博士論文

CLIMATE IMPACT ON ENERGY CONSUMPTION WITH INSULATION AND VENTILATION IMPROVEMENTS OF GREEN BUILDING

グリーンビルディングの断熱と換気の改善による気候がエネルギー消費に与える影響に関する研究

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CLIMATE IMPACT ON ENERGY CONSUMPTION WITH INSULATION AND VENTILATION IMPROVEMENTS OF GREEN BUILDING

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Preface

This thesis research was performed at the Department of Architecture at the University of Kitakyushu. This thesis presents a study which combines insights from the green building field of policy, technology, energy, environmental studies. The focus is set on green building design based on climate characteristics for energy saving and indoor thermal environment improvement by optimization of building envelope insulation and implementation of building ventilation.

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I would like to express my deepest thanks to my parents and my beloved husband for their encouragement, loving considerations and great confidence in me that made me possible to finish this study.

CLIMATE IMPACT ON ENERGY CONSUMPTION WITH INSULATION AND VENTILATION IMPROVEMENTS OF GREEN BUILDING

Abstract

Green building, as a solution to address the current energy and environment issues, has developed twenty years. It has a majority of achievement but are still facing many barriers and challenges. This paper analyzes the shortcomings and misunderstandings in the development of green building and puts forward some reasonable suggestions. The green building development influencing factors were divided into two categories, internal and external. The external factor refers to development status of green building which include policy support, economic benefits, and certification scheme. The internal factor refers to fundamental characteristics of green building which include technologies implementation, building management, and occupants' behavior. This research aims to provide a development roadmap for government, companies and other stakeholders in the perspective of external factors study. As for the internal factors, this paper focus on the aspects of energy saving and indoor thermal environment improvement, in terms of building envelope design and introducing ventilation design strategies based on climate characteristics. The objectives include pointing out the shortcomings of green building design standard requirements and misunderstanding of the implementation of air-conditioning, providing suggestion of regional suitable green building design strategies.

In chapter one, the development of green building background and current global issues related to building construction are reviewed. In addition, the purpose and structure of this research is proposed.

In chapter two, provided a comprehensive survey of the historical and current development of GB worldwide. Detailed analysis of external factors and internal factors are proposed for these countries. Additionally, the barriers and challenges that green building facing to are rise up. based on the barriers mentioned, the aspects of energy saving, and indoor environment improvement are selected to further detailed analysis.

In chapter three, introduced the research methodology and simulation theories. The simulation models

are detailed introduce in this chapter as well. The climate data in this study are mainly employed TMY3 files which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017. The building energy consumption simulation among the 138 stations in U.S. were estimated using EnergyPlus, a validated and physics-based BES program developed by the U.S. Department of Energy (DOE).

In chapter four, summarized the relationship among climate, building energy standard and green building standard. The impact of climate is mainly reflected in the climate division in the energy standard for buildings. The energy-saving indicators of green buildings are generally based on building standards to further enhance the requirements. The climate zone division are roughly coinciding with the topographic trend in America, Japan and China. Only in America, the climate zone is consistent with administrative division. Japan has a more detailed classification of its own climate than ARSHRAE. ASHRAE shows a similar division for the north China. But in the middle area is quite different. Zone 4A across China's three climate zones of hot summer and cold winter, mild, and cold zone areas.

In chapter five, evaluated the distribution rules of energy consumption with climate zone and latitude. There are no obvious distribution rules of total source energy consumption change with climate zone. However, the energy consumption decreases regularly with humidity climate type zone. There is a strong correlation between cooling and heating energy consumption and latitude. The heating energy consumption in the high latitudes is strongly affected by the latitude changes, resulting in a significant increase in total energy consumption throughout the year. Optimizing the insulation performance of building envelopes is one of the main design strategies to achieve building energy efficiency. Based on the rules, this chapter gives green building design strategies suggestion for different latitude area. Suitable Strategies for lower than latitude of 35-degree area is introducing ventilation and shading design. Suitable Strategies for higher than latitude of 35 degrees area: optimizing insulation performance.

In chapter six, followed the suggestion of chapter five, in higher than latitude of 35 degrees area, investigated the insulation of building envelope in terms of opaque area impact on energy saving. The contribution of the performance of the thermal insulation properties to the energy saving in each latitude interval is analyzed. In areas with a latitude below 35 degrees, the optimization of the insulation layer on the building energy-saving effect is not obvious. Energy saving from 3% to 15% improvement of insulation only increase less than 20GJ. Higher than 35-degree areas are suitable to optimize the insulation performance of the envelope structure. With the increase of latitude degree and R-value, the amount of energy saving rises dramatically.

In chapter seven, followed the suggestion of chapter five, in lower than latitude of 35 degrees area, investigated the energy saving potential with the application of ventilation. In America, the most obvious energy-saving effect due to introducing ventilation appears in the latitude of 20-25 degree, reaching 52%. The amount of total energy saving appears in this area. Main contribution of introducing ventilation is to reduce cooling energy consumption. Japan and America have similar conclusions, while China's most energy-efficient regions are located at 25-30 degrees. When the latitude is above 35 degrees, introducing ventilation energy-saving effect is obvious. Therefore, the application of this technology should be considered in the green building design process, and the rating ratio should be increased in the green building evaluation process. Introducing ventilation not only achieves energy saving, but also keep the indoor environment in the acceptable comfort range for occupants. Verification of the applicability of the ASHRAE global climate zoning approach shows that it is not fully applicable.

In chapter eight, the whole summary of each chapter has been presented.

Keywords: building energy consumption; climate zone; latitude gradient; building energy simulation; design strategies

TABLE OF CONTENTS

Preface

Acknowledgements

Abstract

Chapter 1. Background and Purpose of This Study

1.1. Research Background

1.1.1.Climate change and building energy consumption

According to the NASA's report, as of 2018, the global temperature change trajectory is close to the highest stage (Figure 1.1 and Figure 1.2). In the past 13 years, the atmospheric CO2 concentration has increased from 378.21 ppm to 410.02 ppm. The NASA study believes that since the industrial revolution, global temperatures have risen by 0.92 °C, Arctic glaciers have fallen by 12.85% per decade, Antarctic glaciers have fallen by 127 Gt/year (margin: ±39), and sea level averages have been in the 25 years from 1993 to 2018[1]. It rises by 3.3mm/year, and if it continues, the sea level rises by 18-59cm by the end of the century. According to the Intergovernmental Panel on Climate Chang (IPCC), the construction sector consumes 40% of the world's energy and its carbon emissions account for 36% of global carbon emissions[2]. Therefore, energy savings can effectively reduce global carbon emissions. The IPCC's annual report states that greenhouse gas concentration control at 450 ppm is currently an environmentally acceptable limit, but as the global population continues to increase and the economic development of developing countries, greenhouse gas emissions will soon exceed the limit.

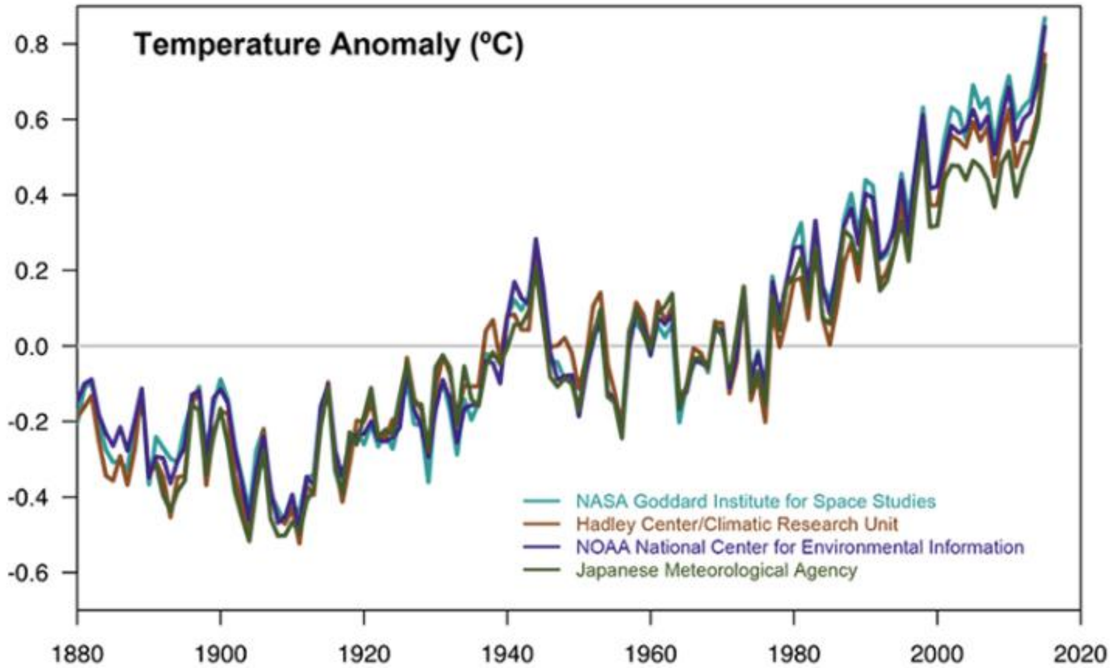

Figure 1.1. Global temperature changes from 1880 to 2020 [1]

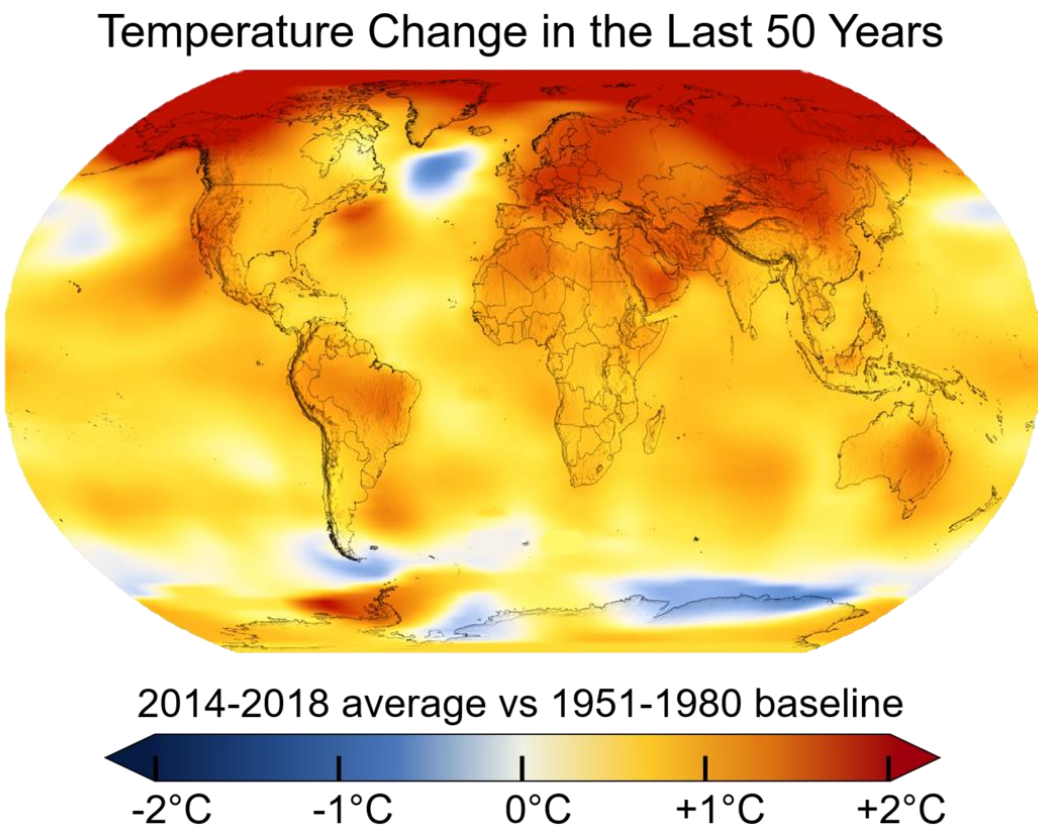

Figure 1.2. Earth surface temperature changes from 1951 to 2018 [1]

1.1.2.Population growth and urbanization

Figure 1.3 shown that although the world population growth trend is gradually slowing, the world population continues to grow, and the global population is expected to exceed 9 billion by 2050[3]. As the population continues to grow, the number of people living in urban areas is increasing year by year. The data source from UNITED NATIONS DESA shows that the 2018 Urban Percentage of Population in Urban Areas is 24.7% higher than in 1950. In the future, it will continue to grow at a rate of 0.898%. It is estimated that by 2050, the proportion of urbanized population will reach 68.4% [4]. At the same time as the urban population increases, the newly added urban construction area will gradually increase. It is estimated that from 2013 to 2020, the world will increase the housing area by 60 billion cubic meters [5]. Along with the continuous growth of the building area, the construction industry consumes a large amount of building materials and energy every year, which also causes the building materials production and construction to seriously affect the environment. Take China as an example, as the most populous country in the world, China's annual urbanization growth rate is 0.8%, and the newly added construction area is about 1.8 billion cubic meters per year, which is basically the same as the world average [5]. Urbanization and rapid economic development have had a negative impact on the environment. Related studies have shown that the urban environment deteriorates and the probability of death due to respiratory diseases in the city increases from 65.42 per 100,000 in 2009 to 73.36 in 2018 [5]. Therefore, how to coordinate the relationship between urbanization and human health is particularly important and urgent.

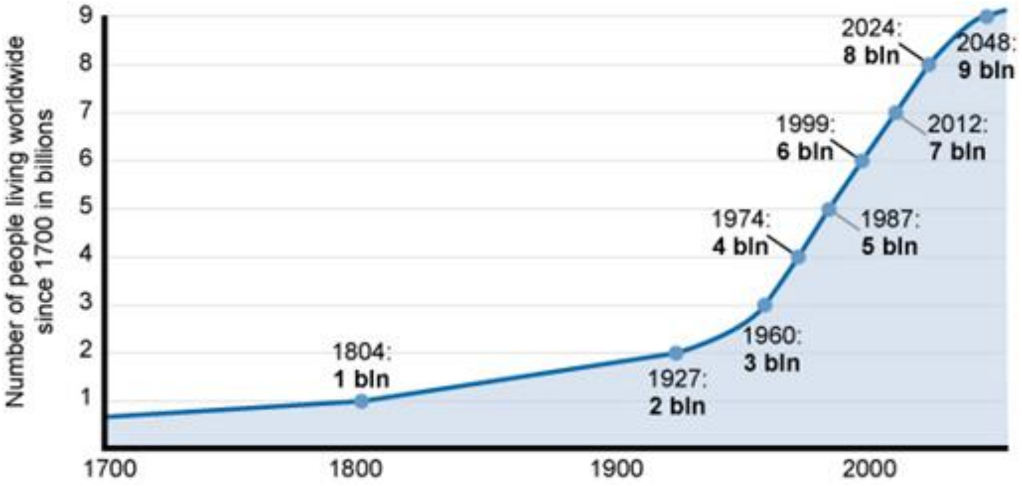

Figure 1.3.Population growth tendency [3]

1.1.3.Problems in the construction sector

The World Watch Institute pointed out in the survey report that the area of the city only accounts for 2% of the total land area, but its greenhouse gas emissions account for more than 70% of the total emissions, 60% of domestic water consumption and consume 76% of the total wood [6]. The expansion of the city means the demolition and construction of the building, which takes up a large area of land resources and consumes a lot of water. The Figure 1.4 and Figure 1.5 give the activities related to building production can place a huge load on the ecological environment, exacerbate environmental damage, and have a negative impact on air quality and urban micro-environment.

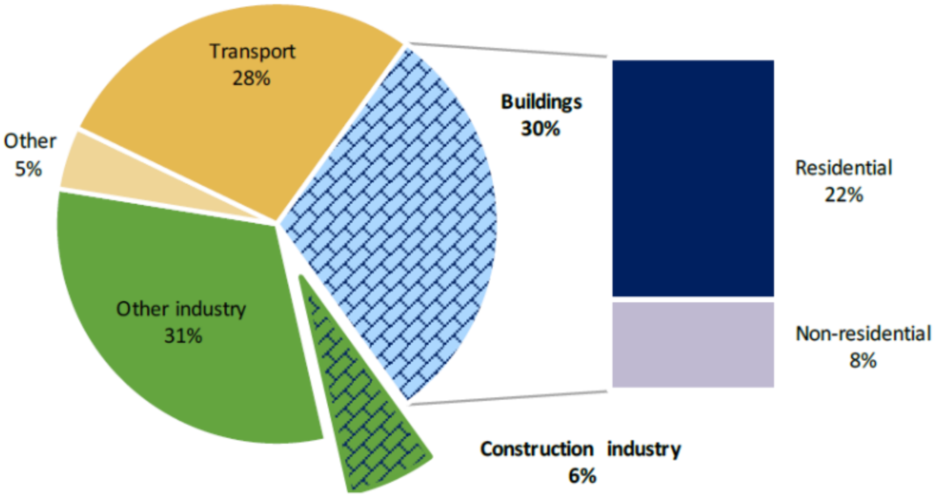

Figure 1.4. Share of global final energy consumption by sector[7]

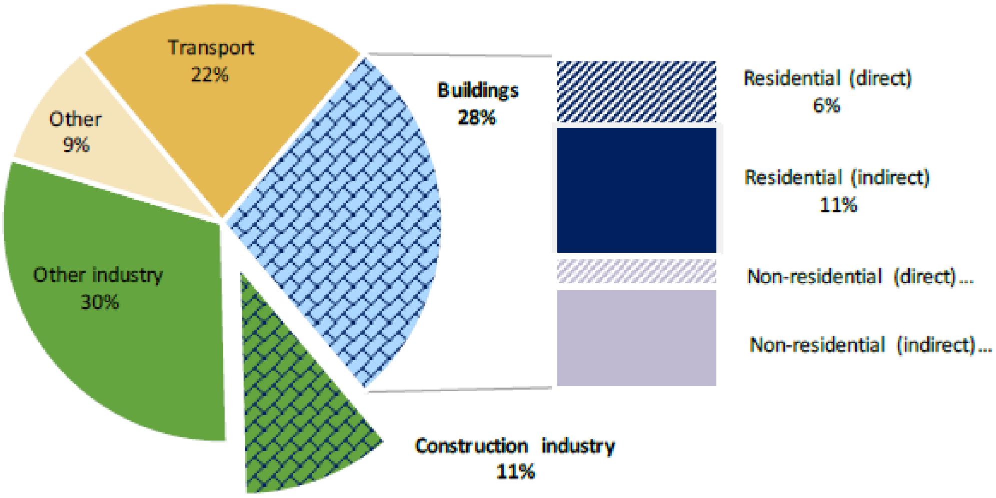

Figure 1.5. Share of global energy-related CO2 emissions by sector[7]

To address these issues, the concept of Green building comes up. It is an integrative process that focuses on the relationship between the built environment and the natural environment (Figure 1.6). Building can have both positive and negative impacts on their surroundings as well as people who inhabit them every day, reduced energy and water use, healthy indoor environment quality, smart material selection and the building ‘s effects on its site are key considerations of a green building. Faced with the shortcomings of the development of the buildings sector, countries have accelerated the development of green buildings and increased the proportion of green buildings.

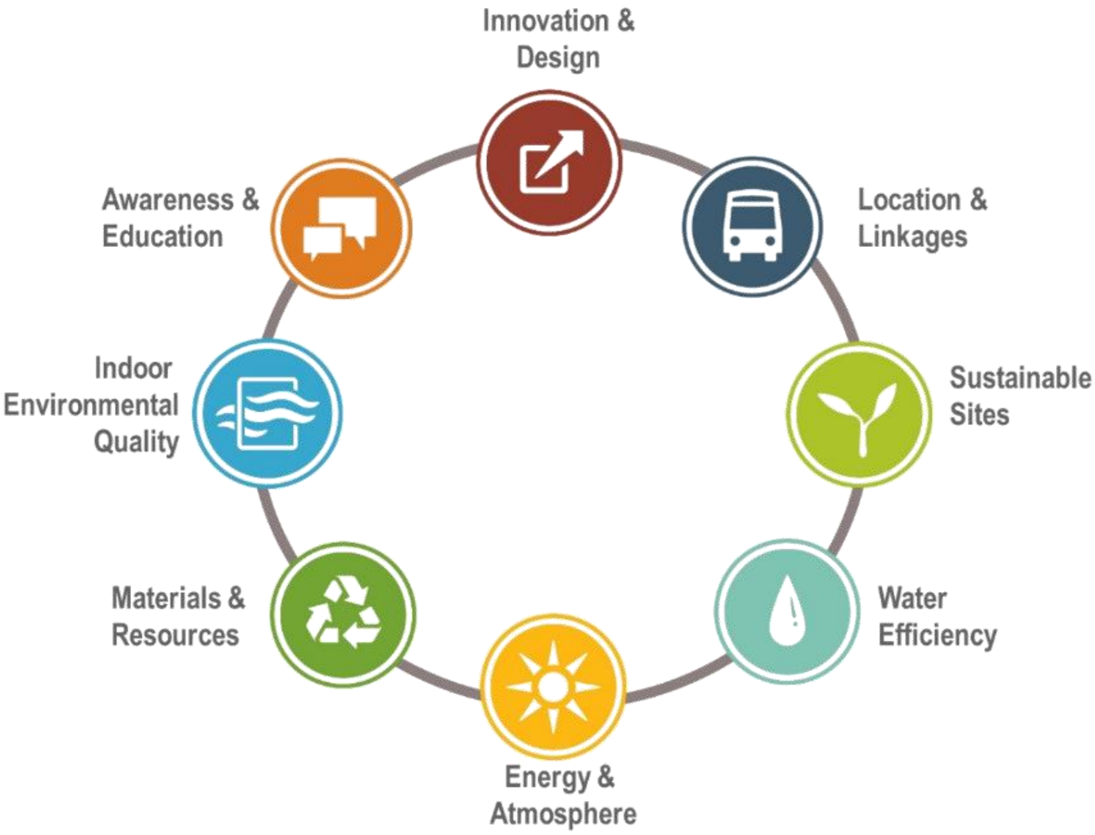

Figure 1.6. The concept of green building

However, green building is still facing many challenges nowadays. Such as lack of policy and economic support for architects and users who are decision making stakeholder employing green building technologies or not. Some people remain doubtful that GBs have not achieved what it promised, including realizing energy conservation[8]. Previous study shows that due to the limitation understanding and mismatching technologies, cause more energy consumption and cost for green building[9].

Large number of buildings that use air conditioners or heating equipment for a long time do not meet the long-term development plan. Applying the building to local climatic conditions can shorten the heating and cooling time, reduce the heating and cooling load to achieve energy saving and emission reduction, and is the fundamental for the development of ecological building design and green building design. Due to the living habits of people in various regions and the imbalance of economic development between regions, climate still plays a vital role in the energy consumption of regional buildings[10]. The building should be regional in nature. The structure, practices and materials of the building must be adapted to local conditions, so that energy conservation and practicality can be achieved throughout the life cycle of its construction and operation, in line with long-term planning.

Most of the energy-saving evaluations of green buildings are concentrated in the design stage of buildings, ignoring the energy consumption and materials input of energy-saving technologies in the production process and how to use equipment properly in operation process. A suitable evaluation model should be constructed to evaluate the energy consumption and environmental load of the green building throughout its life cycle from the perspective of the life cycle of green buildings.

Limitation of knowledge refers to lack of understanding about the concept of GBs used by those who can incorporate GB concepts into a building life cycle, including owners, architects, architectural engineers, construction managers, building operators, occupants, and other stakeholders. The significance of knowledge centers around three main aspects: The advantages of GBs, knowledge of existing green technologies, and cognition of how to use GBs technologies appropriately and efficiently[9].

1.2.Purpose and Significance of This Study

1.2.1. Purpose of This Study

Green building, as a solution to address the current energy and environment issues, has developed twenty years. It has a majority of achievement but are still facing many barriers and challenges. This paper analyzes the shortcomings and misunderstandings in the development of green building and puts forward some reasonable suggestions. The green building development influencing factors were divided into two categories, internal and external. The external factor refers to development status of green building which include policy support, economic benefits, and certification scheme. The internal factor refers to fundamental characteristics of green building which include technologies implementation, building management, and occupants' behavior. This research aims to provide a development roadmap for government, companies and other stakeholders in the perspective of external factors study. As for the internal factors, this paper focus on the aspects of energy saving and indoor thermal environment improvement, in terms of building envelope design and introducing ventilation design strategies based on climate characteristics. The objectives include pointing out the shortcomings of green building design standard requirements and misunderstanding of the implementation of air-conditioning, providing suggestion of regional suitable green building design strategies.

Reducing the energy consumption of buildings under the premise of maintaining human comfort is an important development direction in the field of green building. Through the investigation of the consolidation of green building standards in various countries and the status quo of development, the applicability of green building technology in different countries and regions is determined. This study highlights the goals:

Analyze the current status of green buildings, understand the obstacles to current development, and propose countermeasures ：Analyze the green buildings in more than ten countries and regions in terms of policy, technology, operation and human behavior, summarize the current status of green buildings and enumerate the obstacles currently facing the development of green buildings. In addition, on the technical side, management aspects and user aspects provide useful advice in this regard. And proposes involving integrated management and exploring occupants' behavior and feedback to improve GB efficiency. Meanwhile, providing training and education in using GB technologies for occupants, as well as raising the awareness of local environmental issues, are expected in the future.

Propose energy-saving measures in the construction operation phase to achieve energy-saving purposes for green buildings: While the air conditioning system creates and maintains a good indoor thermal environment, it also causes the current energy consumption of the building to be too high.

Building insulation and introducing ventilation are the main ways to reduce the energy consumption of air-conditioning. By comparing the introducing ventilation and increasing the insulation layer thermal resistance in different latitudes, the energy-saving methods for reducing air-conditioning energy consumption in different latitude areas are given. At the same time, further analysis of the energy saving potential of areas suitable for introducing ventilation technology.

1.2.2.Significance of This Study

The concept of green building covers a wide range of elements and its definition is constantly updated as the construction industry evolves. This paper compares the background and current situation of green building development in different countries and regions. It's summarized the research results of various countries and regions in terms of policy, economy, technology, operation and human behavior, and clarifies the development of green buildings at the present stage. The influence factors were divided into two categories: one external impact and another internal impact. External factors include GB development policy support, economic benefits and certification programs. Internal factors are the development and application of GB technology, the level of building management and the way users interact with GB technology. Based on the above, the obstacles encountered in the development of green buildings are analyzed. The influence of insulation layer, introducing ventilation and windows on energy consumption and environment is analyzed from the aspects of green building energy-saving technology, and suggestions for the future development direction of green buildings are proposed.

From the theoretical level, through the summary of the green building system of each country, the process of green building evolution in various countries is reviewed, and the advantages and disadvantages of the green building systems of various countries are evaluated from various aspects, and the development of green buildings at the present stage is clarified. This study gives the obstacles and future development directions of current green building development, and opinions from two aspects of green building application and research.

Through the analysis of building energy consumption in different latitude of China, Japan and the United States, the energy saving potential of introducing ventilation and optimization of insulation layer is analyzed, and energy-saving technical measures for different latitude are proposed.

1.3. Structure of This Study

In chapter one, the development of green building background and current global issues related to building construction are reviewed. In addition, the purpose and structure of this research is proposed. In chapter two, provided a comprehensive survey of the historical and current development of GB worldwide. Detailed analysis of external factors and internal factors are proposed for these countries. Additionally, the barriers and challenges that green building facing to are rise up. based on the barriers mentioned, the aspects of energy saving, and indoor environment improvement are selected to further detailed analysis.

