending on the real energy performance in practice. For the house and the associated equipment, such a payback period is well within their lifespans. Therefore, if China can fill the knowledge and skill gaps while the developers organise the supply chain well, the proposed NZE house prototype would be affordable in the real projects.

7.2.3 Summary of the creation and interpretation of new knowledge

This research achieves its aim by formulating an affordable NZE townhouse prototype and its conceptual design framework for the low-carbon housing in China. The existing research has not yet identified the low-rise building as a solution for China’s future low-carbon housing development. Therefore, this prototype fills the blank research area of this topic. Also, this research initialises an associated conceptual design framework to help designers transfer the descriptions of the prototype into a holistic design procedure. Such a framework clarifies the technical route and design process for the whole-house integration of energy demand, storage and generation. The study of such a conceptual design framework is also not carried out yet in China’s existing low-carbon building design research. Therefore, the results of this part work satisfied the objective 1 and 2, and they added new knowledge to China’s low-carbon housing research.

Moreover, this research provided interpretations of the prototype and the conceptual design framework's applicability and effectiveness through a real project case study. The results of this part work satisfied the objective 3 and 4. They also provided valuable information to future projects if they would like to implement this prototype and the conceptual design framework:

1) The identification process of the case study project provided detailed criteria to find out suitable cities and locations to implement the prototype. The conclusions about the suitable cities also give future projects a database of possible locations.
2) The explanation about how the prototype extended from a national level general model to a project level baseline building is useful for future project holders. By following the same steps, they could collect relevant references without being restrained by their knowledge of the detailed designs.
3) The descriptions of the detailed design process illustrated how to use the conceptual design framework to develop the detailed designs of building components. The lessons learnt during this process can inform future project stakeholders to avoid the same mistakes. The strategies and designs proved useful in this project can also be directly applied to future projects.
4) The simulation and monitoring methods are replicable to future projects. They can save future projects' design teams considerable time to set up a validation procedure.
5) The simulation and monitoring results are precious to future projects. Based on the analysis of the performances gaps between simulation and monitoring, future projects can project their actual performances better at the early design stage.
6) The cost analysis of this case study brings focus to the problematic area. The suggestions for further cost reduction are informative for future projects to achieve optimal cost for the required performances.

7.3 Lessons learnt and recommendations for future affordable NZE townhouse development in China

In this research, the real project case study highlights several lessons to be learnt. Based on these lessons, this research made some recommendations for future affordable NZE townhouse development in China.

Lesson 1: China's current NZE building technical standard is not ambitious to guide the design of affordable NZE townhouse to achieve its full potential of low carbon performances

The findings in this research identify the following problems of China's current NZE building technical standard:

1) The 10% renewable energy utilisation target is not ambitious enough for townhouses
2) The benefits of energy storage, especially TABS, are not emphasised
3) The possibility of utilising air-source heat pump in Cold Climate Zone of China is not recognised
4) The strategies of building-system integration are not specified, which misses the potential of cost-saving caused by holistic design at an early stage

Based on the above finding, this research made the following recommendations for the future planning and design of the NZE townhouse:

1) The future NZE townhouse project should aim for 50% or above renewable energy utilisation
2) The target of 20% or above renewable energy autonomy rate should set up at the planning stage, in order to promote multi-solutions of energy storage. This level of renewable energy autonomy rate could significantly reduce the cost of the local grid, both construction and operation
3) Promoting the building and air-source heat pump integrated system proposed in this research because the case study demonstrates its capability of enabling cost-saving and providing comfort

4) Utilising the proposed prototype and conceptual design framework to identify suitable cities and project locations at the planning and conceptual design stage, to achieve the most significant cost-saving potential and avoid misapplications

Lesson 2: China's current NZE building technical standard is not detailed enough to guide the construction to comply with the design parameters

In the case study project, the biggest failure in the construction stage is the compliance of airtightness and thermal bridge standard set up in the design stage. These failures directly induce 17.2% cooling load increase in the summer, and the similar influences would be seen in the heating season too. Therefore, it is critical to ensure that the construction quality meets the standard set up in the design.

However, reviewing the case study project's process, it is found that the failure does not come from poor project management or unwillingness of taking the cost increase, but the vast knowledge gap in local design and construction industry. China's current NZE building technical standard emphasised the importance of these two issues, and it referenced some sub design codes to deal with more detailed design and technical issues. However, the practice of the case study points out that the information is not absorbed in the design and construction industry. Moreover, the separate design and technical guidance do not help to solve the problems occurring in the integration areas, which are the main problem areas in this case study project.

Therefore, the recommendation for solving this problem is for China's government to publish regular review and update of the NZE building technical standard. It is also beneficial to involve research institutes to carry on more case studies of the demonstration projects and make the results publicly accessible. These two actions can help the design and construction industry to fill in the knowledge gap more quickly and holistically.

Lesson 3: China's current green building policies do not locate the financial subsidies on the most needed place

Financial subsidies are often needed at the beginning stage of promoting low-carbon housing because the unavoidable cost increase will make them less competitive to the current standard practices.

Through the case study project, this research found that the following three subsidies are the most accessible in Xi'an, as well as in other regions:

1) Direct cash subsidy for the cost increase caused by adding insulation
2) Direct cash subsidy for the installation and generation of renewable energies
3) Indirect financial subsidy on the calculation of constructing area, in order to compromise for the extra land needed for external insulation of the walls.

Unfortunately, the cost analysis of the case study project shows that none of these financial subsidies is beneficial to scale up the NZE townhouse project, because:

1) The case study shows that increasing insulation for such house only takes 1% of the total cost, so the developers can absorb it easily without bothering to go through the complicated paper works
2) The condition of getting the renewable energies subsidy is strict: the project has to get grid license and officially metered figures from power supply bureau; moreover, in many cases, local supply of the equipment is also required, but very often the local supply chain cannot satisfy the specification. This condition can not cover the developers' upfront cost for constructing such a house, because the license will not issue to the developers, but the house purchasers for the ownership of the micro-generations. Therefore, when scaling up such housing, the developers need to make about 12% advance payment without being able to claim them back quickly. This policy harms the developers' motivation to take micro-generations on board
3) When the external wall does not need to get much extra insulation, the land issue will become less sensitive. Therefore, it will not influence the developers much to get a planning permit for the constructed density, or the extra budget they need to purchase the extra land for the added insulation.

Hence, based on the cost analysis result of this research, the following recommendations are made for the policymakers to promote the affordable NZE townhouse in the future:

1) Setting up a financial mechanism to close the knowledge and skill gaps

As explained in section 6.6, the cost increase caused by knowledge and skill gaps of the case study project is the predominant part, which also worries the developers the most. Scaling up a prototype needs knowledgeable labours and stable supply chain to ensure the speed and the quality of production. However, developers are not willing to absorb this part of the cost, because once a developer invests significant money to get the demonstration project done, its competitors can learn from the project without any cost. In reality, it is tough for a developer to apply for patents for a construction project, as patents are usually product or design-based. Also, one developer's subcontractors are open to other developers for the experience and knowledge they learnt in the demonstration project.

Thus, it needs an organisation (such as the Innovation UK in Britain) to organise fund, as well as initialise the design, construction and POE studies for the innovative prototypes. Such an organisation will make sure that the gained knowledge and experiences are publicly accessible and quickly broadcasted to the whole construction and manufacturing industry.

2) Use taxation and low-interest loans to persuade developers taking low-carbon technologies and innovative products at the upfront, and giving the house owners or tenants cash subsidy to motivate them choosing such housing.

As explained above, cash subsidy after a housing project is finished or occupied would not be very attractive to the developers, because it cannot directly ease the financial risks to them. Moreover, the complicated application procedure creates a lot of extra paper works.

On the contrary, special tax codes for tax reduction to those technology-based contracts would effectively help developers to take them on board wherever they can. Also, low-interest rate loan with the condition of achieving performance targets is beneficial to scale up the already tested prototypes. With these upfront financial aids, the developers will feel fewer pressures to deal with the undoubtedly increased capital costs of the new housing products.

Only persuading the developers is still not enough to accelerate the deployment of the NZE townhouse prototype. House owners or tenants need to be encouraged at the same time. As explained in Chapter 4, in order to compromise with the land cost, the NZE townhouse prototype needs to apply in the suburban area. Such locations will increase the house owners or tenants' travelling cost when job opportunities are mainly in the urban area. Therefore, only when the cash subsidy for local micro-generation is enough to cover the increased travelling cost, such housing would become more affordable.

Current feed-in-tariff has reduced to a level which is similar to the grid power price because the government is short of financial resources to cover the cost. However, for the nature of the NZE townhouse prototype proposed in this research, just by step-tariff (both total amount of usage and time of usage) considerable income could be generated for the occupants.

Indeed, the above recommended financial mechanisms need to be developed carefully with the information provided by demonstration projects. Therefore, the most critical thing at the moment is still the financial aid for constructing and testing the prototypes for future low-carbon housing.

7.4 Limitations of this study and the relevant future works

7.4.1 Limitations

Despite successfully helping to develop an NZE performance townhouse project in Xi'an, there are still some critical limitations in this research to be clarified as follows:

Limitation 1: using a single case study for the validation of a prototype proposed for national scale

Due to the time-consuming and heavy-cost nature of construction projects, this research can only carry on one case study. China has enormous variations in climate, population density, economic statuses and supply chain sufficiency in different cities. Even though Xi'an is an excellent example of tier 2 city in Cold Climate Zone, there are other climate zones and tier 3 to 4 cities in China to be further validated.

For the same reason, the confirmed effectiveness of the prototype and conceptual design framework would also restrain by the characters represented by the case study project in this research.

Limitation 2: the validation of the performance carried out in commissioning rather than post-occupancy stage

Restrained by the construction progress of the case study project, within this research’s time scale, the monitoring validation could not involve occupants. There is no doubt that a building’s performances at the commissioning stage can indicate its actual operational performances with high standard accuracy. However, the existing POE studies show that low-carbon buildings bring so many new technologies and components. People are often not familiar with them. The consequence of this is that there are often considerable performance gaps caused by not understanding this new type of buildings or the systems.

Moreover, in this research, there is one critical issue for both economic and energy performance. Whether or not the occupants would accept a cool but humid indoor environment will make about 50% difference in cooling energy consumption. It also decides whether or not dehumidification equipment is a ‘must-have’ device, which again makes the capital cost of systems hugely different. The existing research of indoor thermal comfort lacks study on the whole house radiant cooling effect. Therefore, without the questionnaire survey of the occupants, it is not possible to conclude whether the commissioned indoor thermal performance has been satisfactory.

Limitation 3: this research narrowed the discussion of affordability to its capital and operational costs

In chapter 2, it has concluded that housing affordability is not just the cost of constructing and using a house; it has more extensive links to people’s livelihood. That is why in this research, the terminology of affordable NZE townhouse included the travelling cost. No matter going to work or getting the services needed, the modern city-scale determines that motor travelling is not avoidable. As shown by the reviews in this research, the significant problems of sub-urban living in China at the moment are insufficient infrastructure, poor public services and fewer work opportunities. The NZE townhouse prototype proposed in this research can help to overcome infrastructure problem, but expectably people need to compromise with longer travelling distance to work and services. Therefore, the travelling cost is an essential part of the prototype's affordability.

In this research, the travelling cost is taken care of by the 'location' criteria, both in the theoretical prototype and in the real project case study. However, without detailed monitoring of occupants' travelling cost as well as their perceptions of travelling convenience, it is not convincing that such housing is affordable in terms of travelling.

7.4.2 Future work

Work 1: More case studies in different climate zones and cities

As can be seen in this research, a real project case study is critical to validate the effectiveness of the prototype in terms of its capability of promoting good performances at low cost. There are five major climate zones and four tiers of cities in China. Therefore, a single case study is not enough to validate a prototype's effectiveness at the national scale. However, it is costly and time-consuming to build up a real house according to the prototype and monitor its real performances. This research has been lucky enough to manage a real case study within the research time scale. In the future, even though it is very much needed, it might not be able to develop more real project case studies in other climate zone and cities without large scale funding.

Nevertheless, even it might not be possible to build up so many real houses for monitoring, and simulation study can still carry on. This research shows that simulation results can give the right prediction of achievable performances. With thorough monitoring study of the case in this research, the area and scale of performance gaps can be fully identified and understood. Thus, the simulation study for other climate zones and cities can use this case study's results to project their expected real performances and costs. Such simulation study can still have good accuracy of predicting the prototype and the conceptual design framework's effectiveness in promoting good performances. The cost assumptions made for the achievable performances in other climate zones and cities will also have a reliable benchmark for comparison.

Work 2: Carry on an all-year-round POE study of the case study project after being occupied

As explained above, without POE study, the indoor thermal and energy performance are not entirely validated in real operation. Besides the objective parameters of indoor thermal environment and energy consumptions, the occupants' subjective opinions about their satisfaction of health, comfort and well-being are equally important. Therefore, an all-year-round POE study which combines objective monitoring and subject questionnaire survey is vital to carry out after this research.

Work 3: Cost analysis of the case study project from the occupants' point of view

As addressed in section 7.4.1, this research only briefly investigated the case study project's capital cost and its payback time based on the monitored energy performance. This information can give a brief idea about whether or not such a prototype can be built up at a reasonable cost and achieve its expected performances. If so, it indicates that it is affordable to the occupants to buy/rent and live in such houses.

However, in the terminology of the affordable NZE townhouse, it is highlighted that the affordability calculations need to include occupants' travelling cost. Explained in Chapter 2, travelling cost is an excellent indicator to tell the compromise made among housing's affordability, liveability and occupants' livelihood.

Therefore, additional study about the occupants' travelling cost and convenience needs to carry out in the future. This consequent research can carry out via a questionnaire survey, GPS based monitoring, or a combination of these two methods.

Reference

Alexander, D. 1997. HTB2: Heat Transfer in Buildings (Version2): User manual 2.0c. Available at: http://orca.cf.ac.uk/id/eprint/52842.

Arteconi, A. et al. 2012. State of the art of thermal storage for demand-side management. *Applied Energy* 93, pp. 371–389. Available at: http://dx.doi.org/10.1016/j.apenergy.2011.12.045.

Arteconi, A. et al. 2013. Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering* 51(1–2), pp. 155–165. Available at: http://dx.doi.org/10.1016/j.applthermaleng.2012.09.023.

Ascione, F. et al. 2016. Net zero-energy buildings in Germany: Design, model calibration and lessons learned from a case-study in Berlin. *Energy and Buildings* 133, pp. 688–710. Available at: http://dx.doi.org/10.1016/j.enbuild.2016.10.019.

Attia, S. et al. 2017. Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe. *Energy and Buildings* 155(2017), pp. 439–458. Available at: https://doi.org/10.1016/j.enbuild.2017.09.043.

Attoye, D.E. et al. 2018. A conceptual framework for a Building Integrated Photovoltaics (BIPV) Educative-communication approach. *Sustainability (Switzerland)* 10(10), pp. 1–21. doi: 10.3390/su10103781.

Ba, S. et al. 2011. Formulation of affordable housing system: international experience and policy choices in China (translated from 保障房制度建设：国际经验及中国的政策选择). *Journal of Financial Studies* 12

Bagnasco, M. et al. 2015. *The Construction Sector in China*. Beijing.

Bai, X. 2018. How high is the housing vacancy rate in China? (translated from 中国房子的空置率到底有多高?). Available at: http://finance.ifeng.com/a/20180627/16356475_0.shtml [Accessed: 31 December 2018].

Borysowich, C. 2007. Prototyping Types of Prototypes. Available at: https://it.toolbox.com/blogs/craigborysowich/prototyping-types-of-prototypes-030607 [Accessed: 9 February 2019].

Bourrelle, J.S. et al. 2013. Energy payback: An attributional and environmentally focused approach to energy balance in net zero energy buildings. *Energy and Buildings* 65, pp. 84–92. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.05.038.

Brander, M. 2012. Greenhouse Gases , CO2 , CO2e , and Carbon : What Do All These Terms Mean? *Ecometrica* (August), p. 3.

Calthorpe, P. 2016. China chokes on high-density sprawl. Available at: https://www.cnu.org/publicsquare/china-chokes-high-density-sprawl [Accessed: 2 January 2019].

Cao, J.A. and Keivani, R. 2014. *The more the merrier?-- on the efficiency of government-subsidised housing in China (translated from 多多益善？——论中国 保障性住房的效率)*. London.

CEIC 2018. Per capita housing floor area in China (translated from 中国 人均住房面积). Available at: https://www.ceicdata.com/zh-hans/china/residential-area-per-capita [Accessed: 20 August 2018].

Chegut, A. et al. 2016. Energy efficiency and economic value in affordable housing. *Energy Policy* 97, pp. 39–49. Available at: http://dx.doi.org/10.1016/j.enpol.2016.06.043.

Chen, H. et al. 2004. Compact residential areas: the sustainable development direction of China's future suburban housing? (translated from 紧凑住区：中国未来城郊住宅可持续发展的方向?). *Architect* 107(2)

Chen, W. 2011. Zhu yingxin: It is not suitable to develop 'zero-energy buildings' in China (translated from 朱颖心：中国不适合发展“零能耗建筑”). Available at: http://news.tsinghua.edu.cn/publish/thunews/9663/2011/20111024141532466674014/20111024141532466674014_.html [Accessed: 1 October 2018].

China Economic Net 2017. 保障房闲置问题为何愈演愈烈？. Available at: http://views.ce.cn/view/ent/201706/28/t20170628_23910600.shtml [Accessed: 31 October 2018].

China Economist 2018a. Asian Supermarket Guiyang Flower Orchard Exploration: One Thousand Families Floor Capacity 6.8. Available at: http://westdollar.com/sbdm/finance/news/1350,20180407853630416.html [Accessed: 7 August 2018].

China Economist 2018b. Practical exploration of Guiyang Flower Orchard super market in Asia: the plot ratio of 1000 households in one building reaches 6.8 (translated from 亚洲超级大盘贵阳花果园实探：千户同楼 容积率达6.8). Available at: http://www.boyanjjj.com/2018/fc_0407/22816.html [Accessed: 7 August 2018].

Ching, T.C. 2016. The Types of Cognitive Biases that You Need to be aware of as a Researcher. Available at: https://uxdesign.cc/cognitive-biases-you-need-to-be-familiar-with-as-a-researcher-c482c9ee1d49 [Accessed: 30 November 2018].

Clapp, C. et al. 2010. *Low-Emission Development Strategies (LEDS) : Technical, Institutional and Policy Lessons*. France. doi: 10.1787/5k451mzrnt37-en.

Clivet 2011. Heat Pumps systems from Clivet for year around complete comfort., pp. 57–60.

Commission, X.D. and R. 2015. The No.608 document of Xi'an Development and Reform Commission (translated from 西安市发展与改革委员会第608号文件).

COP21-CMP11 2016. Record: 177 parties signed the Paris Agreement. Available at: http://www.cop21.gouv.fr/en/a-record-over-160-countries-expected-to-sign-the-paris-agreement-in-new-york-on-22-april-2016/ [Accessed: 6 September 2016].

Corgnati, S.P. et al. 2013. Reference buildings for cost optimal analysis: Method of definition and application. *Applied Energy* 102, pp. 983–993. doi: 10.1016/j.apenergy.2012.06.001.

D’Agostino, D. 2015. Assessment of the progress towards the establishment of definitions of Nearly Zero Energy Buildings (nZEBs) in European Member States. *Journal of Building Engineering* 1, pp. 20–32. Available at: http://dx.doi.org/10.1016/j.jobe.2015.01.002.

D’Agostino, D. and Mazzarella, L. 2019. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. *Journal of Building Engineering* 21(September 2018), pp. 200–212. Available at: https://doi.org/10.1016/j.jobe.2018.10.019.

D’Agostino, D. and Parker, D. 2016. *Comprehensive Modeling of Optimal Paths to Reach Nearly Zero Energy Buildings (nZEBs) for New Constructions in Europe*. Florida. Available at: http://www.fsec.ucf.edu/en/publications/pdf/fsec-cr-2026-16.pdf.

D’Agostino, D. and Parker, D. 2018. A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe. *Energy* 149(2018), pp. 814–829. Available at: https://doi.org/10.1016/j.energy.2018.02.020.

Danko, P. 2015. Did Tesla Just Start an Energy Revolution? Available at: https://breakingenergy.com/2015/05/01/did-tesla-just-start-an-energy-revolution/ [Accessed: 26 October 2018].

DBIS 2010. *Estimating the amount of CO2 emissions that the construction industry can influence: supporting material for the Low Carbon Construction IGT report*. London. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/31737/10-1316-estimating-co2-emissions-supporting-low-carbon-igt-report.pdf.

Deng, S. et al. 2014. How to evaluate performance of net zero energy building - A literature research. *Energy* 71(2014), pp. 1–16. Available at: http://dx.doi.org/10.1016/j.energy.2014.05.007.

Department for Communities and Local Government 2007. *Homes for the future: more affordable, more sustainable.* London. doi: 23 July 2007.

DESA 2017a. Probabilistic Population Projections based on the World Population Prospects: The 2017 Revision. Available at: http://esa.un.org/unpd/wpp/.

DESA 2017b. World Population Prospects: The 2017 Revision.

DFID 2001. *Sustainable Livelihoods Guidance Sheets, section 2.1*. London. doi: 10.1002/smj.

Economic Information Daily 2015. Beware of ‘super real estate’ becoming urban ‘burden’ (translated from 警惕“超级楼盘”成为城市“包袱”). Available at: http://www.xinhuanet.com/finance/2015-04/20/c_127708287.htm [Accessed: 7 August 2018].

Elliott, R. 2016. The four categories of prototyping. Available at: https://www.lynda.com/Design-Techniques-tutorials/four-categories-prototyping/486758/536343-4.html [Accessed: 9 February 2019].

European Commission 2016. Paris Agreement. Available at: http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en [Accessed: 6 September 2016].

Faber, O. and Partners 1980. *IEA Annex 1, Computer Modelling of Building Performance: Analyses of Avonbank Simulation*. St. Albans, UK. Available at: https://www.iea-ebc.org/Data/publications/EBC_Annex_01_Avonbank_Level_2.pdf.

Fischer, D. et al. 2016. Impact of PV and variable prices on optimal system sizing for heat pumps and thermal storage. *Energy and Buildings* 128, pp. 723–733. Available at: http://dx.doi.org/10.1016/j.enbuild.2016.07.008.

Fischer, D. and Madani, H. 2017. On heat pumps in smart grids: A review. *Renewable and Sustainable Energy Reviews* 70(May 2016), pp. 342–357. doi: 10.1016/j.rser.2016.11.182.

Friedman, H. et al. 2011. *The Building Performance Tracking Handbook*. Available at: http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+Building+Performance+Tracking+Handbook#0%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+Building+Performance+Tracking+Handbook#4.

Gan, X. et al. 2017. How affordable housing becomes more sustainable? A stakeholder study. *Journal of Cleaner Production* 162, pp. 427–437. Available at: http://dx.doi.org/10.1016/j.jclepro.2017.06.048.

Gao, J. 2001. *Residential housing for the 21st century (translated from 面向二十一世纪得居民住宅)*. Tianjin University.

Glaeser, E. et al. 2016. A Real Estate Boom with Chinese Characteristics. *Journal of Economic Perspectives* 31(October), pp. 1–35. Available at: http://www.nber.org/papers/w22789%0Ahttp://www.nber.org/papers/w22789.ack.

Green Building Institue 2019. The characteristics of the ultra-low-energy buildings' development in China (translated from 我国超低能耗建筑发展的特点). Available at: http://mp.weixin.qq.com/s?__biz=MzIwNjc2MzU3OA==&mid=2247493520&idx=1&sn=4b17fec34dda2a4c42e7381891c79837&chksm=971e04c5a0698dd3f23119c37c9fa28cd8d74e0167c0a139acf829f901b7897e1be43acd655c&mpshare=1&scene=1&srcid=&sharer_sharetime=1573735777708&sharer_sha [Accessed: 14 November 2019].

Green buildings in the EU and USA 2018. Energy planning methods for net zero energy buildings (translated from 净零能耗建筑的能源规划方法). Available at: https://mp.weixin.qq.com/s?__biz=MzIwNjc2MzU3OA==&mid=2247489638&idx=2&sn=f2af1dc6644b750b28e51441b6d1c871&chksm=971dfb33a06a72252e3997617d5849076cc7839d747a399c39a64954a93fb3e89cb0eef88673&mpshare=1&scene=1&srcid=0904BQ1ngw40DiQ3L2VdPdLH## [Accessed: 4 September 2018].

Guo, H. et al. 2016a. Cognizing Population Density Demarcative Line (Hu Huanyong-Line) Based on Space Technology. *Bulletin of Chinese Academy of Sciences* 31(12), pp. 1385–1394. Available at: http://www.bulletin.cas.cn/publish_article/2016/12/20161213.htm.

Guo, Q. et al. 2016b. Measures to enforce mandatory civil building energy efficiency codes in China. *Journal of Cleaner Production* 119, pp. 152–166. Available at: http://dx.doi.org/10.1016/j.jclepro.2016.02.002.

Häkämies, S. et al. 2015. *Heat pumps in energy and cost efficient nearly zero energy buildings in Finland*.

Available at: http://www.vttresearch.com/impact/publications.

Hassler, U. and Kohler, N. 2014. Resilience in the built environment. *Building Research and Information* 42(2), pp. 119–129. Available at: http://dx.doi.org/10.1080/09613218.2014.873593.

Helling, A. and Shaver, L. 2018. *Measuring Community Resilience with the STAR Community Rating System,*. Available at: http://www.starcommunities.org.

Hernandez, P. and Kenny, P. 2010. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings* 42(6), pp. 815–821. Available at: http://dx.doi.org/10.1016/j.enbuild.2009.12.001.

Huo, T. et al. 2019a. China's building stock estimation and energy intensity analysis. *Journal of Cleaner Production* 207(2019), pp. 801–813. Available at: https://doi.org/10.1016/j.jclepro.2018.10.060.