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In chapter seven, followed the suggestion of chapter five, in lower than latitude of 35 degrees area, investigated the energy saving potential with introducing ventilation design strategies. In America, the most obvious energy-saving effect due to introducing ventilation appears in the latitude of 20-25 degree, reaching 52%. The amount of total energy saving appears in this area. Main contribution of introducing ventilation is to reduce cooling energy consumption. Japan and America have similar conclusions, while China's most energy-efficient regions are located at 25-30 degrees. When the latitude is above 35 degrees, the introducing ventilation energy-saving effect is obvious.

In chapter eight, the whole summary of each chapter has been presented.

PREVIOUS STUDY	**CHAPTER ONE** Background and Purpose Of the Study
THEORETICAL SURVEY	**CHAPTER TWO** Survey on the Status and Challenges of Green Building Development in Various Countries
EVALUATION METHOD	**CHAPTER THREE** Theories and Methodology of the Study
INVESTIGATION	**CHAPTER FOUR** Comparison on Climate Zoning and Thermal Standard of Green Building Design
NUMERICAL ANALYSIS	**CHAPTER FIVE** Evaluation of Climate Impact on Building Energy Consumption
	CHAPTER SIX Study on the Thermal Insulation of Building Envelope Opaque Area impact on Energy Consumption
	CHAPTER SEVEN Study on the Energy Saving Potential Introducing Ventilation Design Strategies
CONCLUSION	**CHAPTER EIGHT** Conclusions

Figure 1.7. Research Flow

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Chapter 2. A Survey of the Status and Challenges of Green Building Development in Various Countries

2.1.Introduction

Today's global issues like climate change, energy shortages, increasing environmental pollution, rising population, and rapid urbanization present tremendous challenges to the sustainable development of human society [1]. NASA reports that the global average temperature has increased 1.8°F since 1880 [2]. The rise in global average temperature is expected to be about 4.5°F by 2050 from the CO2 increase alone [3].The world's carbon dioxide (CO2) emissions from energy-related consumption will increase from 32.3 billion metric tons in 2012 to 43.4 billion metric tons in 2040 [4]. Meanwhile, the growing population continues to place a heavier burden on the environment. According to World Population Prospects 2017, during the 13 years from 2005, the world's population had added about 1 billion new-borns, and world population would reach 9.8 billion in 2050 [5]. This increasing population and galloping urbanization are accelerating the demand for energy [1] that will reach 900 EJ primary energy use in 2050 [6].

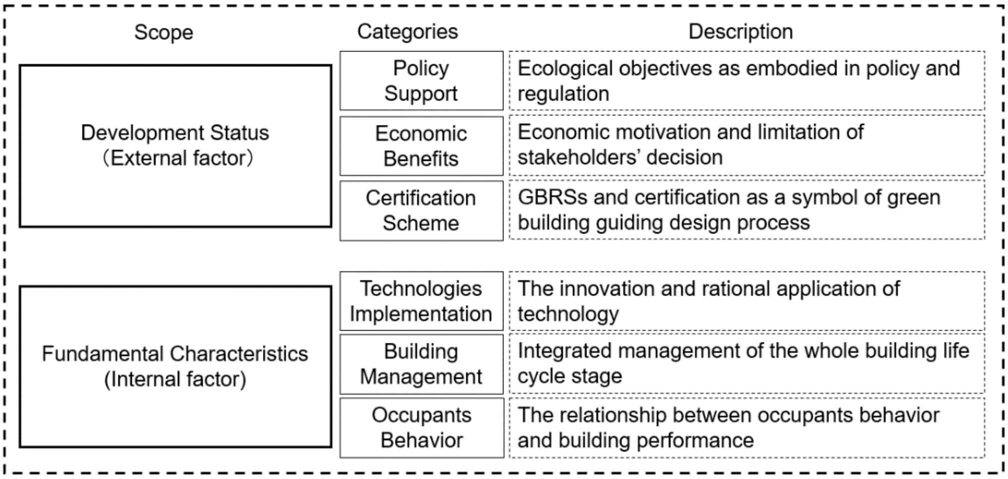
Among those various causes of these problems, the building construction industry has been criticized as being a leading exploiter of a large proportion of primary energy and natural resources [7]. Globally, the industry has made a significant impact on our resources, environment, society, economy, and human health. It consumes 30% of global resources, 15% of global freshwater withdraws, one-fourth of wood harvested, and nearly half of raw materials used [7]. The CO2 released from the energy used to produce tiles, glass, concrete, and other construction materials is more than those of industry and transport [1]. The building sector generates 30% of the world's greenhouse gases [8] and 40%–50% of water pollution to the environment [1]. Additionally, it contributes 40% of the total solid waste in developed countries [9]. To address these issues, GB construction focuses on improving building energy efficiency and alleviating construction's negative impacts on the environment and resources [10]. It can integrate strategies from all building life cycle stages, including siting, design, construction, operation, maintenance, renovation, and deconstruction to reduce the negative impacts on energy, water, materials, and other natural resources. It also can decrease environmental pollution from waste, air and water pollution, indoor pollution, heat islands, stormwater runoff, noise, and more [11]. The introduction and implementation of GBs have indeed achieved reduction in energy consumption and CO2 emission and improvement in water management in many projects. At least in their design proposals, the designers demonstrate their intentions to follow GBs guidance to achieve the best outcome.

Although GB certification programs and the square footage they cover are increasing each year, they are still far from the total floor area of the huge building market. This is partly due to the many restrictions on the promotion of GBs. Also, although extensive research has examined various aspects of GBs, there has been a lack of systematic review of the state of the art and future tendencies from around the world, including developing countries. This paper presents a critical overview of GB development status in various countries and related studies by discussing the research results produced by GB technology implementation, looking at both external and internal factors. The goals of this paper are to draw a clear roadmap for national standard development, policy formulation, and construction design companies, offer guidance for overcoming GB development barriers, and provide a comprehensive reference for future academic researchers.

This paper combines academical articles and conference proceedings by keywords searching, and original contents and data from official web sites of green building evaluation standards in various countries. Relevant literature review of green building development mainly use multiple databases like Web of Science and Scopus [12–14]. Some researches believed Scopus is better in terms of accuracy [12], but also with a wider range of academical literature coverage [15]. They used Scopes to identify the paradigms of GB research and draw the trend of GB development. While some authors use keywords search to collect the relevant articles. Likewise, this study adopted databases and keywords search to identify relative articles of GB and technologies. Additionally, the original official politics of different countries, and GB rating systems all over the world and their current development status were review as well. The contents and data are mainly from the official web site. Some of them are translated from local language to English.

The method of this paper consisted of six elements, of which the structure is shown in Figure 2.1. The first is to identify all factors that influence the development of green building in the world and divide them into two categories - the external and internal. The purpose of this division is to clearly identify the key influencing factors related to different stakeholders in the development of green buildings. The second is to study the history of GB to understand the originally purpose of the concept which is designed to deal with the global energy crisis and environmental problems. It attracted considerable interest from fields as diverse as architectural engineering technologies, economics, human health, and assessment methods over time. The concept continues to develop with a range of opinions. The third is to analyses all influence factors. The external factor refers to development status of green building which include policy support, economic benefits, and certification scheme. A clear roadmap is provided by these three factors analysis for policy formulation and national standard development. The internal factor refers to fundamental characteristics of green building which include technologies implementation, building management, and occupants' behavior. The study of these factors is to offer guidance for designers, engineers, and all stakeholders to deal with GB development barriers. Finally, future trends and tendencies provided a comprehensive reference and potential directions of related studies for future academic researchers.

The structure of this paper is shown in figure 1. Firstly, a comprehensive survey of the historical and current development of GB was summarized in Section 3. The status quo of relevant GBs policies, certification standards and projects achievement in various countries, which stand for external factor, were surveyed and summarized in Section 4. Following that, the internal factor in terms of a detailed fundamental state of GBs with specific technologies was introduced in Section 5. Subsequently, Section 6 focused on the barriers to the adoption of GBs and strategies for overcoming these barriers. Finally, the conclusion was provided in Section 7.



Scope	Categories	Description
Development Status （External factor）	Policy Support	Ecological objectives as embodied in policy and regulation
	Economic Benefits	Economic motivation and limitation of stakeholders' decision
	Certification Scheme	GBRSs and certification as a symbol of green building guiding design process
Fundamental Characteristics (Internal factor)	Technologies Implementation	The innovation and rational application of technology
	Building Management	Integrated management of the whole building life cycle stage
	Occupants Behavior	The relationship between occupants behavior and building performance

Figure 2.1. Factors Influencing GB development

2.2. Background and definition

Green building development can be traced back to the energy crisis in the 1960s, which spurred crucial research and activities to improve energy efficiency and decrease environmental pollution [16]. Combined with the energetic environmental movement of the time, these early experiments led to the contemporary GB movement, which originated from a focus on energy efficient and environmentally friendly building construction practices. The Earth Summit held in 1992, also known as the United Nations Conference on Environment and Development (UNCED), brought forth the Rio Declaration on Environment and Development and Agenda that stimulated the building environmental protection upsurge [17]. In 1990, the first GB rating system, the Building Research Establishment Environmental Assessment Method (BREEAM), which was developed by the Building Research Establishment (BRE) in the UK, presented a systematic method to evaluate the implementation and performance of GBs [18]. Following this point, extensive GB assessment tools were developed by government or third parties of different countries with the aim of addressing the quality of buildings [19].

Green buildings are not easily defined, as the concept continues to develop with a range of opinions. The World Green Building Council (WorldGBC) is a global network of GB councils in over 70 countries. It claims that countries and regions have various characteristics such as history, culture and traditions, distinctive climates conditions, different building types and ages, and environmental, economic, and social priorities that shape GB methods [20]. Green building is not the same across the globe [21]; its definitions represent the requirements of national and regional building industry development. WorldGBC defines green building as aiming to reduce or eliminate negative impacts on the environment during the whole building life cycle, creating positive impacts on the climate and environment [22]. The United States Environmental Protection Agency (EPA) has claimed that "green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle from siting to design, construction, operation, maintenance, renovation, and deconstruction [11]." A generally accepted description in United Kingdom and European Union is that a green building contributes in some way to preserving the environment, with increasingly extending to the idea of well-being of the occupants, both in terms of use of space and quality of air. The concept is closer to that of sustainable buildings and sustainable construction. Apart from energy efficiency, it also includes aspects such as the decrease of CO2 emissions, which seems to differ slightly between the EU and the U.S. [23]. The first GB certification system, BREEAM, could represent the concept of GBs in the UK that focus both on energy efficiency and the well-being of people who live and work in the building [24]. This concept makes green and sustainable buildings interchangeable. Similarly, the GB definition in Japan also shares the meaning with sustainable building, by including energy and resources, materials, and emission of toxic substances, while also seeking to harmonize the building with local aspects and improve human life

[25]. Table 2.1 indicates a selection of GB definitions from different organizations.

Table 2.1. Definitions of GBs

Country	Organization	Definition
USA	World Green Building Council	A GB is a building that, in its design, construction, or operation reduces or eliminates negative impacts, and can create positive impacts, on our climate and natural environment [20].
	U.S. Environmental Protection Agency (EPA)	Green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle, from siting to design, construction, operation, maintenance, renovation, and deconstruction [11].
	U.S. Green Building Council (USGBC)	The planning, design, construction, and operations of buildings with several central, foremost considerations: energy use, water use, indoor environmental quality, material use and the building's effects on its site [26].
UK	Building Research Establishment	The GB Certification BREEAM could represent the concept of GBs that are more sustainable environments that enhance the well-being of the people who live and work in them, help protect natural resources, and make more attractive property investments [24].
Europe	European Commission Delegation	A Sustainable Building contributes in some way to preserving the environment, also increasingly extends to the idea of the well-being of the occupants, both in terms of space usage and air quality [23].
Germany	German Sustainable Building Council (DGNB)	Sustainable building means using and introducing available resources consciously, minimizing energy consumption and preserving the environment [27].
France	Haute Qualite Environment (HQE)	Certificated sustainable building endorse the overall performance of a building and that of the four areas considered by the certification scheme: energy, environment, health and comfort [28].
Australia	Green Building Council Australia	Green Building incorporates principles of sustainable development, meeting the needs of the present without compromising the future [29].
Japan	Architectural Institute of Japan (AIJ)	A sustainable building (green building) is one which is designed: (1) to save energy and resources, recycle materials, and minimize the emission of toxic substances throughout its life cycle; (2) to harmonize with the local climate, traditions, culture, and surrounding

		environment; and (3) to be able to sustain and improve the quality of human life while maintaining the capacity of the ecosystem at the local and global levels [25].
China	Assessment Standard of GBs	Green building refers to a building that saves resources to the extent within the whole life cycle of the building, including saving energy, land, water, and materials while protecting the environment and reducing pollution so it provides people with a healthy, comfortable, efficient use space, and works in harmony with nature [30].
Singapore	Inter-Ministerial Committee on Sustainable Development (IMCSD)	Green building is energy and water efficient, with a high quality and healthy indoor environment, integrated with green spaces and constructed from eco-friendly materials. [31]

Some researchers wanted to demarcate the concept of GBs and sustainability in detail. However, that approach will lead to a narrow understanding of GBs that limit their development. They think although GBs have been developing, the environmental aspect is the core concept [7]. GBs are environmentally and ecologically sound in terms of land, energy, water, and materials. Sustainability is a nonstop development concept that depends on various countries' building practices [32]. It consists of four aspects: environmental, social, economic impacts, and institutional dimension [7,33]. According to different development situations, the concept of sustainability could contain very factor of human activity [34]. Whereas, focusing exclusively on the energy conservation and environmental aspect but neglecting the social, economic, and institutional factors will hinder GB development. At present, although many GB concepts have been successful and are developing in a good direction, there are still many obstacles and misunderstandings about GBs. Section 6 will discuss this in more detail.

2.3.Development status

The development status of GBs stands for external factors, including policy support, economic benefits and certification schemes. Ecological objectives are embodied in policy and regulation. Economic benefits will influence the motivation of stakeholders' decision. Green building certification scheme is being a symbol and as a green building guide for construction process.

2.3.1. Policy support

As noted above, GB is an integrated process of the whole building life cycle, with many components, including energy, water, materials, land, environment, human health, construction, management, and more. Any policy related to these areas can be further related to GBs. The GBs in the United States, the UK, and Japan have entered a relatively mature implementation stage. Those countries have established and improved the GB laws and regulation systems. These laws, regulations, departmental codes, and regional regulations of GBs depend on and complement each other. The perfect and comprehensive legal system provides an important guarantee and premise for the standard development of GB.

In the United States, the GB policies include mandate and incentive-based policies, which both play vital roles in GB implementation [35–37]. The government adopts zoning regulations and building benchmarks to guarantee the realization of GBs objectives. They can be classified at the federal, state and local levels [37,38]. Policies at the federal level are mainly for buildings constructed and occupied by the government. They always focus on internal activities, with the aim to decrease the environmental footprint; examples of these are the Energy Policy Act of 2005 and The Federal Green Construction Guide for Specifiers [39]. Green policies at state levels focus on non-government buildings and require volunteer efforts by private developers [39]. However, some policies cannot adequately pursue local GB objectives. Consequently, many local governments establish their own green policies which are more detailed and likely to promote the involvement of private developers [39,40]. The incentive-based policies are grouped with various strategies, such as tax incentives, financial incentives, density bonuses, and priority permit processing to achieve an environmental agenda. In 2000, the State of New York first adopted a tax-based incentive program for GBs. Many states integrated their financial incentives to the third-party verification system, such as Oregon and Maryland. Following the Oregon statutory directive, the State Department of Energy employed Leadership in Energy and Environmental Design (LEED) as the applicable standard to help a project get a tax credit [39]. California instituted GB guideline in 2004 as the first mandatory policy. The City of Chicago proposed the Chicago Standard, which asks all new municipal construction meet LEED certification. Regulation is regarded as the most powerful policy tool for GB development [41].

There are 60 results in guidance, regulation, and business funds and grants for energy efficiency in buildings from 2008 to 2018 in the UK government website [42]. Building regulation guides the British construction industry, which sets the minimum performance standard for energy-saving performance of buildings, utilization of renewable energy, and carbon emission reduction [43]. The implementation of the building energy efficiency label is one of the effective measures to promote GBs in the UK. Additionally, the British government commissioned the British Research Establishment (BRE) to develop the Sustainable Housing Code, which is a mandated standard that guides the building industry in implementing GBs. Furthermore, since 2008, all new homes in England and new homes funded or recommended by the government and authorities in Wales, as well as all new independent public rental housing in Northern Ireland, will be subject to a mandatory building rating process. BREEAM is widely applied in the UK, due to the fact that professional organizations and the construction industry have been a great effort to progressively make it compulsory to all new buildings and renovation projects [44]. In November 2018, the European Commission presented its strategic long-term vision to reduce greenhouse gas (GHG) emissions, showing how Europe can lead the way to climate neutrality, an economy with net-zero GHG emissions [45]. Sustainable and climate-proofed buildings are required to meet the targets to achieve the climate-neutral Europe by 2050.

Japan is a country with very limited energy and resources. Energy security is always the most significant issue in Japan, especially with the situation of serious global warming problem. Consequently, the Japanese government has been making unremitting efforts to guide the national building energy conservation work and the promotion of GBs through laws, regulations, and policies. Japan has a wide range of relevant laws, regulations, and policies that they keep updating based on development. The policies include mandates, supports, and incentives. In 1979, Japan formulated the Energy Conservation Law, which holds up the basic principles of energy conservation. It strengthens the independent energy management of enterprises. Simultaneously, it standardized the energy-using management relationship and energy-saving behaviors among government, enterprises, and individuals, which provided the working basis for energy conservation management in Japan. The government established standards for constructors to promote the use of energy-saving measures in home construction. For building sellers and renters, it is clearly stipulated that they must provide information to consumers by energy-saving performance labelling. Moreover, the government offered financial incentives that encourage both the GBs construction and development of advanced building technologies. Green retrofits can also earn incentives. The government leads the promotion of the GB rating system (CASBEE), which is jointly developed and promoted by industry, universities, and research institutes. For accreditation of the assessment result, it has two authorization systems. One is the certification system, and another is the local governments' reporting system. The later is the system that the local governments review the assessment result by CASBEE tools in a shorter time than the certification, thus it is usually regarded as a semi-certification system. Currently, 24 Japanese local governments employ the "Sustainable Building Reporting System (SBRS)" regulation targeting the commercial sector and housing sectors (Figure 2.2).

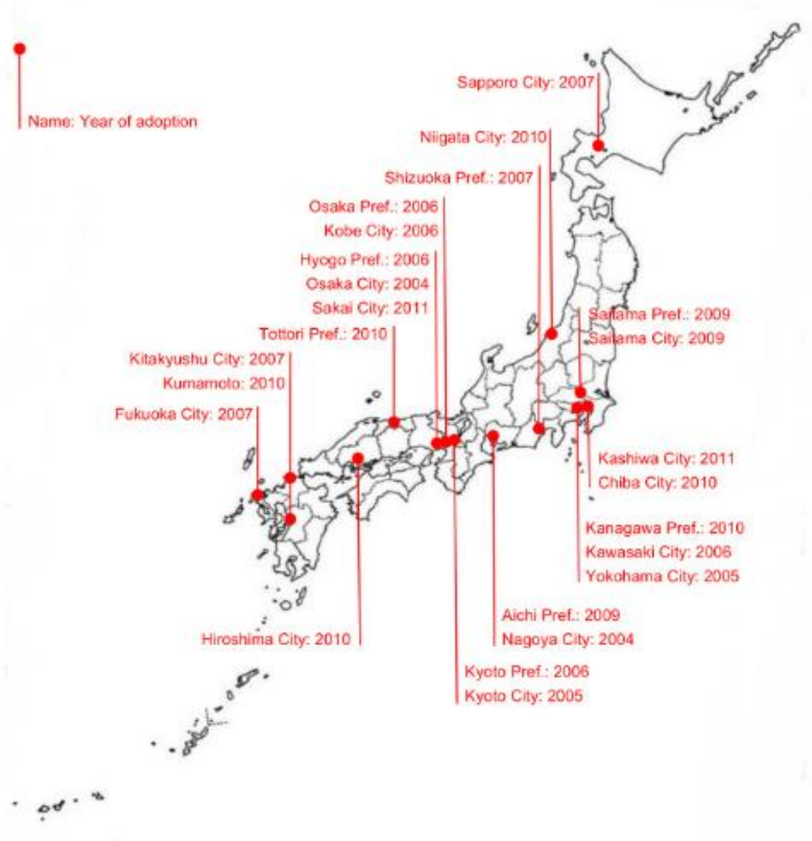


Figure 2.2. Utilization of CASBEE in local governments [46]

Due to the dramatic construction boom and rapid urbanization, GBs in China have significant implications [47,48]. In 2013 the Chinese government issued the Green Building Action Plan, which accelerated China's GB development and promoted the transformation of the development mode of the construction industry. One billion square meters of GBs are expected to be completed from 2015 to 2020. The percentage of certificated GBs area to new urban buildings construction area was 20% in 2015 and is expected to be 50% in 2020. Meanwhile, China emphasizes the development of GBs through a combination of mandates and incentives. Some local governments mandated that all new construction of public buildings meet the requirement for GBs. For example, Shanghai has passed local legislation to establish a mandatory promotion system, stipulating that all new buildings in the city shall comply with the GBs standards. No less than 70% of new public buildings in low-carbon development practice areas and key functional areas are constructed according to the two-star standard or above. The strictest water resource management system is implemented, controlling and managing the total amount of water used by regions and enterprises. Shanghai vigorously promotes water-saving demonstration activities in water-saving parks, campuses, communities, enterprises, and government agencies. By 2020, the water consumption of 10 million yuan of GDP and 10 million yuan of industrial added value in the city will decrease by about 23% and 20%, respectively, compared with 2015 [49].

Finland's industries have set ambitious targets for 2030 that will triple the market share of wood construction, double the value added of the woodworking industries, and decrease the environmental impact by 30% [50]. In Australia, to fulfil the commitment to reduce up to 28% of GHG emissions by 2030 [51], many green-building rating tools have been developed. In India, some government agencies have provided discounts on premium charges. The Ministry of New and Renewable Energy (MNRE) mandates that all government buildings should be at minimum Green Rating for Integrated Habitat Assessment (GRIHA) three stars certified [52]. The Malaysian government has facilitated communication between the private sector and non-profit organizations [53]. Certified GBs can apply for tax and stamp duty exemptions [54]. Eligible GBs in Singapore can get up to a 2% gross floor area (GFA) bonus [55]. In Indonesia, the Quezon City Government passed its GB Ordinance No. SP-1917 (QCGBO) in 2009. All the new buildings and retrofit structures in Quezon City must comply with the Implementing Rules and Regulations (IRR) of the GB ordinance [56]. Green buildings in Vietnam are still in their infancy and facing numerous challenges. Similar to the Singapore Building and Construction Agency, the Vietnam government is developing its own agency to promote GB projects and improve the efficiency of the decision-making framework for GB development. Hanoi and Ho Chi Minh City will be the first pilots before the decision-making model is applied to the whole country [57]. Since 2009 when Vietnam Green Building Council (VGBC) was endorsed to develop LOTUS, a set of market-based green building rating system specifically for the Vietnamese built environment, there has been a continuous increase in awareness of green building benefits among policy makers, investors and industry professionals. National Green Growth Strategy, which issued by the Prime Minister of Vietnam, indicated that the government "require investors to implement green measures when they build new commercial buildings or retrofit old buildings, and will have incentives for manufacturers who make products for green buildings" [58].

The process of promoting GB implementation is slightly different between Western and Eastern countries. In Eastern counties, such as Japan and China, the government organizes the formulation of relevant standards and implements them gradually; even adopting mandatory measures to conduct strict management from the planning and design stage of buildings. Western countries such as the United States differ from this model, adopting federal, state, and local level zoning regulations and employing building standards developed by non-governmental organizations. As the first country to implement green building certification, UK has achieved a relatively advanced level of green building development. Ethic consideration has also played an important role in the development of green buildings. In addition to the relevant policy and economic support, what is more important is that the UK's professional organizations and industrial construction will take sustainable development as their social responsibility. They all see it as their responsibility to develop green buildings, not just for financial support or certification labels.

2.3.2.Economic benefits

Some recent research has focused on the economics of GBs, which is one of the most important factors influencing stakeholders' GB implementation decisions. Ofek et al. (2018) explored factors influencing the investment decisions of three GB interest groups—consumers, architects, and building developers in Israel. They found that potential energy and maintenance savings and increases in real estate values are the main forces driving consumers' decisions [59]. Maintenance savings are one of the vital factors positively related to GB premium size [60]. By contrast, energy price increases and striving for innovation are the main factors influencing developers' decisions [59].

There is a common idea that high technology means high price and that GBs equal high-cost buildings. Some researchers argue that certified GBs cannot save money or even energy. On the contrary, others believe that GBs can contribute significantly to energy and money saving and provide environmentally friendly construction.

Green building projects added extra costs of 1% to 10%, based on Lockwood's research. This is because the green premium includes efficient mechanical systems which are quite expensive and complex extended designing process [61]. Dwaikat and Ali (2018) used the Life Cycle Cost (LCC) method and found that the future cost associated with operation and maintenance is 3.6 times higher than the initial cost of GBs [62]. Davis Langdon (2007) indicates that the initial construction costs of five-star Green Star building are likely to be 3% to 5% higher than conventional buildings, and 8% to 10% or a six-star Green Star project [63]. Ross et al. (2007) developed a financial model that illustrated that LEED certified projects cost 10% more because of the large cost of labour and materials, which accounts for the largest proportion of GB costs [64].

On the other hand, from a maintenance perspective, some researchers suggest that GBs perform better than conventional buildings in terms of energy efficiency and water efficiency, which improves cost efficiency [65]. The Indian researcher Vyas (2015) outlined the potential benefit of Indian government GBs. The average increase in the initial cost is 3.1% for three-star certified GBs and 9.37% for five-star GBs. The discounted payback period for GBs, which considers the time value of money, is 2.04 to 7.56 years for three-star certified projects and 2.37 to 9.14 years for five-star ones. However, Vyas believes that savings from a GBs can cover the incremental cost in GBs [52]. Zhao (2018) investigated the time effects of GB policy on energy performance in low-income house units. Due to reduced energy usage in GBs, financial savings came to 648 dollars per year [66].

2.3.3. Certification schemes

- GBs Rating Systems (GBRSs)

Since the first GB assessment BREEAM issued in 1990, the development of GB aligns with the development of the green building rating system (GBRS). Over forty GBRSs have been developed by governments or third parties with the aim of promoting sustainable buildings [19,67,68]. Using the keyword ‘green buildings’ and ‘green buildings rating system’ and ‘green buildings standard’ on the Internet, and related research papers, there are 49 rating systems summarized specifically for GB design and certification in various countries (Figure 2.3 and Appendix 1). Four-fifth of the systems approximately are used in their own countries. A GBRS defines the attributes of GBs, provides tools to assess the environmental effects of buildings, and identifies specific interventions intended to promote the green building market [69]. Countries develop GBRSs based on the principle of adapting to local conditions and constantly update them in real time to meet GB development needs. In addition, throughout the GB development process, GBRS institutions have played a vital role in promoting GB development. They established a long-term, scientific GB market mechanism through open and fair GB evaluation and certification work.

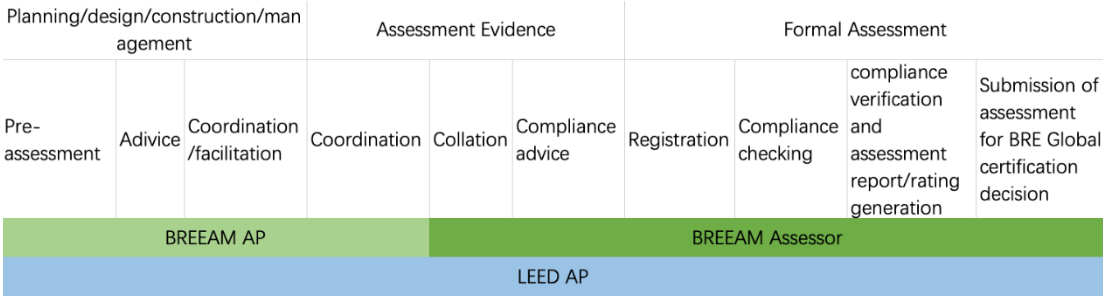
Figure 2.3. Timeline of GBRSs Development [7,39,77–86,56,70–76]

Over the past 20 years, extensive research has focused on GBRS conditions and development. Todd analysed the global trends in LEED certification, including LEED for New Construction Rating System (LEED-NC) and LEED for Existing Buildings: Operations & Maintenance (LEED-EBOM) and individual LEED credits achievement [69]. Ponterosso et al. compared the physically monitored environment of a BREEAM "Excellent" certification office with occupancy comfort and building management system metrics [87]. The concept and framework of Comprehensive Assessment System for Built Environment Efficiency (CASBEE)-City were introduced by Murakami [88]. While other researchers compared selected GBRSs to investigate the different indicators or their capability in promoting GB development, Li et al. (2017) proposed a four-level assessment method comparison that features: (1) general comparisons; (2) category comparisons; (3) criterion comparisons; and (4) indicator comparisons, which are based on 57 articles from three academic databases [89]. Doan (2017) compared four GB rating systems: LEED, BREEAM, CASBEE, and Green Star NZ. Indoor environmental quality, energy, and materials are core common elements of content for the four rating systems [7]. Doan indicated that 408 papers related to BREEAM, LEED, or CASBEE were published in various professional journals since 1998. The number of GB rating papers increased dramatically from 1998 to 2006. Compared to the significantly higher number of papers discussing LEED and BREEAM, the amount of research papers about CASBEE and GREEN Star NZ is limited [7].

Many evaluation criteria have developed a series of sub-evaluation systems tailored to different scales, construction phase, or building type. For example, LEED includes LEED Building Design and Construction (BD+C), LEED Interior Design and Construction (ID+C), LEED Building Operations and Maintenance (O+M), LEED Neighbourhood Development (ND), LEED Homes, and more. CASBEE consists of Construction (housing and buildings), urban (town development), and city management. According to the Construction phase, BREEAM divided into New Construction (NC), BREEAM in-use, BREEAM gas and fit-out. China’s GBRS family includes Green Commercial Building, Green Industrial Building, Green Hospital, Green Museum, and more, classifying subcategories based on building types. These standards will be more targeted to give the appropriate GB construction strategy for a select building type.

- Accredited Professionals (AP)

For better GBRS implementation, many professionals who conduct auditing for achieving GBRS credits were certified. Sometimes they also can help to implement the international application of the GBRS to which the professionals belong. They work closely with the design team and the developers during the entire building construction process. The workflow is shown in Figure 2.4.



<table>
<tr><th colspan="3">Planning/design/construction/management</th><th colspan="3">Assessment Evidence</th><th colspan="4">Formal Assessment</th></tr>
<tr><td>Pre-assessment</td><td>Adivice</td><td>Coordination /facilitation</td><td>Coordination</td><td>Collation</td><td>Compliance advice</td><td>Registration</td><td>Compliance checking</td><td>compliance verification and assessment report/rating generation</td><td>Submission of assessment for BRE Global certification decision</td></tr>
<tr><td colspan="4">BREEAM AP</td><td colspan="6">BREEAM Assessor</td></tr>
<tr><td colspan="10">LEED AP</td></tr>
</table>

Figure 2.4. The certified Accredited Professionals workflow [90]

Of the 49 rating systems in the world, 18 GBRSs have developed an Accredited Professionals certification （Table 2.2）. The other standard systems do not specify the qualification requirements for evaluators. The admission requirements of GBRS professionals are similar. First, BREEAM, German Sustainable Building Council (DGNB, Germany), High Quality Environmental standard (HQE, France), Green Mark (GM, Singapore), Built Environmental Assessment Method (BEAM, Hong Kong), and GRIHA ask that those applying hold a university degree or an equivalent qualification from the construction field with professional working experience. CASBEE even requires that the applicant for AP of new building design and construction hold the First-class architect license [91]. The other GBRSs in Table 3 strongly recommend degree-level education and working experience but it is not compulsory. Almost all the eligible applicants must participate in relevant training courses, in person or online, or take part in a workshop initially. After completing all the aspects of the training courses, they will learn the role of the AP and what a project or development needs to do to meet GBRS targets and sustainability goals. Following the training, the students must pass an examination so they can attain the certification of accredited professionals. LEED does not require participation in the training course but requires that applicants pass the LEED Green Associate (LEED GA) test first, and then take and pass the LEED AP test, to be granted the LEED AP certificate and use of the industry logo. GREENSHIP in Indonesia is similar to LEED that have GA and AP [92]. There are no prerequisites or eligibility requirements for the LEED GA examination. In the LEED and Green Star evaluation process, projects involving LEED AP or Green Star AP will achieve an additional credit.

Table 2.2. Certification requirement for professionals of GBRSs [63–78]

Countries	Standard	Professionals	Education	Working Experience	Training Course	Examination	Extra Credits
America	LEED	LEED GA LEED AP	○	○	○	●	●
	GPR	Certified GB Professional (CGBP)	○	○	●	●	×
	EDGE	EDGE Expert	○	○	●	●	×
	WELL	WELL AP	○	○	○	●	×
United Kingdom	BREEAM	BREEAM Assessor BREEAM AP	●	●	●	●	×
Germany	DGNB	DGNB Registered Professional DGNB Auditors DGNB Consultant	●	●	●	●	×
France	HQE	HQE Référents	●	●	●	●	×
Australia	NABERS/ ABGR	Accredited Assessor	○	○	●	×	×
	GS	Accredited Professional	○	○	●	●	●

NGO	LBC	Living Future Accredited	○	○	●	×	×
Japan	CASBEE	CASBEE Accredited Professional (AP)	●	○	●	•	×
Singapore	GM	Green Mark Manager GMM ） Green Mark Professional	●	●	●	●	×
Hong Kong	BEAM	BEAM Professionals (BEAM Pro)	●	●	●	●	×
Philippine	BERDE	Certified BERDE Professionals	○	○	●	●	×
Malaysia	GBI	Accredited GBI Certifier	○	○	●	●	×
India	GRIHA	GRIHA Certified Professional	●	●	●	●	×
Abu Dhabi	EPRS	Pearl Qualified Professional	○	○	●	●	×
Indonesia	GREENSHIP	GREENSHIP GA GREENSHIP AP	○	○	●	●	×

[1] ●： mandatory； ○ ： strongly recommend； ×： None

- Project achievements

Since BREEAM was promulgated in 1990, it has been carried out in 77 countries for nearly 30 years, with a total of 565,790 certification programs accumulated, ranking the first in the world, accounting for 80% of the total certificated green building projects in the world (Figure 2.5). LEED, which was enacted in 1998, have the widest reach, reaching 167 countries [107]. WELL followed BREEAM as the third widest used in 58 countries [108]. Excellence in Design for Greater Efficiencies (EDGE, America), DGNB, and Living Building Challenge (LBC, America) are used in more than twenty countries [78,109,110]. HQE, The Green Building Assessment (GBA, Canada) and GM are used in 17, 16, and 15 countries, respectively. Assessment Standard of GBs (ESGB, China), and Green Globes (GG, Canada) are tentatively being applied in one country outside their own countries (Figure 2.6). According to the SmartMarket report "Global GBs Trends 2018" jointly released by Dodge Data & Analytics and USGBC, the global GB market is on the rise. 47% of the respondents in the study believe that more than 60% of their construction projects will be certified under a recognized green building system by 2021. Nineteen of these countries are expected to see strong growth over the next three years. The report surveyed more than 2,000 building experts in 86 countries, including architects, contractors, consultants, developers, engineering companies, and investors. Nearly half of those surveyed said they would focus on GB projects over the next three years. Market demand and health factors are key drivers of the building sector's transition to sustainable development, with the future growth of new commercial buildings, institutions, and high-end residential buildings particularly promising. Two-thirds of respondents also said LEED certification makes buildings perform better, while more than half said LEED provides credibility for GBs. Almost two-thirds of those surveyed predicted that GBs would save 6% on operating costs over the next year, with 80% saying the trend would continue over the next five years. With the popularity of operating costs and health benefits, the value of GBs will continue to increase [20].

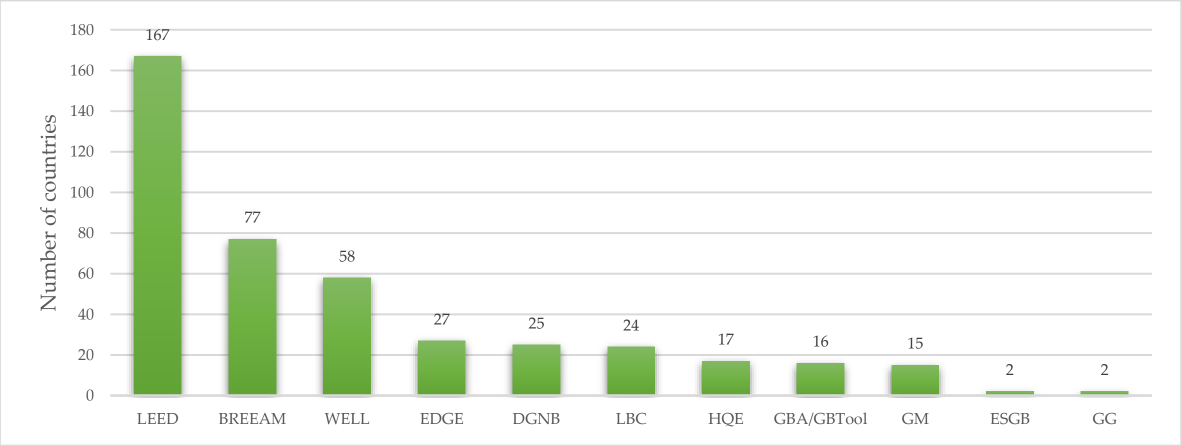


Figure 2.5. Number of countries in which each standard is applied (by 2018) [78,109,119,111–118]

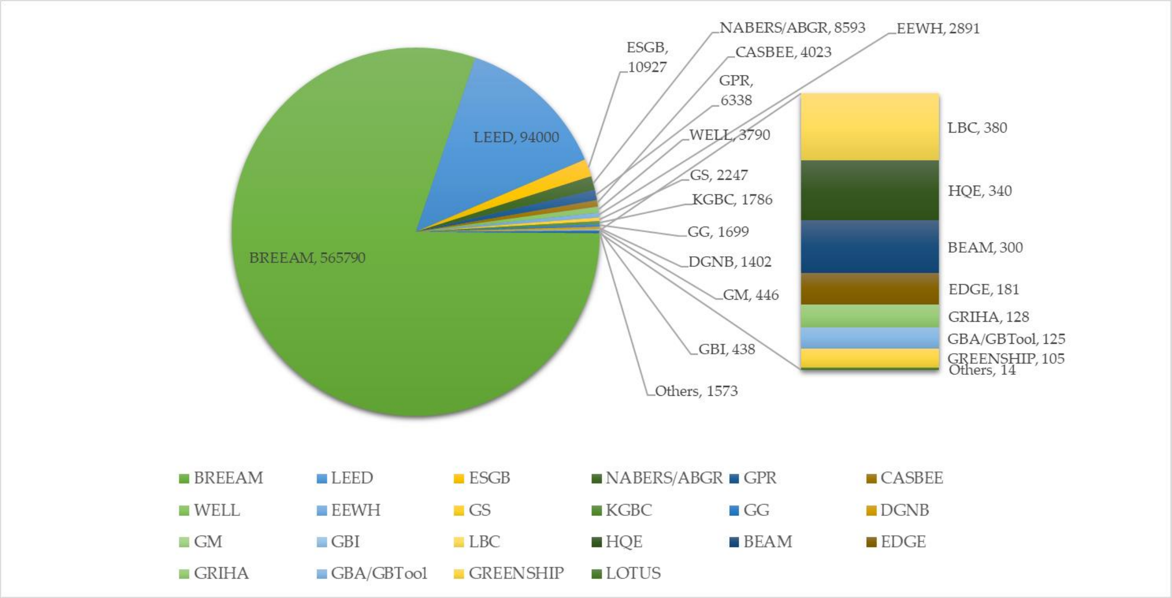


Figure 2.6. Certified GBRS projects [79,81,118–127,108,128,109,111,112,114–117]

The importance of technology in GBs has always been underestimated, particularly in measuring energy performance and its impact on households. In 2016, Green Business Certification Inc. (GBCI) (the global LEED project certification body and a green enterprise certification company) created the Arc certification platform to manage and compare building data through five measurement criteria: energy, water, waste, transportation, and human experience. Tracking performance is the key to future GB certification. Both Arc and LEED v4.1 are designed to provide a quick and easy way to create a healthy living environment to ensure that all GBs perform well from the start of construction to completion and beyond. Arc has now certified 1.5 billion square meters in 80 countries worldwide. The LEED v4.1 rating system introduced in 2019 also provides a new way to improve GB performance. At present, there are 94,000 LEED-certified commercial projects around the world, with an average of 2.2 million square meters of LEED-certified buildings every day.

2.4.Fundamental Characteristics

The fundamental characteristics of GBs stand for internal factors, including GB technologies (GBTs) implementation, building management, and occupant behaviour. The term GBTs refers to technologies integrated into building design and construction to make the building sustainable [129,130]. Managerial aspects of green buildings refer to integrated management of the whole building life cycle stage [131]. The third is the relationship between occupant behavior and building performance.

2.4.1.Technologies application

Adopting GB technologies can offer a range of significant environmental benefits, such as saved land and materials, increased efficiency of water and energy, and improved indoor environmental quality [13,76,130,132]. There are extensive studies on various aspects of GBTs in different contexts. Yin and Li developed a stochastic differential game that transfers GB technologies from academic research institutes to building enterprises in the building enterprises-academic research institutes collaborative innovation (BACI) system, which will promote GB technology transfer and rapid development of urban GBs [133]. Comparing the 49 green building evaluation standards, six categories of land use, energy conservation, water efficiency, material utilization, indoor environment quality improvement, construction management are common significant technologies implemented in green building construction.

General land use measurements mainly solve three issues, how to use properly, how to save efficiently, and how to improve effectively. Firstly, in the perspective of architects and landscapers, outdoor open space and green space for occupants' activities, enough parking space for the increasing usage of cars, and outdoor microclimate design strategies to support natural ventilation and natural lighting for the building indoor environment are vital for the 'use properly' issue. Public facilities sharing is also a method to use land properly. Secondly, with the increasing requirement of space for occupied because of increasing population and rapid urbanization, especially in China, for instance, one of the methods to save the land is setting high plot ratio objective, which means high-rise building increased. Limited land area is another reason that requires to save the land. For example, in Tokyo, people try to give multiple functions in a limited building space, and design alterable space for a various requirement. Thirdly, ecological protection of construction sites is significantly important as well. Most of the GBRs have claimed that try to keep the original ecological system of construction sites, avoiding construction in wetland, habitat, etc.

Building energy conservation measures include three aspects of buildings: envelope, air conditioning, and lighting. Generally, architects, mechanical engineers, and electrical engineers, respectively, are responsible for these three parts. Aktacir, Büyükalaca, and Yilmaz (2010) evaluated the influence of thermal insulation on the building cooling load in Adana, which showed that both the initial and the operating costs of the air-conditioning system were decreased considerably for three evaluated insulation thicknesses [134]. Air conditioning contributes to maintaining thermal comfort, which accounts for a major share of energy consumption. Chua et al. reviewed technologies and strategies for achieving better energy-efficient air conditioning, which can be divided into three aspects: novel cooling devices, innovative systems, and operational management and control [135]. The use of renewable energy technologies has been pivotal for achieving GB goals and certification [131,136]. According to Chan's research, the photovoltaic system not only generates electricity, but also reduces heat gain transmitted into the indoor environment through the building envelope by 13.59% to 38.78% in subtropical Hong Kong [137]. Passive design is believed to have a big energy saving potential. Oropeza-Perez and Østergaard (2014) investigated the energy saving potential of natural ventilation and indicate that an average savings can correspond to 54.4% of the electric cooling demand for 2008 in Mexico [138]. A simulated model to evaluate life cycle GHG emissions of office building envelopes has been developed in Australia, and that model can be used to evaluate he relationship between building energy consumption and GHG emissions to achieve "greenest" outcomes [139].

Similar to energy aspects, water conservation is also vital in GB design due to the limitation of potable water by only 3% of the total earth's surface water [140]. GB are sustainable buildings demanding the water conservation and preventing pollution and recycle treated water ensuring potable water use. It can be divided into outdoor and indoor water use. Architects, landscapers, and engineers engaged in water supply and drainage engineering are responsible for this work in building construction process. Water efficiency refers to reducing the usage of water as well as minimizing wastewater. All the fixtures such as taps, toilets, showerheads, urinals, etc. should be efficiency and be checked periodically for leakage and in good operating conditions [141]. Rainwater harvesting is a cheap and simple technology that can save a lot of water if rain can be collected and treated as potable water. The basic system consists of the collection, distribution, and storage stages. A quantity of non-potable water for water closets, car-washing, and garden watering can come from collected and treated greywater passing through sand filters, or by electrocoagulation techniques. Some other biological and chemical treatments can be utilized as well. Rainwater management is to keep the rainwater stay in the construction site rather than allowing it to run off, which not only benefit for rainwater harvesting but protecting the natural site hydrology conditions. Low-impact development (LID) and green infrastructure (GI) are widely used in rainwater management strategies and techniques [142].

Building materials affect the environment and the human body in all stages of their life cycle production, based on contamination and function [143,144]. Firstly, the evolution process of material selection pays more attention to green and sustainable performance criteria, more than just quality, performance, aesthetics, and cost. Initiatives that have been taken and are being taken from the academic and scientific field to mitigate the effects of climate change associated with the activity of the construction sector. For example, García et al. (2019) have developed more sustainable construction systems, through the replacement of conventional concrete or steel construction elements with timber elements [145]. There are simple and rapid sustainability assessment models specific to timber structures and buildings, whose objective is to design and project timber buildings in the most sustainable way possible, with the ultimate goal of reducing the impact that the construction sector activity has in the environment [146]. Secondly, storage and collection of recyclables material is another important consideration in GB construction. Furthermore, building product disclosure and optimization is a major content in the credit category of Material and Resource. However, it is a big challenge for many other countries because of the complex supply chain management process of building products.

Indoor environment quality is an important variable for GB performance, and its improvement contributes dramatically to GBs and a sustainable environment [147]. Most researchers believe the certified GBs perform better than conventional buildings in terms of IEQ and energy use [148–150]. There are four main variables highlighted in GBRSs to improve IEQ: thermal quality, acoustic quality, visual quality, and indoor air quality (IAQ) [151–153]. Lin et al. found the satisfaction of users in certified GBs is higher than conventional buildings in terms of thermal comfort and IAQ [154]. The view to the outside, aesthetic appearance, less disturbance from heating, ventilation, and air-conditioning noise, and other factors have better outcomes as well [155].

2.4.2.Construction

Construction waste minimization (CWM) is a vital aspect of GBs construction. Lu et al. (2018) has ascertained the effects of GBs on CMW and identified the causes leading to the ascertained effects using quantitative “big data” from government agencies [156]. Building information modelling (BIM) is becoming the central way to coordinate project design and construction activities. EI-Diraby, Krijnen, and Papagelis (2017) built an online system that enables a data-driven approach to building planning, construction and maintenance, which allows all the stakeholders to comment and share views [157]. Lu et al. (2017) provided a “green BIM triangle” classification to establish an up-to-date synthesis on the nexus between BIM and GBs, indicating that the relationship needs to be understood from three dimensions: project stage, green attributes, and BIM attributes [158].

2.4.3. Building management

The managerial aspects of GBs should be integrated into the whole building life cycle, including planning, design, construction, operation, and demolition. Initially, during the planning phase of the project, the research and analysis related to energy and water use should be completed. Meanwhile it should conduct effective and rational discussions around possible integrated design opportunities. Additionally, the project owner can be invited into the main project team workshop to determine the budget, schedule, functional planning requirements, scope, quality, performance, and desired project objectives of the occupants. In the design and construction phase, project team members look for synergies between systems and components. This combination of advantages can help the building achieve a high level of performance, comfort, and environmental benefits [142]. Constantly monitoring and studying building performance in the operation phase is just as important as it is in the design and construction phase [159]. Feedback mechanisms determine whether or not performance goals are being achieved. To achieve those goals, it is critical to provide operational performance information to building operations staff so they can take corrective action when targets are not met. Implementation of an environmental management system (EMS) in the operation phase contributes to a 90% energy saving and 70% water saving, reduces 63% of waste, and lowers accident rates by 20% and 80% of quality complaints from occupants [160]. Management in POE to find out causes of performance gap between the design prediction and actual consumption. The actual performances always worse than the predicted. For example, glass box buildings are notoriously uncomfortable regardless of a very large, sophisticated, expensive and maintenance-intensive system. Architectural designers do not always recognize the high probability of thermal discomfort in glass buildings in hot climate. It often results in higher energy consumption and running costs for the business or to the owner.

2.4.4.Occupant behavior

Along with GB development and building energy and environmental improvements, people are paying increasing attention to the relationship between people and buildings. The concepts and disciplines of a healthy building, post-occupancy evaluation (POE) [161], human factors (ergonomics), and architectural psychology have gradually become the focus of research. Organizational commercial buildings generally adopt centralized control of the electrical equipment. However, for individual residential or office buildings, occupant behavior has a very big impact on architectural performance. Barbosa and Azar give a concept human-in-the-loop approach, which means occupants' comfort and well-being are essential metrics in evaluating building performance, not only energy conservation. Green buildings are believed to be associated with high workplace satisfaction and working productively and creatively [162]. Ries et al. found a 25% growth of productivity when occupants moved from conventional building to a GB [163]. Furthermore, occupants assigned higher acceptance and satisfaction to an indoor environment in a certified GBs compared to conventional buildings [164]. In the operation phase, building performance mainly depends on the occupants, who will help achieve the initial ecological objectives by correctly using devices through a better understanding of GBs.

2.5. Barriers and challenges

- Challenges in various countries

There are three main problems facing GB development in the United States. First, although the government has relatively complete policy support, and the rating systems are widely used in the world, industry and the public remain doubtful. Some people believe that GBs have not achieved what it promised. These promises include realizing energy conservation. LEED- certified commercial buildings does not display significant primary energy savings over comparable non-LEED buildings on average, even not showing reduction in GHG emission associated with building operation [165]. Second, the enthusiasm of architects and designers are not high because most of the policy and economical support is for developers. Architects, as the initial participants and designers of architectural construction, directly determine the basic characteristics and performance of the building. Designers' personal interests, such as capital benefit, enthusiasm for GB application, or social responsibility as a promoter of GB for public is vital for GB implementation. Some architects only design GBs according to the standards but lack understanding of the connotation of GBs and the analysis and application of appropriate technologies. Third, there is a substantial problem in how to persuade the users to buy a GB with extra expenses due to certification fees and other additional active technologies expenses.

In the UK, the situation is better than in America. As the first country to raise the Green Building Rating System, the UK has formed awareness in ethic for the public to build sustainability and environment-friendly. However, poor GB design project still exist due to unreasonable design, which causes higher energy consumption than non-certificated building. Improving architects and designers understanding of the connotation of GBs and the analysis ability on the application of appropriate technologies is significantly important. Europe has presented many concepts related to GB, such as nearly zero energy building (NZEB), and carbon-neutral building (CNB), to address climate change. Great challenges will be accompanied by the realization of the goals. For instants, disconnection between developing innovative technologies for GBs and the lack of utilization, lack of understanding of what GBs, NZEB or CNB means in legislation for the actual building process, and energy targets for green retrofitting of existing building, especially of culture and historic significant buildings, etc., are major challenges the Europe facing.

Japan's GB projects realized many achievements and essentially met its original targets. However, the requirement of CASBEE AP that need to hold the First-class architect license will limit the popularity of GB concept to stakeholders. Moreover, how to interact with end-users and persuade them to recognize the value and real benefits of GBs is significant in the continued development of the GB. Because end-user have a limited understanding of high GB technologies or new equipment to use properly.

In China, relative to the constant introduction of various laws, regulations, standards, and norms, the implementation of incentive policies lags. The concentration of GBs is not spread evenly across different province because of the geographic variables, economy-related variables. and public policies associated with GBs [36]. China has imposed extensive mandatory policies on the promotion of GBs technologies recently, but some of them have not yet reached mature levels, such as prefabricated buildings, which are now heavily promoted to save materials. The public still has questions about the technology. Mandatory widespread adoption could pose potential problems. In addition to policy and economic support, it is more important to foster a sense of responsibility for sustainable development. It is the responsibility of every stakeholder to develop green buildings, not just to meet policy requirements, obtain financial support or obtain a certification label.

- Barriers of GB development

Limitation of standards is one of serious barriers in the external factor of GB development. Such limitations can be divided into three categories: evaluation objects restriction, inapplicability of evaluation methods, and limited professionalism of users. Although lots of GBRSs have developed sub-evaluations for different phases, scales, and types, the standard development cannot keep pace with construction development. The corresponding evaluation criteria cannot be found for many buildings. For instance, the Evaluation Standard for Green Industrial Building (GB/T50878-2013) (ESGIB) was launched in 2014 in China for assessing all industrial building types, such as heavy industry, light industry and so on. However, modern logistics, science and technology research, e-commerce, etc. also belong to the industrial building scale. In the functional operation of these kinds of industrial buildings, no specific production process is given. However, the green industrial building standard identifies many indicators related to parameters of the production process. These indicators are not suitable for the industrial building mentioned above. Comparing with the similar functions of industrial buildings is an optional method for evaluating the sustainable level of the building, but the lack of data and the poor comparability of the chosen industries lead to an unreliable evaluation result. It is critical to develop a standard system as soon as possible that suits the different building types, including general plant and scientific research and development buildings, so GB technology promotion and evaluation on industrial construction can be standardized.

Table 3 illustrated that 16 GBRSs have their own certified AP who can advise on the construction process. These certified experts must undergo rigorous screening, training, and testing before they can be certified to participate in the program. However, the remaining 31 GBRSs have no relevant official certification process, which makes it difficult to guarantee the professional degree of GB engineers or consultants, resulting in the inability of the project to achieve sustainable success with high efficiency. On the other hand, CASBEE has the most rigorous vetting of certification experts. This effectively guarantees the green technology quality of the project but limits the way other engineers want to participate. It will also hinder the promotion and popularization of standards, even overseas promotion. As for the third part of the external factor of GB development, economic obstacles are also significant. Transaction costs are claimed to affect the effectiveness of GBs policy significantly [166]. Marker et al. suggested that the additional costs of GB certification consultants and paperwork are the main barriers of GB development [167]. Sometimes designers and developers are unwilling to use new technologies because they use standard accounting procedures that are unable to recognize the financial advantages.

The dissemination of GBs and adaptation of GB technologies are being hindered because of some barriers, such as greater complexity, limited understanding of sustainability, and high cost [168]. Moreover, some problems have already been revealed in the GB market. Newsham found that LEED-certified buildings consume 18% to 39% less energy per floor area than their conventional counterparts on average, which is based on the comparison of 100 LEED commercial and institutional buildings to the energy use of the general American commercial buildings. Nevertheless, 28% to 35% of LEED-certified buildings are using more energy than their conventional counterparts [67]. Of the LEED certified buildings, 25% cannot save as much energy as predicted in the design process [169]. USGBC has pointed out that the construction method of GBs is not mature enough, and the use of new GB technologies may cause potential risk. Building performance gap between the design prediction and actual consumption is also required to be considered carefully. The building industry should take up these new challenges facing risk management [170].