Huo, T. et al. 2019b. Estimating urban residential building-related energy consumption and energy intensity in China based on improved building stock turnover model. *Science of the Total Environment* 650, pp. 427–437. Available at: https://doi.org/10.1016/j.scitotenv.2018.09.008.

Iersel, V. 2013. *Sustainable growth business models, low-carbon and industrial change*. Available at: https://www.eesc.europa.eu/en/our-work/opinions-information-reports/opinions/sustainable-growth-business-models-low-carbon-economy-and-industrial-change.

Institute of Physics 2018. Electric vehicles could save billions on energy storage. Available at: https://phys.org/news/2018-05-electric-vehicles-billions-energy-storage.html [Accessed: 13 December 2018].

IPCC 2007. *Fourth Assessment Report: Climate Change 2007*. London.

IPCC 2018. *Global warming of 1.5°C: Summary for Policymakers*. Switzerland. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2018/07/SR15_SPM_High_Res.pdf.

Janda, K.B. 2011. Buildings don't use energy: People do. *Architectural Science Review* 54(1), pp. 15–22. doi: 10.3763/asre.2009.0050.

Ji, N. 2018. Xi 'an, the hottest city in half a century, experienced 10 heat waves and 41 hot days this summer (translated from 半个世纪以来今夏最热 西安经历10轮高温41个高温日). Available at: http://sx.sina.com.cn/news/b/2018-09-02/detail-ihinpmnr6614094.shtml [Accessed: 8 April 2019].

Jiang, Y. 2018. Jiang Yi: China's future low-carbon energy system (translated from 江亿：我国未来的低碳能源系统). Available at: http://mp.weixin.qq.com/s?__biz=MzA5Njg3Njc0NQ==&mid=2650982024&idx=2&sn=a2263820874bde1b4646306b3e573a2e&chksm=8b5f072ebc288e385157131cb38d94e67c67eb571f9453215b89d0ec819934d427e01660a7be&mpshare=1&scene=1&srcid=#rd [Accessed: 21 December 2018].

Jones, P. et al. 2015. *SOLCER House*. Cardiff. Available at: https://www.researchgate.net/publication/310244330.

Ju, P. 2002. The Low-rent Housing System in China. In: *Construction of Low-rent Housing System in China*., pp. 1–12. Available at: http://www.lth.se/fileadmin/hdm/alumni/papers/hd2002/hd2002-02.pdf.

Judkoff, R. and Neymark, J. 2013. Twenty years on!: Updating the iea bestest building thermal fabric test cases for ashrae standard 140. *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association* (July), pp. 63–70.

Kosanović, S. et al. 2018. *Sustainable and resilient building design _ approaches, methods and tools*. Kosanović, S. et al. eds. Dublin: TU Delft Open.

Kreuder, L. and Spataru, C. 2015. Assessing demand response with heat pumps for efficient grid operation in smart grids. *Sustainable Cities and Society* 19, pp. 136–143. Available at: http://dx.doi.org/10.1016/j.scs.2015.07.011.

Kurnitski, J. et al. 2011. Cost optimal and nearly zero (nZEB) energy performance calculations for residential buildings with REHVA definition for nZEB national implementation. *Energy and Buildings* 43(11), pp. 3279–3288. Available at: http://dx.doi.org/10.1016/j.enbuild.2011.08.033.

Li, C. 2013. *Liveability of High-rise Housing Estates – Case studies in the inner city of Tianjin , China*. Cardiff University. Available at: https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.600596.

Li, D. 2005. *A Research on the Developments of Different Forms of Townhouse*. Tianjin: Tianjin University. Available at: http://gb.oversea.cnki.net/KCMS/detail/detail.aspx?filename=2006052946.nh&dbcode=CMFD&dbname=CMFDREF.

Li, H. and Liu, Y. 2015. Effect of several methods for generating typical meteorological year on building energy consumption. *HV&AC* 45(9), pp. 59–63.

Li, M. et al. 2018. Study on population distribution pattern at the county level of China. *Sustainability (Switzerland)* 10(10), pp. 1–16. doi: 10.3390/su10103598.

Li, Z. 2006. *The Space Environment Design and Construction of Townhouse Residence Community-Major in structure project of the building and civil engineering*. Sichuan: Sichuan University. Available at: http://discovery.scu.edu.cn/primo-explore/search?query=any,contains,Townhouse社区空间环境设计及营造——以成都“君临天下”项目为例&tab=all_tab&search_scope=all_resource&sortby=rank&vid=scu2&lang=zh_CN&offset=0.

Liang, Z. et al. 2016. Heat wave, electricity rationing, and trade-offs between environmental gains and economic losses: The example of Shanghai. *Applied Energy* 184, pp. 951–959.

Lin, K. 2013. *Investigating reducing building energy use at urban scale in Taipei*. Cardiff University. Available at: http://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.585274.

Lin, Y. 2018. An institutional and governance approach to understand large-scale social housing construction in China. *Habitat International* 78(June), pp. 96–105. Available at: https://doi.org/10.1016/j.habitatint.2018.06.001.

Litman, T. 2018. *True Affordability: Critiquing the International Housing Affordability Survey*. Available at: https://www.vtpi.org/ihasc.pdf.

Liu, H. 2008. *The theory of present and future living mode research*. Tianjin: Tianjin University. Available at: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD2009&filename=2009073853.nh&v=MzAwNjhIZG5KckpFYlBJUjhlWDFMdXhZUzdEaDFUM3FUcldNMUZyQ1VSN3FmWXVSdEZ5SG1XcnZBVjEyN0Y3Ty8=.

Liu, S. et al. 2017a. Energy, Economic and Environmental Analyses of the CO2 Heat Pump System Compared with Boiler Heating System in China. *Energy Procedia* 105, pp. 3895–3902. Available at: http://dx.doi.org/10.1016/j.egypro.2017.03.803.

Liu, Y. et al. 2017b. The stories about the santytown relocations (translated from 棚改货币化安置的那些事儿). Available at: https://wallstreetcn.com/articles/3007957 [Accessed: 2 November 2018].

Lizana, J. et al. 2018. Energy flexible building through smart demand-side management and latent heat storage. *Applied Energy* 230(May), pp. 471–485. Available at: https://doi.org/10.1016/j.apenergy.2018.08.065.

Lomas, K.J. et al. 1997. Empirical validation of building energy simulation programs. *Energy and Buildings* 26(3), pp. 253–275. doi: 10.1016/s0378-7788(97)00007-8.

Lu, Y. et al. 2015. Design optimization and optimal control of grid-connected and standalone nearly/net zero energy buildings. *Applied Energy* 155, pp. 463–477. Available at: http://dx.doi.org/10.1016/j.apenergy.2015.06.007.

Luthander, R. et al. 2015. Photovoltaic self-consumption in buildings: A review. *Applied Energy* 142, pp. 80–94. Available at: http://dx.doi.org/10.1016/j.apenergy.2014.12.028.

Ma, J. 2011. *The research of the characteristic of contemporary townhouse*. Tianjin: Tianjin University. Available at: https://kns.cnki.net/KCMS/detail/detail.aspx?dbcode=CMFD&dbname=CMFD2012&filename=1012022370.nh&v=MzI2OTVuVUw3SlZGMjZITE82SE5MTHI1RWJQSVI4ZVgxTHV4WVM3RGgxVDNxVHJXTTFGckNVUjdxZll1UnRGeUg=.

Ma, P. et al. 2015. Energy storage and heat extraction - From thermally activated building systems (TABS) to thermally homeostatic buildings. *Renewable and Sustainable Energy Reviews* 45, pp. 677–685. Available at: http://dx.doi.org/10.1016/j.rser.2015.02.017.

Ma, Z. et al. 2018. Affordable housing brings about socio-spatial exclusion in Changchun, China: Explanation in various economic motivations of local governments. *Habitat International* 76(August 2017), pp. 40–47. Available at: https://doi.org/10.1016/j.habitatint.2018.05.003.

Man, J.Y. 2011. *Affoardable housing in China*. Beijing. Available at: https://www.lincolninst.edu/sites/default/files/pubfiles/1871_1184_lla110104.pdf.

Marszal, A.J. et al. 2011. Zero Energy Building - A review of definitions and calculation methodologies. *Energy* *and Buildings* 43(4), pp. 971–979. Available at: http://dx.doi.org/10.1016/j.enbuild.2010.12.022.

Martin, L. and March, L. 1972. *Urban Space and Structures*. Martin, L. and March, L. eds. New York: Cambridge University Express.

Matulka, R. and Wood, D. 2013. The history of the Light Bulb. Available at: https://www.energy.gov/articles/history-light-bulb [Accessed: 26 October 2018].

Milne, M. 2008. Climate Consultant. Available at: http://www.energy-design-tools.aud.ucla.edu/climate-consultant/ [Accessed: 24 April 2019].

Ministry of Land & Resources and State Development & Reform Commission of China 2006. *Notice on the promulgation and implementation of the catalogue of projects for restricted land use (2006 version) and catalogue of projects for prohibited land use (2006 version) (translated from 关于发布实施《限制用地项目目录（2006年本）》和《禁止用地项目目录（2006年本）》的通知)*. Available at: http://www.gov.cn/zwgk/2006-12/18/content_471717.htm.

Moffatt, S. and Kohler, N. 2008. Conceptualizing the built environment as a social–ecological system. *Building Research and Information* 36(3), pp. 248–268. doi: 10.1080/09613210801928131.

My-peer Toolkit 2018. Data collection methods. Available at: http://mypeer.org.au/monitoring-evaluation/data-collection-methods/ [Accessed: 17 November 2018].

National Academy of Engineering and National Research Council 2010. Annual mean distribution of direct radiation. In: *The Power of Renewables Opportunities and Challenges for China and the United States (2010)*. Washington, DC: The National Academies Press, p. 44. Available at: https://doi.org/10.17226/12987 [Accessed: 13 February 2019].

National Assembly for Wales 2018. *Low Carbon Housing: the Challenge*. Cardiff. Available at: www.assembly.wales/SeneddCCERA.

National Bureau of Statistics of China 2018. *Personal income and consumer spending in 2017 (translated from 2017年居民收入和消费支出情况)*. Beijing.

National Statistics Bureau of China 2018a. China’s population 1978 – 2017. Available at: http://data.stats.gov.cn/easyquery.htm?cn=C01&zb=A0301&sj=1980.

National Statistics Bureau of China 2018b. The construction and installation project cost index of the capital cities’ housing in the first half of 2018 (translated from 2018年上半年省会城市住宅建安工程造价指标). Available at: https://www.shigoog.com/down/201810/17/doc471.html.

Navarro, L. et al. 2016. Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system. *Renewable Energy* 85, pp. 1334–1356. doi: 10.1016/j.renene.2015.06.064.

Neill, J. 2007. Qualitative versus Quantitative Research : Key points in a classic debate Qualitative versus. Available at: http://wilderdom.com/research/QualitativeVersusQuantitativeResearch.html [Accessed: 17

November 2018].

Neymark, J. et al. 2011. IEA BESTEST multi-zone non-airflow in-depth diagnostic cases. *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association* (November), pp. 169–176.

NHBC Foundation 2011. *ZERO CARBON COMPENDIUM-Who's doing what in housing worldwide*. Knowl Hill.

Nimlyat, P.S. 2014. Computer Simulations In Buildings: Implications For Building Energy Performance. *IOSR Journal of Engineering* 4(3), pp. 56–62. doi: 10.9790/3021-04345662.

NUMBEO 2018. Property Prices Index for Country 2018 Mid-Year. Available at: https://www.numbeo.com/property-investment/rankings_by_country.jsp?title=2018-mid [Accessed: 25 July 2018].

Pan, S. 2019. The relationship between commuting radius and metropolitan area (translated from 通勤半径与都市圈的关系). Available at: http://mp.weixin.qq.com/s?__biz=MzA4MTA1MjkzNg==&mid=2653691426&idx=1&sn=b288a6560267fd19e2b6684cdad2b76b&chksm=84426a45b335e3532cd8d0255557bf6084fa582c5787c846285927532f0d233407f84b56430a&mpshare=1&scene=1&srcid=#rd [Accessed: 11 February 2019].

Park, S.H. et al. 2014. Evaluation of the thermal performance of a Thermally Activated Building System (TABS) according to the thermal load in a residential building. *Energy and Buildings* 73, pp. 69–82. Available at: http://dx.doi.org/10.1016/j.enbuild.2014.01.008.

Rodrígueza, L.R. et al. 2018. Contributions of heat pumps to demand response: A case study of a plus-energy dwelling. *Applied Energy* 214(January), pp. 191–204. Available at: https://doi.org/10.1016/j.apenergy.2018.01.086.

Romaní, J. et al. 2018. Control concepts of a radiant wall working as thermal energy storage for peak load shifting of a heat pump coupled to a PV array. *Renewable Energy* 118, pp. 489–501. Available at: https://doi.org/10.1016/j.renene.2017.11.036.

Sarniak, R. 2015. 9 Types of Research Bias and How To Avoid Them. Available at: https://www.quirks.com/articles/9-types-of-research-bias-and-how-to-avoid-them [Accessed: 30 November 2018].

Sartori, I. et al. 2012. Net zero energy buildings: A consistent definition framework. *Energy and Buildings* 48, pp. 220–232. Available at: http://dx.doi.org/10.1016/j.enbuild.2012.01.032.

Saunders et al. 2012. How to write a methodology (2018) - Dissertation Help. Available at: https://writepass.com/journal/2017/08/write-methodology-dissertation-help/ [Accessed: 15 November 2018].

Schaefer, A. and Ghisi, E. 2016. Method for obtaining reference buildings. *Energy and Buildings* 128, pp. 660–672. Available at: http://dx.doi.org/10.1016/j.enbuild.2016.07.001.

Schmelas, M. et al. 2017. Savings through the use of adaptive predictive control of thermo-active building systems (TABS): A case study. *Applied Energy* 199, pp. 294–309. Available at: http://dx.doi.org/10.1016/j.apenergy.2017.05.032.

Senthilingam, M. 2015. How smartphones are improving city life in Singapore. Available at: https://edition.cnn.com/2015/06/24/tech/big-data-urban-life-singapore/index.html [Accessed: 26 October 2018].

Shen, C. and Li, X. 2016. Dynamic thermal performance of pipe-embedded building envelope utilizing evaporative cooling water in the cooling season. *Applied Thermal Engineering* 106, pp. 1103–1113. Available at: http://dx.doi.org/10.1016/j.applthermaleng.2016.06.073.

Shen, C. and Li, X. 2017. Energy saving potential of pipe-embedded building envelope utilizing low-temperature hot water in the heating season. *Energy and Buildings* 138, pp. 318–331. Available at: http://dx.doi.org/10.1016/j.enbuild.2016.12.064.

Shepard, W. 2015. Half the houses will be demolished within 20 years": On the disposable cities of china. Available at: https://www.citymetric.com/skylines/half-houses-will-be-demolished-within-20-years-disposable-cities-china-1470 [Accessed: 20 October 2017].

Shi, W. et al. 2016. Affordable housing policy in China: New developments and new challenges. *Habitat International* 54, pp. 224–233. Available at: http://dx.doi.org/10.1016/j.habitatint.2015.11.020.

Soflaei, F. et al. 2017. Socio-environmental sustainability in traditional courtyard houses of Iran and China. *Renewable and Sustainable Energy Reviews* 69(September 2015), pp. 1147–1169. doi: 10.1016/j.rser.2016.09.130.

State Council of China 2016. Notice of the state council on printing and distributing the comprehensive work plan for energy conservation and emission reduction during the 13th five-year plan period (translated from: 国务院关于印发"十三五"节能减排综合工作方案的通知). Available at: http://www.gov.cn/zhengce/content/2017-01/05/content_5156789.htm%0AAccess [Accessed: 29 September 2018].

Stene, J. et al. 2018. *State-of-the-Art Analysis of Nearly Zero Energy Buildings - Norway (Country report IEA HPT Annex 49)*. Blindern: SINTEF Academic Press. Available at: http://www.zeb.no/index.php/reports/item/406-state-of-the-art-analysis-of-nearly-zero-energy-buildings-country-report-iea-hpp-annex-40-task-1-norway.

Stone, P.. 1973. *The Structure, Size and Costs of Urban Settlements*. London: The Syndics of Cambridge University Express.

Stone, P.A. 1970. *Urban Development in Britain: Standards, Costs and Resources, 1964-2004: Volume 1 Population Trends and Housing*. London: The Syndics of the Cambridge University Press.

Sun, L. 2012. *Sustainable peri-urban residential settlement development in china: Evaluation of three cases in Tianjin*. Cardiff University.

Survey and Research Center for China Household Finance 2017. *TREND IN THE HOUSING MARKET AND HOUSING VACANCY RATE IN URBAN CHINA*. Chengdu.

Swan, L.G. and Ugursal, V.I. 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews* 13(8), pp. 1819–1835. doi: 10.1016/j.rser.2008.09.033.

Tan, R. 2017. The Evolution, Characteristics and Orientation of China’s Affordable Housing System. 34(2), pp. 101–108.

Tapsuwan, S. et al. 2018. Preferences for sustainable, liveable and resilient neighbourhoods and homes: A case of Canberra, Australia. *Sustainable Cities and Society* 37(October 2017), pp. 133–145. Available at: https://doi.org/10.1016/j.scs.2017.10.034.

THE CONVERSATION 2017. When some US firms move production overseas, they also offshore their pollution. Available at: http://theconversation.com/when-some-us-firms-move-production-overseas-they-also-offshore-their-pollution-75371 [Accessed: 11 January 2019].

The State Council of China 2013. Forwarding the Ministry of Housing and Urban-rural Development’s green building action plan (translated from 国务院办公厅关于转发发展改革委住房城乡建设部绿色建筑行动方案的通知). Available at: http://www.gov.cn/zwgk/2013-01/06/content_2305793.htm [Accessed: 10 November 2018].

The world bank database 2018. The world bank database - Population density (people per sq. km of land area), 1961-2017. Available at: https://data.worldbank.org/indicator/EN.POP.DNST?locations=NL-GB-BD.

The World Bank Group 2019. Global Map of Direct Normal Radiation. Available at: https://globalsolaratlas.info [Accessed: 25 March 2019].

The World Commission on Environment and Development 1987. *Our Common Future*. Available at: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.

Thygesen, R. and Karlsson, B. 2013. Economic and energy analysis of three solar assisted heat pump systems in near zero energy buildings. *Energy and Buildings* 66, pp. 77–87. Available at: http://dx.doi.org/10.1016/j.enbuild.2013.07.042.

Thygesen, R. and Karlsson, B. 2017. An analysis on how proposed requirements for near zero energy buildings manages PV electricity in combination with two different types of heat pumps and its policy implications – A Swedish example. *Energy Policy* 101(November 2016), pp. 10–19. Available at: http://dx.doi.org/10.1016/j.enpol.2016.11.025.

Vale, L.J. et al. 2014. What Affordable Housing Should Afford: Housing for Resilient Cities. *Cityscape: A Journal of Policy Development and Research* 16(2), p. 22.

VANSN 2016. The most detailed analysis of ‘compound villa’ (translated from “合院别墅”最详细的分析). Available at: http://mp.weixin.qq.com/s?__biz=MjM5NzAwMjk4Mw==&mid=2652318725&idx=1&sn=aa427c7e2703939411c9e2bcffc5fecd&chksm=bd03278d8a74ae9bfd2c12aaeb5209f490996b8110540395d505fccc671f1b01a35a29f48f59&mpshare=1&scene=1&srcid=0715Bk0dKrLBE1zpfWQCzDbJ#rd [Accessed: 1 April 2019].

Wallbaum, H. et al. 2012. Indicator based sustainability assessment tool for affordable housing construction technologies. *Ecological Indicators* 18, pp. 353–364. Available at: http://dx.doi.org/10.1016/j.ecolind.2011.12.005.

Walton-Warwick, L. 2017. Electric cars can power buildings from the parking lot. Available at: https://www.futurity.org/electric-cars-power-buildings-1462852/ [Accessed: 13 December 2018].

Wang, J. et al. 2018a. Environmental impacts of short building lifespans in China considering time value. *Journal of Cleaner Production* 203(November), pp. 696–707. Available at: https://doi.org/10.1016/j.jclepro.2018.08.314.

Wang, J. et al. 2018b. What can the '45-minute rule' of commuting tell us - the subway card swiping data (translatedf from 通勤的"45分钟定律"从地铁刷卡数据能看出什么). Available at: http://mp.weixin.qq.com/s?__biz=MzI3NDQzMDkxNQ==&mid=2247487259&idx=1&sn=34faf5918becb74d1b8bdd75cd4fd440&chksm=eb1561b7dc62e8a189107561f62088c7d4e8a9e67e9f3ce38c948d4233a5ba35a6c59916c3cf&mpshare=1&scene=1&srcid=#rd [Accessed: 6 December 2018].

Wang, Y. 2018. Wang yeqiang, a researcher at the Chinese academy of social sciences: China's housing vacancy rate is not as severe as expected (translated from 社科院研究员王业强：中国住房空置率没有想象的那么严重). Available at: https://finance.qq.com/a/20181017/008602.htm [Accessed: 31 December 2018].

Wang, Z. et al. 2018c. Learning urban resilience from a social-economic-ecological system perspective: A case study of Beijing from 1978 to 2015. *Journal of Cleaner Production* 183, pp. 343–357. Available at: https://doi.org/10.1016/j.jclepro.2018.02.128.

Wei, Z. and Chiu, R.L.H. 2018. Livability of subsidized housing estates in marketized socialist China: An institutional interpretation. *Cities* 83(December 2017), pp. 108–117. Available at: https://doi.org/10.1016/j.cities.2018.06.013.

Wells, L. et al. 2018. A review of Net Zero Energy Buildings with reflections on the Australian context. *Energy and Buildings* 158, pp. 616–628. Available at: http://dx.doi.org/10.1016/j.enbuild.2017.10.055.

WHO 2009. Guidelines for Indoor Air Quality: Dampness and Mould. Available at: http://www.euro.who.int/__data/assets/pdf_file/0017/43325/E92645.pdf.

Wilson, P. 2016. Air Conditioning and Temperature, Relative Humidity and Dew Points. Available at: https://www.mrfixitbali.com/air-conditioning/temperature-humidity-dew-point-251.html [Accessed: 26 July 2019].

Wu, F. 1996. Changes in the structure of public housing provision in urban China. *Urban Studies* 33(9), pp. 1601–1627. doi: 10.1080/0042098966529.

Wu, J. et al. 2016. Evaluating the risk of Chinese housing markets: What we know and what we need to know. *China Economic Review* 39(71003060), pp. 91–114. Available at: http://dx.doi.org/10.1016/j.chieco.2016.03.008.

Wu, L. 2001. Preface. In: Lv, J. et al. eds. *Modern Urban Housing in China 1840 - 2000*. 1st ed. Munich, London: New York: Prestel Verlag, p. 9.

Xiao, Y. and Qiao, Z. 2009. The Problems and Countermeasures for Implementing Green Green Building in China. In: *International Conference on Information Management, Innovation Management and Industrial Engineering*. Xi'an

Xu, C. et al. 2017. Thermodynamic and environmental evaluation of an improved heating system using electric-driven heat pumps: A case study for Jing-Jin-Ji region in China. *Journal of Cleaner Production* 165, pp. 36–47. Available at: http://dx.doi.org/10.1016/j.jclepro.2017.07.087.

Xu, W. 2017. Research and practice of near zero energy buildings in China (translated from 中国近零能耗建筑的研究和实践). *Science & Technology Review* 35(10). Available at: https://freewechat.com/a/MzIxMTQwMzM1Mg==/2247484509/1.

Xu, X. 2007. *A Research on the Architectural Space Of Townhouse*. Tianjin: Tianjin University.

Xu, X. et al. 2010. Active pipe-embedded structures in buildings for utilizing low-grade energy sources: A review. *Energy and Buildings* 42(10), pp. 1567–1581. Available at: http://dx.doi.org/10.1016/j.enbuild.2010.05.002.

Yan, Q. et al. 2015. The worries about "the biggest real estate project in China (translated from "中国第一大盘" 隐忧). Available at: http://news.hexun.com/2015-04-28/175360993.html [Accessed: 7 August 2018].

Yao, L. 2010. *The report of a study on low-income housing in China (translated from 中国低收入阶层住房研究报告)*.

Ye, L. et al. 2015. Developments of Green Building Standards in China. *Renewable Energy* 73, pp. 115–122. Available at: http://dx.doi.org/10.1016/j.renene.2014.05.014.

Yi, F. and Su, J. 2019. 2018: a historic turning point -- China's population begins to decline (translated from 2018年:历史性的拐点—中国人口开始负增长). Available at: http://www.sohu.com/a/286146842_177992 [Accessed: 11 January 2019].

Yi, L. 2012. Expert of China's Meteorological Administration: there are more and more 'furnace' cities (translated from 国家气候中心专家："火炉"城市越来越多). Available at: http://www.cma.gov.cn/2011xwzx/2011xqhbh/2011xdtxx/201208/t20120816_182112.html [Accessed: 8 April 2019].

Yi, X. 2018. Why the cash subsidy of santytown relocations will push up the housing price? (translated from 棚改货币化安置为何会推高房价？). Available at: http://opinion.jrj.com.cn/2018/07/14012424815139.shtml [Accessed: 2 November 2018].

You, X. 2018. City image | Sleeps in China's largest concrete forest and I dream of Manhattan (translated from 城市映像｜睡在这个中国最大的水泥森林里，我梦到了曼哈顿). Available at: https://www.thepaper.cn/newsDetail_forward_2121319 [Accessed: 10 January 2019].

Yu, Y. 2017. Not involving tall buildings at all in Xiongan will do more harm than good (translated from 雄安不建高楼大厦弊多利少). Available at: http://www.caogen.com/blog/infor_detail/95221.html [Accessed: 12 November 2018].

Zaidah, Z. and Zainal, Z. 2007. Case study as a research method. *Jurnal Kemanusiaan* 9(Journal Article), pp. 1–6. doi: 10.1177/15222302004003007.

Zero Carbon Hub 2014. *Zero Carbon Homes and Nearly Zero Energy Buildings UK Building Regulations and EU Directives*. Zero Carbon Hub.

Zhang, L. et al. 2018. Policies to enhance the drivers of green housing development in China. *Energy Policy* 121(June), pp. 225–235. Available at: https://doi.org/10.1016/j.enpol.2018.06.029.

Zhang, Q. et al. 2017. Techno-economic analysis of air source heat pump applied for space heating in northern China. *Applied Energy* 207, pp. 533–542. Available at: https://doi.org/10.1016/j.apenergy.2017.06.083.

Zhang, Q. 2019. 分析了633个中国城市之后，我们发现五分之二都在流失人口. Available at: http://mp.weixin.qq.com/s?__biz=MzAxMzA2MDYxMw==&mid=2651567128&idx=1&sn=9574a24262df7e0ebbe4e04b5e1938f9&chksm=80574b72b720c2641f5c2e8eb6145ffa59a69d4bea5aa9e662c73264aee66e35f84eb88ba651&mpshare=1&scene=1&srcid=0111O2G6rFaEQ9q1iM7uoaE8#rd [Accessed: 11 January 2019].

Zhang, X. and Li, H. 2018. Urban resilience and urban sustainability: What we know and what do not know? *Cities* 72(August 2017), pp. 141–148. Available at: https://doi.org/10.1016/j.cities.2017.08.009.

Zhao, S.X.B. et al. 2017. How big is China’s real estate bubble and why hasn’t it burst yet? *Land Use Policy* 64, pp. 153–162. Available at: http://dx.doi.org/10.1016/j.landusepol.2017.02.024.

Zhao, X. 2012. The dark horse Guizhou HLC Group: made 8 billion yuan turnover by one single project and has jumped to top 20 of the real estate development companies in China (translated from 黑马宏立城：一盘卖80亿跻身20强). Available at: http://gz.leju.com/news/2012-07-12/07393918806.shtml [Accessed: 7 August 2018].

Zhihu Forum 2018. How to evaluate Guiyang Flower Orchard - ‘China’s biggest housing project’? (translated from 如何评价贵阳花果园 -‘中国第一大盘’？). Available at: https://www.zhihu.com/question/46642458 [Accessed: 5 August 2018].

Zhihu Forum 2019. When did China enter negative population growth?(translated from 中国何时进入人口负增长?). Available at: https://www.zhihu.com/question/280352877 [Accessed: 11 January 2019].

Zhu, K. and Li, L. 2015. The main problems in the construction and management of social housing in China and the reform proposals (translated from 中国保障房建设管理的主要问题及改革建议). *Theory Journal* 11, pp. 83–88. doi: 10.14110/j.cnki.cn-37-1059/d.2015.11.012.

Zhuo, X. and Zhang, Y. 2019. The new transformation of urban population in China: ‘the balance between north and south’ turns to ‘the south is fast and the north is slow’ (translated from 中国城市人口新变局：“南北均衡”转向“南快北慢”). Available at: https://view.inews.qq.com/a/20190208A0GMPA00 [Accessed: 9 February 2019].

Zou, P.X.W. et al. 2007. Understanding the key risks in construction projects in China. *International Journal of Project Management* 25(6), pp. 601–614. doi: 10.1016/j.ijproman.2007.03.001.

Zou, Y. 2014. Contradictions in China's affordable housing policy: Goals vs. structure. *Habitat International* 41, pp. 8–16. Available at: http://dx.doi.org/10.1016/j.habitatint.2013.06.001.

Appendix 1 Introduction of the simulation tool HTB2 and the details of monitoring equipment

HTB2 treats the interior spaces in a building as individual zones. These zones are linked to each other and also to the external environment by walls, doors, windows and ventilation paths. The HVAC systems operate as networks under a controlled schedule. This tool also considers the internal gains of heat and moistures as well. These thermal factors generate heat fluxes, air movements and moisture movements, which directly affect the temperature and humidity levels of the indoor spaces (Alexander 1996). Figure A3-1 represents the processes and interactions of a building in HTB2 setting.

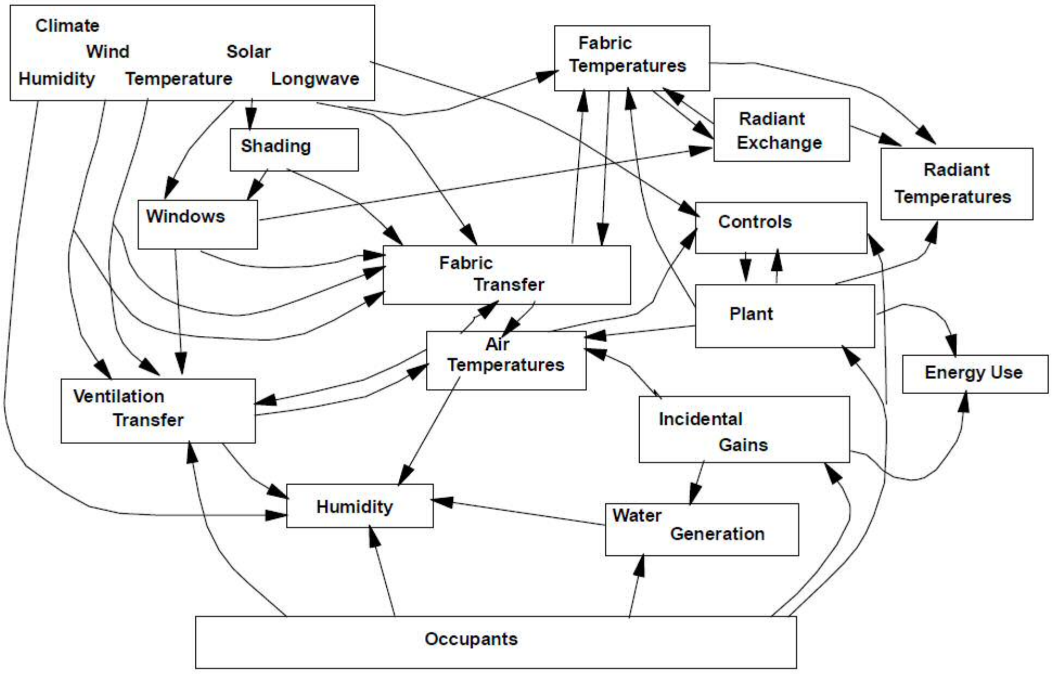


Figure A1-1 Fundamental Building Processes and Interactions in HTB2 (Alexander 1997)

The tool divides time into intervals and assumes that each heat transport mechanism remains constant and independent of the others during that time interval (see Figure A3-2). At the end of each interval, HTB2 calculates a new set of conditions throughout the run. The time interval, which usually is less than one minute, helps to achieve more accurate and detailed results.

Input data files in HTB2 are gathered at three levels (Figure A3-3), reflecting the three levels of subroutines in the tool itself broadly. All these files can be created directly, or be obtained by editing standard files. They are opened and modified by using Windows Notepad. It is fair to say that HTB2 is not the most accessible numerical simulation tool to be used by architects or other designers heavily relying on graphic interactions. HTB2 does have its schematic tool to present the building elements and the links among them in a symbolic schematic way to help the visualisation. However, all the input data of HTB2 are text-based. In a coding language format, this creates difficulties for those designers with less engineering background. However, the most significant advantage of HTB2 is that each part of the input data can be edited separately and done by different people. This structure provides excellent flexibility to the interdisciplinary design team to organise the data input. It also largely speeds up the simulation process at the concept development stage, by being able to run multi-scenarios tests all in one go.

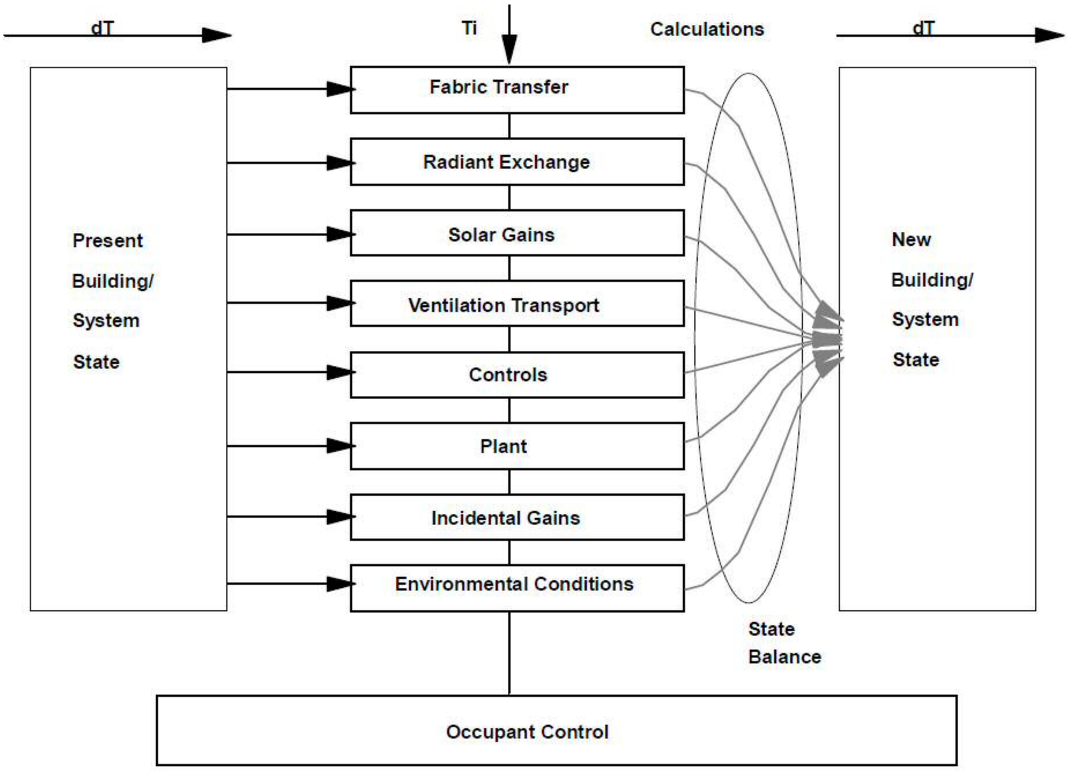


Figure A1-2 Partitioning of Time and Processes in HTB2 (Alexander 1997)

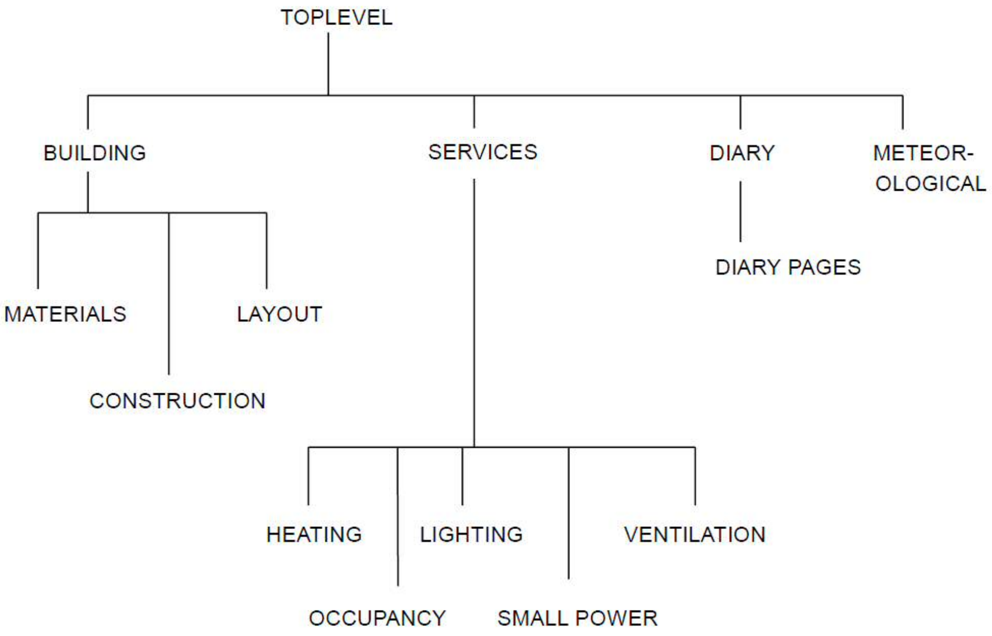


Figure A1-3 HTB2 hierarchical file structure (Alexander 1997)

There are six output types, as follows (Alexander 1997):

> *LOG - typically the screen output created during the run, this output type warns of errors during the input and run stages, and marks the progress of a run.*
>
> *INFO - contains run information, such as filenames, space volumes, element types. It is created immediately after the input stage and is useful in checking input integrity. For instance, a standard U-value is calculated for each construction type, which can then be compared against expectations. This file is also useful in documenting runs, as it contains a log of all files and key data used within a run. Postprocessor programs may use this file to aid interpretation of data in the other output files.*
>
> *REPORT - records interval averages of critical data resulting from the simulation. The default condition stores the necessary information required to construct an energy balance for each space of the building. The default interval is hourly, although this can be altered to any interval from one timestep to one day.*

> *PROFILE - records instantaneous temperature and heat flux profiles (slices) through selected building elements at selected intervals, or as triggered snapshots.*
>
> *LOGGER - records instantaneous data asynchronously, when the value of (user) selected variables change by more than a specified amount. This allows the time-history of a variable to be recorded, to a resolution of one timestep, without generating enormous file sizes.*
>
> *SAVE STATE - records the fabric temperature conditions each midnight. This file is not meant to be an 'output' as such, but rather to be a means of restarting a simulation from a known point.*

Figure A3-4 shows the fundamental relationship between the components of HTB2 and the data files.

The first two are standard outputs which record and note the progress of a run. They can be produced by HTB2 as soon as the simulation starts. The remaining four outputs are optional, which can be selected as required in the 'TOPLEVEL' file. The 'Report File', also known as '*.BLK' file, is the most commonly used as it contains all the simulation results. It can be opened by a program named HTB2VIEW, which is a post-processor translating the machine coded format *.BLK file into numerical and graphic data. It is possible to view the year-round data of selected parameters for each space separately. The displayed (filtered) results can then export to a spreadsheet for further analysis.

In terms of the accuracy of the simulation tool, HTB2 was once compared with other 22 tools against the measured results and proved to be one of the most accurate tools (Lomas et al., 1997). Therefore, it is confident to use HTB2's simulation results to compare with the standards and guide the detailed HVAC system design.

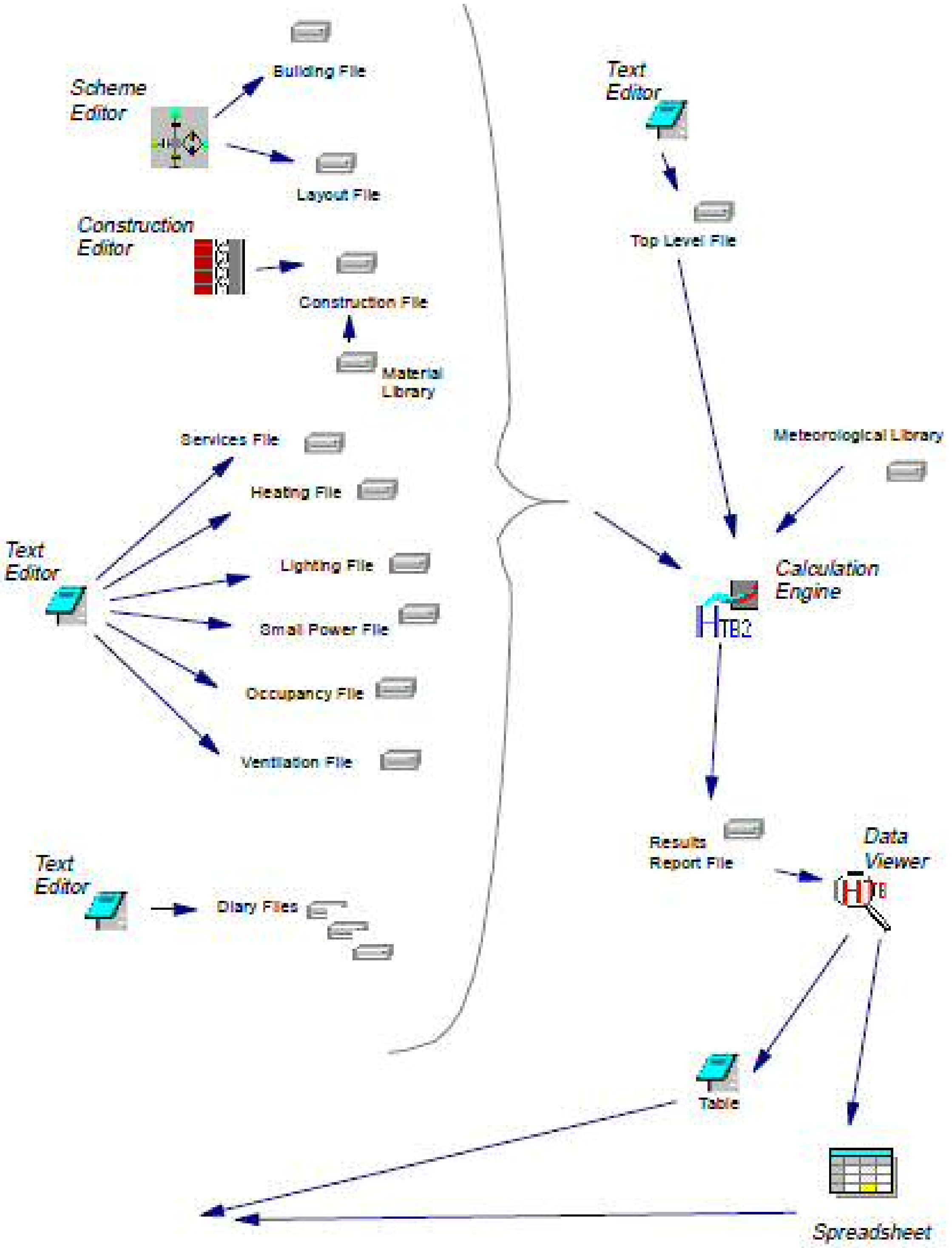


Figure A1-4 Relationship of Files and Utilities in HTB2 (Alexander 1997)

Table A1-1 The monitored subjects, the relevant equipment and installation information

Subject	Floor	Equipment	Supplier & Instrument code	Location	Measurement	Parameters	Notes
Electricity	**0F**	Multi-channel multifunction AC power meter	Pilot SPM20-1	Indoor switch box	The total ground floor electricity consumptions	$E_{SPM20-1}$	$E_{app1} = E_{SPM20-1} - E_{CTC-L1} - E_{CTC-V1} - E_{CTC-AC} + E_{CTC-Fridge}$
		Split core current transformer	Pilot CTC-L1		Lighting electricity consumption of the ground floor	E_{CTC-L1}	
		Split core current transformer	Pilot CTC-V1		Socket 1 electricity consumption in the kitchen (fridge and smoke extractor)	E_{CTC-V1} $E_{CTC-Fridge}$	$E_{CTC-Fridge}$ is secondary data, which calculated out from E_{CTC-V1} because the energy used by the smoke extractor belongs to ventilation energy consumption. It can be extracted out from the E_{CTC-V1} because both of these two energy use have regular schedule and distinct power needs. Even they sometimes overlap, the total energy use at the overlapped time can divide with high accuracy.
		Split core current transformer	Pilot CTC-C		Socket 2 electricity consumption in the kitchen (all the cooking devices)	E_{CTC-C}	This part of energy use belongs to appliances energy consumptions but will be displayed and analysed separately.
		Split core current transformer	Pilot CTC-AC		The individual attached air-conditioner	E_{CTC-AC}	This part of energy use belongs to cooling energy consumption
		Three-phase wireless multifunction AC power meter	Pilot PMAC903-Z1	Outdoor switch box	Electricity consumption of the car charging pile socket	E_{CAR}	This part of energy use does not count in the house's energy consumption. The record is for getting the living associated carbon footprint and cost, which is to be studied by this research in the future.

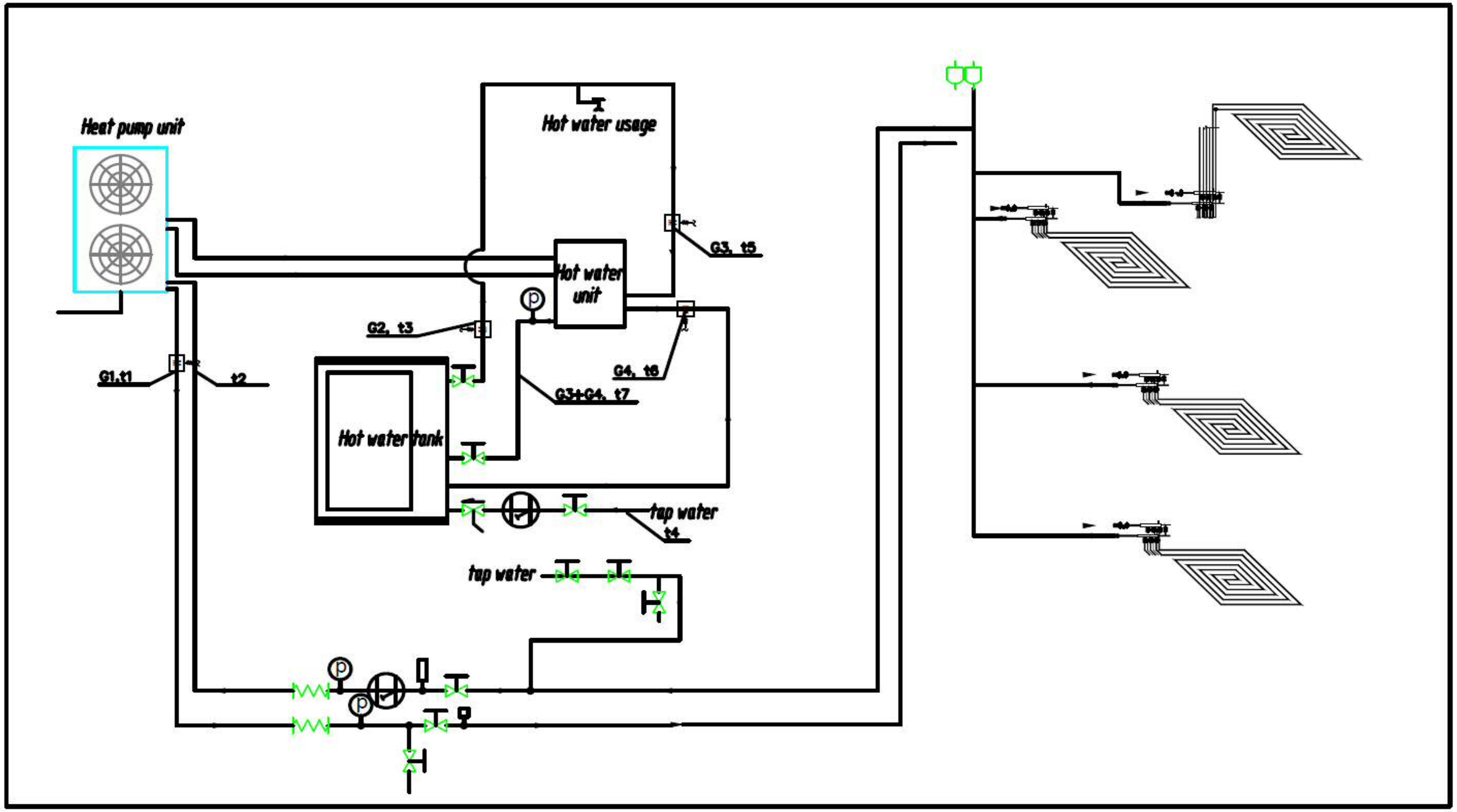
Subject	**Floor**	**Equipment**	**Supplier & Instrument code**	**Location**	**Measurement**	**Parameters**	**Notes**
Electricity	**1F**	Multi-channel multifunction AC power meter	Pilot SPM20-2	Indoor switch box	The total first-floor electricity consumptions	$E_{SPM20\text{-}2}$	$E_{app2} = E_{SPM20\text{-}2} - E_{CTC\text{-}L2} - E_{CTC\text{-}V2} + E_{CTC\text{-}small1}$
		Split core current transformer	Pilot CTC-L2		Lighting electricity consumption of the first floor	$E_{CTC\text{-}L2}$	
		Split core current transformer	Pilot CTC-V2	Indoor switch box	Electricity consumption of bathroom socket (small appliances and electric bath heater)	$E_{CTC\text{-}V2}$ $E_{CTC\text{-}small1}$	$E_{CTC\text{-}small1}$ is secondary data, which calculated out from $E_{CTC\text{-}V2}$ because the energy used by the electric bath heater belongs to heating energy consumption. It can be extracted out from the $E_{CTC\text{-}V2}$ because it has a distinct schedule and energy use than small appliances.
	2F	Multi-channel multifunction AC power meter	Pilot SPM20-3	Indoor switch box	The total second-floor electricity consumptions	$E_{SPM20\text{-}3}$	$E_{app3} = E_{SPM20\text{-}3} - E_{CTC\text{-}L3} - E_{CTC\text{-}V3} + E_{CTC\text{-}small2} - E_{CTC\text{-}V4}$
		Split core current transformer	Pilot CTC-L3		Lighting electricity consumption of the third floor	$E_{CTC\text{-}L3}$	
		Split core current transformer	Pilot CTC-V3		Electricity consumption of bathroom socket (small appliances and electric bath heater)	$E_{CTC\text{-}V3}$ $E_{CTC\text{-}small2}$	Same as $E_{CTC\text{-}small2}$
		Split core current transformer	Pilot CTC-V4		The MVHR socket	$E_{CTC\text{-}V4}$	$Q_{ventilation} = E_{CTC\text{-}V4} + E_{CTC\text{-}V1} - E_{CTC\text{-}Fridge}$
		Three-phase multi-function electric meter	Pilot SPM93-HP1		The heat pump unit socket	$E_{SPM93\text{-}HP}$	$Q_{HP} = E_{SPM93\text{-}HP1} * EER$