Limitation of knowledge refers to lack of understanding about the concept of GBs used by those who can incorporate GB concepts into a building life cycle, including owners, architects, architectural engineers, construction managers, building operators, occupants, and other stakeholders. The significance of knowledge centres three main aspects: the advantages of GBs, knowledge of existing green technologies, and cognition of how to use GBs technologies appropriately and efficiently.

First, the advantages of GBs is basic knowledge stakeholders need, otherwise they will have no incentive to implement GBs [171–173]. Liu et al. believe elements like subjective knowledge, social trust in the organizations responsible, perceived usefulness, and the attitude of users towards green-certified buildings are among the vital psychological determinants of intention to adopt green certified building [174]. Darko and Chan evaluated GBT adoption in developing countries and concluded that publicity through media and educational and training programs for developers, constructors, and policymakers are the top two strategies to promote GBT adoption [175]. Second, in terms of knowledge of existing green technologies, sometimes people recognize the necessity to implement GBs but lack the knowledge of which technologies are available to do that. Tsantopoulos et al.(2018) reported on the public perceptions and attitudes toward green roofs, vertical trellises, or gardens, and showed that most citizens are willing to improve aesthetics with no awareness of the environmental benefits [176]. Hobman and Frederiks (2014) conducted a large national survey with over 900 Australian energy consumers who had not to subscribed to the National GreenPower Programme and concluded that one of the main reasons was limited knowledge, awareness, and availability of the green electricity programme [177]. Additionally, those who might finance the construction may fail to recognize the benefits of integration, or may mistakenly assume that existing building methods are already effective and therefore do not seem to require new technology. Third, the cognition of how to use GB technologies appropriately and efficiently is lacking. Incorrect use of technology not only precludes positive results, it also may bring a negative impact and crisis. There are several technologies implemented in GBs construction by mistake. For example, some scholars questioned whether external insulation is required in temperate and subtropical regions. There is a temperature difference between the two sides of the building walls, so heat preservation materials should be added to prevent the temperature difference from causing heat transfer to save energy. However, in a warm region, where there may only be a small temperature difference between the two sides of the building, insulation will be required less, or no insulation may be needed at all. The outdoor temperature in a warm region may often be in a range between 18°C ~ 25°C—a comfort zone. However, as the sun shines through the window, the house becomes very hot, and the lower U-value of building envelop is, the less heat will be able to escape (if the house is not well-ventilated naturally). Instead, the air conditioner needs to be turned on to cool the house, which will lead to extra energy consumption.

- Future trends and tendencies

To realize the scale-up and implementation of GBs, a mountain of further effort is still necessary. According to the above review and analysis, GB development can be improved in two respects. First, from the policy and incentive side. It still requires clear and multiple policy support for the stakeholders and broad range of building types. In a word, GBs require not only environmental innovation but also institutional innovation. Second, from the economic side, cost-benefits are the most effective and direct drivers for successful GB implementation. In addition to cost savings from improved energy efficiency, the potential value added to the property should be investigated in future research. Additional costs of GB certification consultants and paperwork should receive more government support. Third, the evaluation content and application mode of GB evaluation standards need to be more rigorous and standardized. International standards should take into account the local climate and culture. The project should not adopt inappropriate technology or adopt high and new technology without considering the economic impacts and should not blindly pursue multiple certifications. Fourth, social responsibility or ethic consideration of individual and public need to be improved urgently which can fundamentally promote the development of GB.

The internal factors consist of the technology, management, and occupants. First, the technology field related to GBs is quite broad, encompassing land, energy, water resources, materials, building structure, indoor environment to construction technology, and more. Every aspect of technology development is crucial to GB development. This requires the joint efforts and cooperation of all relevant technical personnel and researchers, as well as constantly upgraded related technologies, so as to achieve the maximum benefit of technical solutions and meet the evolution of the end users' motivation and the surrounding environment. The well-developed GB technology is not only the study of a single technology but also the ability to integrate multiple technologies and enable various stakeholders to continually participate in the process of GB construction. Second, based on the implementation of multiple technologies, an integrated management methodology is necessary to handle all aspects of GBs. Currently, this role is played by GB consultants, most of whom are certified professionals. It is expected that all stakeholders can attain basic knowledge that enables them to improve the efficiency and flexibility of management systems. Third, from the occupants' perspective, enhancing their feedback is essential, because they directly impact the successful implementation of GBs. Therefore, knowledge of GBs is extremely important not only for engineers but also for occupants. In the operation phase, successful building performance mainly depends on occupants who contribute to achieving the initial ecological objective by correctly using devices because they have a better understanding of GBs. In addition, it is critical to seriously study occupants' behavior, to help human-oriented design and realize a healthier building environment. Providing training and education in using GBTs, and to develop better awareness of local environmental issues is expected in the future.

2.6. Summary

This paper reported on a comprehensive survey of the historical and current development of GB worldwide. The concept of GB evolves as a holistic approach to deal with various problems caused by the construction industry. Green building is subject to continuous development of new technologies; integrated management of building operation; consistent standards of certification systems; and proper adjustment of policies, all of which have a significant impact on GB development. Method applied in this paper is to group the impact factor into two aspects: (1) external factors, including policy support, economic benefits, and certification schemes of GBs; and (2) the internal factors, associated with the development and application of GB technology, the level of building management, and how users interact with the GB technology. Based on the external and internal factors, this paper analysed GB development barriers and challenges.

The development status of GBs in the United States and Europe, the United Kingdom, Japan, China, and some other countries are presented in this paper. the United States, the United Kingdom, Europe, and some Western countries have already entered into a mature period. The focus of their recent work is on the application of intelligent GB technologies that ensures smart buildings or ‘healthy’ buildings which proposed by the International WELL Building Institute (IWBI) [178], and consequently addresses the economic and social challenges caused by unmatched technologies and limited knowledge. Japan has a wide range of relevant laws, regulations, and policies, but keeps updating them based on development. This paper has found that GBs in China have significant implications; as a national strategy, the development of GB is leading the construction field on the road of sustainable development. However, in China, there is a regional imbalance of GB development because the concentration of GBs and economic strength varies across its different provinces. In the process of promoting the implementation of GBs, Eastern counties, such as Japan and China, have mainly developed government programs. In contrast, Western countries such as the United States have adopted federal-, state-, and local-level zoning regulations and employ building standards developed by non-government organizations. Although each country has made many achievements in the development of GB, this paper also reveals that a common problem is the lack of a systematic social education scheme that can provide a clear understanding about the concept of GB to those who can incorporate it into a building life cycle.

The economy of GBs is the basic driving force and decision-making benchmark of its development. The ongoing debate over the economics of GBs seems on where the potential financial saving be made, in the initial investment in GBs, or later operation costs or reduced resource use. All of these could depend on individual cases. Surely this remain as one of interesting area for further studies. Green Building Rating Systems are developed and applied by most countries all over the world as a guideline to achieve sustainable building construction goals. This paper summarizes 47 certification standards related to GBs in the world. LEED in the United States and BREEAM in the United Kingdom have the largest market shares. The certification expert mechanism guarantees the professional quality of consultants and project quality, but only in 16 certification standards. Other standards need to be enhanced in this regard. The importance of economic aspects of GBs was emphasized in much of the literature, but detailed analyses are limited.

This extensive survey suggests that most GB studies focus on certification standard analysis and comparison, and technologies solutions in terms of energy performance, water efficiency, and indoor environmental quality. This paper provides useful recommendations from the technologies side, management side, and occupants side, finding that there is low participation among stakeholders, especially occupants participating in the development of GB in many countries. Mismatching technologies utilization due to lack of knowledge requires more consideration in future researches. This paper proposed involving integrated management and exploring occupants' behaviour and feedback to improve GB efficiency. Meanwhile, providing training and education in using GB technologies for occupants, as well as raising the awareness of local environmental issues, are expected in the future.

Appendix A

No.	Time Issued	Standard	Countries	Leading Organization	Full Name
1	1990	BREEAM	United Kingdom	Building Research Establishment Ltd. (BRE)	Building Research Establishment's Environmental Assessment Method
2	1993	BEPAC	Canada	The University of British Columbia	Building Environmental Performance Assessment Criteria
3	1998	LEED	United States	U.S. Green Building Council (USGBC)	Leadership in Energy and Environmental Design
4	2002	PromisE	Finland	VTT Technical Research Station	The Finnish Environmental Assessment and Classification System
5	2010	BEAM Plus	Hong Kong	Hong Kong Green Building Council and the BEAM Society Limited	Built Environmental Assessment Method
6	1997	EcoEffect	Sweden	The Royal Institute of Technology, Stockholm and the University of Gavle	——
7	1998	GBA/GBTool	Canada	International framework committee (IFC)	The Green Building Assessment (GBA)
8	1999	NABERS/ABGR	Australia	The Office of Environment and Heritage (OEH)	National Australian Built Environment Rating System/Australian Building Greenhouse Rating system
9	1999	EEWH	China (Taiwan)	National Council for Sustainable Development under the Ministry of the Interior (MOI)	Green Building Labeling System
10	1999	Eco-Quantum	Netherlands	IVAM	——
11	2000	GG	Canada	ECD Energy and Environment Canada	Green Globes
12	2000	BEAT	Denmark	Danish Building Research Institute （SBI）	Building Evaluation Assessment Tool
13	2000	Ecoprofil	Norway	Norwegian Building Research Institute (SINTEF Byggforsk)	Ökoprofil

14	2001	CASBEE	Japan	Japan Sustainable Building Consortium (JSBC)	Comprehensive Assessment System for Building Environmental Efficiency
15	2002	CEPAS	Hong Kong	Building Department of Hong Kong Special Administrative Region of the People’s Republic of China	Comprehensive Environmental Performance Assessment Scheme
16	2002	KGBC	Korea	Korea Green Building Council	Korea Green Building Certification System
17	2003	GS	Australia	Green Building Council Australia	Green Star
18	2003	TGBRS	India	The Energy and Resources Institute (TERI)	Teri Green Building Rating System
19	2004	GRIHA	India	The Energy and Resources Institute (TERI)	Green Rating for Integrated Habitat Assessment
20	2005	HQE	France	Cerway	Haute Qualite Environment
21	2005	Si-5281	Israel	Standard Institute of Israel	Israel Standard 5281: Building with Reduced Environmental Impact
22	2005	GM	Singapore	Building and Construction Authority (BCA)	Green Mark
23	2006	LBC	America	International Living Future Institute	Living Building Challenge
24	2006	GPR	America	Built It Green	GreenPint Rated
25	2006	ASGB	China	Ministry of Housing and Urban-Rural Development of People’s Republic of China	Assessment Standard for Green Building
26	2006	DGNB	Germany	The German Sustainable Building Council (Non-profit organization)	Deutscbe Gesellschaft Fur Nachhaltiges Bauen
27	2006	CSH	United Kingdom	Department for Communities and Local Government	Code for Sustainable Homes
28	2007	EPRS	Abu Dhabi	Abu Dhabi Urban Planning Council GBI	Estidama Pearl Rating System

29	2007	ISBT	NGO	International Initiative for a Sustainable Built Environment (Non-profit organization)	International SBTool
30	2007	SICES	Mexico	The Mexico Green Building Council (MGBC)	Sustainable Building Rating Tool / Sistema de Calificación de Edificación Sustentable
31	2008	NGBS	America	National Association of Home Builders (NAHB)	National Green Building Standard
32	2008	AQUA-HQE	Brasil	Vanzolini Foundation at the Polytechnic University of Sao Paulo	Alta Qualidade Ambientale
33	2008	LiderA	Portugal	Manuel Duate Pinheiro, Ph.D.	The Sistema de Acaliacao da Sustentabilidade (Certification System of Environmentally Sustainable Construction)
34	2009	ITACA Protocal	Italy	Institute for Innovation, Procurement Transparency and Compatibility Environmental-National Association of Regions and Automomous Provinces (ITACA)	Protocollo Itaca
35	2009	GBI	Malaysia	Architectural Association of Malaysia （PAM）	Green Building Index
36	2009	BERDE	Philippine	Philippine Green Building Council (PHILGBC)	Building for Ecologically Responsive Design Excellence
37	2009	GSAS	Qatar	Gulf Organization for Research & Development	Global Sustainability Assessment System
38	2009	VERDE	Spain	Green Building Council España (GBCE)	Herramienta VERDE
39	2010	GPRS	Egypt	Egypt Green Building Council	The Green Pyramid Rating System Levels

40	2010	LOTUS	Vietnam	Vietnam Green Building Council （VGBC）	——
41	2010	GREENSHIP	Indonesia	Green Building Council Indonesia	——
42	2010	TREES	Thailand	Thai Green Building Institute	Thai's Rating of Energy and Environmental Sustainability
43	2010	BNB	GERMANY	the Federal Ministry of the Interior, Building and Community	Assessment System for Sustainable Building
44	2012	ARZ BRS	Lebanon	Lebanon Green Building Council （LGBC）	ARZ Building Rating System
45	2013	IGBC	India	Indian Green Building Council	Indian Green Building Council Rating system
46	2014	EDGE	America	International Finance Corporation –World bank group Green	Excellence in Design for Greater Efficiencies (EDGE)
47	2014	WELL	America	The International WELL Building Institute (IWBI)	——
48	2017	CASA Colombia	Colombia	Consejo Colombiano de Construccion Sostenibe (CCCS)	——
49	2018	CEDBIK-Konut	Turkey	Turkey Green Building Council	Cevre Dostu Yesil Binalar Dernegi

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Chapter 3. Theories and Methodology of the Study

3.1. Introduction

The survey of green building development summarized a lot of barriers and challenges and provide the future research trend. With the aim to develop regional suitable green building design strategies to realize energy saving and indoor thermal environment improvement, a series of building simulation work with different tools were employed. The chapter will introduce the collected data sources, simulation model, and the theory of the simulation tools.

3.2. Climate data collection and meteorological software

3.2.1. Climate data collection

The climate data in this study are mainly employed Typical Meteorological Year (TMY) files which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017. TMY files are created with the general principles from the International Weather for Energy Calculations (IWEC) Typical Meteorological Years that was published in 2001[1].

3.2.2. Typical Meteorological Year (TMY)

Meteorological parameters are the main factors affecting the indoor thermal environment of buildings and the energy consumption of air conditioning heating. In recent years, with the scientific development of statistical reorganization theory and methods of building climate data and the mature development of computer simulation analysis technology, the dynamic simulation method of building energy conservation has become the core technology and important tool for building energy conservation research and practice. At present, there are several software that simulate building energy consumption, such as DOE2, HASP/ACLD, DESIGNBUIDER, etc. No matter what kind of calculation program is running, it is necessary to input typical meteorological year data representing local outdoor climate characteristics—8760 hours of outdoor weather. The accuracy of outdoor meteorological parameters is related to the formulation of the initial stage of building design and the accuracy of the simulation calculation of building energy consumption. The typical meteorological year database used for the simulation of building energy consumption requires a large amount of complete and original meteorological data to ensure the standard data produced can represent local climate laws and characteristics.

The Typical Meteorological Year (TMY) is a year in which a region has typical climatic characteristics. It is selected from long-term, continuous meteorological parameters. The internationally recognized record of representing a regional climate is 30 years. The meteorological parameters that make up the typical meteorological year include various meteorological indicators such as temperature, humidity, wind speed, solar radiation, cloud cover, and sunshine hours. The climatic characteristics of a certain region are a combination of various meteorological parameters. The concept of a typical meteorological year is used in various energy fields. For example, in the utilization of resources such as wind power generation and solar photovoltaic heat, typical years are also required as design reference years. Due to the different emphasis of the use of meteorological resources in different fields, the selection and weighting of meteorological parameters are not the same.

Since the architectural design, the envelope structure and the thermal comfort of the indoor personnel are to be solved in the field of building science, the typical meteorological year for building energy consumption simulation is the dry bulb temperature and dew point temperature which have the greatest impact on the building energy consumption. Meteorological parameters such as wind speed and solar radiation. The most direct indicator of a region or hot or cold is the dry bulb temperature. The dew point temperature characterizes the local humidity index and its corresponding relationship with the same time temperature, and has a direct relationship with the energy consumption of air conditioning, dehumidification and other equipment; wind speed is related to natural ventilation and evaporative cooling and cooling; solar radiation has a more direct impact on the heat and shading of buildings, and is an important natural resource that must be used effectively and sometimes circumvented. So far, according to the global satellite exchange data, the US Department of Energy website has provided and publicly released the typical meteorological years in various regions of the world and made important contributions to this field.

3.2.3.Climate zone and Degree Day

Climate zones are defined by two parameters; temperature and moisture which are combined to create hygrothermal maps. Knowing climate zone and building accordingly is one of the basic tenants of building science. Moisture, extreme temperatures and inclement weather require completely different building techniques to ensure longevity and efficiency. When the building climate zone decided, it can be the basis for selecting techniques and materials that are safe, cost effective, and efficient to install and provide an energy efficient building envelope[2].

The most widely used method to determine climate zone is using degree days. They are essentially a simplified representation of outside air-temperature data. The degree day is a unit of measure for calculating the heating condition or the cooling condition. Currently, the commonly used degree day is used as the number of days of heating or the number of days of cooling. The greater the number of days of heating, the lower the temperature of the brightening, and the higher the degree of coldness, indicating that the temperature is higher. If the heating day value is zero, then the average daily temperature is higher than the heating reference temperature. Similarly, if the average daily temperature is lower than the cooling reference temperature, the cooling day is zero. Degree is a function of time integral, which can be described as the time range defined by the function, and the time varies with temperature. There are two factors that determine the interval of the function. One is to determine the reference temperature using the somatosensory temperature as a measure, and the other is to control the background climate. After determining the reference temperature, the measurement result is subtracted from the reference temperature after the temperature measurement for the whole day, and finally the difference is integrated, and the daily result is totaled. By accumulating the results over time, you can calculate the heating and cooling time during this time.

From a theoretical point of view, the degree day is a measure of the energy consumption of building air conditioning. When the building adopts air-conditioning heating, the indoor and outdoor temperature difference causes the indoor to transfer heat to the outside. When the air conditioner is cooling, the indoor and outdoor temperature difference causes the outdoor to transfer heat to the indoor. The total number of degree day in a period of time is the sum of the differences in heating or cooling during this period. The number of degree day of air conditioning directly represents the energy consumption of the building in a certain period of time under local climatic conditions. Therefore, the degree day is of great significance to building energy conservation, operation and air conditioning design. In energy monitoring and target planning, the total of degree day of weekly or monthly can also be used to monitor heating and cooling costs for climate-controlled buildings, and annual figures can be used to estimate future costs.

3.3. EnergyPlus and OpenStudio for building energy consumption simulation

3.3.1. Simulation model

Since 2006, DOE has worked with three national laboratories, the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), and Lawrence Berkeley National Laboratory (LBNL), to develop reference building energy models for most common commercial buildings in the U.S[3,4]. These models provide a common starting point to measure the process of energy efficiency goals for commercial buildings (Table 3.1). It can be used for research to assess new technologies, optimized design, develop energy code, and to conduct ventilation, and indoor environment studies[5]. The prototype models include 16 commercial building types in 17 climate location (across all 8 U.S. climate zones) that represent 70% of the commercial building stock approximately, and with three vintages (new, pre-1980, and post-1980 construction). The data sources of these models include Commercial Building Energy Consumption Survey (CBECS), ASHRAE building energy efficiency standard system, etc. EnergyPlus and OpenStudio software were integrated with the reference building models development which are published and updated regularly on the official website of DOE in an instant available EnergyPlus file format[6]. EnergyPlus related documents include EnergyPlus software readable file (.idf), EnergyPlus software simulation results (.html format), input/output summary table, meteorological data (.epw format).

Table 3.1. DOE Prototype Building Type [4]

Building Type	**No. of Floors**	**Gross Floor Area (m^2)**
Small Office	1	511
Medium Office	3	4982
Large Office	12*	46320
Primary School	1	6871
Secondary School	2	19592
Stand-alone Retail	1	2294
Strip Mall	1	2090
Supermarket	1	4181
Quick Service Restaurant	1	232
Full-Service Restaurant	1	511
Small Hotel	4	4013
Large Hotel	6*	11345
Hospital	5*	22422
Outpatient Healthcare	3	2804
Warehouse (non-refrigerated)	1	4835
Mid-rise Apartment	4	3135

* Plus basement

The medium office building model is employed for this study. The basic geometrical model is a three-story office building with a gross floor area of 4982.19m^2. Window distributed evenly along four facades with 33% window-to-wall ratio (Figure 3.1). Floor to floor height is 3.96m, including 2.74m floor to ceiling height and 1.22m above-ceiling plenum. That glazing sill height is 1.02m (top of the window is 2.33m high with 1.31m high glass). Each floor has four perimeter zones and one core zone, accounts for 40% and 60% of total floor area respectively (Figure 3.1). The design parameters are set according to CBECS and ASHRAE 90.1 (0). Details of each thermal zone summary is listed in Appendix 1.

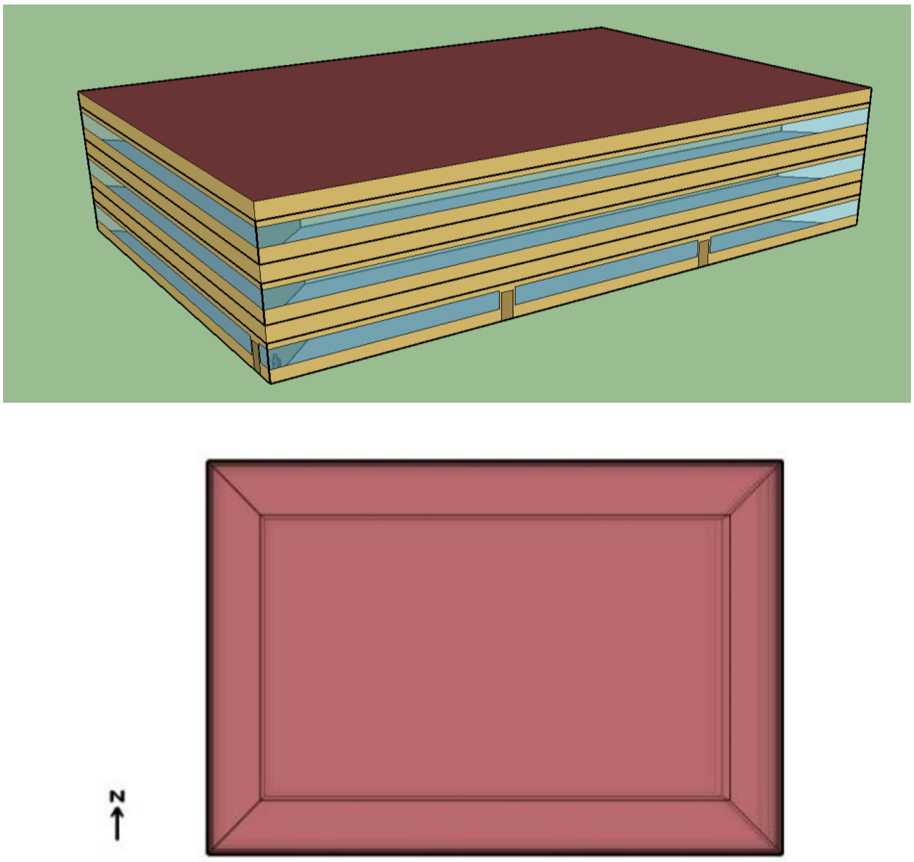


Figure 3.1. Building shape and building plan of the prototype building model.

Medium Office Prototype Building Parameters List [5]

Categories	Parameters	Value
Construction	Exterior walls	Steel-Frame Walls 10.16mm. Stucco+15.88 mm. gypsum board + wall insulation+15.88 mm. gypsum board
	Roof	Built-up roof: Roof membrane + roof insulation + metal decking
	Window	Hypothetical window with weighted U-factor and SHGC
HVAC	System	MZ VAV (multizone variable air volume)
	Heating	Furnace
	Cooling	PACU (packaged air-conditioning unit)
	Thermostat Setpoint	23.8℃ cooling / 21℃ heating
	Thermostat Setback	26.7℃ cooling / 15.6℃ heating
Internal Loads	Occupancy	18.6 m^2/person
	Outside air requirements	9.44L/s/person
	Lighting	9.69 W/ m^2
	Service Water Heating	Storage tank Natural gas
	Water temperature setpoint	60 ℃

✓ Air-conditioning for all year

Firstly, the standard model was simulated for 138 selected cities in the United States (Figure 3.2 and Appendix 2). The principle of city selection is to select at least one city or more at each latitude. At the same time, with 5-degree latitude as a section, at least one representative city is selected for all climate types included in each interval. Then the energy consumption of all the selected cities were simulated using TMY climate file to evaluate the climate impact. And with the objective to summarize a distribution rule of energy consumption with latitude gradient.

✓ Thermal resistance increase

Then 47 of the 138 selected cities were simulated with 5 different thermal resistance values. The selection principle is the same as before because not only just one city selected based on the previous selection principle in the 138 cities. The number of the selected cities are enough for the second term selection.

- ✓ Introducing ventilation and air-conditioning intermittent operation

The 47 selected cities in the thermal resistance cases were used for introducing ventilation in mild season simulation as well.

Figure 3.2. Simulation locations.

3.3.2. Energy Simulation and EnergyPlus

EnergyPlus is an integrated simulation that all three of the major parts, building, system, and plant, must be solved simultaneously. Building part simulate the impact of building envelope with the outdoor environment and indoor thermal load. System module is to simulate the air conditioning system of air transport equipment, fan coil and the related control device. The equipment module simulates refrigerating machine, boiler, cooling tower, energy storage equipment, power generation equipment, pump and other cold and hot source equipment.

3.3.3.Mathematical and Physical Analysis

The thermal load simulation in EnergyPlus employed heat balanced method. The basis of the heat balance model is to guarantee the conservation of energy. The heat balance equation contains the unsteady heat transfer through the envelope and the change caused by meteorological data. The major assumption is that the surfaces of the room can be treated as entities with uniform surface temperatures, uniform long- and shortwave irradiation, diffuse radiating surfaces, and one-dimensional heat conduction within [7]. Figure 3.3 shows the relationships between four distinct processes for a single opaque surface, including outside surface heat balance, the wall conduction process, the inside face heat balance, and the air heat balance.

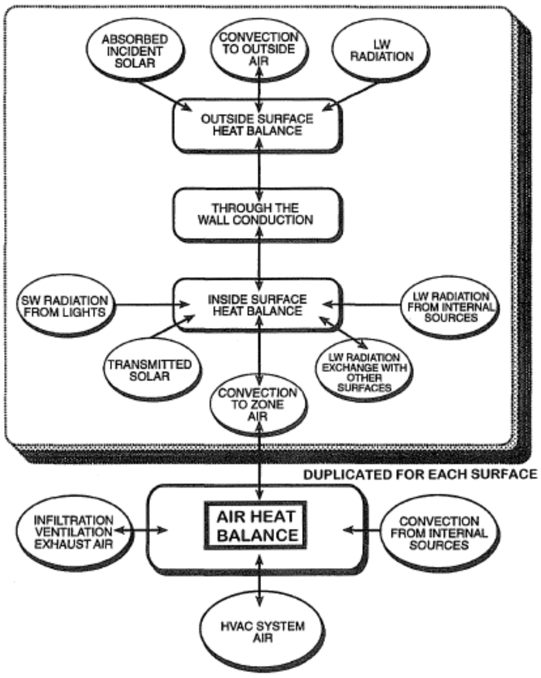


Figure 3.3. Schematic of heat balance process in a zone [7]

(1) Basis for the zone and air system integration

The EnergyPlus formulation of the solution scheme with heat balance on the zone air is:

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{sl} \dot{Q}_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \tag{3.1}$$

Where:

$\sum_{i=1}^{sl} \dot{Q}_i$ = sum of the convective internal loads;

$\sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z)$ = convective heat transfer from the zone surface;

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$ = heat transfer due to interzone air mixing;

$\dot{m}_{inf} C_p (T_\infty - T_z)$ = heat transfer due to infiltration of outside air

$\dot{Q}_{sys}$ = air systems output;

$C_z \frac{dT_z}{dt}$ = energy stored in zone air.

$$C_z = \rho_{air} C_p C_T \tag{3.2}$$

Where:

ρ_{air} = zone air density;

C_p = zone air specific heat;

C_T = sensible heat capacity multiplier.