Subject	**Floor**	**Equipment**	**Supplier & Instrument code**	**Location**	**Measurement**	**Parameters**	**Notes**
Electricity	**2F**	Three-phase multi-function electric meter	Pilot SPM93-DHW1	Indoor switch box	The hot water tank socket	$E_{SPM93\text{-}DWH}$	$Q_{electric} = E_{SPM93\text{-}DWH1}$ * 99% (based on electric heaters' general efficiency)
Heat flow	**2F**	Electromagnet flowmeter	Asmik DN50-1	The main supply water pipe of the heat pump system	The flow volume of the pipe G1	The heating or cooling energy consumption	Q1=G1*c*(t1-t2)
		Water temperature sensor	ZeeTee TW-1 & TW-2	The main supply and return water pipe of the heat pump system	The supply water temperature t1, the return water temperature t2,		
		Electromagnet flowmeter	Asmik DN25-1	The outlet water pipe of the hot water tank	The flow volume of the pipe G2	The total domestic hot water energy consumption	Q2=(G2-G3)*c*(t3-t4)+ $e_{lectric}$
		Water temperature sensor	ZeeTee TW-3 & TW-4	The outlet water pipe of the hot water tank The toped up tap-water inlet pipe	The outlet water pipe of the hot water tank t3, the tap-water temperature t4		
		Electromagnet flowmeter	Asmik DN25-2	The inlet water pipe of the hot water unit (the return hot water)	The flow volume of the pipe G3	The recycled heat from the heat pump	Q3=(G3+G4)*c*t7-G3*t5-G4*t6
		Electromagnet flowmeter	Asmik DN25-3	The inlet water pipe of the hot water unit (the pre-heated tap water)	The flow volume of the pipe G4		
		Water temperature sensor	ZeeTee TW-5	The inlet water pipe of the hot water unit (the return hot water)	The water temperature of the pipe t5		
		Water temperature sensor	ZeeTee TW-6	The inlet water pipe of the hot water unit (the pre-heated tap water)	The water temperature of the pipe t6		

Subject	Floor	Equipment	Supplier & Instrument code	Location	Measurement	Parameters	Notes
		Water temperature sensor	ZeeTee TW-7	The outlet water pipe of the hot water unit	The water temperature of the pipe t7		
Indoor thermal environment	**0F**	Temperature and relative humidity sensor	ZeeTee DSE31Q-1	Living room	The indoor space's dry-bulb air temperature and relative humidity	T1, RH1	$Td = RH * (A+B*T) + C + C*T - 19.2$ $A = 0.1980$, $B = 0.0017$, $C = 0.8400$ Td – Dewpoint air temperature (°C); T- dry-bulb air temperature (°C); RH – relative humidity (%)
			ZeeTee DSE31Q-2	Dining room		T2, RH2	
			ZeeTee DSE31Q-3	Kitchen		T3, RH3	
	1F		ZeeTee DSE31Q-4	Second main bedroom		T4, RH4	
			ZeeTee DSE31Q-5	Guest room		T5, RH5	
	2F		ZeeTee DSE31Q-6	Main bedroom		T6, RH6	
			ZeeTee DSE31Q-7	Kids room		T7, RH7	
Indoor air quality (IAQ)	**0F**	Multifunction wireless portable IAQ sensor	Shenzhen Institute of Building Research CO, Ltd My Air II IAQ-1	Dining room table	The indoor chemical and particle pollutants	HCHO PM2.5 TVOC CO_2 T_{IAQ} RH_{IAQ}	The monitored pollutants level is used to control the switch of the MVHR
MVHR recovery rate and leakage identification	**2F**	Temperature and relative humidity sensor	ZeeTee MVHR1	The main pipes before and after the MVHR plant	Air dry-bulb temperature and RH of the fresh air inlet pipe (from outside)	T8, RH8	MVHR heat recovery rate $\eta\% = (T9 - T8) / (T10 - T8)$
			ZeeTee MVHR2		Air dry-bulb temperature and RH of the fresh air outlet pipe (to the rooms)	T9, RH9	

Subject	**Floor**	**Equipment**	**Supplier & Instrument code**	**Location**	**Measurement**	**Parameters**	**Notes**
			ZeeTee MVHR3		Air dry-bulb temperature and RH of the recycled air inlet pipe (from the rooms)	T10, RH10	
			ZeeTee MVHR4		Air dry-bulb temperature and RH of the recycled air outlet pipe (to outside)	T11, RH11	
Occupancy	**0F**	Movement detectors	ZeeTee DSE61R-1	Living room	Whether there are occupants in this room or not	RT1	When all the sensors can not identify human movements and the IAQ is good, the MVHR will automatically switch off to save ventilation energy.
			ZeeTee DSE61R-2	Dining room		RT2	
			ZeeTee DSE61R-3	Kitchen		RT3	
	1F		ZeeTee DSE61R-4	Second main bedroom		RT4	
			ZeeTee DSE61R-5	Guest room		RT5	
	2F		ZeeTee DSE61R-6	Main bedroom		RT6	
			ZeeTee DSE61R-7	Kids room		RT7	
Outdoor weather	**Roof**	Vantage Pro2 Weather station	DAVIS 6162CEU	Open space on the roof	Outdoor dry-bulb air temperature	T_w	Used to make dynamic control of the HP system
					Outdoor relative humidity	RH_w	
					Barometric pressure	P	
					Wind speed	v	
					Wind direction	D	
					Rainfall amount	V	
					Ultraviolet level	U	
					Total horizontal solar radiation intensity	I	

Figure A1-5 Schematic of the air-to-water multi-supply system (provided by the developer)



Appendix 2 The suitable cities for the proposed prototype of the affordable NZE townhouse

Table A2-1 The suitable provinces for the proposed prototype of the affordable NZE townhouse

References	THU DataPi, 2019 (also referenced the data from The Urban Construction Statistic Yearbooks)	The Urban Construction Statistic Yearbook 2017								
Original data	Figure 3 The change of China's density between 2010 and 2016	Table 2-1 National Urban Population and Construction Land by Province								
The criteria for filtering	The suitable city should expect a considerable population increase in the future, or else they would not need to stretch new housing to its sub-urban area	The appropriate city should have sufficient sub-urban land for new housing construction within its administrative borderline			The appropriate city should have an established and active metropolitan area to provide enough jobs and business opportunities for decent livelihoods to the current and future population		The appropriate city should already have had a density of more than 1000 people/km^2 in its city centre. Its current central density needs to be at least 3.6 times more than its metropolitan density*.			
The applied rules for filtering	The province/municipality's population density did not experience a significant reduction between 2010 and 2016	The province/municipality's central city area vs. metropolitan area ratio should be equal or less than 4% （the average figure of Tokyo, Seoul, Paris, London, New York as in Table 4.4）			The province/municipality's population density should not yet reach the targeted 1000 people/km^2 but already established with more than 350 people/km^2		More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density
		central urban area (km^2)	metropolitan area (km^2)	ratio (%)	metropolitan population	metropolitan density (people/km2)	urban population	urban area (km2)	central density (people/km2)	ratio
Beijing	X	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Tianjin	√	1088	11760	9.2%	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Hebei	√	2120	47775	4.4%	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Shanxi	√	1178	33893	3.5%	17462700	515	11389400	3297.75	3454	6.7
Neimenggu	√	1269	147077	0.9%	12184700	83	[redacted]	[redacted]	[redacted]	[redacted]

References	THU DataPi, 2019 (also referenced the data from The Urban Construction Statistic Yearbooks)	The Urban Construction Statistic Yearbook 2017								
Original data	Figure 3 The change of China's density between 2010 and 2016	Table 2-1 National Urban Population and Construction Land by Province								
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		central urban area (km^2)	metropolitan area (km^2)	ratio (%)	metropolitan population	metropolitan density (people/km2)	urban population	urban area (km2)	central density (people/km2)	ratio
Liaoning	√	2644	78915	3.4%	33974900	431	22650900	12799.79	1770	4.1
Jilin	X	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Heilongjiang	X	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Shanghai	X	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Jiangsu	√	4427	67020	6.6%	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Zhejiang	√	2829	54532	5.2%	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Anhui	√	2039	39381	5.2%	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Fujian	√	1517	46495	3.3%	28976400	623	12770200	4473.89	2854	4.6
Jiangxi	√	1454	41959	3.5%	22644700	540	11478900	2421.59	4740	8.8

References	THU DataPi, 2019 (also referenced the data from The Urban Construction Statistic Yearbooks)	The Urban Construction Statistic Yearbook 2017								
Original data	Figure 3 The change of China’s density between 2010 and 2016	Table 2-1 National Urban Population and Construction Land by Province								
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		central urban area (km^2)	metropolitan area (km^2)	ratio (%)	metropolitan population	metropolitan density (people/km2)	urban population	urban area (km2)	central density (people/km2)	ratio
Shandong	√	4971	90404	5.5%						
Henan	√	2685	46235	5.8%						
Hubei	√	2341	90877	2.6%	45872700	505	22202700	8084.1	2746	5.4
Hunan	√	1709	49166	3.5%	30978900	630	17831700	4591.99	3883	6.2
Guangdong	√	5911	95054	6.2%						
Guangxi	√	1414	68540	2.1%	26449400	386	11289300	5789.43	1950	5.1
Hainan	√	324	17138	1.9%	6900400	403	2989900	1444.67	2070	5.1
Chongqing	X									
Sichuan	√	2832	82433	3.4%	46970400	570	24759500	8359.03	2962	5.2

References	THU DataPi, 2019 (also referenced the data from The Urban Construction Statistic Yearbooks)	The Urban Construction Statistic Yearbook 2017								
Original data	Figure 3 The change of China's density between 2010 and 2016	Table 2-1 National Urban Population and Construction Land by Province								
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The applied rules for filtering	The province/municipality's population density did not experience a significant reduction between 2010 and 2016	The province/municipality's central city area vs. metropolitan area ratio should be equal or less than 4% （the average figure of Tokyo, Seoul, Paris, London, New York as in Table 4.4）			The province/municipality's population density should not yet reach the targeted 1000 people/km^2 but already established with more than 350 people/km^2		More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density
		central urban area (km^2)	metropolitan area (km^2)	ratio (%)	metropolitan population	metropolitan density (people/km2)	urban population	urban area (km2)	central density (people/km2)	ratio
Guizhou	√	986	34177	2.9%	15005200	439	7331400	3184.43	2302	5.2
Yunnan	√	1142	84818	1.3%	17896800	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Xizang	√	148	31301	0.5%	970800					
Shaanxi	√	1287	49055	2.6%	18389300	375	10748300	2620.92	4101	10.9
Gansu	√	869	87442	1.0%	10465500	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Qinghai	√	200	166332	0.1%	2502100	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Ningxia	√	458	23697	1.9%	4124100	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Xinjiang	√	1244	238458	0.5%	10719000	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Note: ■ The black area means these data are not reviewed because the city does not satisfy the criteria before these data are needed

*** China's ratio (3.6) = 66.5% * (Tokyo's ratio (5.5) + Seoul's ratio (8.0) + Paris' ratio (21.8) + London's ratio (7.0) + New York's ratio (9.6))/5**

The urbanisation rate in 2015 is China (55.5%), Japan (91.4%), South Korea (81.6%), France (79.7%), UK (82.6%), and USA (81.7%). Comparing the urbanisation rate, China is only 66.5% of the five major countries' average figure (83.4%). Therefore, the assumption is that China's central /metropolitan density ratio (3.6) is also the same as of these five major cities' average level. Tokyo 5.5, Seoul 8.0, Paris 21.8, London 7.0, and New York 9.6. It is to assume that the selected Chinese cities could carry on urbanising until its population density develops to a similar level as these major cities' average level. In the meantime, the selected Chinese cities should also have had developed to China's current national average level. The density ratios of Tokyo, Seoul, Paris, London, and New York calculated from Table 4.4

Table A2-2 The suitable cities for the proposed prototype of the affordable NZE townhouse

References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
Original data		2-2 National Urban Population and Construction Land by City								Figure 3	http://jtyss.ndrc.gov.cn/zdxm/
The criteria for filtering		The suitable city should have an established and active metropolitan area to provide enough jobs and business opportunities for decent livelihoods of extra population	The appropriate city should already have had a density of more than 1000 people/km^2 in its city centre. Its current central density needs to be at least 3.6 times more than its metropolitan density.							Rich in the mean distribution of direct solar radiation	The suitable city is better to have an established underground or light railway transport system. Otherwise, it should have developed renewable energy sourced public transport system
The rules for filtering		The province has already got established big (1-5 million population) or ultra-big cities (over 5 million to 10 million population)	More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density				Locate in 400 kWh/m^{2}yr or above zones	Underground or light railway transport system is existed, under construction, or already passed planning permit*
			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
Shanxi	Taiyuan	3691700	3709700	1000	3710	4371700	1500	2914	1.3		
	Datong	1588900	1259700	130	9675	1610000	2080	774	12.5	√	X
Liaoning	Shenyang	5905900	5119100	1610	3180	7194700	5116	1406	2.3		
	Dalian	3827900	4009700	1523	2633	4606500	5244	878	3.0		
	Anshan	1487000	1406000	626	2247	1581000	792	1996	1.1		
	Haicheng	1079200	234300	104	2253	1142100	2581	443	5.1	√	X
	Fushun	1404600	1307200	606	2159	1428600	1410	1013	2.1		

Appendix 2 The suitable cities for the proposed prototype of the affordable NZE townhouse

References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
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			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
Fujian	Fuzhou	2796700	2809400	1219	2304	3546500	2444	1451	1.6		
Fujian	Fuqing	1366900	352100	225	1568	1651100	2030	813	1.9		
	Xiamen	2310300	3473700	348	9975	5227500	1699	3077	3.2		
	Putian	2396000	741000	244	3037	2875000	2284	1259	2.4		
	Quanzhou	2485500	1360000	539	2523	3190500	892	3577	0.7		
	Jinjiang	1135600	335000	60	5583	2307600	649	3556	1.6		
	Nanan	1635600	307600	130	2366	1976900	2036	971	2.4		
	Longyan	1018000	443000	200	2215	1026700	4901	209	10.6	√	X

References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
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			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
Jiangxi	Nanchang	3057500	2774700	359	7731	3659400	3095	1182	6.5	√	2 lines constructed, 5 lines are under construction
Jiangxi	Jiujiang	1052300	758300	176	4321	1125100	1572	716	6.0	√	X
	Ganzhou	2357300	1661700	328	5062	2932200	5366	546	9.3	√	X
	Yichun	1146200	588600	88	6689	1278000	2532	505	13.3	√	X
	Fengcheng	1478800	374200	63	5978	1482800	2845	521	11.5	√	X
	Fuzhou	1695200	796600	128	6222	1741900	3428	508	12.2	√	X
	Shangrao	1489000	726800	92	7899	1607100	1770	908	8.7	√	X

Appendix 2 The suitable cities for the proposed prototype of the affordable NZE townhouse

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The rules for filtering		The province has already got established big (1-5 million population) or ultra-big cities (over 5 million to 10 million population)	More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density				Locate in 400 kWh/m^{2}yr or above zones	Underground or light railway transport system is existed, under construction, or already passed planning permit*
			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
Hubei	Wuhan	8536500	8684800	1452	5981	11953100	8569	1395	4.3	√	12 lines constructed, 10 lined are under construction
	Shiyan	1184300	700900	411	1707	1313600	8916	147	11.6	√	X
Hubei	Yichang	1264000	964000	541	1782	1314000	4234	310	5.7	√	X
	Xiangyang	2265000	1234500	374	3298	2383900	3673	649	5.1	√	X
	Zaoyang	1150000	326000	438	745						
	Erzhou	1107700	441600	247	1788	1135000	1596	711	2.5		
	Zhongxiang	1069600	274000	175	1566	1079600	4403	245	6.4	√	X

References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
Original data		2-2 National Urban Population and Construction Land by City								Figure 3	http://jtyss.ndrc.gov.cn/zdxm/
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			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
	Hanchuan	1142500	376000	85	4444	1155900	1632	708	6.3	√	X
	Jingzhou	1081800	856600	89	9657	1122900	1576	713	13.6	√	X
	Macheng	1169500	275800	251	1098	1199000	3604	333	3.3		
	Suizhou	1739500	508000	266	1910	1872500	1425	1314	1.5		
Hubei	Xiantao	1565000	404000	240	1683	1601000	2519	636	2.6		
	Qianjiang	1015600	427400	311	1373	1031600	2004	515	2.7		
	Tianmen	1670000	301000	324	928						
Hunan	Changsha	2826600	5320300	1200	4434	5320300	1200	4434	1.0		
	Liuyang	1400000	260000	28	9319	1515000	5008	303	30.8	√	X

Appendix 2 The suitable cities for the proposed prototype of the affordable NZE townhouse

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			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
	Zhuzhou	1297200	1145100	863	1327	1297200	883	1469	0.9		
	Liling	1051900	247500	114	2175	1115900	2158	517	4.2	√	X
	Hengyang	1221100	1453000	189	7688	1545100	698	2215	3.5		
	Leiyang	1586000	569000	50	11460	1798000	2678	671	17.1	√	X
Hunan	Yueyang	1070000	859000	161	5335	1107000	1313	843	6.3	√	X
	Changde	1403900	949000	332	2858	1659500	2798	593	4.8	√	X
	Yiyang	1359000	666600	109	6116	1458500	1851	788	7.8	√	X
	Yongzhou	1175800	558600	100	5586	1273800	3193	399	14.0	√	X
	Lianyuan	1198000	180800	25	7232	1236000	1895	652	11.1	√	X

References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
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The criteria for filtering		The suitable city should have an established and active metropolitan area to provide enough jobs and business opportunities for decent livelihoods of extra population	The appropriate city should already have had a density of more than 1000 people/km^2 in its city centre. Its current central density needs to be at least 3.6 times more than its metropolitan density.							Rich in the mean distribution of direct solar radiation	The suitable city is better to have an established underground or light railway transport system. Otherwise, it should have developed renewable energy sourced public transport system
The rules for filtering		The province has already got established big (1-5 million population) or ultra-big cities (over 5 million to 10 million population)	More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density				Locate in 400 kWh/m^{2}yr or above zones	Underground or light railway transport system is existed, under construction, or already passed planning permit*
			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
Guangxi	Nanning	4469500	3333300	865	3853	5593100	9947	562	6.9	√	2 lines constructed, 3 lines are under construction
	Liuzhou	1796200	1788600	502	3565	2343300	3555	659	5.4	√	X
	Guilin	1304500	938100	613	1531	1375100	2767	497	3.1		
Guangxi	Qinzhou	1508100	377800	354	1066	1570900	4767	330	3.2		
	Guigang	2015000	447000	302	1483	2033200	3533	575	2.6		
	Guiping	2017400	203700	74	2771	2021500	4074	496	5.6	√	X
	Yulin	1118100	745900	302	2470	1324100	1251	1058	2.3		
	Beiliu	1515000	230800	135	1705	1549200	2457	631	2.7		

References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
Original data		2-2 National Urban Population and Construction Land by City								Figure 3	http://jtyss.ndrc.gov.cn/zdxm/
The criteria for filtering		The suitable city should have an established and active metropolitan area to provide enough jobs and business opportunities for decent livelihoods of extra population	The appropriate city should already have had a density of more than 1000 people/km^2 in its city centre. Its current central density needs to be at least 3.6 times more than its metropolitan density.							Rich in the mean distribution of direct solar radiation	The suitable city is better to have an established underground or light railway transport system. Otherwise, it should have developed renewable energy sourced public transport system
The rules for filtering		The province has already got established big (1-5 million population) or ultra-big cities (over 5 million to 10 million population)	More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density				Locate in 400 kWh/m^2yr or above zones	Underground or light railway transport system is existed, under construction, or already passed planning permit*
			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
	Hezhou	1201200	244600	78	3136	1221700	5677	215	14.6	√	X
	Hechi	1008700	350700	124	2828	1019100	6209	164	17.2	√	X
	Laibin	1133600	323900	92	3521	1155500	4363	265	13.3	√	X
Hainan	Haikou	1710500	1520000	562	2703	2484200	2315	1073	2.5		
Sichuan	Chengdu	8115500	7667200	1277	6003	9854600	3640	2707	2.2		
Sichuan	Jianyang	1490000	366000	112	3268	1540000	2213	696	4.7	X	
	Zigong	1487400	1163800	778	1495	1637400	1438	1139	1.3		
	Luzhou	1519500	1516200	411	3686	1855600	2132	870	4.2	X	
	Mianyang	1732600	1381000	481	2874	2141700	2751	778	3.7	X	

Appendix 2 The suitable cities for the proposed prototype of the affordable NZE townhouse

References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
Original data		2-2 National Urban Population and Construction Land by City								Figure 3	http://jtyss.ndrc.gov.cn/zdxm/
The criteria for filtering		The suitable city should have an established and active metropolitan area to provide enough jobs and business opportunities for decent livelihoods of extra population	The appropriate city should already have had a density of more than 1000 people/km^2 in its city centre. Its current central density needs to be at least 3.6 times more than its metropolitan density.							Rich in the mean distribution of direct solar radiation	The suitable city is better to have an established underground or light railway transport system. Otherwise, it should have developed renewable energy sourced public transport system
The rules for filtering		The province has already got established big (1-5 million population) or ultra-big cities (over 5 million to 10 million population)	More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density				Locate in 400 kWh/m^{2}yr or above zones	Underground or light railway transport system is existed, under construction, or already passed planning permit*
			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
	Suining	1488700	550700	316	1743	1557500	1876	830	2.1		
	Neijiang	1402400	645000	279	2312	1548000	1569	987	2.3		
	Leshan	1160700	768500	368	2086	1333000	2506	532	3.9	X	
	Nanchong	1942700	1300000	420	3095	2282700	2527	903	3.4		
	Meishan	1201700	540300	254	2131	1297100	1796	722	3.0		
	Yibin	1127900	1039300	146	7101	1467700	1835	800	8.9	X	
Sichuan	Dazhou	3036500	1020500	160	6378	3094500	3462	894	7.1	X	
	Bazhong	1358900	435800	160	2719	1485900	2566	579	4.7	X	
	Ziyang	1084600	332800	187	1781	1139100	1633	698	2.6		

Appendix 2 The suitable cities for the proposed prototype of the affordable NZE townhouse

References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
Original data		2-2 National Urban Population and Construction Land by City								Figure 3	http://jtyss.ndrc.gov.cn/zdxm/
The criteria for filtering		The suitable city should have an established and active metropolitan area to provide enough jobs and business opportunities for decent livelihoods of extra population	The appropriate city should already have had a density of more than 1000 people/km^2 in its city centre. Its current central density needs to be at least 3.6 times more than its metropolitan density.							Rich in the mean distribution of direct solar radiation	The suitable city is better to have an established underground or light railway transport system. Otherwise, it should have developed renewable energy sourced public transport system
The rules for filtering		The province has already got established big (1-5 million population) or ultra-big cities (over 5 million to 10 million population)	More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density				Locate in 400 kWh/m^2yr or above zones	Underground or light railway transport system is existed, under construction, or already passed planning permit*
			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
Guizhou	Guiyang	2450000	2850000	1230	2317	3338900	2526	1322	1.8		
	Panzhou	1295000	132700	30	4423	1304800	4057	322	13.8	√	X
	Zunyi	2194000	1050000	532	1976	2194000	5382	408	4.8	X	
	Anshun	1186600	464900	146	3187	1256500	2703	465	6.9	X	
	Bijie	1763000	335100	170	1970	1793000	3412	525	3.7	X	
Yunnan	Kunming	4430200	3932200	1783	2206	4491900	5675	792	2.8		
	Qujing	1273000	786000	104	7593	1387400	4388	316	24.0	√	X
Yunnan	Xuanwei	1549800	287600	50	5752	1622800	6054	268	21.5	√	X