If the air capacitance is neglected, the steady-state system output must be:

$$-\dot{Q}_{sys} = \sum_{i=1}^{sl} \dot{Q}_i + \sum_{i=1}^{N_{surface}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) \tag{3.3}$$

(2) Conduction through the wall

The wall conduction process plays a significant role in the overall heat balance procedure because it links the outside and inside heat balance. EnergyPlus is using Conduction Transfer Functions (CTFs) to formulate the wall conduction process. The general form is shown by the following equation:

$$q_{ki}^{"}(t) = -Z_0 T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_0 T_{O,t} + \sum_{j=1}^{nz} Y_j T_{O,t-j\delta} + \sum_{j=1}^{nq} \emptyset_j q_{ki,t-j\delta}^{"} \tag{3.4}$$

for the inside heat flux, and

$$q_{ko}^{"}(t) = -Y_0 T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_0 T_{O,t} + \sum_{j=1}^{nz} X_j T_{O,t-j\delta} + \sum_{j=1}^{nq} \emptyset_j q_{ko,t-j\delta}^{"} \tag{3.5}$$

for the outside heat flux (q“=q/A)

Where:

X_j = outside CTF coefficient, j=0, 1, … nz;

Y_j = cross CTF coefficient, j=0, 1, … nz;

Z_j = inside CTF coefficient, j=0, 1, … nz;

$\emptyset_j$ = flux CTF coefficient, j=1, 2, … nq;

T_i = inside face temperature;

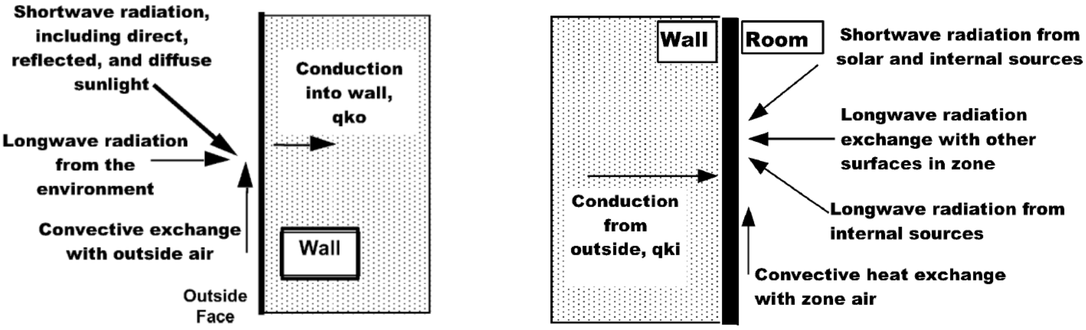
T_o = outside face temperature;

$q_{ko}^{"}$ = conduction heat flux on outside face;

$q_{ki}^{"}$ = conduction heat flux on inside face.

The subscript of the variables following the comma stands for the time period for the quantity in terms of the time step δ. The first terms in the left series have been separated from the rest so that facilitated solving for the current temperature in the solution. The terms of nz and nq depend on the wall structure.

(3) Surface heat balance process



a. Outside b. Inside

Figure 3.4. Heat Balance Control Volume Diagram

The heat balance on the outside face is:

$$q''_{\alpha sol} + q''_{LWR} + q''_{conv} - q''_{ko} = 0 \tag{3.5}$$

Where:

q''_{ko} = conduction flux into the wall, (a/A);

$q''_{\alpha sol}$ = absorbed direct and diffuse solar radiation flux;

q''_{LWR} = net longwave radiation flux exchange with the air and surroundings;

q''_{conv} = convective exchange flux with outside air.

All items in formula 1 are positive for net flux to the face except the conduction term, which is taken to be positive in the direction from outside to inside of the wall traditionally. The first three terms can be combined with an equivalent temperature of sol-air temperature.

The heat balance on the inside face is:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0 \tag{3.6}$$

Where:

q''_{LWX} = net longwave radiant exchange flux between zone surfaces;

q''_{SW} = net shortwave radiation flux to surface from light;

q''_{LWS} = longwave radiation flux from equipment in zone;

q''_{ki} = conduction flux through the wall;

q''_{sol} = transmitted solar radiation flux absorbed at surface;

q''_{conv} = convective heat flux to zone air.

3.3.4. Effect of thermal insulation on heat transfer process

Air heat balance equation is employed in this study. The convective internal load is the sum of heat transferred to the zone air from all types of internal gains, including people, lights, equipment etc. Interzone air mixing refers to the heat transfer to the zone air from all the transfers of air from other thermal zone. The interior enveloped structure of the room is lightweight structure, which has little heat storage capacity and limited influence on the indoor thermal environment. In this study, it is assumed that the heat transfer from the inner wall to the interior is neglected. The air systems output is heat transfer directly to the zone air by HVAC systems. In ventilation buildings, there is no HVAC system so that the air systems output is neglected.

Therefore, in ventilation building, the heat balance on the zone air is:

$$q_{int\cdot conv} + q_{surf\cdot conv} + q_{out} - q_{stor} = 0$$

Where

$q_{stor} =$ zone air heat balance air energy storage rate (W);

$q_{int\cdot conv}$ = zone air heat balance internal convective heat gain rate (W);

$q_{surf\cdot conv}$ = zone air heat balance surface convection rate (W);

q_{out} = zone air heat balance outdoor air transfer rate (W).

These factors together determine the indoor heat gains and temperature changes. As the outdoor climate changes day and night, the intensity and direction of heat transfer through all parts of the envelope may change, and the final heat left inside determines the change trend of indoor thermal environment in the next day. The daily net heat gain of the room is expressed as:

$$Q_{net} = \int_{0}^{24} \left(q_{int\cdot conv}(t) + q_{surf\cdot conv}(t) + q_{out}(t) \right)$$

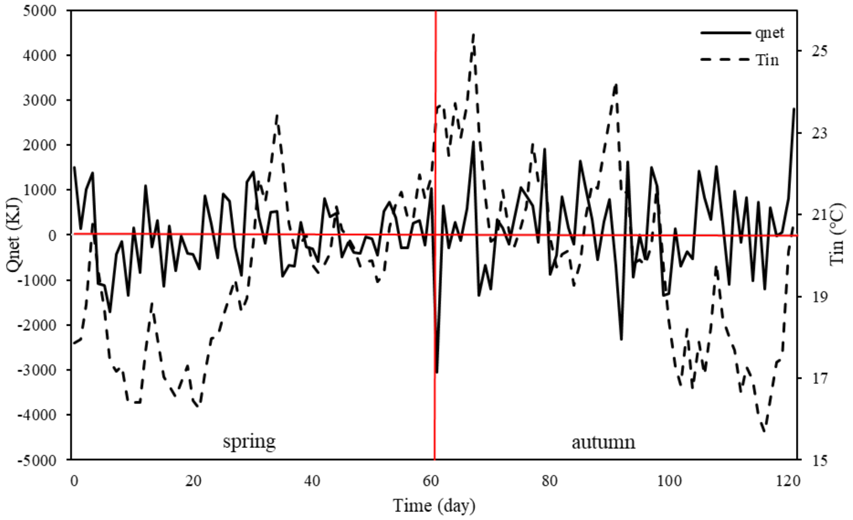


Figure 3.5. Variation of air energy storage and indoor air temperature

Figure 3.5 is the change curve of daily net heat gain and average indoor air temperature in summer, mild season and winter. It shows that the net heat of the room varies from positive to negative depending on the outdoor climate, and the net heat fluctuates greatly. Outdoor climate and indoor thermal condition have a great influence on the daily net heat gain of natural ventilation room. At the beginning of summer, the outdoor climate is hot, while the indoor temperature is still low, so most of the time, heat from the outdoor into the indoor. As the heat enters the room, the indoor air temperature gradually increases. The total heat entering the room during July to August is almost equal to the total heat leaving the room. The indoor air temperature is relatively stable. From late September, the climate turns cool, and most of the time, the room net heat is negative, and the indoor air temperature gradually drops. The indoor and outdoor heat transfer in winter is similar to that in summer, only in the opposite direction.

External wall insulation directly affects the heat transferred into the interior through the external wall, thus affecting the indoor thermal environment. The coupling heat transfer between the external wall and indoor air is realized by convection heat transfer between the inner surface and indoor air. The heat transfer is expressed as:

$$q^{"}_{conv} = h_i(T_a - T_{si})$$

T_a is the air temperature of the zone and T_{si} is the surface temperature of external wall. h_i is the convection coefficient of inner face of the wall.

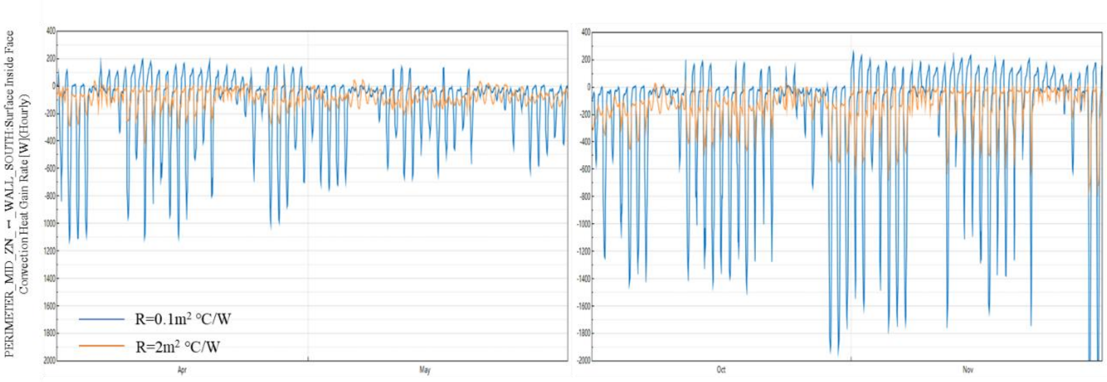


Figure 3.6. Heat transferred by convection between external wall and the zone air

Figure 3.6 shows that the inner surface of the external wall and indoor air exchange heat gradually when the thermal resistance of different insulation layers of the external wall is different. It shows that in a ventilated room, the heat transfer through the external walls to the indoor air fluctuates greatly by hour, and the direction is constantly changing. Heat released from the wall into the indoor is negative, heat dissipation which means heat gains by the wall is positive. This shows that the external wall insulation has a dual function, which reduces the incoming indoor heat through the wall while preventing the heat emission to the outside. The heat emitted from the inner surface of the external wall decreases with the increase of thermal resistance of the insulation layer.

3.4. Summary

This chapter introduced the research methodology and simulation theories. The simulation models are detailed introduce in this chapter as well. The climate data in this study are mainly employed TMY3 files which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017. The building energy consumption simulation among the 138 stations in U.S. were estimated using EnergyPlus, a validated and physics-based BES program developed by the U.S. Department of Energy (DOE).

Appendix A. Zone summary of Medium Office Building.

Zone	**Area [m²]**	**Conditioned [Y/N]**	**Volume [m³]**	**Multipliers**	**Gross Wall Area [m²]**	**Window Glass Area [m²]**	**Lighting [2] [W/m²]**	**People [m²/person]**	**Number of People**	**Plug and Process [W/m²]**
CORE_BOTTOM	953	Yes	2,859	1	0	0	9.69	20	48	8.07
TOPFLOOR_PLENUM	1,609	Yes	2,145	1	197	0	0.00	-	80	8.07
MIDFLOOR_PLENUM	1,609	Yes	2,145	1	197	0	0.00	-	80	8.07
FIRSTFLOOR_PLENUM	1,609	Yes	2,145	1	197	0	0.00	-	80	8.07
CORE_MID	953	Yes	2,859	1	0	0	9.69	20	48	8.07
CORE_TOP	953	Yes	2,859	1	0	0	9.69	20	48	8.07
PERIMETER_TOP_ZN_3	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_TOP_ZN_2	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_TOP_ZN_1	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_TOP_ZN_4	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_BOT_ZN_3	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_BOT_ZN_2	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_BOT_ZN_1	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_BOT_ZN_4	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_MID_ZN_3	201	Yes	603	1	133	63	9.69	20	10	8.07
PERIMETER_MID_ZN_2	127	Yes	382	1	88	42	9.69	20	6	8.07
PERIMETER_MID_ZN_1	201	Yes	603	1	133	63	9.69	20	10	8.07

PERIMETER_MID_ZN_4	127	Yes	382	1	88	42	9.69	20	6	8.07
TOTAL[1]	4,827		20,918		1,916	632			482.7	
AREA WEIGHTED AVERAGE							10.00	20		
1. Only volume, and gross wall area include unconditioned space.										
2. Listed lighting power density is based on applicable requirements in ASHRAE Standard 90.1-2004. The actual inputs for the models are based on appliable codes and standards										

Appendix B. Simulation cities (ASHRAE 169-2013 Table A-4 United States Stations and Climate Zone)

Country/LOCATION	WMO#	Lat	Long	CZ
SAN JUAN L M MARIN INTL AP	785263	18.43	–66.00	1A
AGUADILLA/BORINQUEN	785140	18.5	–67.13	1A
WAKE ISLAND	912450	19.28	166.64	1A
HILO INTERNATIONAL AP	912850	19.72	–155.05	1A
KONA INTL AT KEAHOL	911975	19.73	–156.03	1A
KAHULUI AIRPORT	911900	20.9	–156.43	1A
BARBERS POINT NAS	911780	21.3	–158.07	1A
KEY WEST INTL ARPT	722010	24.55	–81.75	1A
MARATHON AIRPORT	722016	24.73	–81.05	1A
MIAMI INTL AP	722020	25.82	–80.30	1A
NAPLES MUNICIPAL	722038	26.15	–81.78	2A
LAREDO INTL AIRPORT	722520	27.55	–99.47	2B
ST PETERSBURG CLEAR	722116	27.9	–82.68	2A
SOUTHWEST PASS	994010	28.9	–89.43	2A
HONDO MUNICIPAL AP	722533	29.36	–99.17	2B
DEL RIO INTERNATIONAL AP	722610	29.37	–100.92	2B
HOUSTON BUSH INTERCONTINENTAL	722430	29.99	–95.36	2A
NEW ORLEANS LAKEFRONT AP	722315	30.04	–90.03	2A
ALEXANDRIA INTERNATIONAL	747540	31.33	–92.55	2A
SAN ANGELO MATHIS FIELD	722630	31.35	–100.49	3B
NACOGDOCHES (AWOS)	722499	31.58	–94.72	3A
DAVIS-MONTHAN AFB	722745	32.17	–110.88	2B
YUMA INTL AIRPORT	722800	32.65	–114.60	2B
CASA GRANDA (AWOS)	722748	32.95	–111.77	2B
FORT WORTH ALLIANCE	722594	32.98	–97.32	2A
TRUTH OR CONSEQUENCES MUNI AP	722710	33.24	–107.27	3B
LUKE AFB/PHOENIX	722785	33.53	–112.38	2B
MARCH AFB/RIVERSIDE	722860	33.88	–117.27	3B
ATHENS BEN EPPS AP	723110	33.95	–83.33	3A
CANNON AFB/CLOVIS	722686	34.38	–103.32	4B

SANTA BARBARA MUNICIPAL AP	723925	34.43	–119.84	3C
PRESCOTT LOVE FIELD	723723	34.65	–112.42	4B
LOMPOC (AWOS)	722895	34.67	–120.47	3C
EDWARDS AFB	723810	34.9	–117.88	3B
LITTLE ROCK AFB	723405	34.92	–92.15	3A
SANTA MARIA PUBLIC ARPT	723940	34.92	–120.47	3C
ALBUQUERQUE INTL ARPT	723650	35.04	–106.62	4B
NEW BERN CRAVEN CO REGL AP	723095	35.07	–77.05	3A
SAN LUIS CO RGNL	722897	35.23	–120.63	3C
BAKERSFIELD MEADOWS FIELD	723840	35.43	–119.06	3B
ASHEVILLE REGIONAL ARPT	723150	35.43	–82.54	4A
GALLUP SEN CLARKE FLD	723627	35.51	–108.79	5B
OKLAHOMA CITY/WILEY	723544	35.53	–97.65	3A
PASO ROBLES MUNICIPAL ARPT	723965	35.67	–120.63	3C
MONTEREY PENINSULA	724915	36.58	–121.85	3C
MERCURY DESERT ROCK AP	723870	36.62	–116.03	4B
NORFOLK NAS	723085	36.93	–76.28	3A
PAGE MUNI (AMOS)	723710	36.93	–111.45	5B
WISE/LONESOME PINE	724117	36.98	–82.53	4A
SAN JOSE INTL AP	724945	37.36	–121.93	3C
CALIENTE (AMOS)	724870	37.62	–114.52	4B
LIVERMORE MUNICIPAL	724927	37.69	–121.82	3C
CEDAR CITY MUNICIPAL AP	724755	37.7	–113.10	5B
LAMAR MUNICIPAL	724636	38.07	–102.68	4B
NAPA CO. AIRPORT	724955	38.21	–122.28	3C
ST LOUIS LAMBERT INT'L ARPT	724340	38.75	–90.37	4A
UKIAH MUNICIPAL AP	725905	39.13	–123.20	3C
PRICE/CARBON COUNTY	724700	39.62	–110.75	5B
MORGANTOWN HART FIELD	724176	39.64	–79.92	5A
EAGLE COUNTY AP	724675	39.64	–106.92	6B
WILMINGTON NEW CASTLE CNTY AP	724089	39.67	–75.60	4A
COLUMBUS PORT COLUMBUS INTL A	724280	39.99	–82.88	4A
UNIV OF ILLINOIS WI	725315	40.03	–88.27	5A

WASHINGTON (AWOS)	725117	40.13	–80.28	5A
RED BLUFF MUNICIPAL ARPT	725910	40.15	–122.25	3B
AKRON WASHINGTON CO AP	724698	40.17	–103.23	5B
BELMAR-FARMINGDALE	724084	40.18	–74.13	4A
GREELEY/WELD (AWOS)	724768	40.43	–104.63	5B
VERNAL	725705	40.43	–109.52	6B
MANSFIELD LAHM MUNICIPAL ARPT	725246	40.82	–82.52	5A
TOLEDO EXPRESS AIRPORT	725360	41.59	–83.80	5A
ROCK SPRINGS ARPT	725744	41.59	–109.07	6B
CRESCENT CITY FAA AI	725946	41.78	–124.24	4C
MONTAGUE SISKIYOU COUNTY AP	725955	41.78	–122.47	5B
LOGAN-CACHE AIRPORT	724796	41.79	–111.85	5B
LANDER HUNT FIELD	725760	42.82	–108.73	6B
ESTHERVILLE MUNI	726499	43.4	–94.75	6A
NORTH BEND MUNI AIRPORT	726917	43.42	–124.25	4C
JUNEAU/DODGE CO	726509	43.43	–88.70	5A
WATERVILLE (AWOS)	726073	44.53	–69.68	6A
YELLOWSTONE LAKE (RAMOS)	726664	44.54	–110.42	7A
RED WING	726564	44.58	–92.48	6A
SALEM MCNARY FIELD	726940	44.91	–123.00	4C
WAUSAU MUNICIPAL ARPT	726463	44.93	–89.63	6A
AURORA STATE	726959	45.25	–122.77	4C
DILLON AIRPORT	726796	45.26	–112.55	6B
LA GRANDE MUNI AP	726884	45.29	–118.01	5B
WALLA WALLA CITY COUNTY AP	727846	46.1	–118.29	5B
LIDGERWOOD (RAMOS)	727534	46.1	–97.15	6A
KELSO WB AP	727924	46.12	–122.89	4C
HOULTON INTL ARPT	727033	46.12	–67.79	7A
HANFORD	727840	46.57	–119.60	5B
FARGO HECTOR INTERNATIONAL AP	727530	46.93	–96.81	6A
LORING AFB/LIMESTON	727125	46.95	–67.88	7A
HOQUIAM AP	727923	46.97	–123.94	4C
OLYMPIA AIRPORT	727920	46.97	–122.90	4C

LEWISTOWN MUNICIPAL ARPT	726776	47.05	–109.47	6B
TWO HARBORS	727444	47.05	–91.75	7A
HANCOCK HOUGHTON CO AP	727440	47.17	–88.51	6A
SHELTON/SANDERSON	727925	47.24	–123.15	4C
STAMPEDE PASS	727815	47.29	–121.34	5B
GREAT FALLS	727760	47.45	–111.38	6B
BREMERTON NATIONAL	727928	47.48	–122.75	5C
DESTRUCTION ISLAND	994070	47.67	–124.48	4C
SIDNEY-RICHLAND	727687	47.7	–104.20	6B
QUILLAYUTE STATE AIRPORT	727970	47.93	–124.56	5C
ORR	726544	48.02	–92.87	7A
SMITH ISLAND	994180	48.32	–122.83	5C
FRIDAY HARBOR	727985	48.52	–123.02	5C
ROSEAU MUNI (AWOS)	727477	48.85	–95.70	7A
ADAK NAS	704540	51.88	–176.65	7A
SHEMYA AFB	704140	52.72	174.12	8A
DUTCH HARBOR	704890	53.9	–166.55	7A
ANNETTE ISLAND AP	703980	55.04	–131.57	5A
COLD BAY ARPT	703160	55.21	–162.72	7A
SITKA JAPONSKI AP	703710	57.05	–135.36	5A
JUNEAU INT'L ARPT	703810	58.36	–134.58	6A
SKAGWAY AIRPORT	703620	59.46	–135.31	6A
ILIAMNA ARPT	703400	59.75	–154.92	7A
SEWARD	702770	60.12	–149.45	7A
SPARREVOHN AFS	702350	61.1	–155.57	7A
SAINT MARY`S (AWOS)	702005	62.07	–163.30	8A
NORTHWAY AIRPORT	702910	62.96	–141.95	8A
BIG DELTA ALLEN AAF	702670	64	–145.72	8A
FAIRBANKS INTL ARPT	702610	64.82	–147.86	8A
TIN CITY AFS (AWOS)	701170	65.57	–167.92	8A
INDIAN MTN AFS AWOS	701730	66	–153.70	8A
SHISHMAREF (AWOS)	701195	66.27	–166.05	8A
FORT YUKON	701940	66.57	–145.27	8A

KOTZEBUE RALPH WEIN MEMORIAL	701330	66.89	–162.60	8A
BETTLES FIELD	701740	66.92	–151.51	8A
AMBLER	701718	67.1	–157.85	8A
ANAKTUVUK PASS	701625	68.13	–151.73	8A
POINT HOPE (AWOS)	701043	68.35	–166.80	8A
CAPE LISBURNE(AWOS)	701040	68.88	–166.13	8A
BARTER ISLAND (DEW)	700860	70.13	–143.63	8A
DEADHORSE	700637	70.19	–148.48	8A
BARROW W POST-W ROGERS ARPT	700260	71.29	–156.76	8A

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Chapter 4. Comparison on Climate Zoning and Thermal Standard of Green Building Design

4.1. Introduction

Buildings are the largest consumers of energy all over the world and will continue to be a reason of rising energy demand in the future[1]. Globally, building sector accounts for 32% of total final energy consumption[2]. Building energy codes, also known as “energy standard for buildings”, “thermal building regulations”, “energy conservation building codes”, or “energy efficiency building codes”, are used by governments to limit buildings’ pressure on the energy and environment in the meanwhile providing occupants with comfort and modern living conditions [1]. Building technologies and design elements are included in energy codes, such as building envelope; heating, ventilation, and air conditioning (HVAC) systems; lighting; and service water heating systems [2].

Building energy efficiency standard, as used by local and state enforcement entities are typically tied to the dominant climate within an enforcement jurisdiction, where the dominant climate is based upon a 30-year average of local to regional surface observations[3]. Different countries have their own climatic regionalization method based on their specific climate conditions. Based upon surface observations ASHRAE, in partnership with the Department of Energy, the United States have developed climate zone maps for the global countries (Figure 4.1). The difference between ASHRAE international climate zone and local climate division of Japan and China will be analyzed.

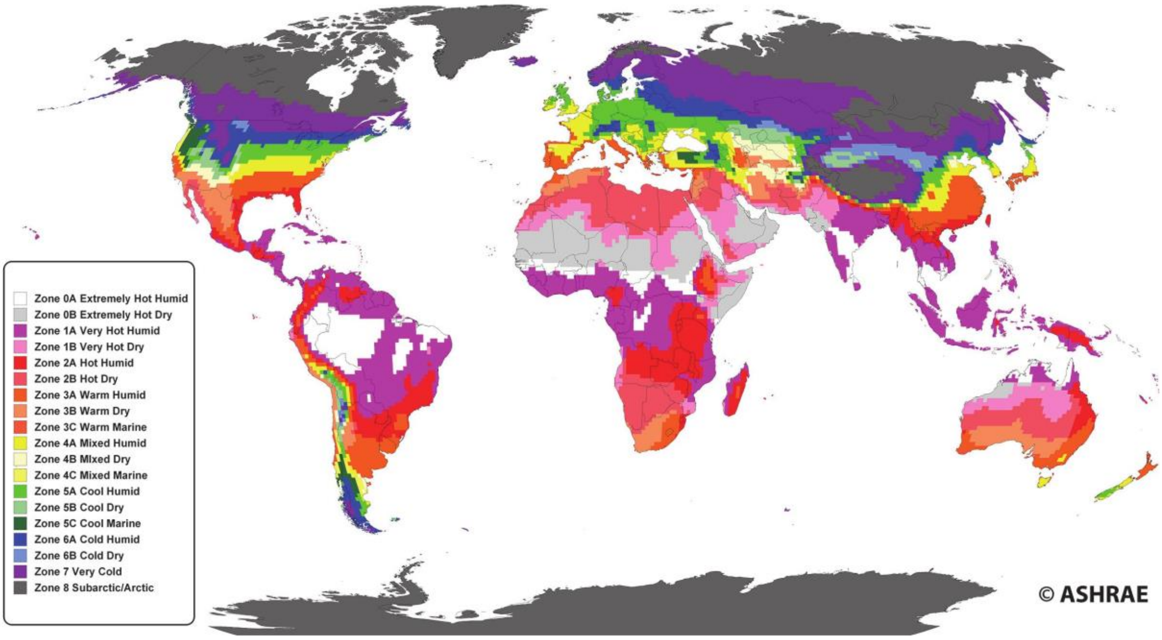


Figure 4.1 ASHRAE world climate zone map[4]
(Source: ANSI/ASHREA Standard 169-2013 Climate Data for Building Design Standard)

The energy-saving indicators of green buildings are generally based on building standards to further enhance the requirements. However, sometime the enhancement will not decrease the energy consumption dramatically, but even increase the cost of the extra technologies input. The key indicators enhancement requirement for LEED, CASBEE, and ESGB were summarized in this chapter.