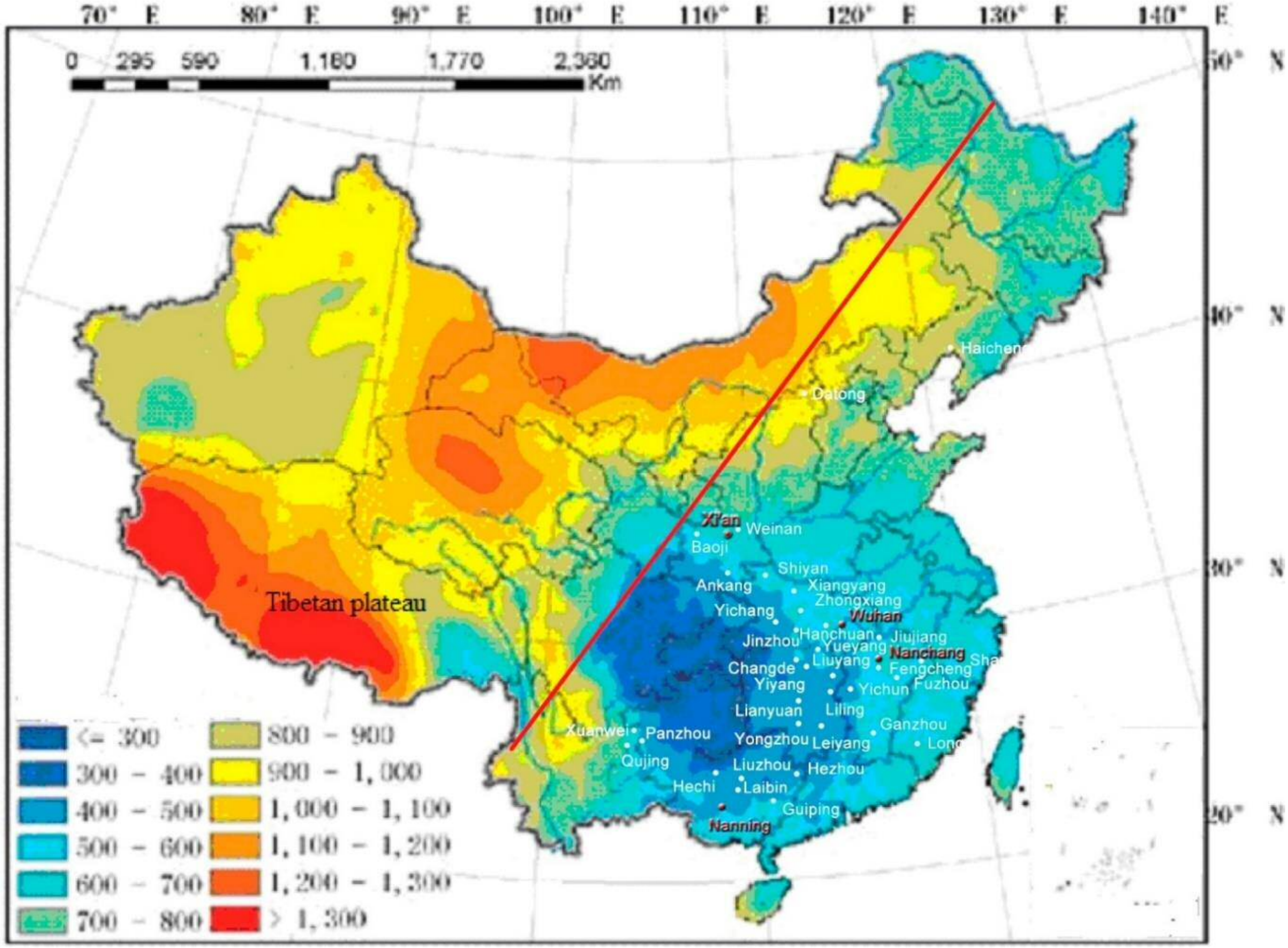
References		The Urban Construction Statistic Yearbook 2017								Kabir et al., 2018	National Development and Reform Commission - Department of Basic Industries (2019)
Original data		2-2 National Urban Population and Construction Land by City								Figure 3	http://jtyss.ndrc.gov.cn/zdxm/
The criteria for filtering		The suitable city should have an established and active metropolitan area to provide enough jobs and business opportunities for decent livelihoods of extra population	The appropriate city should already have had a density of more than 1000 people/km^2 in its city centre. Its current central density needs to be at least 3.6 times more than its metropolitan density.							Rich in the mean distribution of direct solar radiation	The suitable city is better to have an established underground or light railway transport system. Otherwise, it should have developed renewable energy sourced public transport system
The rules for filtering		The province has already got established big (1-5 million population) or ultra-big cities (over 5 million to 10 million population)	More than 1000 people/km^2 in its city centre			Existing central density is at least 3.6 times more than its metropolitan density				Locate in 400 kWh/m^{2}yr or above zones	Underground or light railway transport system is existed, under construction, or already passed planning permit*
			urban population	urban area (km2)	central density (people/km2)	metropolitan population	metropolitan area (km2)	metropolitan density (people/km2)	ratio		
Shaanxi	Xi'an	7337000	4938600	809	6107	7349200	5441	1351	4.5	√	4 lines constructed, 5 lines are under construction
	Baoji	1406100	873600	156	5589	1472300	3625	406	13.8	√	X
	Weinan	1302400	547200	267	2049	1348900	2390	564	3.6	√	X
	Ankang	1012800	347000	160	2169	1031200	3644	283	7.7	√	X

Resource: 1. The urbanisation rate in 2015 (United Nations, Department of Economic and Social Affairs, Population Division, 2018)

2. Central density vs metropolitan ratio: Chinese cities – see noted reference in this table

🟩 Tier 2 city 🟨 Tier 3 city 🟦 Tier 4 city

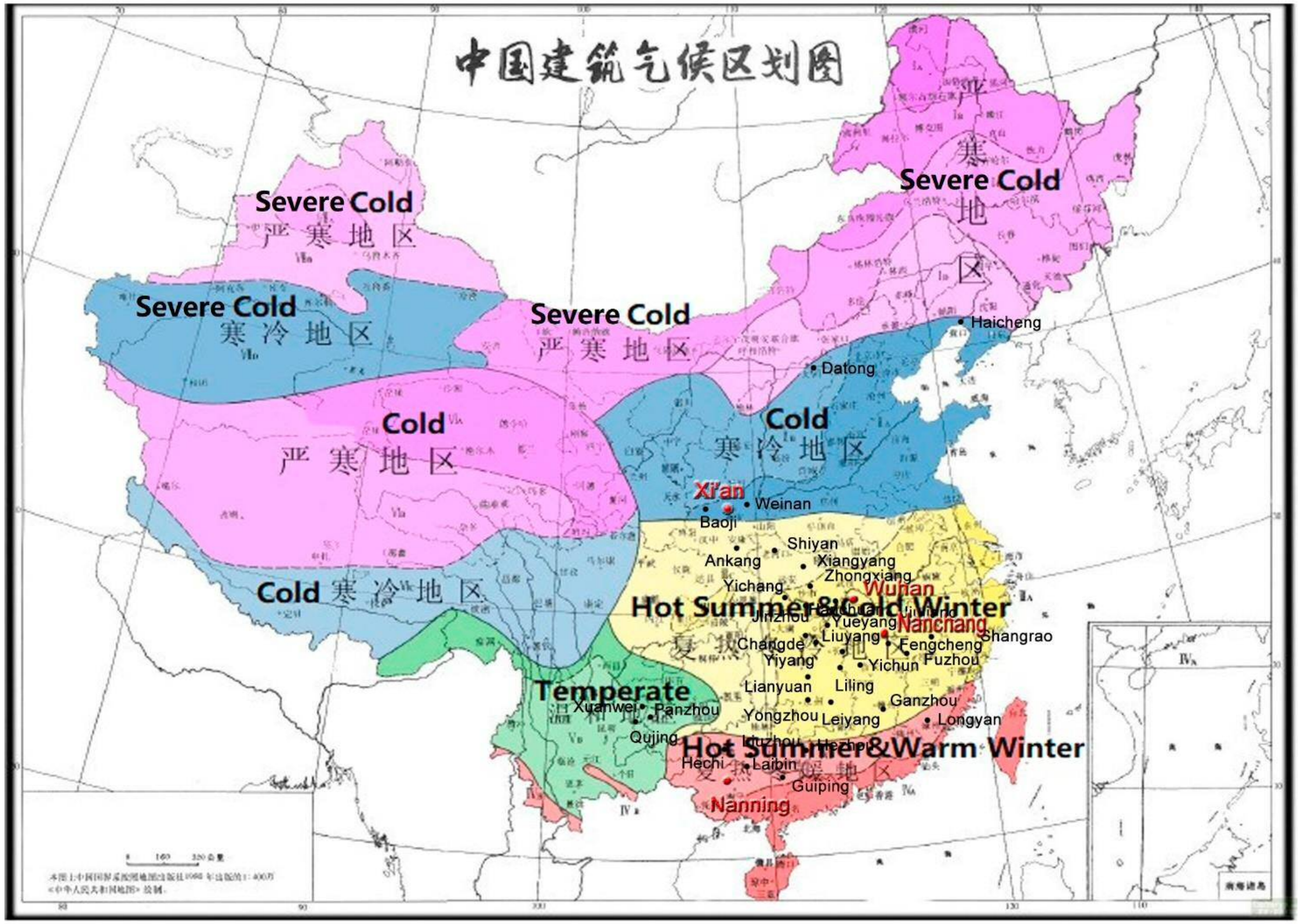
Figure A2-1 Annual mean distribution of direct solar radiation (kWh/m^2) of the 38 cities satisfying the conditions of the prototype



Note: White dot cities are the ones satisfying all the other conditions except the transport criteria. In contrast, red dot cities are fully satisfied cities.

Source: The original map of solar resource distribution comes from Papay and Zhongxian (2010).

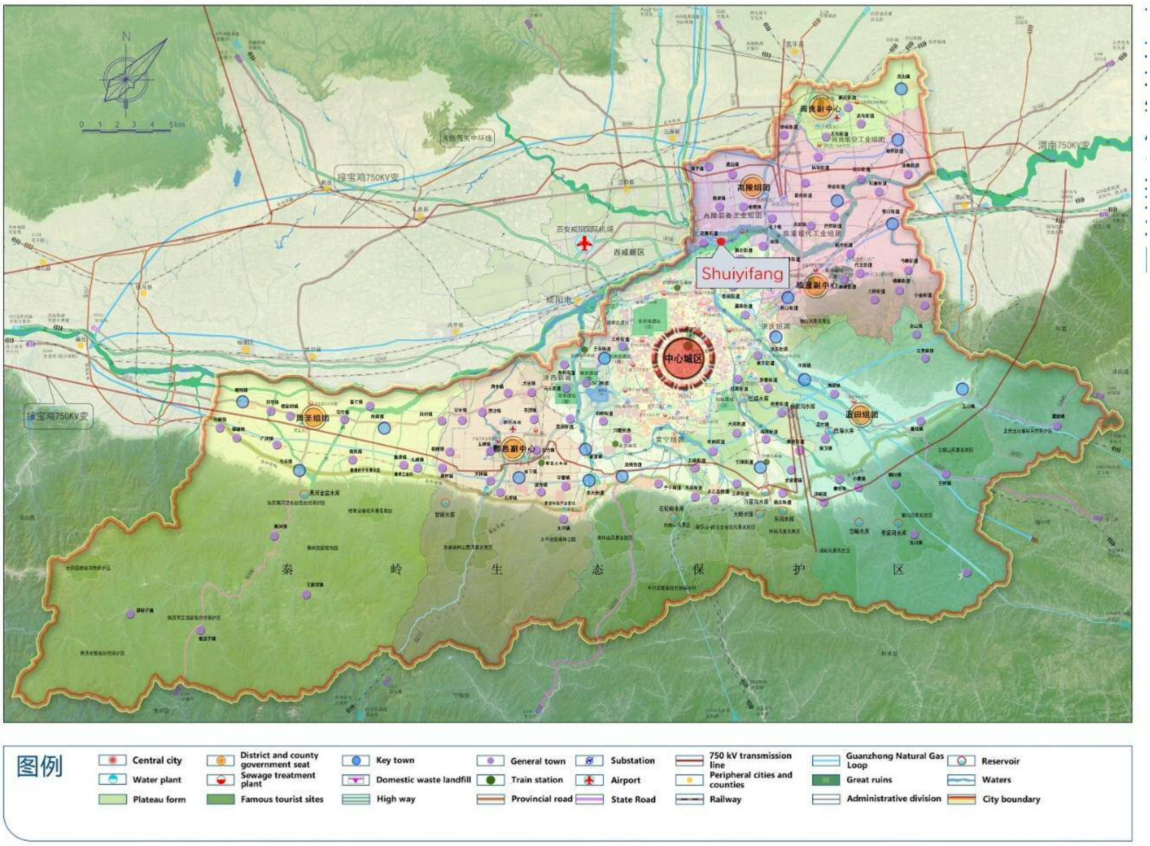
Figure A2-2 Climate zones distribution of the 38 cities satisfying the conditions of the affordable NZE townhouse concept



Source: The original map of climate zone distribution comes from *Code for thermal design of the civil building* (GB50176-2016) Figure A.0.3

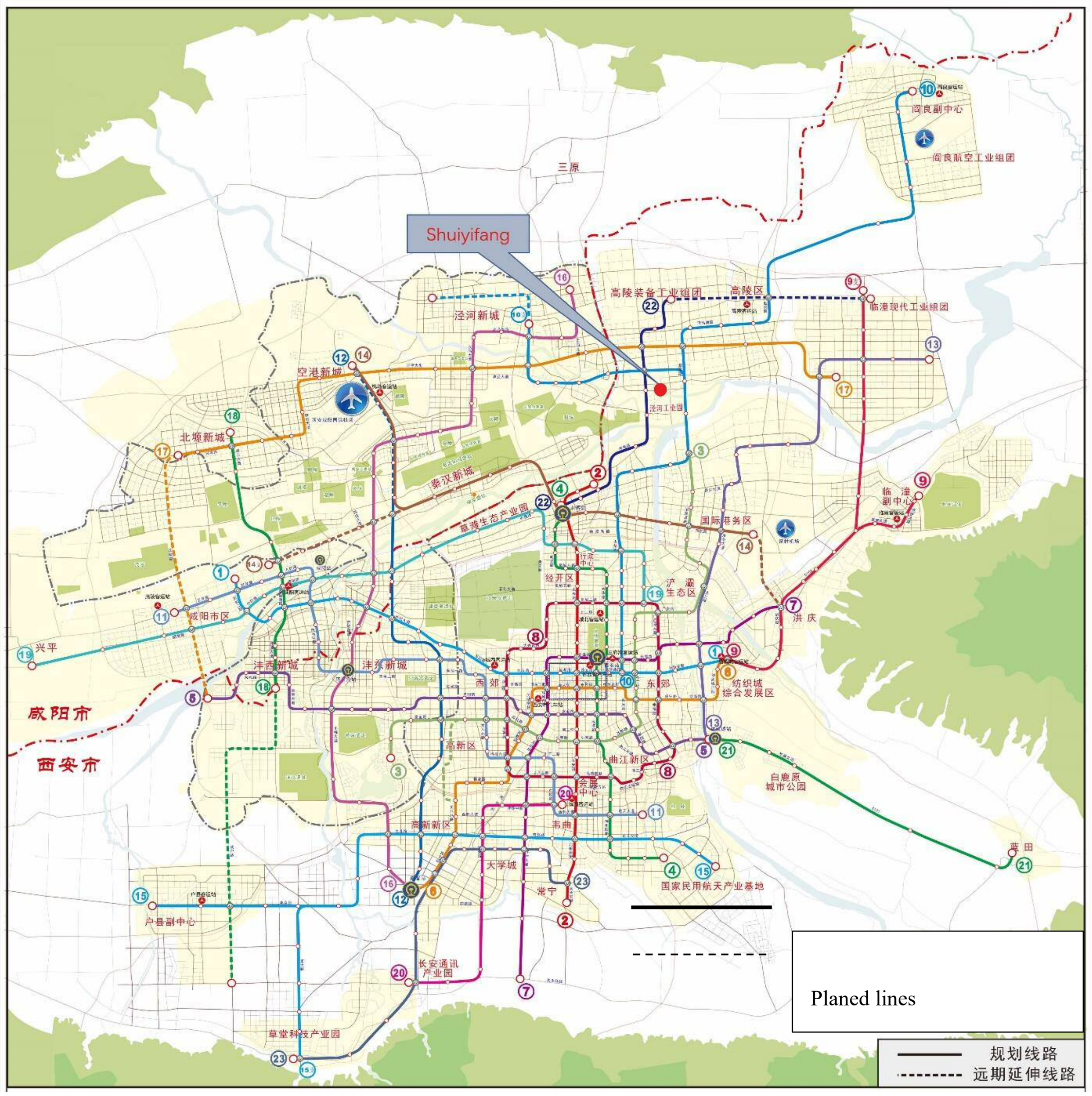
Appendix 3 The relevant background information of the case study project

Figure A3-1 The geographic location of the case study project



Source: Xi’an City Planning & Design Institute (2018)

Figure A3-2 The underground and light-rail lines around the case study project



Source: Xi’an City Planning & Design Institute (2018)

Table A3-1 The case study project's site conditions against the requirements of the prototype set up at the national level

Condition	**Actual situation**	**Criteria**	**Actual situation**	**Source**
Within 30 km in a radius of tier 2 to 4 cities' centres in China	25.9 km from Xi'an city centre	Expect considerable central urban population increase in the future	Since the implementation of the new household registration policy in 2017, the population of Xi 'an has increased by more than 1.05 million. Notably, a total of 795,000 people moved in from outside the city between 1st January 2018 and 31 December 2018.	http://www.sohu.com/a/294663031_114988
		Sufficient sub-urban land for new housing construction	Gaoling district has a relatively enough land supply for housing. Since 2014, there have been more than 8 'top 50 of China' real estate development company purchasing large area of land in this district	1. http://www.f-mai.com/article/detail/id/2428 2. http://sx.leju.com/news/2018-04-13/09356390371574427739908.shtml
		Have an established and active metropolitan area to provide enough jobs and business opportunities for decent livelihoods to the current and future population	In 2017, China's top companies, such as Zhejiang Geely Holding Group (manufacturing) and Jingdong (e-commerce), launched their sub-companies or commercial centre in Gaoling. The total signed investment of 28 projects in Gaoling within 2017 has reached over 50.8 billion Yuan.	http://www.f-mai.com/article/detail/id/2428
Costs people no more than 1 hour private or public one-way pass commuting time daily	55 mins car trip to Xi'an city centre and 35 mins car trip to Gaoling district centre	Have an established (including under construction) underground or light railway transport system	An 18.7 km light rail (line 22) between the North high-speed train station of Xian and Gaoling district has been under planning. There will be a station near the site. See Figure A2-2.	http://xa.bendibao.com/ditie/xl_472.shtml
In the 400 kWh/m^{2}yr or above mean distribution of direct solar radiation zones	In the 500-600 kWh/m^{2}yr or above mean distribution of direct solar radiation zone	In the 400 kWh/m^{2}yr or above mean distribution of direct solar radiation zones	In the 500-600 kWh/m^{2}yr or above mean distribution of direct solar radiation zones.	See Figure A1-1.

Appendix 4 The relevant parameter settings for weather analysis

Table A4-1 Calculation of regulated cooling load based on the standard weather data of Xi’an

Date	WDH_20	DDH_28	Date	WDH_20	DDH_28	Date	WDH_20	DDH_28	Date	WDH_20	DDH_28
	Kh	Kh		Kh	Kh		Kh	Kh		Kh	Kh
2011/4/26	0	0.2	2011/6/12	11.66943	0	2011/7/7	16.3135	18	2011/7/31	42.956	42.8
2011/4/27	0	2.2	2011/6/14	0	10.3	2011/7/8	40.44395	2.1	2011/8/1	12.82751	49.2
2011/5/5	0	11	2011/6/15	0	42.7	2011/7/9	38.5776	6.3	2011/8/2	1.8709	36.7
2011/5/6	0	12.1	2011/6/16	0	8.6	2011/7/10	47.44968	0	2011/8/3	23.75743	35.2
2011/5/7	0	2.3	2011/6/17	0	1.1	2011/7/11	22.45763	0	2011/8/4	15.89625	48.5
2011/5/8	0	8.6	2011/6/18	0	39	2011/7/12	17.66614	0	2011/8/5	42.95795	25.8
2011/5/9	0	11.2	2011/6/19	0	70.2	2011/7/13	7.06623	18.1	2011/8/6	63.5959	15.1
2011/5/10	0	5.3	2011/6/20	0	48.3	2011/7/14	23.41564	60.3	2011/8/7	19.72101	25.9
2011/5/20	0	13	2011/6/21	2.81464	1.9	2011/7/15	52.1656	60.4	2011/8/8	19.77134	14.7
2011/5/23	0	0.3	2011/6/22	1.30449	7.3	2011/7/16	38.32856	36.2	2011/8/9	6.58493	10.2
2011/5/24	0	14.2	2011/6/23	5.41599	43.5	2011/7/17	42.8839	48.6	2011/8/10	11.80076	17.3
2011/5/25	0	16.5	2011/6/24	22.74889	49.3	2011/7/18	38.34121	14.3	2011/8/11	16.17528	28
2011/5/26	0	15.9	2011/6/25	25.77723	59	2011/7/19	70.15239	28.2	2011/8/12	38.46741	36
2011/5/27	0	1.3	2011/6/26	0.09016	0	2011/7/20	74.67053	33.4	2011/8/13	55.54171	34.3
2011/5/29	0	65.8	2011/6/27	3.80029	0	2011/7/21	74.99641	34.7	2011/8/14	86.45891	49.8
2011/5/30	0	64.1	2011/6/28	0.14896	16.9	2011/7/22	93.59243	65	2011/8/15	10.83698	29.7
2011/5/31	0.37513	0.9	2011/6/29	0	42.6	2011/7/23	86.57686	67.1	2011/8/16	27.46948	0
2011/6/1	0	1.5	2011/6/30	15.2507	0	2011/7/24	85.28759	65.8	2011/8/17	2.73615	17.5
2011/6/5	0	4.6	2011/7/1	20.50633	0	2011/7/25	51.42526	19.9	2011/8/18	1.16016	18.5
2011/6/6	0	16	2011/7/2	24.62978	0	2011/7/26	64.41024	41.1	2011/8/19	0	17.6
2011/6/8	1.20876	0.1	2011/7/3	14.48708	0	2011/7/27	80.06313	69.7	2011/8/20	0.13174	6.8
2011/6/9	0.34497	37.1	2011/7/4	41.07018	0.1	2011/7/28	98.61935	92.8	2011/8/21	0.14264	3.2

Date	WDH_20	DDH_28	Date	WDH_20	DDH_28	Date	WDH_20	DDH_28	Date	WDH_20	DDH_28
	Kh	Kh		Kh	Kh		Kh	Kh		Kh	Kh
2011/6/10	0	3.4	2011/7/5	70.0757	27.7	2011/7/29	115.9609	39.4	2011/8/22	0.96926	9.1
2011/6/11	0.44308	0	2011/7/6	57.68369	28.1	2011/7/30	75.65857	34.9	2011/8/23	3.16198	0
2011/8/24	2.12833	0.8	2011/8/28	18.88483	28.7	2011/9/1	37.47528	0	2011/9/14	0	16.5
2011/8/25	4.64969	3.4	2011/8/29	32.77702	24.2	2011/9/11	0	12.4	Total	WDH_20	DDH_28
2011/8/26	2.16048	23.5	2011/8/30	1.84208	29.3	2011/9/12	0	7	days	kKh	kKh
2011/8/27	11.29871	16.5	2011/8/31	22.9895	0	2011/9/13	0	23.1	109	2.32	2.42

Note: 1. There is no Wet-bulb temperature record in the standard weather data, and HTB2 cannot simulate Wet-bulb temperature either. Thus, in this research dewpoint temperature is used to replace the Wet-bulb temperature for calculating the cooling load. According to the definition of Wet-bulb temperature and dew point temperature, the former will always be slightly higher but not far from the latter. Therefore, the estimated cooling load in this research will be marginally lower than the regulated calculation method. However, because dew point temperature is used all the way through theoretical assumption, simulation and monitoring, it has the same calculation error. This will not influence the comparison among the speculative hypothesis, simulation and monitoring.

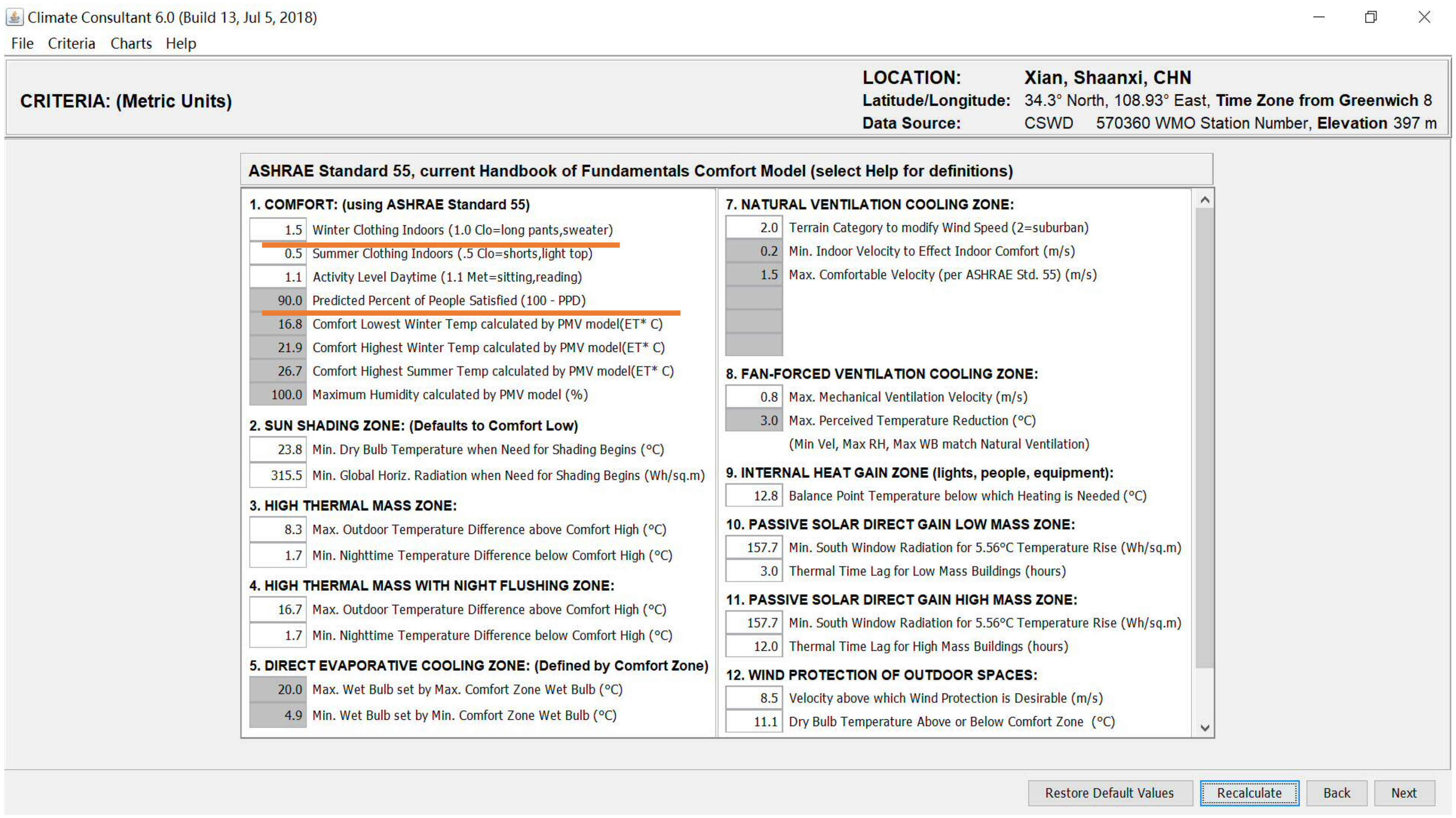
2. By scanning the standard weather, The research found that there are 109 days in a year which have either dew point temperature higher than 20 ℃ or Dry-bulb temperature higher than 28℃. Such a result leads to 2.32 kKh of WDH_20 and 2.42 kKh of DDH_20. Based on the equation ‘ ’ regulated in GB/T51350-2019, the calculated cooling load is 11.3 kWh/m^{2}yr.