4.2. The U.S. Building Energy Efficiency Standard and LEED

4.2.1. Development of the U.S building energy efficiency standard

The United States accounts for a quarter of the world's energy consumption and is the world's largest energy consumer [3]. In response to the oil crisis, the federal government enacted the *Energy Policy and Energy Conservation Act* in 1975 and the *Resource Conservation and Recovery Act* in 1976. In 1978, the *National Energy Conservation Policy Act* and the *Public Power Company Management Policy Act* were promulgated. In order to comprehensively promote energy conservation and environmental protection, the United States issued the *Energy Policy Act of 1992*. In 2005, the United States passed the *Energy Policy Act of 2005*, which comprehensively modified and improved the *Energy Policy Act of 1992* to meet the actual needs of the world energy pattern in the new century. Energy codes and standards play a significant role by setting minimum requirements for energy efficient design and construction. Energy codes specify how building must be constructed or perform, which are written in mandatory, enforceable language. For example, *International Building Code* (IBC), a complete building code for residential and commercial buildings, published by the International Code Council (ICC). Energy standard describe how building should be constructed to be energy efficient. They are not mandatory, but provided as national recommendations, with some variation for regional climate. In order to make it easy for jurisdictions to incorporate the provisions of the energy standards directly into the laws or regulations of states and local governments, some energy standards are written in mandatory, enforceable language. American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) is one of this kind of national organization.

The first national building energy standard in United State is American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 90, which was published in 1975. In 1982, it was separated into non-residential (90.1) and residential (90.2) standards (ASHRAE 1989, 1993). Since its inception, the standard has been upgraded eleven times until 2019, resulting in significant increases in building energy efficiency. In 2009, the International Code Council (ICC) found the Sustainable Building Technology Committee (SBTC), which cooperated with American Institute of Architects (AIA), American Society for Testing and Materials International (ASTM International), ASHRAE, USGBC and the Illuminating Engineering Society (IES) to release the International Green Construction Code (IgCC) in 2012. The standard contains the whole building life cycle influence aspects, such as emission reduction, energy and resource efficiency improvement, land use, etc.

4.2.2. Thermal Climate Zone

The Climatic Data for Building Design Standard (ASHRAE Standard 169-2013) provides a comprehensive source of climate data for use in building design and related equipment standards. The data in the standard serves directly ANSI/ASHRAE/IESNA standards 90.1, 90.2, and ASHRAE Handbook - Fundamentals. The building climate zones in this standard are first divided into 9 different zones using the heating and cooling degree-days for the location. The data has completely revised and updated from Standard 169-2006. An additional Climate Zone 0 with humid (0A) and dry (0B) zones has been added. After defining the climate zone, the standard defines the climate type and divides the climate into dry climate, humid climate and maritime climate. The classification method of climate type is shown in the following Table 4.1:

Table 4.1. U.S. Thermal Climate Zone Definitions[4]

Climate Type	Definition
Humid (A)	Locations that are not Marine (C) and not Dry (B)
Dry (B)	If 70% or more of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is $P < 20.0 \times (T+ 14)$; If between 30% and 70% of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is $P < 20.0 \times (T+ 7)$; If 30% or less of the precipitation, P, occurs during the high sun period, then the dry/humid threshold is $P < 20 \times T$. Where P = annual precipitation, in. (mm) T = annual mean temperature, °C Summer or high sun period = April through September in the Northern Hemisphere and October through March in the Southern Hemisphere Winter or cold season = October through March in the Northern Hemisphere and April through September in the Southern Hemisphere
Marine (C)	a. Mean temperature of coldest month between –3°C and 18°C; b. Warmest month mean < 22°C; c. At least four months with mean temperatures over 10°C; d. Dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. The cold season is October through March in the Northern Hemisphere and April. through September in the Southern Hemisphere.

The definition method of climate zoning is shown in Table 4.2 below. Figure 4.2 is the climate zoning map of the United States.

Table 4.2. U.S. Thermal Climate Zone Definitions[4]

Climate Zone	Characteristic	Thermal Index
0	Extremely Hot Humid (0A), Extremely Hot Dry (0B)	6000<CDD10℃
1	Very Hot Humid (1A), Very Hot Dry (1B)	5000<CDD10℃≤6000
2	Hot Humid (2A), Hot Dry (2B)	3500<CDD10℃≤5000
3	Warm Humid (3A), Warm Dry (3B), Warm Marine (3C)	CDD10℃<3500 and HDD18℃≤2000
4	Mixed Humid (4A), Mixed Dry (4B), Mixed Marine (4C)	CDD10℃<3500 and 2000<HDD18℃≤3000
5	Cool Humid (5A), Cool Dry (5B), Cool Marine (5C)	CDD10℃<3500 and 3000<HDD18℃≤4000
6	Cold Humid (6A), Cold Dry (6B)	4000<HDD18℃≤5000
7	Very Cold	5000<HDD18℃≤7000
8	Subarctic	7000<HDD18℃

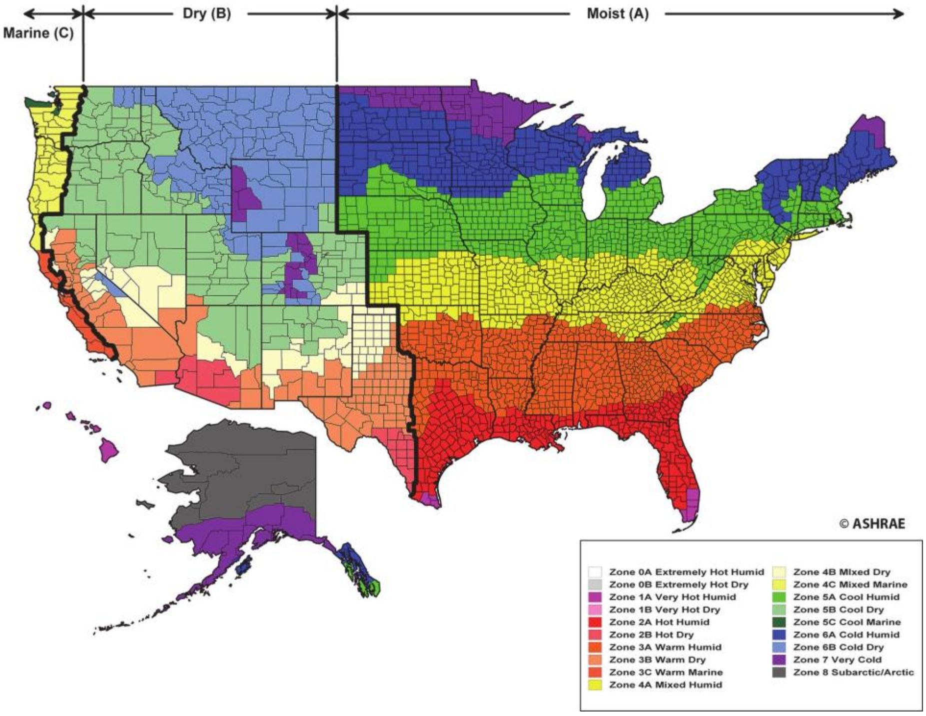


Figure 4.2 U.S. climate zone map[5]

A comparison between the climatic zones of the United States (Figure 4.2) and the topographic map (Figure 4.3a) shows that the three zones with different climatic types in the zoning roughly coincide with the topographic trend. The wet climate zone is located in the lower altitudes of the eastern United

States, the maritime climate zone is located in the narrow coastal zone of the west coast, and the dry climate zone is located in the plateau region of the Cordillera mountains and the Rocky Mountains in the western United States.

By comparing the United States climate division (Figure 4.2) with the administrative division (Figure 4.3b), it can be seen that the boundary of the climate division is obviously highly coincident with the boundary of the state administrative division. The boundary does not show a curve shape with the change of the terrain, but more shows a linear shape consistent with the United States administrative division. Especially in the northern part of the boundary between the dry and wet climate zones, the boundary between the climate zones overlaps with the boundaries of Montana, Wyoming, Colorado, and North Dakota, south Dakota, Nebraska, and Kansas.

a. topography map [6]

b. administrative map [7]

Figure 4.3 The relationship between thermal zones and topography and administrative zones in USA

Therefore, it can be judged that the climate zones in the ASHRAE standard of the United States should be based on the division of meteorological data and partially adjusted according to the boundary of administrative divisions. The climate zoning should consider both climate and administrative factors.

4.2.3. Energy Standard for Buildings Except Low-Rise Residential Buildings (ASHRAE 90.1-2016)

4.2.3.1 Development Process

In 1999, the ASHRAE Board of Directors voted to place that Standard 90.1 is a dynamic document undergoing continuous maintenance. With the publication of 90.1-2001, new building energy standards began to be published by ASHRAE in its entirety on a three-year cycle, with issuing versions of Standard 90.1 in 2004, 2007, 2010, 2013, 2016 and planning for a new version in 2019. Users are allowed to know the time when new editions published by this cycle. Most states have set building efficiency standards for residential and commercial buildings since the 1970s. ASHRAE and the IECC are also regularly updated and then adopted by state and local governments on their own merits. By

December 2018, five states have adopted standard more than 2013 version, as shown in Figure 4.4. Five states have adopted 2010 version or equivalent standard, and nine have adopted standard version between 2010 and 2013. Eight states (white area) do not have any standards applicable or prior to 2004 standards. The number of states failing to adopt building efficiency standards decreased slightly from 2013, when 11 states did.

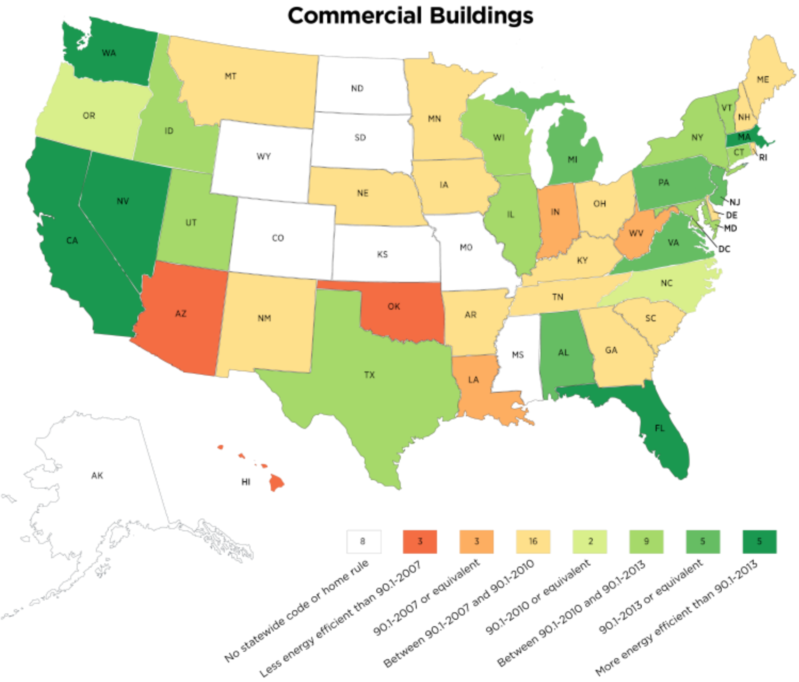


Figure 4.4 Status of State Energy Code Adoption in USA (Updated as of December 2018) [8]

4.2.3.2 Evaluation Index of Building Envelope

(1) Thermal Transmittance (U-Value)

Thermal Transmittance, also known as U-value, is the coefficient of heat transmission through a structure, which can be a single or a composite, divided by the temperature difference between the structure. The units of U-value are W/m^2K. U-value measures how effective a material is an insulator.

(2) Thermal Resistance (R-Value)

R-Value means the ability that materials resist heat conduction to go through. It is the reciprocal of thermal transmittance that is only used for signifying single material or single heat flow route. The unit of this measure is m^2K/W. A hither figure indicates better performance, which is in contrast to the lower figure desired for thermal transmittance.

(3) Solar Gain Heat Coefficient (SGHC)

The SGHC is the fraction of the incident solar radiation admitted through the fenestration assembly, including directly transmitted and absorbed and subsequently released inward. The number is between 0 and 1. Solar heat gain can improve the indoor environment in winter because of the free heat but may lead to overheating in the summer. The balance with an appropriate SHGC is important.

Table 4.3. Thermal performance design partition indexes and requirement of ASHRAE 90.1 (Non-residential, Steel-framed wall, vertical fenestration 0% to 40% of wall with metal framing and operable window)

Climate Zone	Steel-framed Wall		Window Max. U		Window Max. SHGC	
	2010	2016	2010	2016	2010	2016
1 (A, B)	0.705	0.705	6.81	3.69	0.25	0.22
2 (A, B)	0.705	0.705	4.26	3.69	0.25	0.25
3 (A, B, C)	0.479	0.435	3.69	3.41	0.25	0.25
4 (A, B, C)	0.365	0.365	3.12	2.61	0.40	0.36
5 (A, B, C)	0.365	0.315	3.12	2.61	0.40	0.38
6 (A, B)	0.365	0.277	3.12	2.56	0.40	0.40
7	0.365	0.277	2.56	2.27	0.45	0.45
8	0.365	0.212	2.56	1.99	0.45	0.45

4.2.4. ASHREA 90.1 and LEED

Leadership in Energy and Environmental Design (LEED) is one of the most popular green building certification schemes used worldwide[9]. It is developed by U.S. Green Building Council (USGBC), including a set of rating systems for the design, construction, operation, and maintenance of green buildings, homes, and neighborhoods that aims to help building owners and operators be environmentally responsible and use resources efficiently. The current new version of LEED is LEED v4, which updated July 25, 2019. In the Energy and Atmosphere (EA) chapter, one of the pre-requisites is Minimum Energy Performance, which requires an improvement of 5% energy saving for new construction in the proposed building performance rating compared with the baseline building according to ASHRAE Standard 90.1-2010. Following the criteria, the credit Optimize Energy Performance demonstrate a percentage improvement in the proposed building compared with the baseline. Points are awarded according to Table 4.4.

Table 4.4. Points for percentage improvement in energy performance

New Construction	Major Renovation	Points (except schools, healthcare)
6%	4%	1
8%	6%	2
10%	8%	3
12%	10%	4
14%	12%	5
16%	14%	6
18%	16%	7
20%	18%	8
22%	20%	9
24%	22%	10
26%	24%	11
29%	27%	12
32%	30%	13
35%	33%	14
38%	36%	15
42%	40%	16
46%	44%	17
50%	48%	18

The energy efficiency measures focus on load reduction and HVAC-related strategies appropriate for the facility. It is achieved by whole-building energy simulation during the design process and account for the results in design decision making.

4.3. The Japan Building Energy Efficiency Standard and CASBEE

4.3.1.Development of the Japan building energy efficiency standard

When the first oil crisis hit in 1973, Japan's demand for crude oil accounted for 80% of its total primary energy demand. Since then, the Japanese government has been committed to strengthen the formulation of energy conservation policies and made great achievements, among which the Laws on Reasonable Use of Energy (Energy Conservation Law for short) first promulgated in 1979 played an extremely important role[10]. Energy Conservation Law of 2008 version expands the scope of buildings and the energy conservation program is submitted. In addition, small and medium-sized buildings over 300m^2 are required to apply energy conservation management, and at the same time, the guidance and suggestion on thermal insulation property of building materials are put forward[11].

Japan has issued a set of building energy standards for commercial and residential buildings under the Energy Conservation Law, including Criteria for Clients on the Rationalization of Energy Use for Buildings (CCREUB) issued in 1979 by the Ministry of International Trade and Industry (MITI) and the Ministry of Construction (MoC), Design and Construction Guidelines on the Rationalization of Energy Use for Houses (DCGREUH) issued by MoC in 1980, and Criteria for Clients on the Rationalization of Energy Use for Houses (CCREUH), issued by MITI and MoC in 1980 [10]. In 2013, Japan has completed the integration of these three standards, and integrated it into a standard – Building Energy Conservation 2013 (BEC2013), as the beginning of the long-term strategy until 2050 for energy-saving in the buildings[12]. From April 2017, compliance with the standard have been mandatory for large scale (over 2,000m^2 or more) non-residential buildings under the Building Energy Efficiency Act[13]. It is expected to be mandatory for all new buildings and residences by 2020. Japan has also fostered a number of non-regulatory programs to promote building energy efficiency, including an Energy Conservation Center of Japan (ECCJ), the CASBEE rating system for green buildings, and Building-Housing Energy-efficiency Labeling System (BELS).

4.3.2. Thermal Climate Zone

In the old version of building energy efficiency standard, the thermal climate region is divided into six zones, while in the new standard BEC2013, it is changed into eight zones according to HDD18℃ (Table 4.5). Zone 1 and Zone 2 located in northern Japan, with cold winters and cool summers. Zones 3 and 4 are located in central Japan. Zone 5 and 6 located in southern Japan, with warm winters and hot summers.

Table 4.5. Japan thermal performance design partition indexes and requirement

1999 Version	2013 Version	Thermal Index
I	1	4500≤HDD18℃
	2	3500≤HDD18℃<4500
II	3	3000≤HDD18℃<3500
III	4	2500≤HDD18℃<3000
	5	2000≤HDD18℃<2500
IV	6	1500≤HDD18℃<2000
V	7	500≤HDD18℃<1500
VI	8	HDD18℃<500

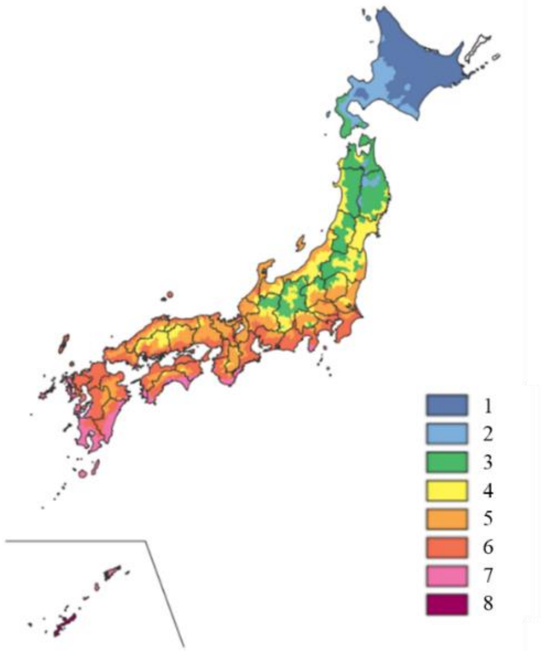


Figure 4.5 Japan climate zone map[5]

Comparing the climate zone maps (Figure 4.5) and administrative zoning maps (Figure 4.6b) and topographic maps (Figure 4.6a), it shows that the boundary of thermal zones is highly consistent with the topographic conditions of Japan. In the middle land of Chubu, Tohoku and Kanto, with the highest altitude (about 4000m), are thermal zone 3. The area with altitude of about 2000m, including the middle of Chugoku area, is thermal zone 4. With the decrease of altitude, the distribution is thermal zone 5 and zone 6. The boundary of climate division and administrative division rarely coincide.

a. topography map b. administrative map

Figure 4.6 The relationship between thermal zones and topography and administrative zones in Japan

4.3.3. Building Energy Efficiency Act

Act on the Improvement of Energy Consumption Performance of Buildings (Building Energy Efficiency Act) was newly established in July 8, 2015. This Act provides for regulatory measures for mandatory compliance with BEC2013 for large-scale non-residential buildings. BEC2013 adopts envelope performance (PAL*) to evaluate envelope performance, and primary energy consumption amount (E_T) of equipment and plug load to evaluate the energy efficiency performance for non-residential buildings (Figure 4.7).

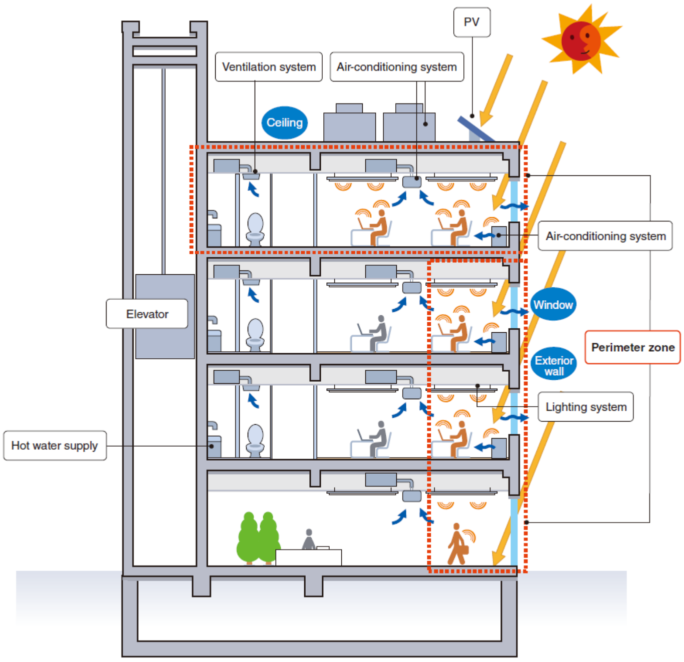


Figure 4.7 Conception of Envelope Performance (PAL*) and Primary Energy Consumption Amount (E_T) [13]

$$\text{PAL*}=\frac{annual\ thermal\ load\ of\ perimeter\ zone\ of\ each\ floor\ (MJ/year)}{total\ floor\ space\ of\ perimeter\ zone\ (m^2)} \tag{4.1}$$

The standard values of PAL * are based on the thermal climate zone in BEC2013 and the building type (Table 4.6). Perimeter zone is defined inside space that is within 5 horizontal meters of the centerline of the wall of each floor in contact with the outside air, the inside space of the floor directly below the roof, and the inside space that is directly above the floor in contact with the outside air (Figure 4.8). 201 kinds of standard room usage conditions are set up for energy calculation based on the survey of actual usage conditions in Japan.

Table 4.6. PAL* Standard Value (MJ/m^2/year) [14]

Building type		Thermal climate zone							
		1	2	3	4	5	6	7	8
Offices		480	480	480	470	470	470	450	570
Hotels	Guest-room	650	650	650	500	500	500	510	670
	Banquet hall	990	990	990	1260	1260	1260	1470	2220
Hospitals	Ward	900	900	900	830	830	830	800	980
	Non-ward	460	460	460	450	450	450	440	650
Stores engaged in sale of goods		640	640	640	720	720	720	810	1290
Schools		420	420	420	470	470	470	500	630
Restaurants		710	710	710	820	820	820	900	1430
Halls	Libraries	590	590	590	580	580	580	550	650
	Gymnasiums	790	790	790	910	910	910	910	1000
	Cinemas	1490	1490	1490	1510	1510	1510	1510	2090

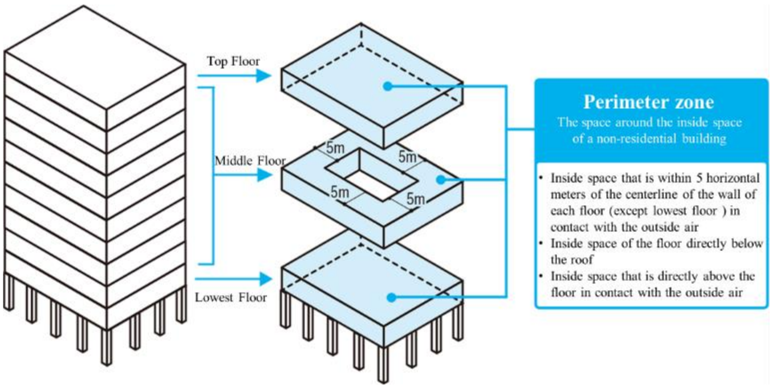


Figure 4.8 Perimeter Zone [15]

$$E_T = E_{AC} + E_V + E_L + E_W + E_{EV} + E_M - E_S \tag{4.2}$$

Where, E_{AC}, E_V, E_L, E_W, E_{EV}, E_M stand for the primary energy consumption amount of air-conditioning system, ventilation system, lighting system, hot water supply, elevator, and other (plug load). E_S stand for the reduction amount of primary energy consumption through PV and cogeneration system (Figure 4.9).

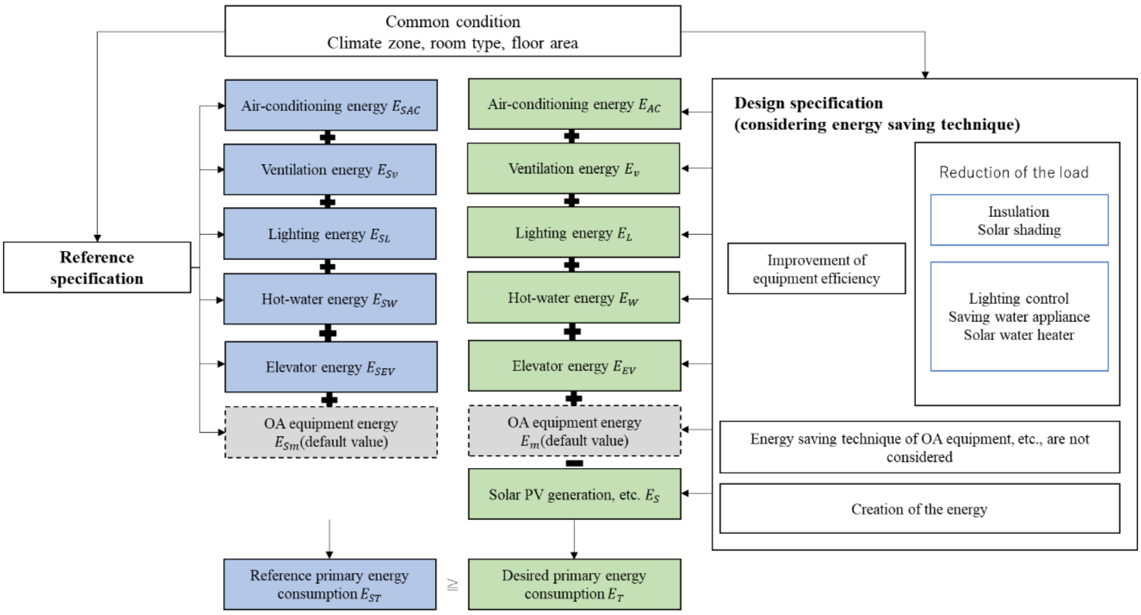


Figure 4.9 Calculation of Primary Energy Consumption for Commercial Buildings [16]

There are three-fold standards applied in the Building Energy Efficiency Act, energy consumption performance standards (BEC2013), certification standards, and residential construction client standard. Non-residential building is assessed based on the annual load standard Building PAL* Index (BPI) and Building Energy Index (BEI)[13].

$$\text{BPI}= \frac{Design\ PAL*}{Standard\ PAL*} \tag{4.3}$$

$$\text{BEI}= \frac{Design\ primary\ energy\ consumption\ of\ the\ building\ subject\ to\ assessment}{Standard\ primary\ energy\ consumption\ of\ the\ building\ subject\ to\ assessment}$$

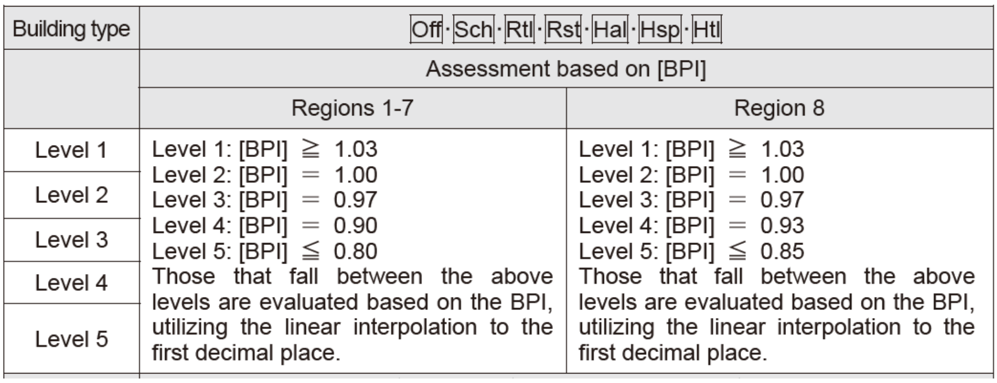
$$= \frac{E_T}{E_{ST}} = \frac{(E_{AC}+E_V+E_L+E_W+E_{EV}+E_M-E_S)\times 10^{-3}}{(E_{SAC}+E_{SV}+E_{SL}+E_{SW}+E_{SEV}+E_{SM})\times 10^{-3}} \tag{4.4}$$

For non-residential buildings, BEI should be equal to or less than 1 in BEC2013 which is mandatory requirement. Envelope performance is exempt from application in BEC2013 but should be equal to or less than 1 in the certification standard which is improvement plan. While BEI is no more than 0.8 in certification standard.