3. There is another criterion in GB/T51350-2019, though, that ‘only those days which have both Dry-bulb temperature ≥28℃ and RH ≥70% are considered as cooling days’. This criterion means all the shaded days in Table A4-1 should not be considered for cooling load with the purpose of energy saving. This criterion would further reduce the cooling period to 69 days, which leads to 2.07 kKh of WDH_20 and 1.93 kKh of DDH_20. Based on the equation ‘ ’ regulated in GB/T51350-2019, the cooling load of China’s NZE standard housing for Xi’an is 9.97 kWh/m^{2}yr.

4. The actual setting of cooling days in the simulation is between 15th June and 31st August (78 days), and heating days between 1st December and 28th February (90 days). This setting follows Shaanxi Province’s local standard - ‘Design standard for energy efficiency of residential buildings (DBJ 61-65-2011)’.

5. For this case study, with the 150.8m^2 cooled floor area, the average regulated cooling load per day for these 78 days would be 9.97*150.8/78=19.3 kWh/day.

Appendix 4 The relevant parameter settings for weather analysis



CRITERIA: (Metric Units)

LOCATION: **Xian, Shaanxi, CHN**
Latitude/Longitude: 34.3° North, 108.93° East, **Time Zone from Greenwich** 8
Data Source: CSWD 570360 WMO Station Number, **Elevation** 397 m

ASHRAE Standard 55, current Handbook of Fundamentals Comfort Model (select Help for definitions)

1. COMFORT: (using ASHRAE Standard 55)
1.5 Winter Clothing Indoors (1.0 Clo=long pants,sweater)
0.5 Summer Clothing Indoors (.5 Clo=shorts,light top)
1.1 Activity Level Daytime (1.1 Met=sitting,reading)
90.0 Predicted Percent of People Satisfied (100 - PPD)
16.8 Comfort Lowest Winter Temp calculated by PMV model(ET* C)
21.9 Comfort Highest Winter Temp calculated by PMV model(ET* C)
26.7 Comfort Highest Summer Temp calculated by PMV model(ET* C)
100.0 Maximum Humidity calculated by PMV model (%)

2. SUN SHADING ZONE: (Defaults to Comfort Low)
23.8 Min. Dry Bulb Temperature when Need for Shading Begins (°C)
315.5 Min. Global Horiz. Radiation when Need for Shading Begins (Wh/sq.m)

3. HIGH THERMAL MASS ZONE:
8.3 Max. Outdoor Temperature Difference above Comfort High (°C)
1.7 Min. Nighttime Temperature Difference below Comfort High (°C)

4. HIGH THERMAL MASS WITH NIGHT FLUSHING ZONE:
16.7 Max. Outdoor Temperature Difference above Comfort High (°C)
1.7 Min. Nighttime Temperature Difference below Comfort High (°C)

5. DIRECT EVAPORATIVE COOLING ZONE: (Defined by Comfort Zone)
20.0 Max. Wet Bulb set by Max. Comfort Zone Wet Bulb (°C)
4.9 Min. Wet Bulb set by Min. Comfort Zone Wet Bulb (°C)

7. NATURAL VENTILATION COOLING ZONE:
2.0 Terrain Category to modify Wind Speed (2=suburban)
0.2 Min. Indoor Velocity to Effect Indoor Comfort (m/s)
1.5 Max. Comfortable Velocity (per ASHRAE Std. 55) (m/s)

8. FAN-FORCED VENTILATION COOLING ZONE:
0.8 Max. Mechanical Ventilation Velocity (m/s)
3.0 Max. Perceived Temperature Reduction (°C)
(Min Vel, Max RH, Max WB match Natural Ventilation)

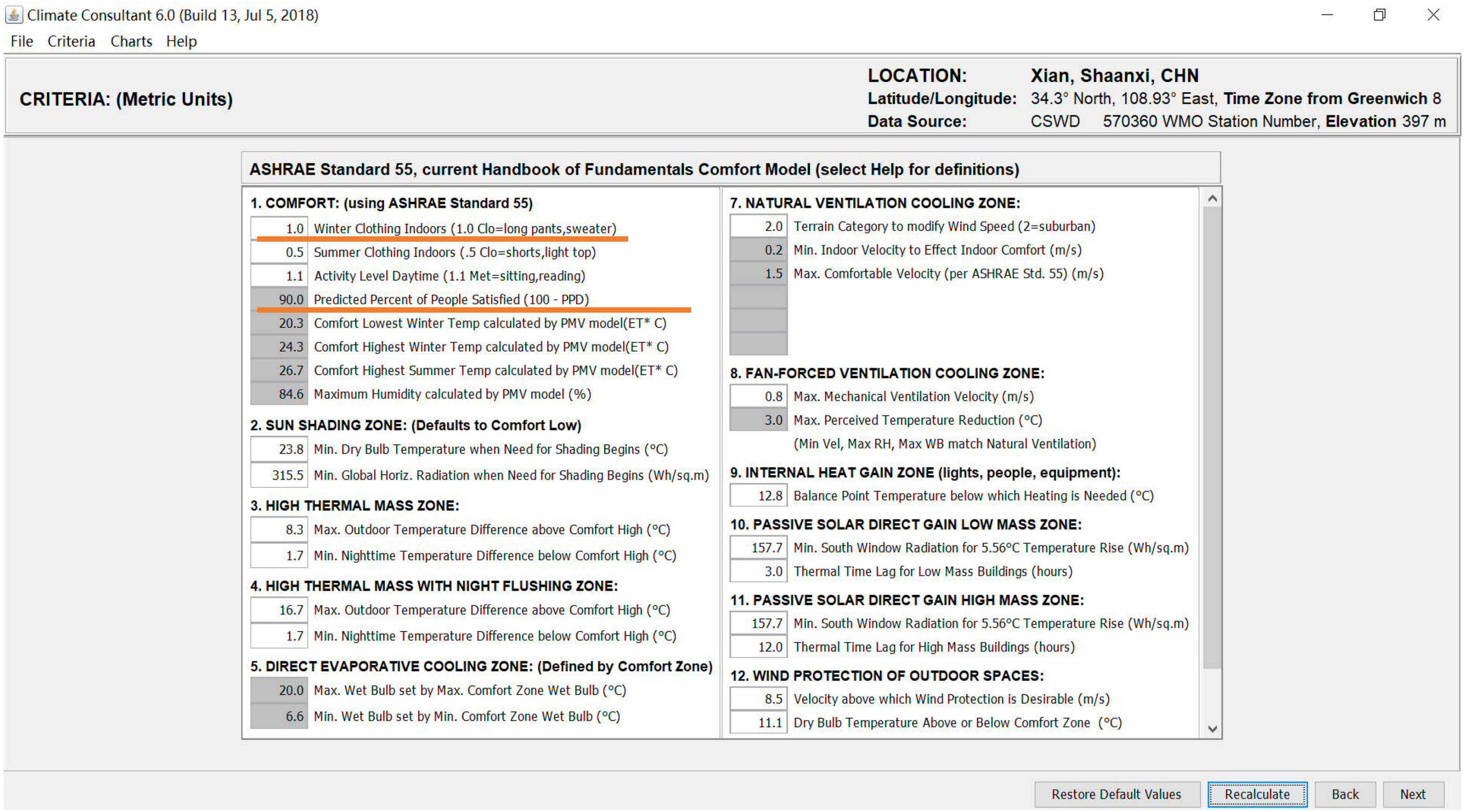
9. INTERNAL HEAT GAIN ZONE (lights, people, equipment):
12.8 Balance Point Temperature below which Heating is Needed (°C)

10. PASSIVE SOLAR DIRECT GAIN LOW MASS ZONE:
157.7 Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
3.0 Thermal Time Lag for Low Mass Buildings (hours)

11. PASSIVE SOLAR DIRECT GAIN HIGH MASS ZONE:
157.7 Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
12.0 Thermal Time Lag for High Mass Buildings (hours)

12. WIND PROTECTION OF OUTDOOR SPACES:
8.5 Velocity above which Wind Protection is Desirable (m/s)
11.1 Dry Bulb Temperature Above or Below Comfort Zone (°C)

(a)



CRITERIA: (Metric Units)

LOCATION: Xian, Shaanxi, CHN
Latitude/Longitude: 34.3° North, 108.93° East, **Time Zone from Greenwich** 8
Data Source: CSWD 570360 WMO Station Number, **Elevation** 397 m

ASHRAE Standard 55, current Handbook of Fundamentals Comfort Model (select Help for definitions)

1. COMFORT: (using ASHRAE Standard 55)

1.0 Winter Clothing Indoors (1.0 Clo=long pants,sweater)
0.5 Summer Clothing Indoors (.5 Clo=shorts,light top)
1.1 Activity Level Daytime (1.1 Met=sitting,reading)
90.0 Predicted Percent of People Satisfied (100 - PPD)
20.3 Comfort Lowest Winter Temp calculated by PMV model(ET* C)
24.3 Comfort Highest Winter Temp calculated by PMV model(ET* C)
26.7 Comfort Highest Summer Temp calculated by PMV model(ET* C)
84.6 Maximum Humidity calculated by PMV model (%)

2. SUN SHADING ZONE: (Defaults to Comfort Low)

23.8 Min. Dry Bulb Temperature when Need for Shading Begins (°C)
315.5 Min. Global Horiz. Radiation when Need for Shading Begins (Wh/sq.m)

3. HIGH THERMAL MASS ZONE:

8.3 Max. Outdoor Temperature Difference above Comfort High (°C)
1.7 Min. Nighttime Temperature Difference below Comfort High (°C)

4. HIGH THERMAL MASS WITH NIGHT FLUSHING ZONE:

16.7 Max. Outdoor Temperature Difference above Comfort High (°C)
1.7 Min. Nighttime Temperature Difference below Comfort High (°C)

5. DIRECT EVAPORATIVE COOLING ZONE: (Defined by Comfort Zone)

20.0 Max. Wet Bulb set by Max. Comfort Zone Wet Bulb (°C)
6.6 Min. Wet Bulb set by Min. Comfort Zone Wet Bulb (°C)

7. NATURAL VENTILATION COOLING ZONE:

2.0 Terrain Category to modify Wind Speed (2=suburban)
0.2 Min. Indoor Velocity to Effect Indoor Comfort (m/s)
1.5 Max. Comfortable Velocity (per ASHRAE Std. 55) (m/s)

8. FAN-FORCED VENTILATION COOLING ZONE:

0.8 Max. Mechanical Ventilation Velocity (m/s)
3.0 Max. Perceived Temperature Reduction (°C)
(Min Vel, Max RH, Max WB match Natural Ventilation)

9. INTERNAL HEAT GAIN ZONE (lights, people, equipment):

12.8 Balance Point Temperature below which Heating is Needed (°C)

10. PASSIVE SOLAR DIRECT GAIN LOW MASS ZONE:

157.7 Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
3.0 Thermal Time Lag for Low Mass Buildings (hours)

11. PASSIVE SOLAR DIRECT GAIN HIGH MASS ZONE:

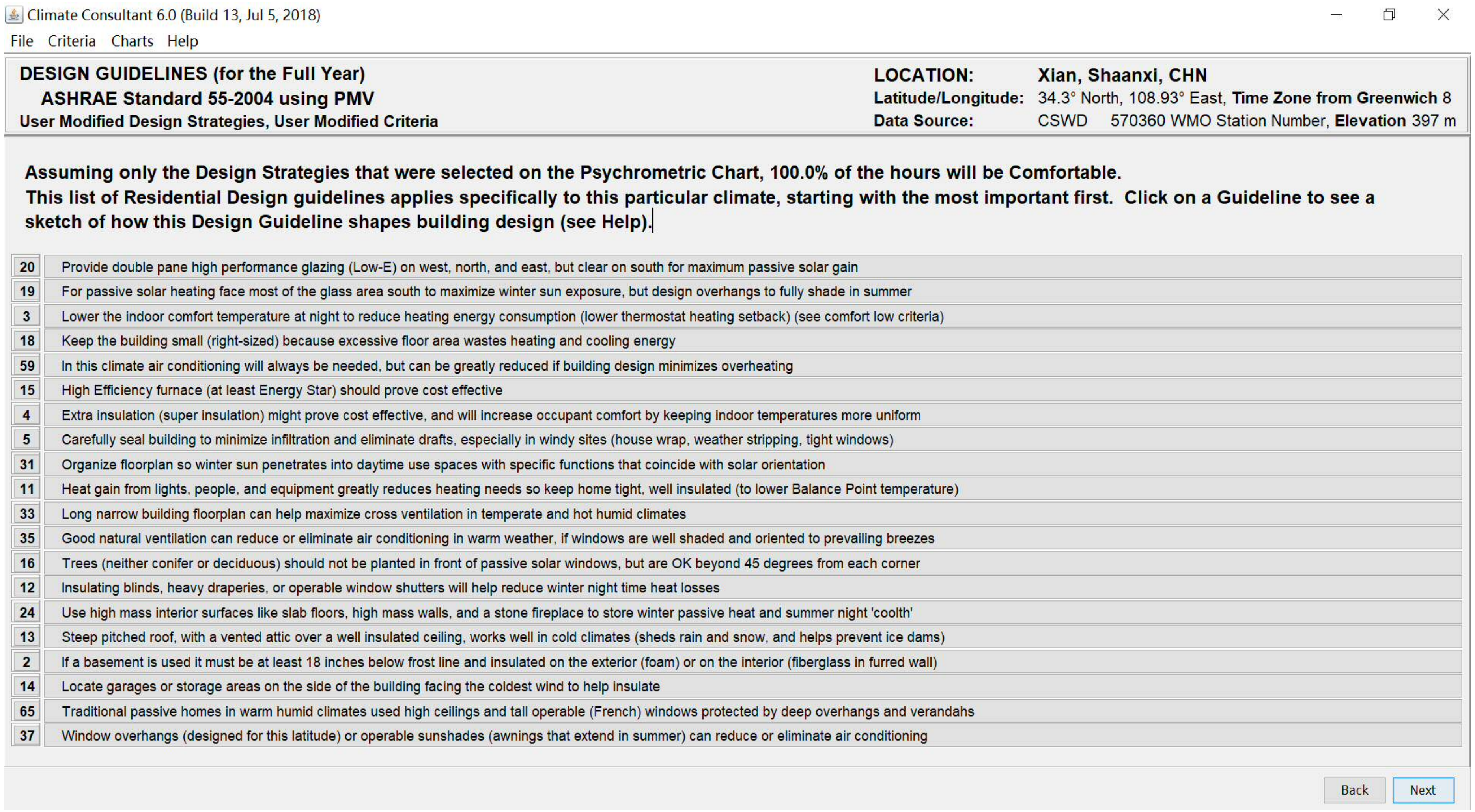
157.7 Min. South Window Radiation for 5.56°C Temperature Rise (Wh/sq.m)
12.0 Thermal Time Lag for High Mass Buildings (hours)

12. WIND PROTECTION OF OUTDOOR SPACES:

8.5 Velocity above which Wind Protection is Desirable (m/s)
11.1 Dry Bulb Temperature Above or Below Comfort Zone (°C)

(b)

Figure A4-1 Comfort criteria setting comparison



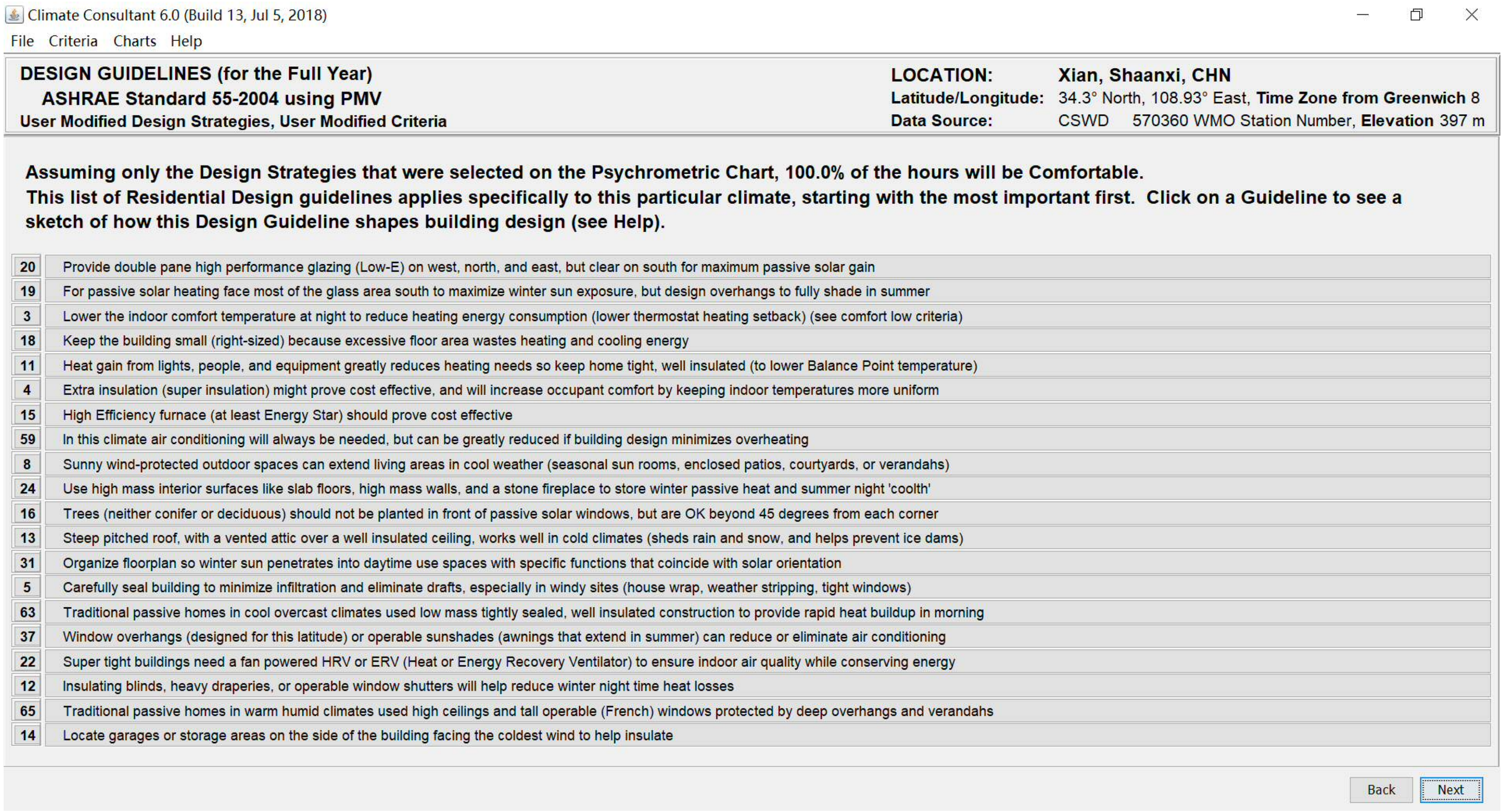
DESIGN GUIDELINES (for the Full Year)
ASHRAE Standard 55-2004 using PMV
User Modified Design Strategies, User Modified Criteria

LOCATION: **Xian, Shaanxi, CHN**
Latitude/Longitude: 34.3° North, 108.93° East, **Time Zone from Greenwich** 8
Data Source: CSWD 570360 WMO Station Number, **Elevation** 397 m

Assuming only the Design Strategies that were selected on the Psychrometric Chart, 100.0% of the hours will be Comfortable.
This list of Residential Design guidelines applies specifically to this particular climate, starting with the most important first. Click on a Guideline to see a sketch of how this Design Guideline shapes building design (see Help).

20	Provide double pane high performance glazing (Low-E) on west, north, and east, but clear on south for maximum passive solar gain
19	For passive solar heating face most of the glass area south to maximize winter sun exposure, but design overhangs to fully shade in summer
3	Lower the indoor comfort temperature at night to reduce heating energy consumption (lower thermostat heating setback) (see comfort low criteria)
18	Keep the building small (right-sized) because excessive floor area wastes heating and cooling energy
59	In this climate air conditioning will always be needed, but can be greatly reduced if building design minimizes overheating
15	High Efficiency furnace (at least Energy Star) should prove cost effective
4	Extra insulation (super insulation) might prove cost effective, and will increase occupant comfort by keeping indoor temperatures more uniform
5	Carefully seal building to minimize infiltration and eliminate drafts, especially in windy sites (house wrap, weather stripping, tight windows)
31	Organize floorplan so winter sun penetrates into daytime use spaces with specific functions that coincide with solar orientation
11	Heat gain from lights, people, and equipment greatly reduces heating needs so keep home tight, well insulated (to lower Balance Point temperature)
33	Long narrow building floorplan can help maximize cross ventilation in temperate and hot humid climates
35	Good natural ventilation can reduce or eliminate air conditioning in warm weather, if windows are well shaded and oriented to prevailing breezes
16	Trees (neither conifer or deciduous) should not be planted in front of passive solar windows, but are OK beyond 45 degrees from each corner
12	Insulating blinds, heavy draperies, or operable window shutters will help reduce winter night time heat losses
24	Use high mass interior surfaces like slab floors, high mass walls, and a stone fireplace to store winter passive heat and summer night 'coolth'
13	Steep pitched roof, with a vented attic over a well insulated ceiling, works well in cold climates (sheds rain and snow, and helps prevent ice dams)
2	If a basement is used it must be at least 18 inches below frost line and insulated on the exterior (foam) or on the interior (fiberglass in furred wall)
14	Locate garages or storage areas on the side of the building facing the coldest wind to help insulate
65	Traditional passive homes in warm humid climates used high ceilings and tall operable (French) windows protected by deep overhangs and verandahs
37	Window overhangs (designed for this latitude) or operable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning

(a) Winter Clothing 1.5 Clo



DESIGN GUIDELINES (for the Full Year)
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LOCATION: **Xian, Shaanxi, CHN**
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This list of Residential Design guidelines applies specifically to this particular climate, starting with the most important first. Click on a Guideline to see a sketch of how this Design Guideline shapes building design (see Help).

20	Provide double pane high performance glazing (Low-E) on west, north, and east, but clear on south for maximum passive solar gain
19	For passive solar heating face most of the glass area south to maximize winter sun exposure, but design overhangs to fully shade in summer
3	Lower the indoor comfort temperature at night to reduce heating energy consumption (lower thermostat heating setback) (see comfort low criteria)
18	Keep the building small (right-sized) because excessive floor area wastes heating and cooling energy
11	Heat gain from lights, people, and equipment greatly reduces heating needs so keep home tight, well insulated (to lower Balance Point temperature)
4	Extra insulation (super insulation) might prove cost effective, and will increase occupant comfort by keeping indoor temperatures more uniform
15	High Efficiency furnace (at least Energy Star) should prove cost effective
59	In this climate air conditioning will always be needed, but can be greatly reduced if building design minimizes overheating
8	Sunny wind-protected outdoor spaces can extend living areas in cool weather (seasonal sun rooms, enclosed patios, courtyards, or verandahs)
24	Use high mass interior surfaces like slab floors, high mass walls, and a stone fireplace to store winter passive heat and summer night 'coolth'
16	Trees (neither conifer or deciduous) should not be planted in front of passive solar windows, but are OK beyond 45 degrees from each corner
13	Steep pitched roof, with a vented attic over a well insulated ceiling, works well in cold climates (sheds rain and snow, and helps prevent ice dams)
31	Organize floorplan so winter sun penetrates into daytime use spaces with specific functions that coincide with solar orientation
5	Carefully seal building to minimize infiltration and eliminate drafts, especially in windy sites (house wrap, weather stripping, tight windows)
63	Traditional passive homes in cool overcast climates used low mass tightly sealed, well insulated construction to provide rapid heat buildup in morning
37	Window overhangs (designed for this latitude) or operable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning
22	Super tight buildings need a fan powered HRV or ERV (Heat or Energy Recovery Ventilator) to ensure indoor air quality while conserving energy
12	Insulating blinds, heavy draperies, or operable window shutters will help reduce winter night time heat losses
65	Traditional passive homes in warm humid climates used high ceilings and tall operable (French) windows protected by deep overhangs and verandahs
14	Locate garages or storage areas on the side of the building facing the coldest wind to help insulate

(b) Winter Clothing 1.0 Clo

Figure A4-2 Recommended design strategies for the set comfort criteria

Appendix 5 Energy performance calculations

Table A5-1 Manufacturer's information about heat pump efficiency under different conditions

Supply water temperature	The external dry-bulb temperature in summer					
	25°C			30°C		
°C	Cooling capacity kW	Electricity consumptions kW	EER	Cooling capacity kW	Electricity consumptions kW	EER
7.0	12.8	3.0	4.3	12.4	3.3	3.8
9.0	13.8	3.0	4.6	13.4	3.3	4.1
11.0	14.7	3.1	4.7	14.3	3.4	4.2
13.0	15.7	3.1	5.1	15.3	3.4	4.5
15.0	16.7	3.2	5.2	16.2	3.5	4.6
Supply water temperature	The external dry-bulb temperature in winter					
	0°C			5°C		
°C	Heating kW	Electricity consumptions kW	COP	Heating capacity kW	Electricity consumptions kW	COP
30.0	12.5	3.2	3.9	13.4	3.2	4.2
35.0	12.2	3.5	3.5	13.1	3.5	3.7
40.0	11.8	3.8	3.1	12.7	3.9	3.3
45.0	11.4	4.1	2.8	12.3	4.2	2.9
50.0	10.8	4.5	2.4	11.8	4.6	2.6

Note: 1. The above figures are provided by the heat pump's manufacturer – Trine.

2. According to the standard weather data used for simulation, the average external dry-bulb temperature of Xi'an is 3.2°C in the winter and 26.1°C in the summer. In the meantime, the assumed water supply temperature is 30°C in the winter and 26.1°C in the summer.

3. As can be seen in the table, EER goes higher when the water temperature goes higher in the summer. Still, to be conservative for the heat pump's efficiency, the calculation takes EER at15°C for reference.

4. The COP is calculated as (3.2-0)/(5-0)=(COP-3.9)/(4.2-3.9), so COP=4.09

5. The EER is calculated as (26.1-25)/(30-25)=(5.2- EER)/(5.2-4.6), so COP=5.07

Table A5-2 Example of MVHR recovery rate calculation (15th January, based on standard weather data)

Hours	Supply air temperature	External Air Temperature	Return Air Temperature	MVHR energy recovery rate
	℃	℃	℃	%
	T_s	T_{out}	T_r	$(T_s-T_{out})/(T_r-T_{out})$
0	16.623	0.2	20.451	81.1%
1	16.62	-1	20.381	82.4%
2	16.61	-1.5	20.344	82.9%
3	16.593	-1.8	20.321	83.1%
4	16.57	-2.2	20.294	83.4%
5	16.537	-2.6	20.265	83.7%
6	16.495	-3.4	20.223	84.2%
7	16.466	-3.2	20.422	83.3%
8	16.438	-4.6	20.315	84.4%
9	16.394	-6.1	20.31	85.2%
10	16.319	-4.6	20.147	84.5%
11	16.234	-4.6	20.122	84.3%
12	16.184	-3.7	20.466	82.3%
13	16.15	-2.3	20.333	81.5%
14	16.102	-0.2	20.433	79.0%
15	16.069	1.5	20.451	76.9%
16	16.045	3.1	20.516	74.3%
17	16.052	3.9	20.694	72.4%
18	16.118	4.5	21.111	69.9%
19	16.2	4.1	20.937	71.9%
20	16.248	2.8	20.885	74.4%
21	16.278	0.3	20.647	78.5%
22	16.29	-0.5	20.59	79.6%
23	16.304	-1.5	20.517	80.9%

Table A5-3 Example of PV energy generation calculation
(28th August, based on standard weather data)

Solar radiation	Installed area	PV efficiency	Charging efficiency	Circuit loss	Inverter loss	Orientation correction	Angle of inclination	Power generated
Wh	m^2	%	%	%	%	15 degrees to the southeast	20 degrees against horizon	KWh
See weather data	29m^2	17%	100%	10% discount	5% discount	COS 15 degrees	COS 20 degrees	See the equation in the note
	Based on the manufacturer's information					Based on the site condition		
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
21.5	29	0.17	1	0.9	0.95	0.9659	0.9397	0.08
103.6	29	0.17	1	0.9	0.95	0.9659	0.9397	0.40
300.7	29	0.17	1	0.9	0.95	0.9659	0.9397	1.15
429.2	29	0.17	1	0.9	0.95	0.9659	0.9397	1.64
425.8	29	0.17	1	0.9	0.95	0.9659	0.9397	1.63
523.3	29	0.17	1	0.9	0.95	0.9659	0.9397	2.00
561.3	29	0.17	1	0.9	0.95	0.9659	0.9397	2.15
543.7	29	0.17	1	0.9	0.95	0.9659	0.9397	2.08
626.0	29	0.17	1	0.9	0.95	0.9659	0.9397	2.39
396.8	29	0.17	1	0.9	0.95	0.9659	0.9397	1.52
159.9	29	0.17	1	0.9	0.95	0.9659	0.9397	0.61
77.4	29	0.17	1	0.9	0.95	0.9659	0.9397	0.30
42.9	29	0.17	1	0.9	0.95	0.9659	0.9397	0.16
2.7	29	0.17	1	0.9	0.95	0.9659	0.9397	0.01
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00
0	29	0.17	1	0.9	0.95	0.9659	0.9397	0.00

Note: PV generated power = (Solar radiation * installation area * PV efficiency * Charging efficiency * Circuit loss discount * Invertor loss discount * Orientation correction * Angel of inclination)/1000. The subcontractor provides the equation.

Table A5-4 Example of wind turbine energy generation calculation
(29th August, based on standard weather data)

Time	Wind speed	Wind speed after height correction	Wind speed that exceeds the kicking off point	Power generated
Hours of the day	m/s	m/s	m/s	kWh
	Hourly average	$V_h = V_{10}*(H/10)^{0.143}$	＞2.5	Efficiency factor *power per unit area*area =0.38*(1/2)ρv^3*(π/4*d^2)
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	2	2.05	0	0
11	2	2.05	0	0
12	1	1.03	0	0
13	2	2.05	0	0
14	3	3.08	3.08	0.024
15	2	2.05	0	0
16	3	3.08	3.08	0.024
17	4	4.11	4.11	0.056
18	3	3.08	3.08	0.024
19	3	3.08	3.08	0.024
20	2	2.05	0	0
21	2	2.05	0	0
22	0	0	0	0
23	2	2.05	0	0

Appendix 6 Calibration of the simulated results after monitoring

This modelling calibration is carried out after the commissioning monitoring, because the commisioned conditions are significantly different from the designed ones:

- There were no occupants and internal gains of heat and moisture due to occupancy activities.
- One side neighbour was not cooled.
- The air-tightness level did not achieve the designed target.

Therefore, it is necessary to calibrate the simulated results to verify the accuracy of the prototype's predicted performances (Table A6-1).

Through calibration, it is found that the monitored energy consumption does have a gap to the simulated results under similar indoor and outdoor conditions. However, the difference is within an acceptable accuracy range (-12.0% to 8.8% for cooling load, see Table A6-2; and less than 1 °C for temperature variations, see Figure A6-1).

Because HTB2 can not simulate out the heat transfer through the thermal bridges, it is not able to draw a conclusion whether and how much the range of inaccuracy is caused by such effect. However, Figure A6-1 (a) and (b) does show a correlation which indicates that thermal bridges could be the reason. A6-1 (a) shows that the predicted indoor try-bulb temperature of the uncooled kitchen is higher than the monitored results. On the contrary, the predicted indoor try-bulb temperature of the cooled living room is lower than the monitored results. This indicates that the coolth was delivered from the cooled slab to the uncooled slab. Such an effect could benefit the uncooled room's thermal comfort. However, it would consume more energy than HTB2's prediction, which does not take the heat transfer through linked slabs into account.

Table A6-1 Comparison of the designed, monitored and calibrated conditions

28-29 Aug (monitored outside condition is similar to the standard weather data)					
Features	**Design assumptions (final)**	**Monitored in commissioning**	**Calibration 1**	**Calibration 2**	**Note**
Occupancy	4 adults and 1 kid	None	None	None	Design assumption is based on China's housing policies. In commissioning no occupants were involved.
Heat transfer to neighbours	None	To one side neighbour	To one side neighbour	To one side neighbour	Design assumption is based on the occupied situation when every house operates at a similar time. In commissioning, one side of the neighbour was not occupied.
Air-tightness (air change per hour at 50 Pa)	0.8	Not directly monitored	1.2	1.2	The calculated natural ventilation rate through indirect monitoring is 0.83 air change per hour. Therefore, the calibration assumes 1.2 air change per hour at 50 Pa to be the infiltration rate.
Operation schedule	24 hours	8.5 hours a day	24 hours	8.5 hours a day	The 24 hours operation is required by China's NZE building standard for a normalised calculation. The 8.5 hours operation is the one implemented in real practice.
Supply water temperature	20 °C Constant	18-20 °C Variable	19.5 °C Constant	19.5 °C Constant	The variable supply water temperature was delivered on purpose in the commissioning to avoid condensation while increasing the heat pump's efficiency. HTB2 can not simulate such a dynamic water temperature. Therefore, the average operation temperature is taken as the constant water layer temperature.

Table A6-2 Comparison of the designed, monitored and calibrated energy performance

28-29 Aug 2019 (monitored outside condition is similar to the standard weather data)					
Features	**Design assumptions (final)**	**Monitored in commissioning**	**Calibration 1**	**Calibration 2**	**Note**
Average daily cooling load (kWh)	47.7	65.1	70.8	57.3	The cooling load accuracy is between +8.8 % (calibration 1) and -12.0% (calibration 2) comparing with the actually monitored figure.
the EER for converting to the energy consumption	5.07	3.7	5.07	3.7	5.07 is based on the manufacturer's lab conditions. 3.7 is a calculated average figure from monitoring data.
Heat pump energy consumption (kWh)	9.4	17.7	14.0	15.5	The accuracy of cooling energy consumption is -20.9% (calibration 1) to -12.4% (calibration 2). The reason for the low accuracy of calibration 1 is due to the assumed EER, which is too high to achieve in practice

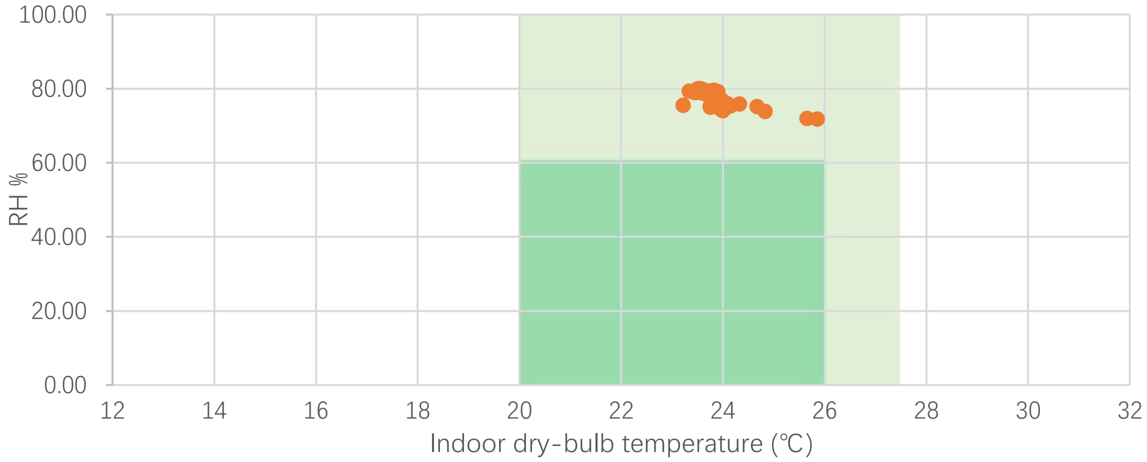
Another result to be highlighted is that the predicted RH level is generally 10-20% higher than the monitored figures. This result demonstrates that the condensation risk is controllable through dynamic supply water temperature, which is based on the dewpoint temperature of both indoor and outdoor conditions. The monitored results indicate that even if the occupants and their activities will result in internal heat and moisture gain, the condensation risk would still be low.

The results of Calibration 2 also show that shortening and shifting the operation hours have three advantages. Firstly, it benefits the occupants by consuming about 19.1% less energy (Table A6-2, predicted cooling load reduces from 70.8 kWh per day to 57.3 kWh per day). Secondly, it can avoid operating the heat pump in the grid's morning peak time (6:00-10:00) and evening peak time (18:00-22:00) (Figure A6-2). Thirdly, it can maximise the utilisation of local renewable generation, therefore, reduce the micro-generation's interruption to the grid (Figure A6-3).

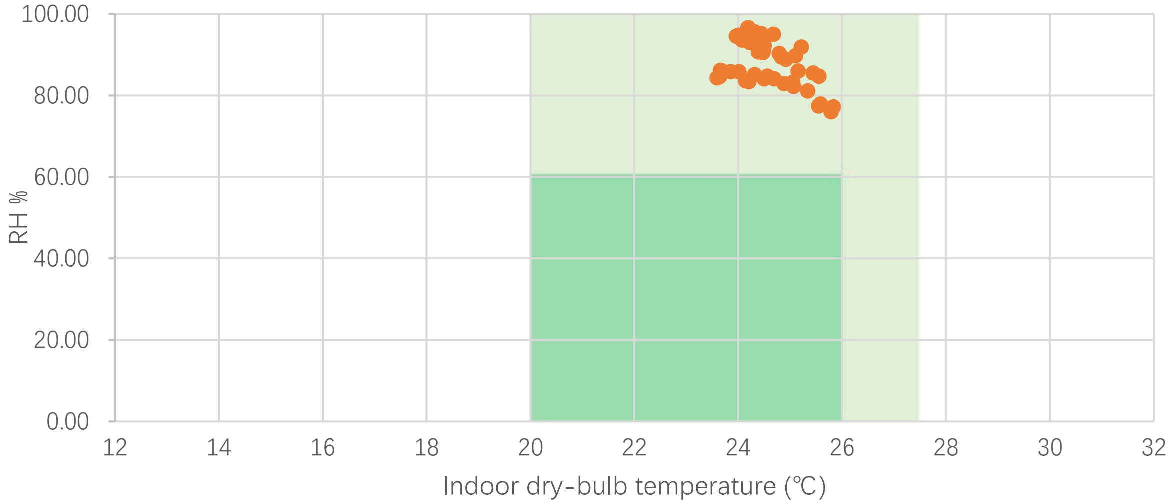
In the meantime, the indoor dry-bulb temperature only increases less than 1 °C when operating time is shortened, which does not compromise the occupants' thermal comfort (Figure A6-1). This is because the heavy thermal masses created by the thermally activated fabrics can provide passive cooling when the heat pump is not running.

Therefore, bringing all the above and previous modelling and monitoring together, it can be concluded that:

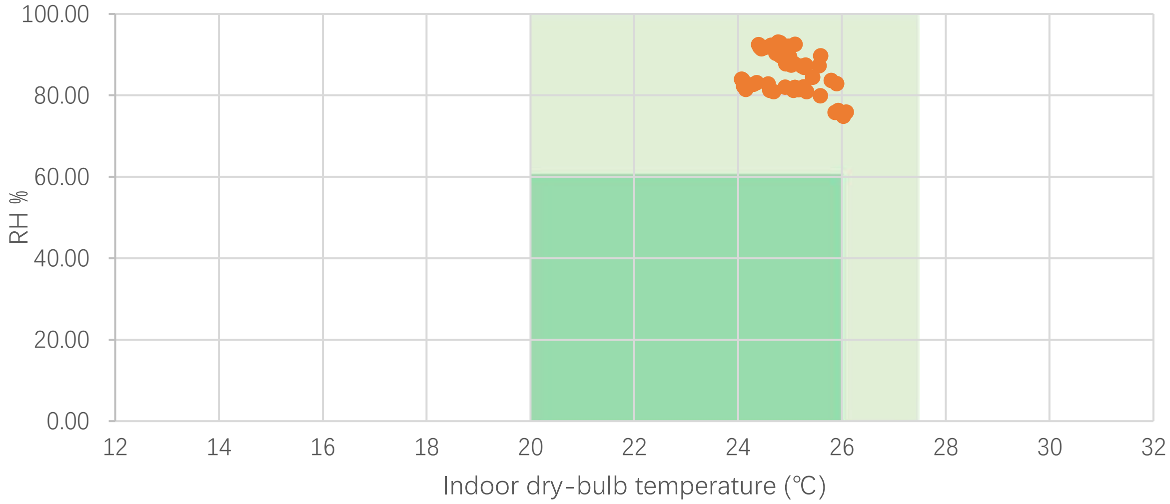
- The prototype's theoretical and simulated performances have good accuracy to guide the practice to achieve the targets.
- Besides the influence of uncooled neighbour, the energy performance gaps are mainly from poorer air-tightness and indicated thermal bridges.
- The thermally activated building storage creates a passive cooling effect and enables the intermittent operation of the heat pump system. Therefore, it brings the opportunity to further reduce energy consumptions in real practice.
- With dynamic water supply temperature, the condensation risks are significantly reduced. The indoor thermal comfort is also achieved.



Monitored

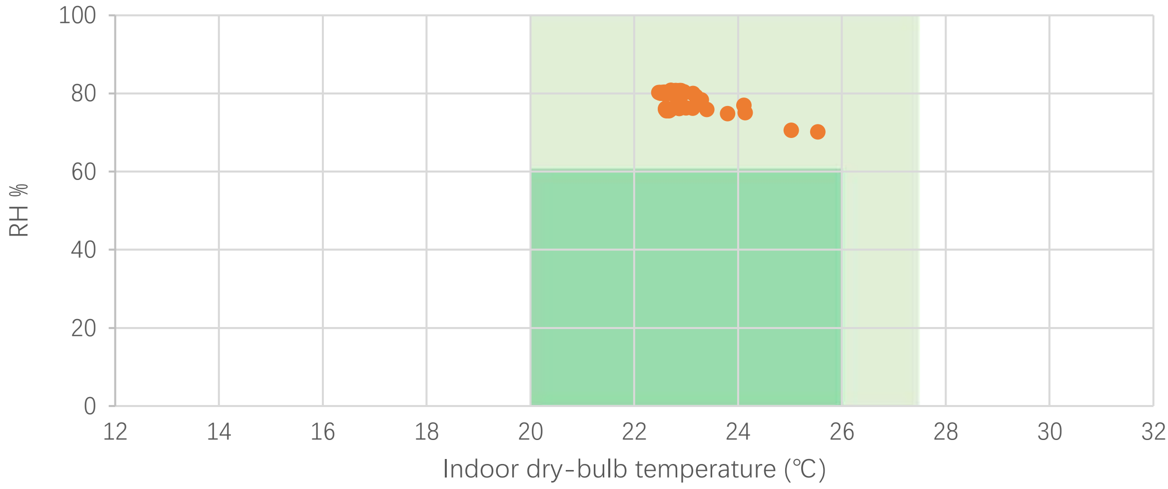


Simulated – 24 hours operation

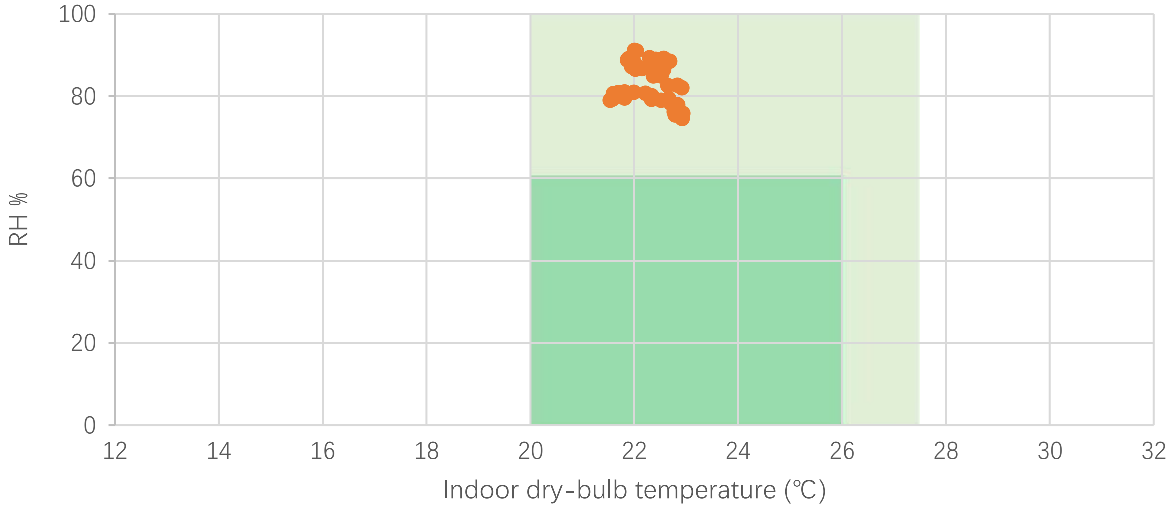


Simulated – 8.5 hours operation

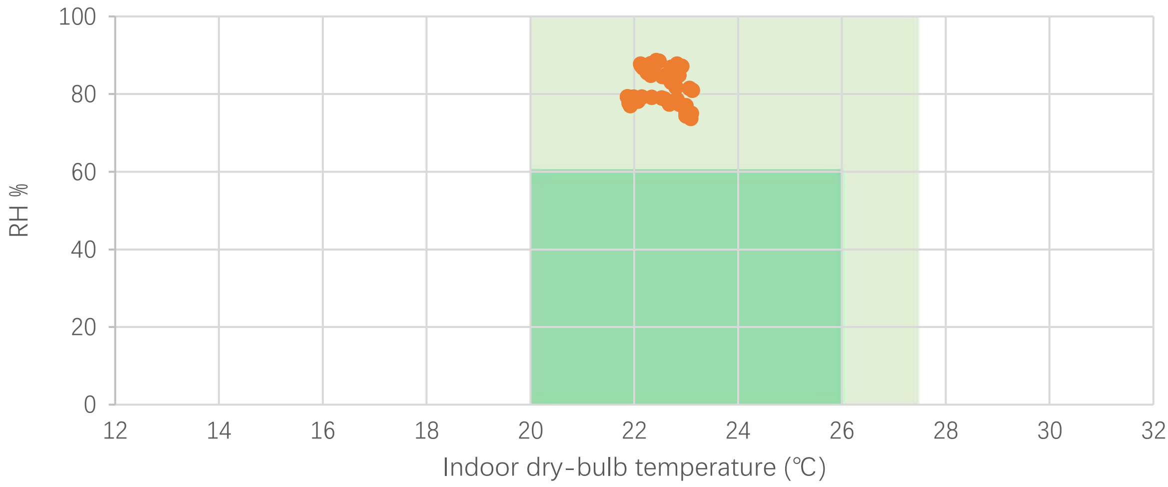
(a) Ground floor kitchen (north-facing)



Monitored

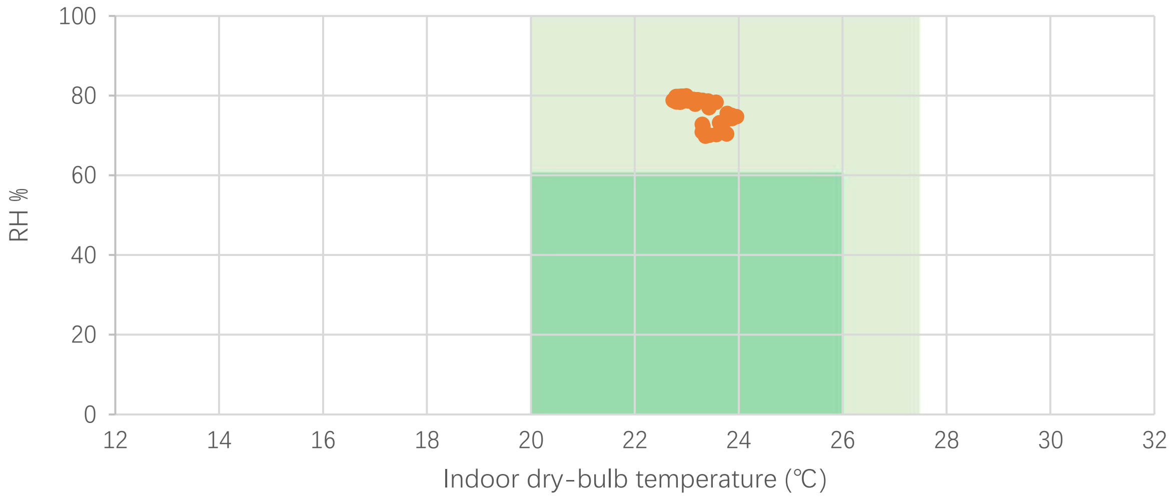


Simulated – 24 hours

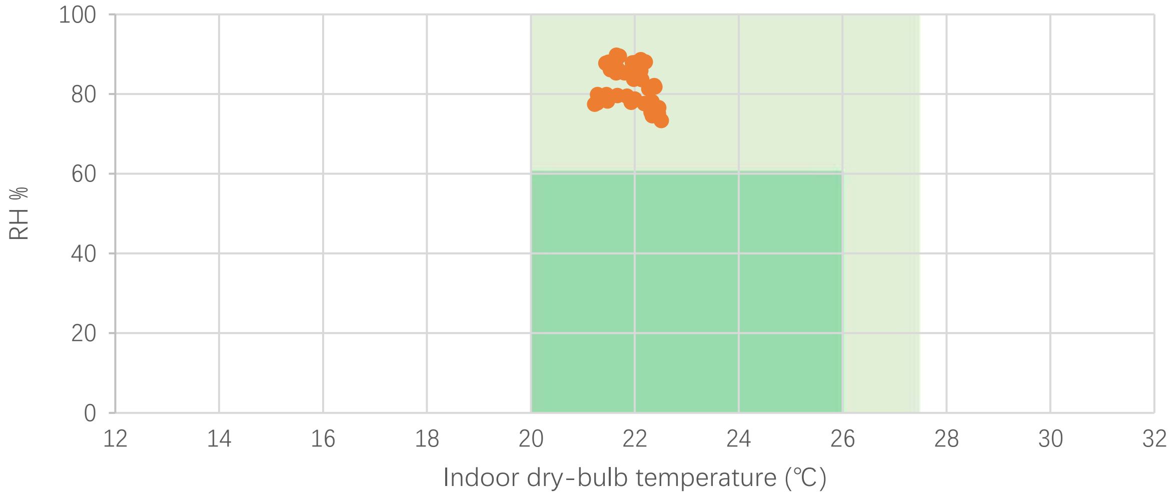


Simulated – 8.5 hours

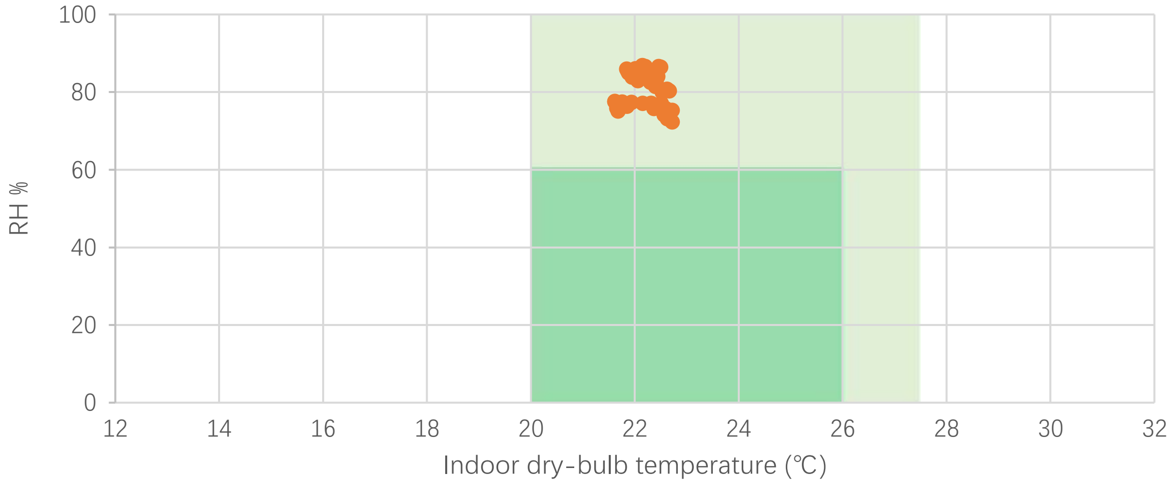
(b) Living room (south-facing)