4.3.4. BEC2013 and CASBEE

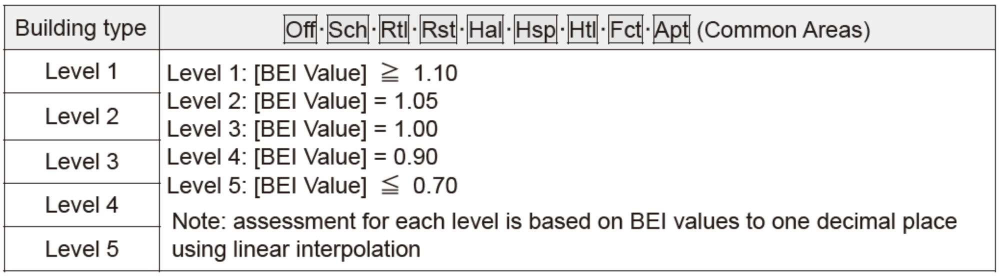
Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) is a green building rating system developed by the Japan Sustainable Building Consortium to assess the environmental efficiency of buildings. CASBEE assessment of energy is based on methods in accordance with BEC2013. Non-residential building is assessed based on the annual load standard BPI, which stand for Building PAL* Index as well [17]. Table 4.7 and Table 4.8 shows the evaluation standard of heat load on the outer surface of building and efficiency in building service system.

Table 4.7. Evaluation standard of heat load on the outer surface of buildings [17]



Building type	Off·Sch·Rtl·Rst·Hal·Hsp·Htl	
	Assessment based on [BPI]	
	Regions 1-7	Region 8
Level 1	Level 1: [BPI] ≧ 1.03 Level 2: [BPI] ＝ 1.00 Level 3: [BPI] ＝ 0.97 Level 4: [BPI] ＝ 0.90 Level 5: [BPI] ≦ 0.80 Those that fall between the above levels are evaluated based on the BPI, utilizing the linear interpolation to the first decimal place.	Level 1: [BPI] ≧ 1.03 Level 2: [BPI] ＝ 1.00 Level 3: [BPI] ＝ 0.97 Level 4: [BPI] ＝ 0.93 Level 5: [BPI] ≦ 0.85 Those that fall between the above levels are evaluated based on the BPI, utilizing the linear interpolation to the first decimal place.
Level 2		
Level 3		
Level 4		
Level 5		

Table 4.8. Evaluation standard of efficiency in building service system [17]



Building type	Off·Sch·Rtl·Rst·Hal·Hsp·Htl·Fct·Apt (Common Areas)
Level 1	Level 1: [BEI Value] ≧ 1.10 Level 2: [BEI Value] = 1.05 Level 3: [BEI Value] = 1.00 Level 4: [BEI Value] = 0.90 Level 5: [BEI Value] ≦ 0.70 Note: assessment for each level is based on BEI values to one decimal place using linear interpolation
Level 2	
Level 3	
Level 4	
Level 5	

4.4. The China Building Energy Efficiency Standard vs GB/T50378-2019

4.4.1.Development of the China building energy efficiency standard

The major developed countries firstly set building energy efficiency standard because of oil crisis in the 1970s. However, China developed the standards relatively later until the 1980s[11]. There are four stages of development.

1) research preparation stage (early 1980s to 1986). The focus of the work is to investigate the energy used by civil buildings and to study the formulation of building energy saving technology and standards.
2) pilot demonstration stage (1987-1992). The government promoted new wall materials and energy-saving buildings through "points (two pilot cities) and areas (eight provinces and cities)".
3) institutional establishment (1993-2005). The focus is to establish a legal, administrative and technical support system for building energy saving. During this period, China issued building energy efficiency standards covering climate zones, residential buildings and public buildings. and
4) improving the system and strengthening the implementation stage (from 2006 to now). The focus of the work is to improve the existing legal, administrative, technical and management systems for building energy conservation, implement building energy conservation standards and retrofit existing buildings, and apply green buildings and renewable energy in building energy conservation.

In 1997, the *Energy Conservation Law* was issued firstly. Following that, the *Renewable Energy Law* was issued in 2005. In the same year of 2005, the Regulations for the Civil Building Energy Efficiency (GB50189-2005) was developed, which proposed to reach the target of 50% energy saving. The current new version of this standard is GB50189-2015[18].

4.4.2. Thermal Climate Zone

Code for Thermal Design of Civil Building (GB50176-2016) adapt the building thermal design to the regional climate and ensure the basic indoor thermal environment requirements. This division is mainly applicable for thermal design of buildings, so it is based on the actual needs of thermal design of buildings and in accordance with the current relevant standards and codes. The thermal design of the building is mainly concerned with winter and summer insulation, which is mainly related to the temperature conditions in winter and summer. Therefore, with the average temperature of the coldest month (i.e., January) and hottest month (i.e., July) of the year as the main index of the partition, and the number of days with the average temperature ≤5℃ and ≥25℃ as the auxiliary index, the whole country is divided into five zones, i.e., serve cold, cold, hot summer cold winter, hot summer warm and winter, and mild in winter. Corresponding design requirements are put forward. There are two levels for the thermal zone division. The first level of zone indexes and design requirements are shown in Table 4.9. Compared with the index of the first class (the mean temperature of the coldest and hottest months), this index not only represents the degree of cold and hot climate, but also reflects the duration of cold and hot weather (Table 4.10). The zone diagram is shown in Figure 4.10. The secondary division is no longer expressed in the form of zoning map, but in the form of a table to give the area of each city. In this way, the understanding deviation caused by complex figures can be avoided[19].

Table 4.9.China thermal performance design partition first class indexes and requirement [19]

First class climate zone	Thermal Index	
	Primary index	Auxiliary index
Severe Cold (1)	$t_{min \cdot m} \leq -10°C$	$145 \leq d_{\leqslant 5}$
Cold Zone (2)	$-10°C < t_{min \cdot m} \leq 0°C$	$90 \leq d_{\leqslant 5} < 145$
Hot Summer Cold Winter (3)	$0°C < t_{min \cdot m} \leq 10°C$	$0 \leq d_{\leqslant 5} < 90$
	$25°C < t_{max \cdot m} \leq 30°C$	$40 \leq d_{\geqslant 25} < 110$
Hot Summer Warm Winter (4)	$10°C < t_{min \cdot m}$	$100 \leq d_{\geqslant 25} < 200$
	$25°C < t_{max \cdot m} \leq 29°C$	
Mild Temperature (5)	$0°C < t_{min \cdot m} \leq 13°C$	$0 \leq d_{\leqslant 5} < 90$
	$18°C < t_{max \cdot m} \leq 25°C$	

Table 4.10. China thermal performance design partition second class indexes and requirement[19]

Climate zone	**Thermal Index**	**Winter Requirement**	**Summer Requirement**
SC A（1A)	6000≤HDD18℃	Very high, must	Without considering
SC B（1B)	5000≤HDD18℃<6000	High, must	Without considering
SC B（1B)	3800≤HDD18℃<5000;	Must be satisfied	Can be without considering
C A (2A)	2000≤HDD18℃<3800; CDD26℃≤90	Shall be satisfied	Can be without considering
C B (2B)	2000≤HDD18℃<3800; CDD26℃>90	Shall be satisfied	Appropriately considering both natural ventilation and shading
HSCW A (3A)	1200≤HDD18℃<2000	Shall be satisfied	Shall be satisfied, and attach importance to natural ventilation and shading
HSCW B (3B)	700≤HDD18℃<1200	Shall be satisfied	Shall be satisfied, and emphasize natural ventilation and shading
HSWW A (4A)	500≤HDD18℃<700	Appropriately be satisfied	Shall be satisfied, and emphasize natural ventilation and shading
HSWW B (4B)	HDD18℃<500	Can be without considering	Shall be satisfied, and emphasize natural ventilation and shading
M A (5A)	CDD26℃<10； 700≤HDD18℃<2000	Shall be satisfied	Without considering
M B (5B)	CDD26℃<10； HDD18℃<700	Appropriately be satisfied	Can be without considering

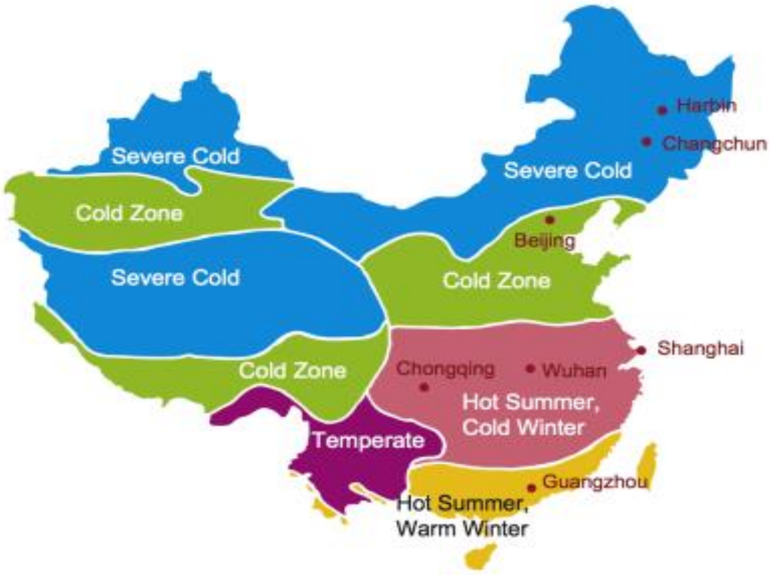
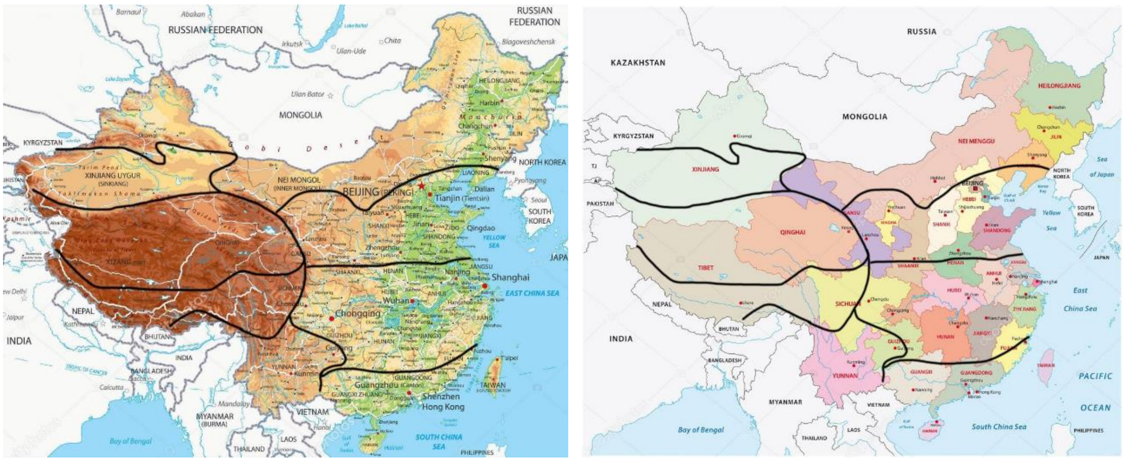


Figure 4.10 China thermal climate zone map

In order to further understand the relationship between climate zoning and Chinese topography and administrative zoning, a comparison is made between climate zoning maps and administrative zoning maps and topographic maps. It can be seen from Figure 4.11b that the boundary of climate division and administrative division rarely coincide, but in some areas the trend is roughly the same. For example: Qinghai and Gansu, Guangdong and Jiangxi, Hunan and so on.

Figure 4.11a is the result of overlapping the thermal zones with the topographic map of China. It can be seen that the boundary of thermal zones is highly consistent with the topographic conditions of China. For example, the dividing line between severe cold and cold zones in the east is basically in line with the direction of the ancient Great Wall in the north, which is often the boundary of the agricultural and pastoral areas in the north. The line between the cold and the hot summer cold winter zones in the east basically coincides with the Qinling Mountains-Huaihe River, which is usually regarded as the dividing line between the north and the south of China. The dividing line between hot summer cold winter and hot summer warm winter zones in the east is located on the line of Nanling Mountains. The other major boundaries are in line with the boundaries of the Qinghai-Tibet plateau, the Yunnan-Guizhou plateau and the Tianshan Mountains.

Due to the influence of topography on climate, China's climate zones classification is basically based on meteorological parameters, without considering the factors of provincial administrative regionalization.



a. topography map b. administrative map

Figure 4.11 The relationship between thermal zones and topography and administrative zones in China

4.4.3. Civil Building Energy Efficiency (GB50189-2015)

Civil Building Energy Efficiency is the first building design reference for non-residential buildings. It is updated the newest version in 2015. The standard establishes a typical public building model database representing the characteristics and distribution characteristics of public buildings in China, and determines the energy saving target on this basis. The limits of the thermal performance of the building envelope were formulated, and the requirements were made according to the building classification and the building thermal zone (Table 4.11).

Table 4.11.China thermal performance design partition indexes and requirement[20]

Climate zone	Wall U	Window U	Window SHGC (East, South, West / North)
Severe Cold (A, B)	0.38	2.2	NA
Severe Cold (C)	0.43	2.3	NA
Cold (A, B)	0.5	2.4	0.48/-
Hot Summer Cold Winter (A, B)	0.6	2.6	0.40/0.44
Hot Summer Warm Winter (A, B)	0.8	3	0.35/0.44
Temperature (Mild) (A, B)	0.8	3	0.40/0.44

4.4.4. GB50189-2015 vs GB/T50378-2019

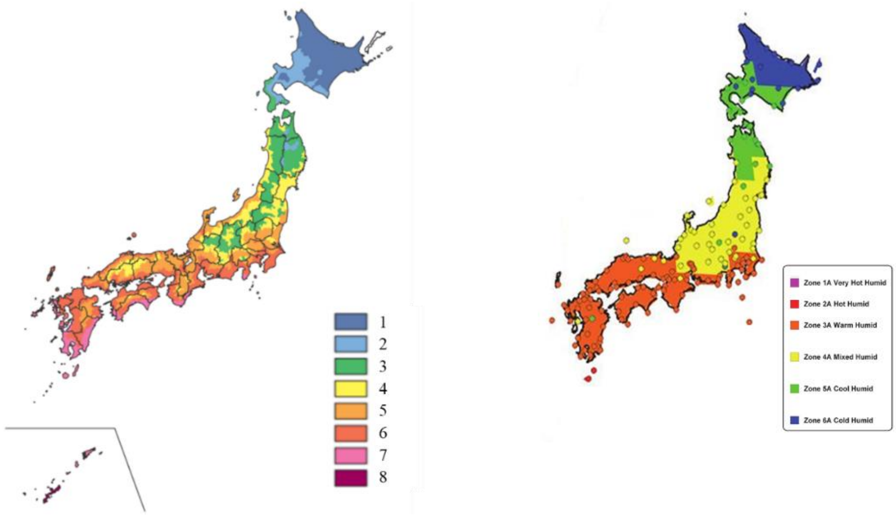
Green buildings in China are mainly aimed at newly built residential buildings, office buildings, shopping malls, hotels and other public buildings. The concept is to maximize resource conservation (energy saving, land saving, water saving and material saving), environmental protection and pollution reduction, and improve living comfort, health and safety during the entire life cycle of the building (planning and design, construction process, operation stage, demolition). China's green building development has entered a rapid development stage since 2004, when it was clearly proposed to vigorously develop energy-saving and land-saving housing, and stricter standards were formulated and enforced. The first green building rating system in China is *Assessment Standard for Green Building GB50378-2006* and updated in 2014 and 2019. The current new version of green building rating system is *Assessment Standard for Green Building GB50378-2019*

The green building requirement in terms of energy saving related to the building envelope design is the credit of Thermal Performance Optimization of Envelope (section 7.2.4 of standard). The thermal performance of the envelope is required to be increased by 5%, 10% or 15% compared with GB50189-2015 (Table 4.11), with 5 points, 10 points and 15 points respectively.

4.5.Comparative Analysis

4.5.1. Comparison of Climate Zone

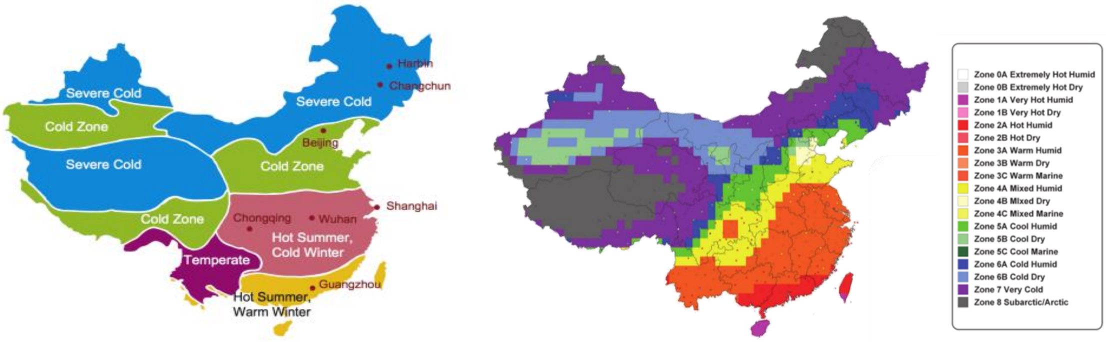
Figure 4.12 shows two kinds of thermal zones classification method according to Japan and America. The comparison shows that Japan has a more detailed classification of its own climate. ASHRAE Zone 3A area almost covers zone 5, 6, and 7 of BEC2013. Moreover, the area of ASHRAE 4A is subdivided into zone 3, 4, 5, and 6 of BEC2013. According to the partition map of ASHRAE, it can be seen that it is highly correlated with the latitude distribution. The boundary of climate partition of ASHRAE is basically parallel in east-west direction, that is, parallel in latitude. In contrast, the zoning map of BEC2013 shows that the thermal zones, besides being affected by latitude, also show the rule of change from the central land to the coast. The effects of these two climatic divisions on building energy consumption will be discussed in detail in chapter 5.



a. BEC2013 b. ASHRAE 169-2013

Figure 4.12 Japan climate zone map[5]

Figure 4.13 shows two kinds of thermal zones classification method according to China and America. The comparison shows that China has a more detailed classification of its own climate. According to the partition map of GB 50176-2016, it can be seen that it is almost correlated with the latitude distribution. The boundary of climate partition of GB 50176-2016 is basically parallel in east-west direction, that is, parallel in latitude. In contrast, the zoning map of ASHRAE shows that the thermal zones, besides being affected by latitude, also partially adjusted according to the boundary of administrative divisions. In the southeast region of China, the boundaries of 6A, 5A, 4A, and 3A of ASHRAE thermal zones are obvious in the northeast - southwest direction. The dividing lines of 4A and 5A basically coincide with the administrative divisions. This led to a very different division of thermal zone from GB 50176-2016, especially in China's hot summer and cold winter zone areas, mild zone areas, and cold zone areas in the east.



b. GB 50176-2016 b. ASHRAE 169-2013

Figure 4.13 China climate zone map[5]

4.5.2. Comparison of Building Energy Standard in Terms of Building Envelopes

In the America ASHRAE 90.1 Standard, it had regulations on the ceiling, wall, ground, and windows in the form of both thermal resistance (R-value) and thermal transmittance (U-value) for each climate zone condition. The Japanese BEC2013 standard had regulations on the part of building envelopes with a composite indicator PAL for non-residential buildings, which makes the comparison among the three countries comprehensively. Generally, the requirement of residential building is higher than non-residential buildings in terms of building envelope design. In order to see the difference trend of energy saving design standards among the three countries, the difference of non-residential building design standards will be predicted by the comparison of residential design standards. For residential buildings, BEC2013 standard regulates the part of building envelopes with U-value according to different climate zone. 1200≤HDD18℃<2000 (Zone 3 of America, Zone 6 of Japan, Zone HSCW of China) climate zone is taken as the comparison example. Design Standard for Energy Efficiency of Residential Building in Hot Summer and Cold Winter Zone JGJ134-2010 is the current standard for residential building in China.

Table 4.12. Comparison of thermal performance requirements of residential building in $1200 \leq HDD18℃ < 2000$ zone area of America, Japan and China (W/m^2K)

Envelopes	ASHRAE 90.1-2010	BEC 2013	JGJ134-2010
Ceiling/Roof	0.153-0.312	0.24	0.8-1.0
Wall	0.365-0.592	0.53	1.0-1.5
Floor	0.188-0.496	0.24-0.34	1.5-2.0
Fenestration	3.41-3.69	4.07-6.51	2.3-4.7
Door			2.0-3.0
Window (SHGC)	0.25	SHGC < 0.74 or with sunshade component; SHGC < 0.49 or SHGC < 0.74 with sunshade component or windows with blinds	Summer:0.25-0.45 Winter: ≥ 0.6
Skylight	3.92	——	——
Opening ratio	——	——	0.45(S);0.35(E/W);0.4(N)

Table 4.13.Comparison of thermal performance requirements of non-residential building in $1200 \leq HDD18℃ < 2000$ zone area of America and China (W/m^2K)（Steel-framed wall, vertical fenestration 0% to 40% of wall with metal framing and operable window)）

Envelopes	ASHRAE 90.1-2010	GB50189-2015
Ceiling/Roof	0.312	0.4-0.5
Wall	0.479	0.6-0.8
Floor	0.296	0.7
Fenestration	3.41	2.6
Window (SHGC)	0.25	0.40/0.44 （E, S, W/N）
Skylight	3.92	2.6

Table 4.12 shows that the thermal performance requirement of building envelopes in ASHRAE 90.1-2010 standard is higher than that of the Japanese and Chinese Standard for residential buildings. Table 4.13 compare the ASHRAE 90.1-2010 and GB50189-2015 which shows that the same result for non-residential building. However, the fenestration thermal transmittance requirement in GB50189-2015 is smaller than that of ASHRAE 90.1-2010.

In the America ASHRAE 90.1 Standard, there is classifications for the roof and wall. Roofs are divided into insulation entirely above deck, metal building, attic and other. While walls include mass, metal building, steel-framed, wood-framed and other for above grade and below-grade wall. Additionally, floors are divided mass, steel joist, wood-framed and others as well. In the residential part of Japanese BEC 2013, there are U-value requirement for different construction structure. Comparatively, the roof and wall classification in China is simpler. However, there is additional requirement on air tightness of windows and doors in Chinese standard that America and Japan do not have.

4.5.3. Comparison of Green Building Standard in Terms of Building Envelopes

LEED and CASBEE adopt composite indicators to evaluate the energy efficiency of the building including building envelopes contributes. While the thermal performance improvement can be evaluate based on the percentage of U-value decrease directly in GB50189-2019. Another evaluation option is similar with LEED and CASBEE that based on the whole building energy saving percentage by simulation. The requirement of green building rating systems in these three countries

4.6. Summary

This chapter summarized the relationship among climate, building energy standard and green building standard. energy standard for buildings. The impact of climate is mainly reflected in the climate division in the energy standard for buildings. The energy-saving indicators of green buildings are generally based on building standards to further enhance the requirements.

The climate zone division are roughly coinciding with the topographic trend in America, Japan and China. Only in America, the climate zone is consistent with administrative division.

Japan has a more detailed classification of its own climate than ARSHRAE. ASHRAE Zone 3A area almost covers zone 5, 6, and 7 of BEC. Moreover, the area of ASHRAE 4A is subdivided into zone 3, 4, 5, and 6 of BEC2013.

ASHRAE shows a similar division for the north China. But in the middle area is quite different. Zone 4A across China’s three climate zones of hot summer and cold winter, mild, and cold zone areas.

Actually, in the strategic design stage of project, the overall building energy consumption simulation method required powerful computer and is time-consuming. Meanwhile, the simulation calculation ability of the architect was highly required. There needs to be a general conclusion as to how much the improvement of the envelope can contribute to the overall building energy saving, and how its contribution capacity will change with the change of climate zone and latitude. These questions need to be further investigated.

The common point of green building standards in these three countries is that they all require further optimization of envelope performance on the basis of existing building energy-saving design standards, so as to achieve the purpose of energy saving. However, the question is whether such design requirements can be applied everywhere. If passive design strategies such as ventilation are adopted to realize energy saving, will excessive improvement of the performance of the envelope or high air tightness design affect heat dissipation in ventilated buildings or even cause additional energy consumption in ventilated buildings? These questions also need to be discussed in detail.

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Chapter 5. Evaluation of Climate Impact on Building Energy Consumption

5.1. Introduction

In the strategic design stage of project, the overall building energy consumption simulation method required powerful computer and is time-consuming. Meanwhile, the simulation calculation ability of the architect was highly required. There needs to be a general conclusion as to how much the improvement of the envelope can contribute to the overall building energy saving, and how its contribution capacity will change with the change of climate zone and latitude. These questions will be discussed in this chapter. High energy consumption, climate change, environmental pollution, greenhouse gas emissions (GHG), rising population, and rapid urbanization nowadays constitute the main concern of society[1,2]. It has indicated that the global demand for oil is expected to grow by 39% from 2007 to 2035, and by 50% increased for coal and natural gas[3]. The United States accounts for a quarter of the world's energy consumption and is the world's largest energy consumer[4]. In 2018, the energy demand grew by 2.9% that largely driven by China, US and India, accounted for two thirds of the growth together. The most notable increase compared with the recent historical average was in the United States, where energy consumption rose by an astonishing 3.5 percent, the fastest growth in 30 years and in sharp contrast to the downward trend of the past decade[5].

A greater requirement in the energy conservation has been reflected in many sectors, including the building sector which is criticized a leading cause of these issues[1,6]. In global perspectives, buildings and construction account for 36% of global final energy use and 39% of CO_2 emissions in 2017[7]. In the last twenty years, the increase in energy consumption in buildings has been modest in US and EU countries[3,8,9]. The staggering increase in energy consumption in 2018 has a lot to do with weather impacts. In particular, there were unusually large number of hot and cold days in many of the world's major demand centers, especially in the United States, China and Russia, where increased demand for cooling and heating services helped explain the strong growth in energy consumption in each of these countries. In the US, unusually, both heating and cooling days have increased (as defined by the National Oceanic and Atmospheric Administration). In the past few years, hot weather has tended to coincide with cold weather and vice versa. As a result, the combined number of heating and cooling days in the US in 2018 reached the highest since the 1950s, boosting energy demand[5].

The design strategies for building with energy saving purpose relies heavily on the characteristics of their local climate, which varies considerably from region to region. Researchers has investigated various building design strategies and technologies across different climate zones in the world. The interests include building envelope thermal performance[10–14], photovoltaic system implementation[15–17], natural ventilation potentials[18–22], etc., in a specific climate type or comparative study in various climate zones within a country or in different countries. Additionally, some researchers have studied building energy consumption with the perspective of climate change.

Existing studies focus largely on building energy consumption at a specific region or compare several locations. However, there is less study on summarizing the regional distribution characteristics with the change of location with different climate zones and latitude gradient. It is critical to understand the variation rules in order to utilize appropriate technology more effectively. The object of this study is to assist policy makers and architects in recognizing quantitatively the building energy consumption distribution rules with the latitude gradient, and in properly developing sustainable strategies considering local climatic characteristics.

In this study, we have provided and early effort to estimate and understand regional building energy consumption with the change of climate zone and latitude by analyzing available climate data at 138 locations from the United States. Building energy consumption in different locations were calculated using Building Energy Simulation (BES). The paper is organized as follows. Firstly, we describe the methodology with regard to climate data, BES, and energy consumption calculation. Next, we present and discuss the results by different climate zones and latitude gradient in the United States, followed by a summary of key findings at the end.