Monitored

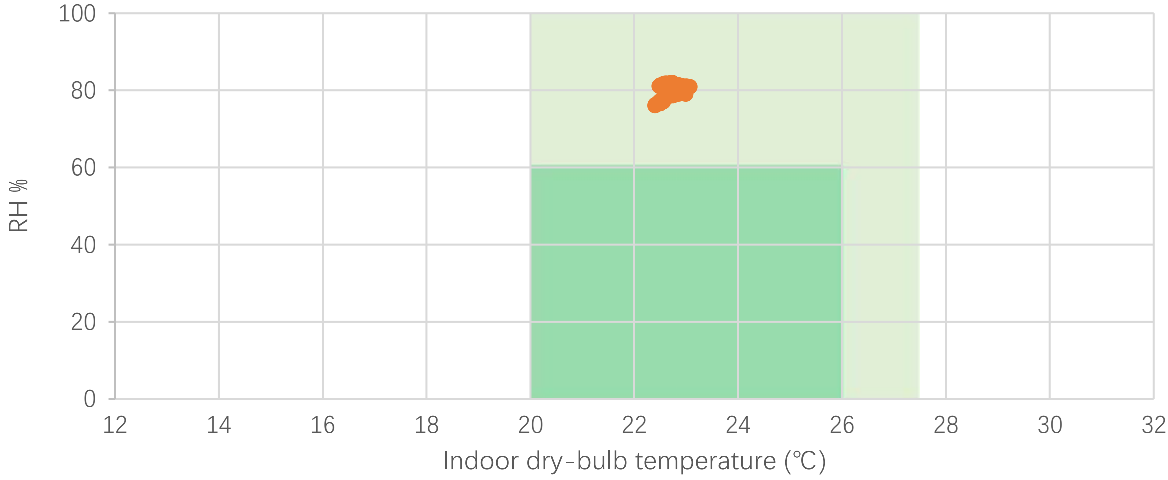


Simulated – 24 hours

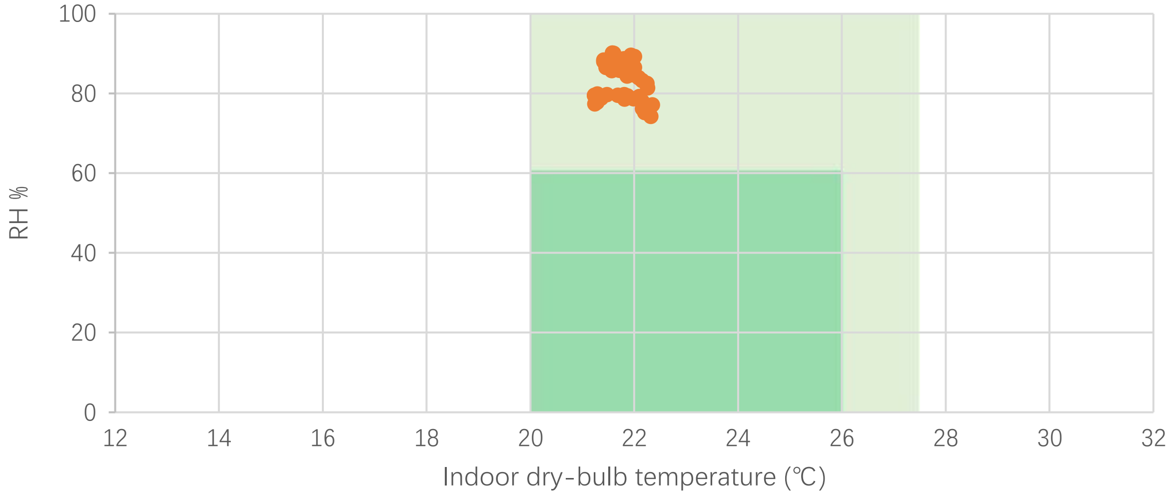


Simulated – 8.5 hours

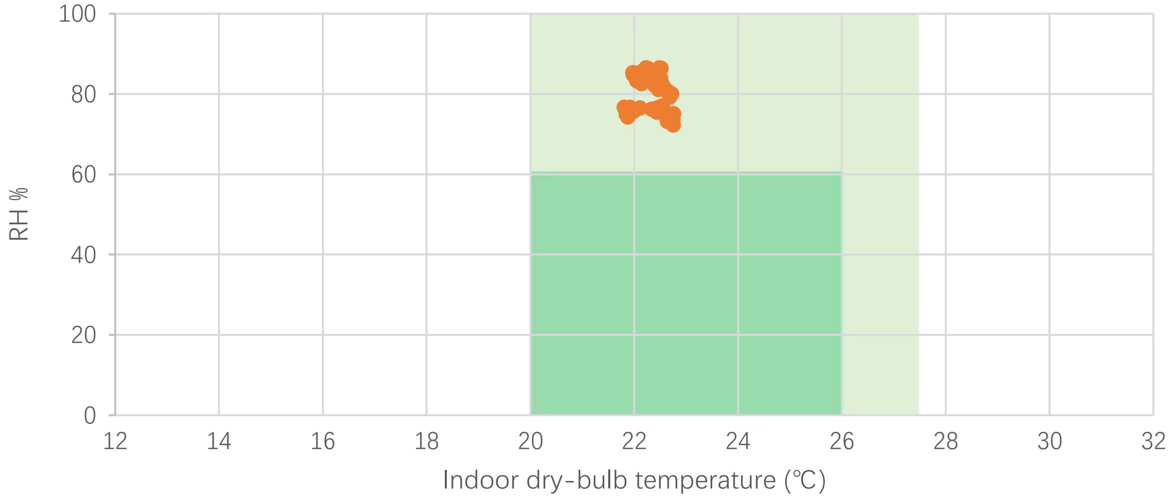
(c) First-floor second main bedroom (south-facing)



Monitored

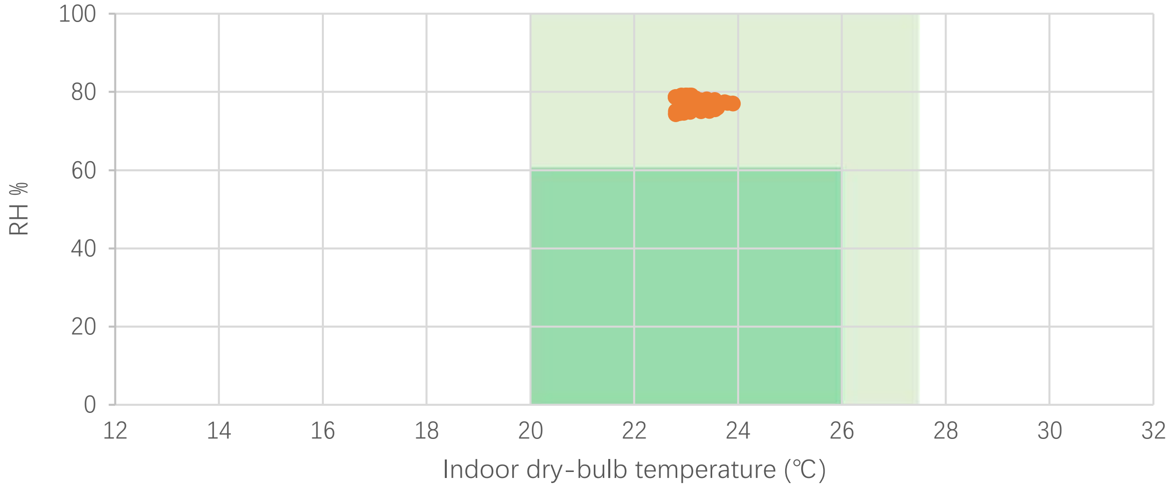


Simulated – 24 hours

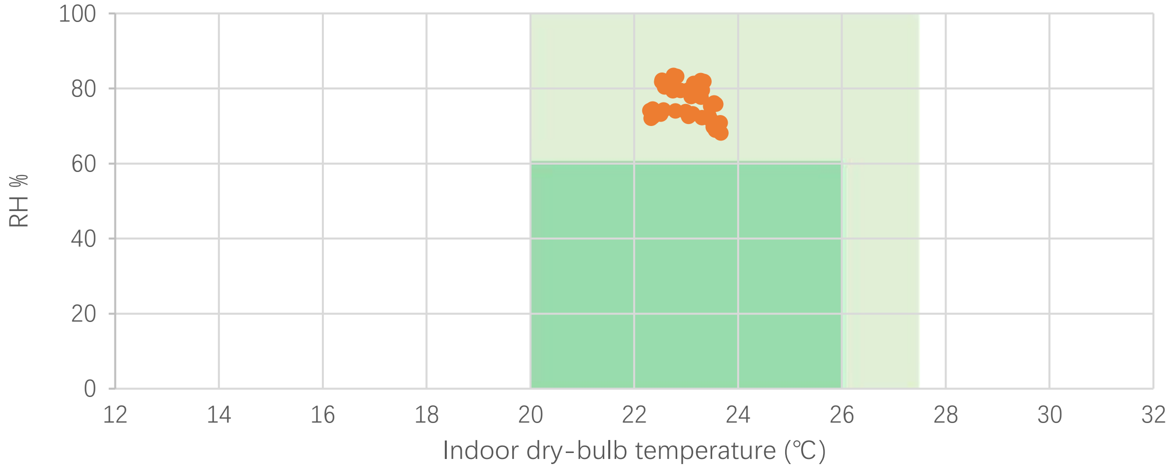


Simulated – 8.5 hours

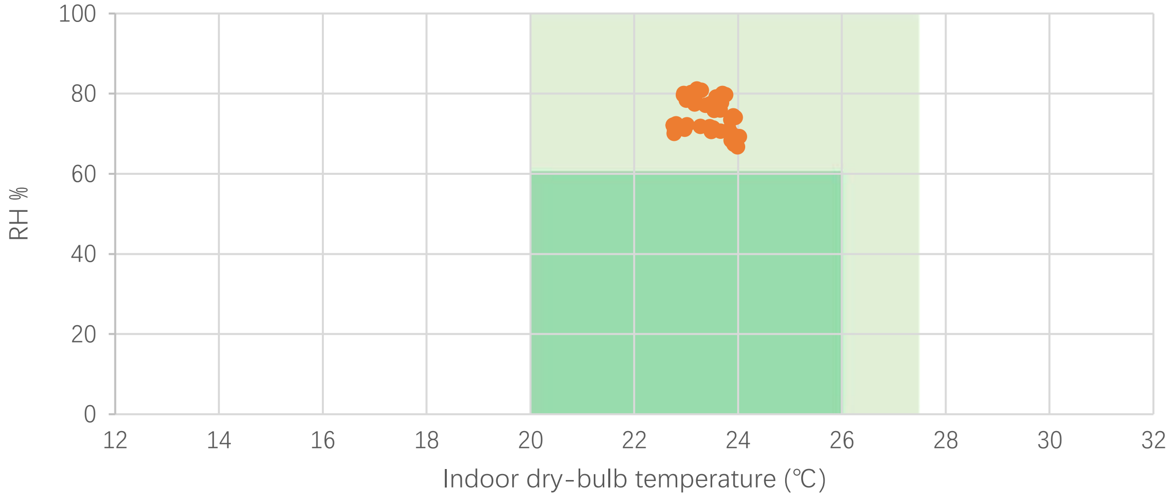
(d) First-floor the guest's bedroom (north-facing)



Monitored

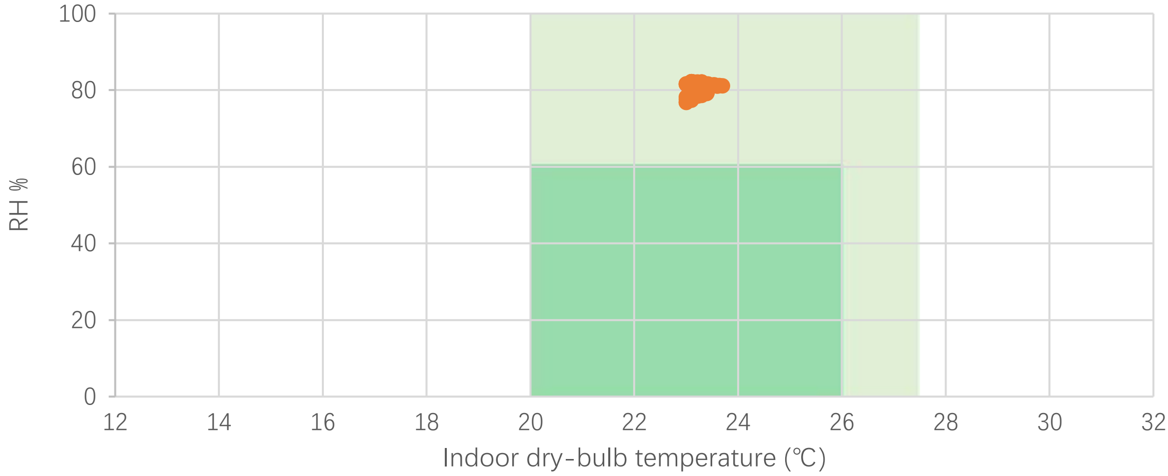


Simulated – 24 hours

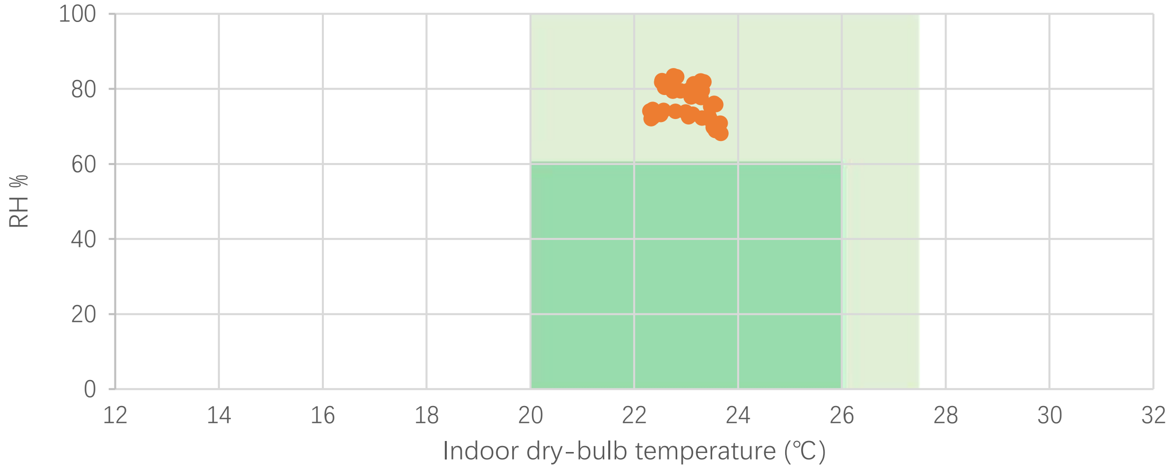


Simulated – 8.5 hours

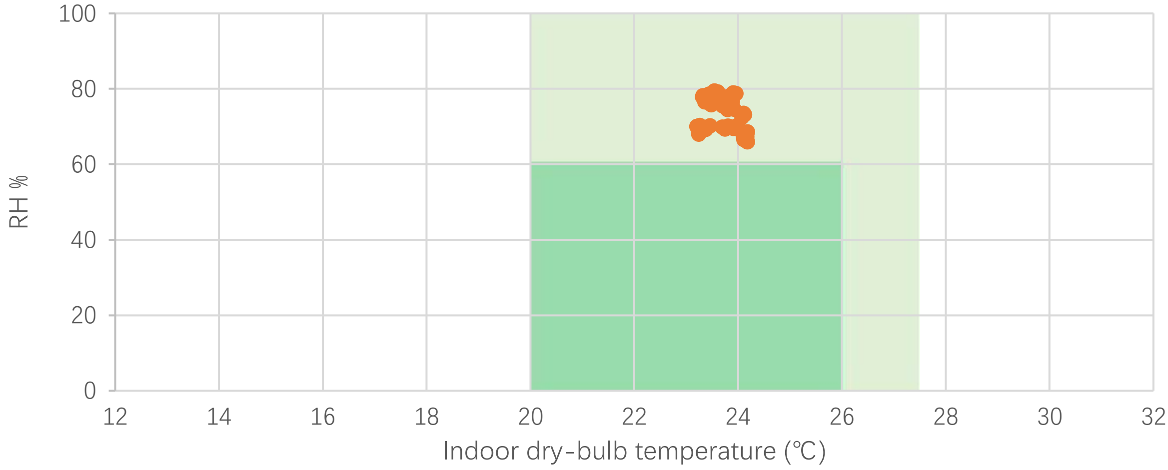
(e) Second-floor Main bedroom (South-facing)



Monitored



Simulated – 24 hours



Simulated – 8.5 hours

(f) Second-floor Kids' bedroom (North-facing)

Figure A6-1 The indoor dry-bulb temperatures and RH distributions of August 28-29 (similar indoor and outdoor conditions between simulation and monitoring)

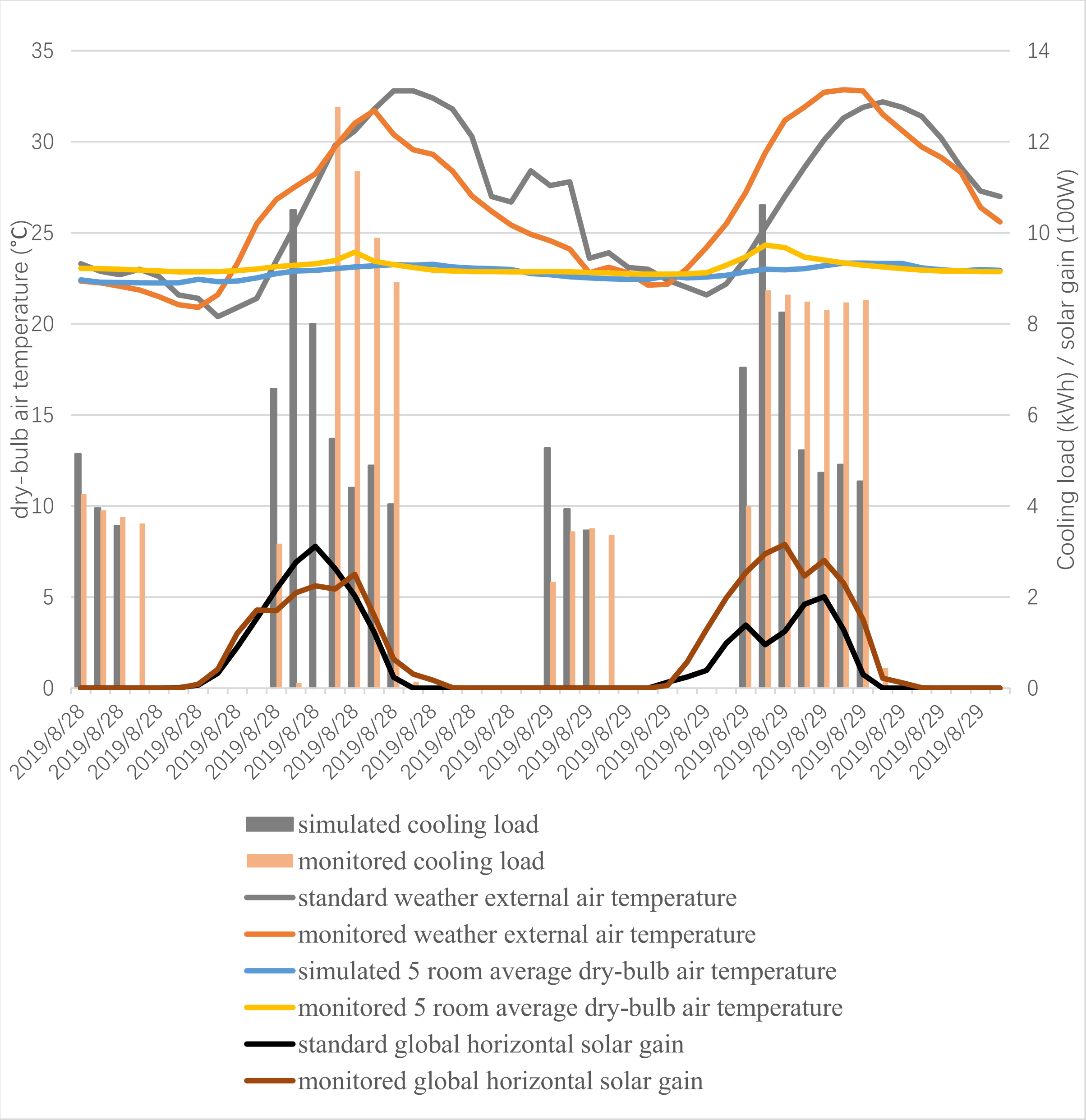


Figure A6-2 Comparison of the simulated and monitored cooling load associated with the indoor and outdoor conditions (8.5 hours operation)

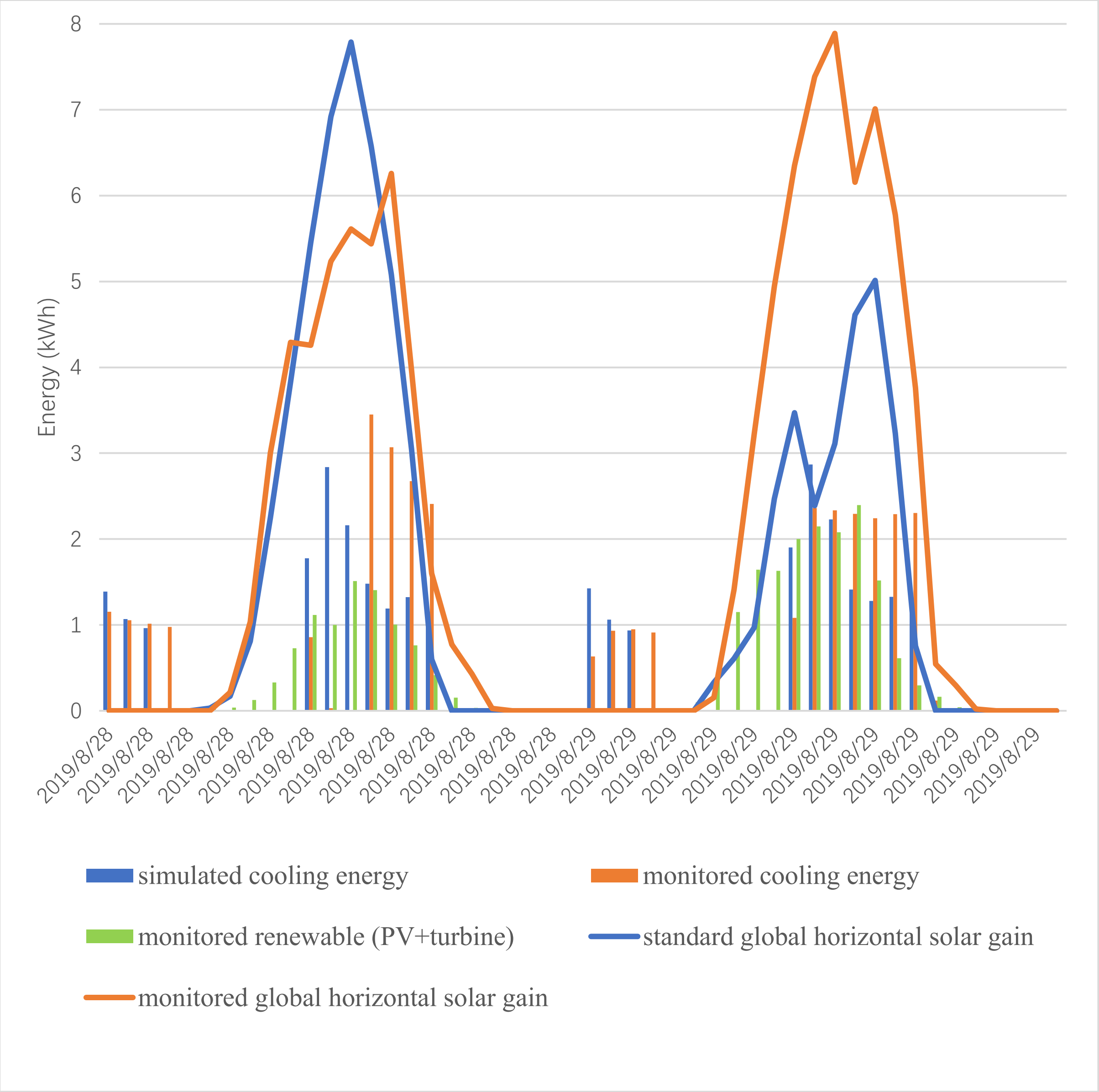


Figure A6-3 Comparison of the simulated and monitored energy consumptions with the renewable generations (8.5 hours operation)