5.2.Simulation model

The simulation model adopted the prototype building developed by the U.S. Department of Energy (DOE). It was developed for most common buildings to serve as starting points for analysis related to energy efficiency research. The intent of the reference building models is to characterize the energy performance of typical building types under typical operations. It combined several sources in a sensible way to represent typical performance. To better organize the efforts, it divided the model inputs into program, form, fabric, and equipment.

Table 5.1. Building energy model input categories

Program	Form	Fabric	Equipment
Location	Number of floors	Exterior walls	Lighting
Total floor area	Aspect ratio	Roof	HVAC systems types
Plug and process loads	Window fraction	Floors	Water heating equipment
Ventilation requirements	Window locations	Windows	Refrigeration
Occupancy	Shading	Interior partitions	Component efficiency
Space environmental conditions	Floor height	Internal mass	Control settings
Service hot water demand	orientation	Infiltration	
Operating schedules			

The building program includes the activity, location, occupancy, plug and process loads, service water heating demand, and schedules. Figure 5.1 shows the example of HVAC heating and cooling setpoints schedule (Figure 5.1).

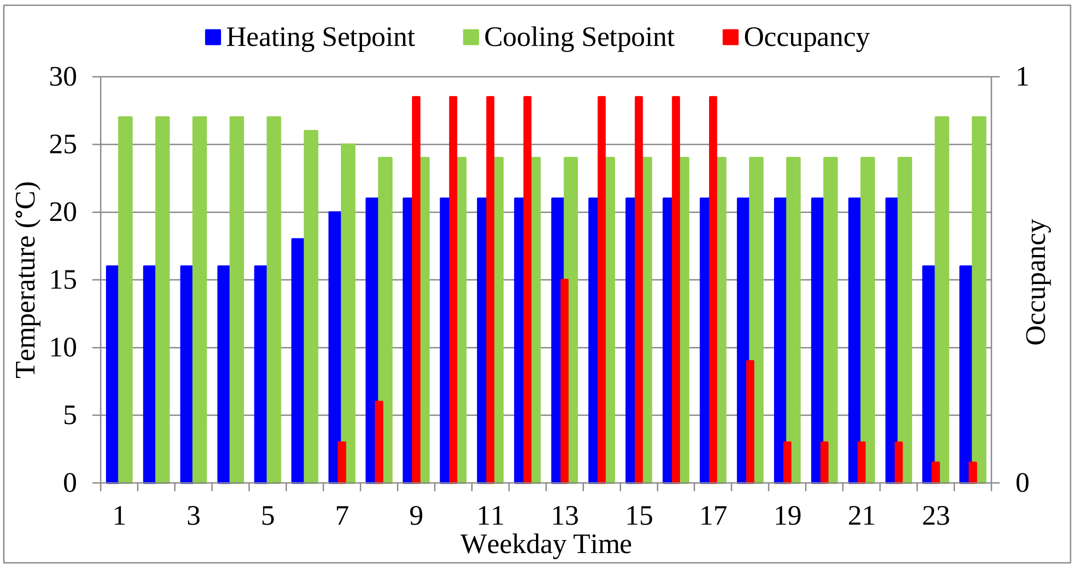


Figure 5.1. HVAC heating and cooling setpoint schedule

The total source energy consumption is the sum of heating and cooling load. The heating load consists two parts, electricity heating for dehumidify of reheat and gas heating for room air heating. The source energy was calculated with a conversion factor. Therefore, the heating source energy consumption is calculated as:

$$E_{heating} = \text{Electricity for heating} * 3.167 + \text{Gas for heating} * 1.084 \tag{5.1}$$

Cooling source energy consumption is calculated as:

$$E_{cooling} = \text{Electricity for cooling} * 3.167 \tag{5.2}$$

Total source energy consumption is calculated as:

$$\mathrm{E} = E_{heating} + E_{cooling} \tag{5.3}$$

5.3. Simulation result and discussion

Figure 5.2 shows the geographic map of the 138 selected locations in the United States and their total source energy consumption (reflected by the size of the points). The principle of locations selection is to select at least one station or more at each latitude. At the same time, with 5-degree latitude as a section, at least one representative station is selected for all climate types within each interval. Here, the first part discusses the distribution characteristics of building energy consumption with the change of climate zone. The second part shows the distribution rules with latitude gradient.

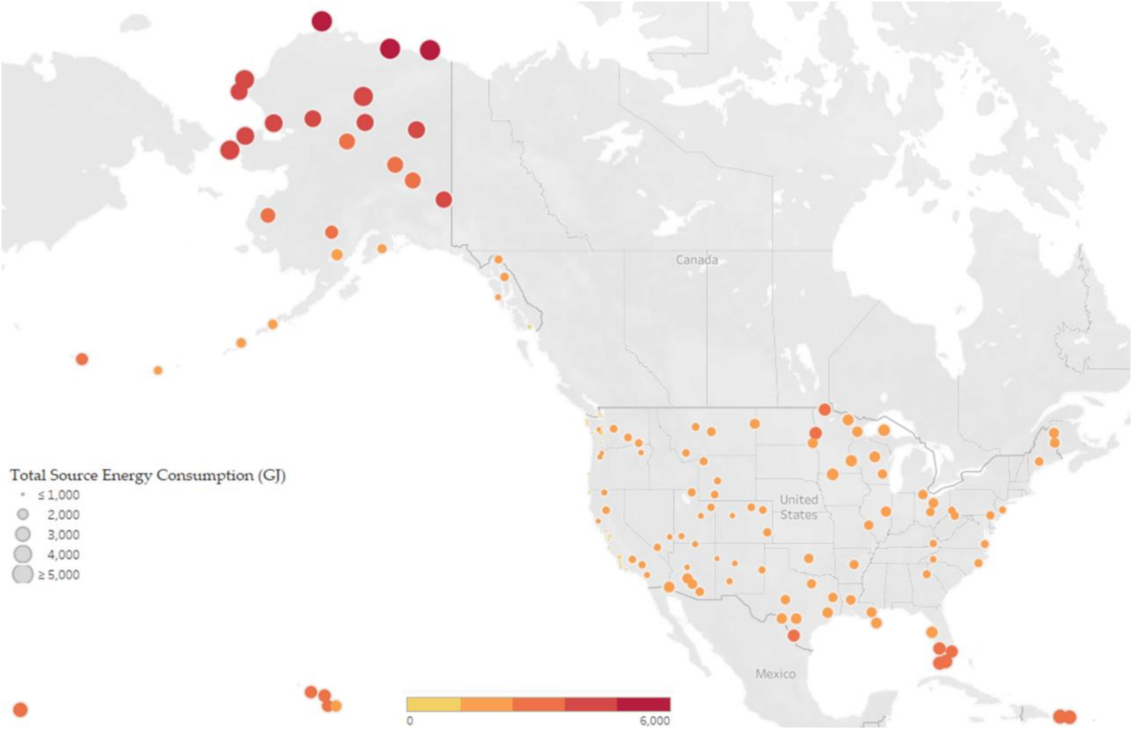


Figure 5.2. Geographic map of total source energy consumption in 183 locations of U.S.

5.3.1. Energy consumption distribution rules with climate zones changes

Figure 5.3 presents the total source energy consumption with box plot at each climate zones. Clear differences in energy consumption are observed in hot climate zone (Zone 1 and 2) and subarctic climate zone (Zone 8), where consume more energy than the others. There is no significant difference in warm (Zone 3), mixed (Zone 4) and cold (Zone 5 and 6) climate zone area. However, if focus on Zone 3 for example, considering the influence of humidity on energy consumption, it is impossible to find out an obvious distribution rule that the energy consumption decreases regularly with A, B, C (Humid, Dry and Marine) climate types. The same trend is in Zone 4 and Zone 5 as well. It reveals that the energy consumption in these areas are mainly influenced by the humidity, larger than temperature. Figure 5.4 and Figure 5.5 shows details of energy consumption for heating and cooling, separately. Zone A is always consuming the most amount of heating energy compared with Zone B and Zone C. The heating source energy increases generally with the zone number from 1 to 8. Zone 7 and Zone 8 shows dramatical grow of heating energy consumption. On the contrary, the trend of the cooling source energy consumption is opposite. The most amount of cooling energy consumption occurs at Zone 1 and decrease generally with the zone number increase. Zone A and Zone B in each climate zone consume similar amount of energy for cooling, but Zone C consumes lower clearly than the other two zone types.

From the perspective of climatic zoning in terms of humidity, whether it is cooling and heating energy consumption or total energy consumption, it shows a significant distribution rules with the change of humidity. From the perspective of climatic zoning in terms of degree days, there is a clear distribution and change rule of building cooling and heating energy consumption with climatic zoning. However, the distribution rule of total building energy consumption and climatic zoning is not obvious. Therefore, the following step we introduced a new perspective from the latitude gradient, to investigate the variation characteristics of energy consumption change with latitude.

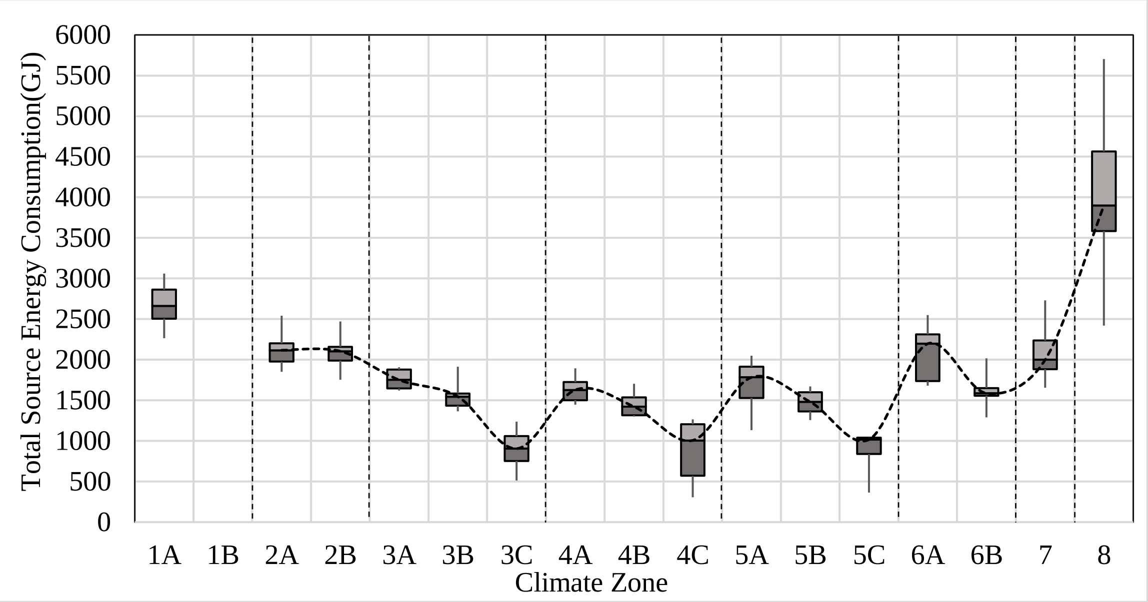


Figure 5.3. Office Building Source Energy Consumption in Each Climate Zone in U.S.

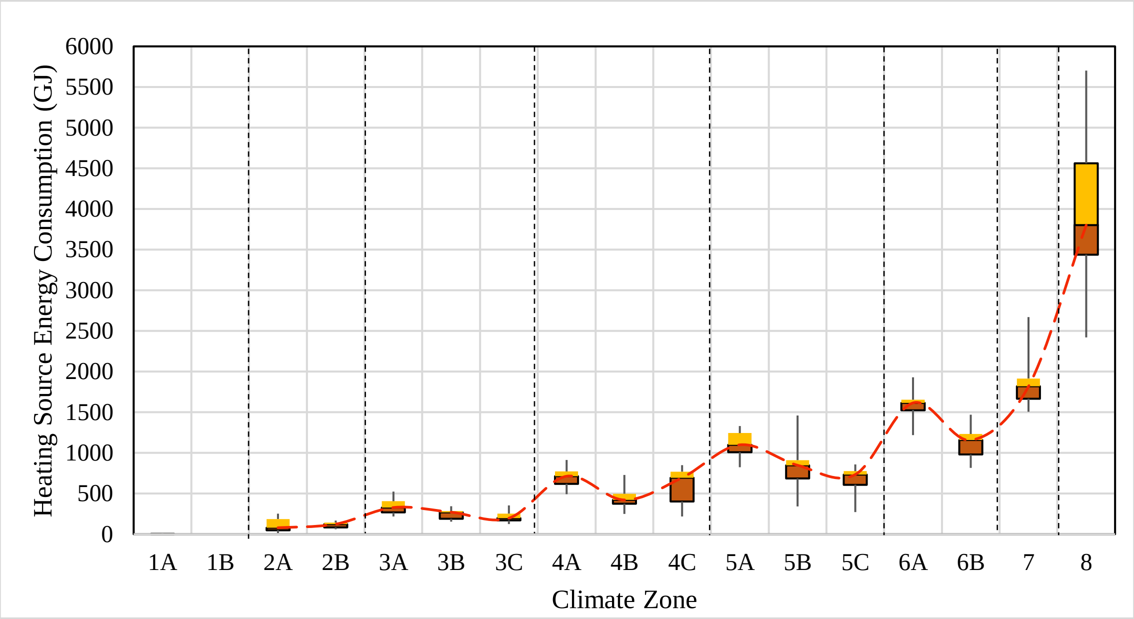


Figure 5.4. Office Building Heating Source Energy Consumption in Each Climate Zone in U.S.

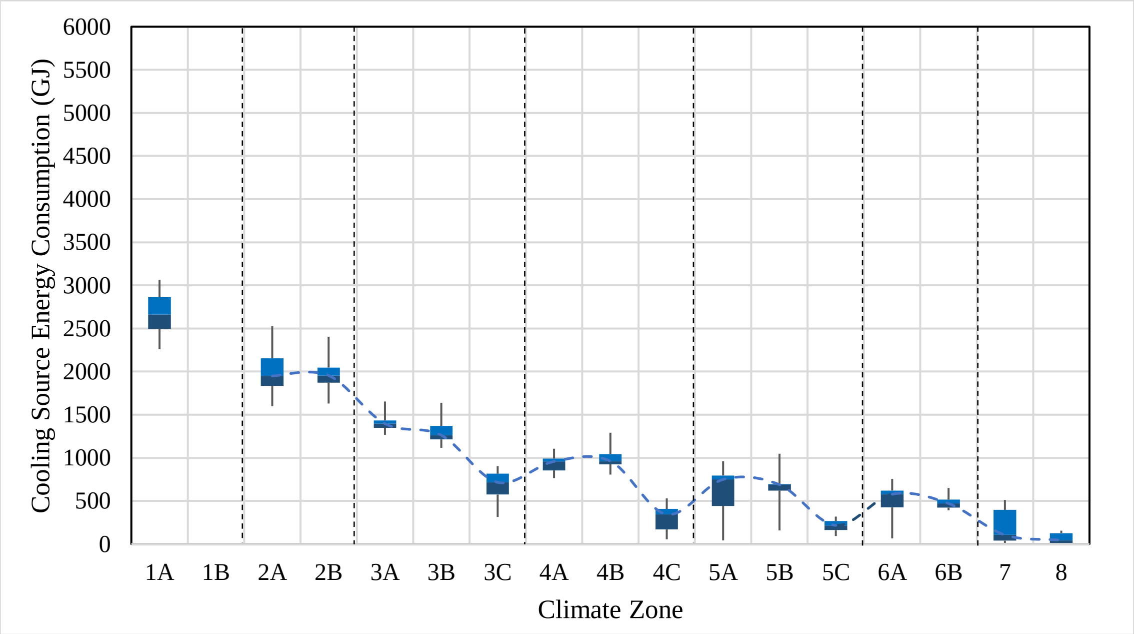


Figure 5.5. Office Building Cooling Source Energy Consumption in Each Climate Zone in U.S.

Figure 5.6, Figure 5.7 and Figure 5.8 show the fitting analysis result of energy consumption and latitude distribution of Climate type A, B and C, respectively. The fitting degree is 0.8-0.9, which means there is strong correlation between the cooling and heating energy consumption and the latitude gradient. The areas of latitude 30 to 50 degree include all of the three climate types of A, B and C (red dash frame highlighted). Compared with Zone B, Zone A spend more heating energy but similar amount energy of cooling energy with Zone B. According to the definition of three climate types (Figure 5.9), Zone A has higher humidity, which needs extra heating energy to dehumidify, resulting in higher heating energy consumption. Zone C is a marine climate with milder temperatures in summer and lower energy consumption in cooling.

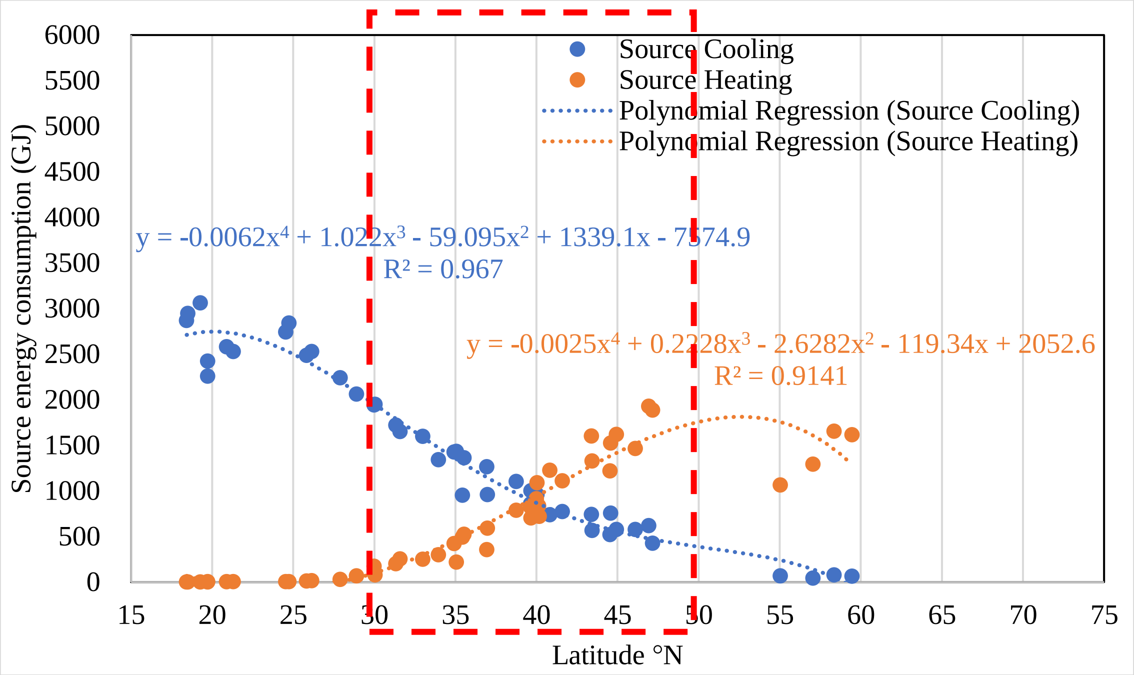


Figure 5.6.Fitting analysis of energy consumption and latitude distribution of Climate Type A

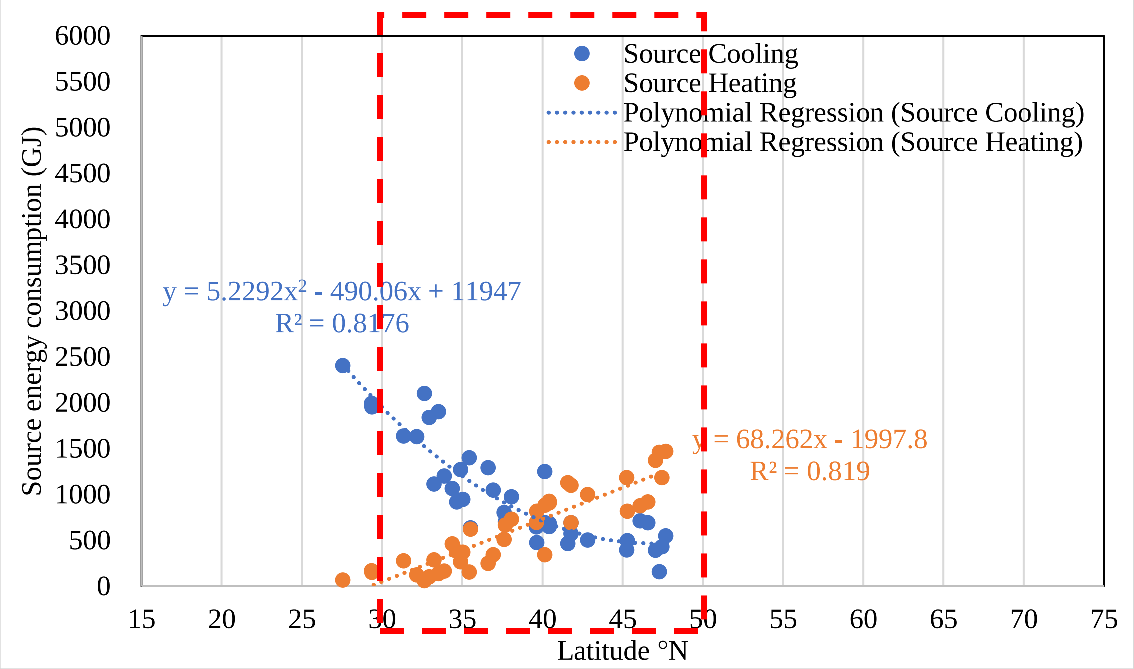


Figure 5.7.Fitting analysis of energy consumption and latitude distribution of Climate Type B

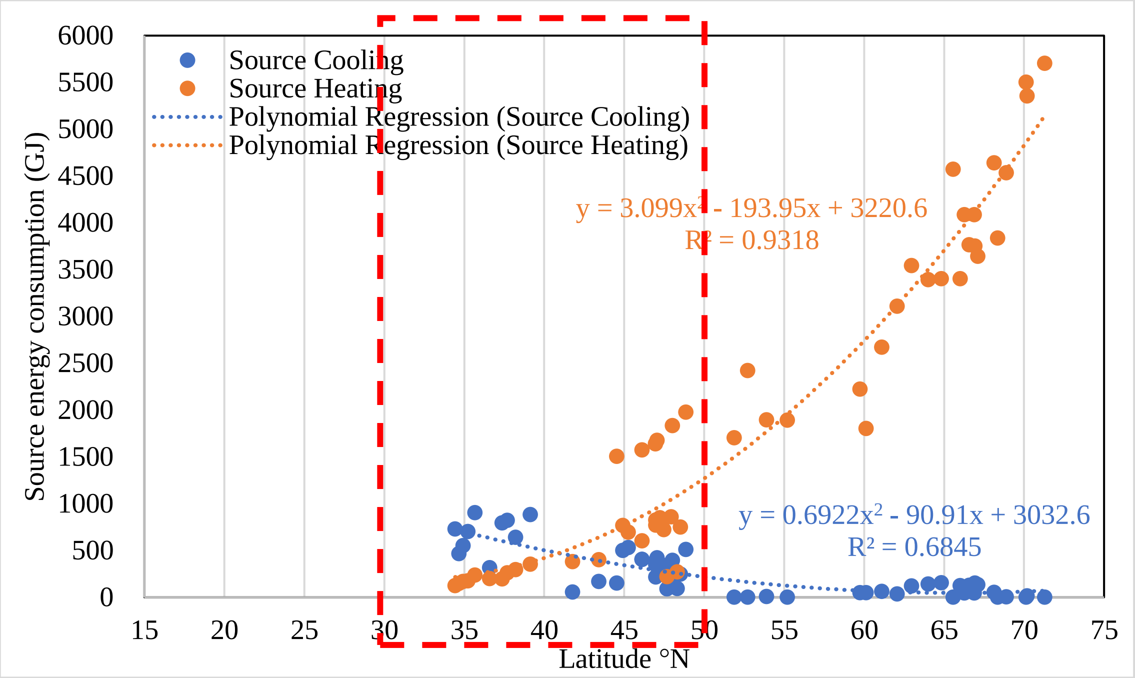
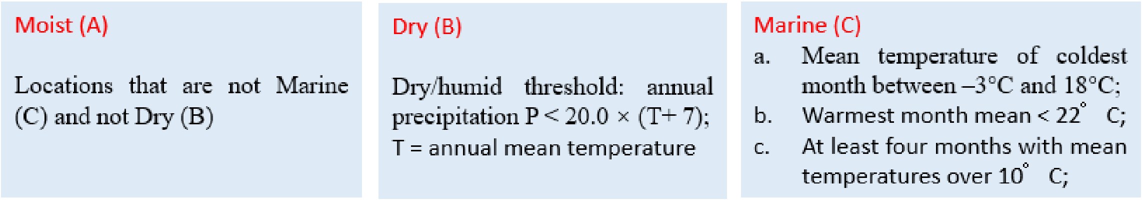


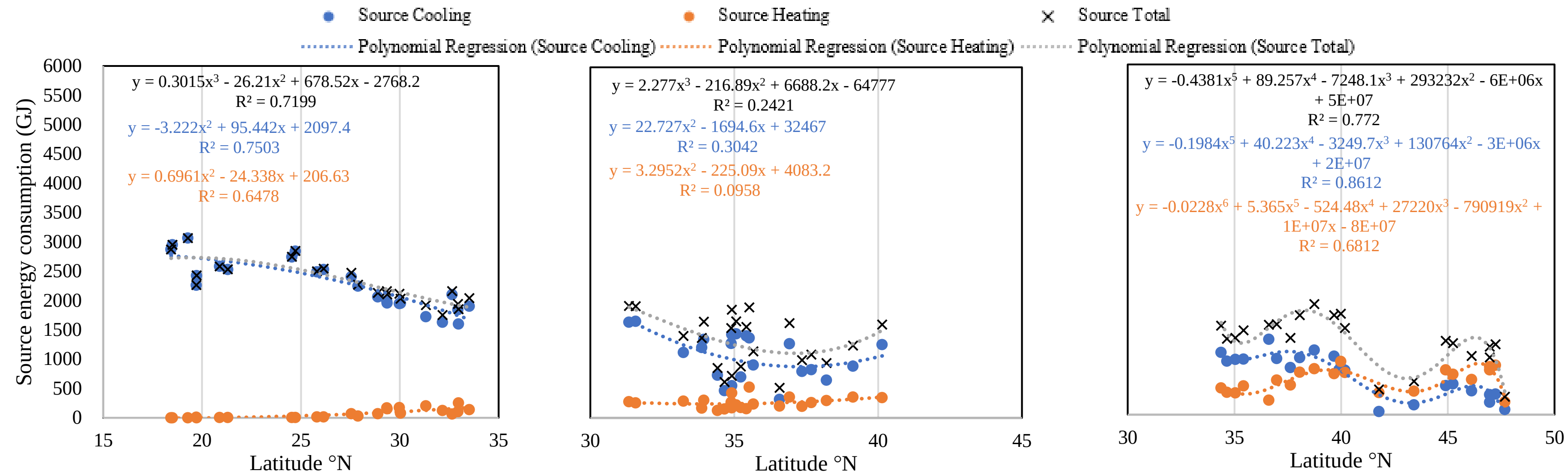
Figure 5.8.Fitting analysis of energy consumption and latitude distribution of Climate Type C



Moist (A)	Dry (B)	Marine (C)
Locations that are not Marine (C) and not Dry (B)	Dry/humid threshold: annual precipitation P < 20.0 × (T+ 7); T = annual mean temperature	a. Mean temperature of coldest month between –3°C and 18°C; b. Warmest month mean < 22° C; c. At least four months with mean temperatures over 10° C;

Figure 5.9.Definition of A, B, C climate types

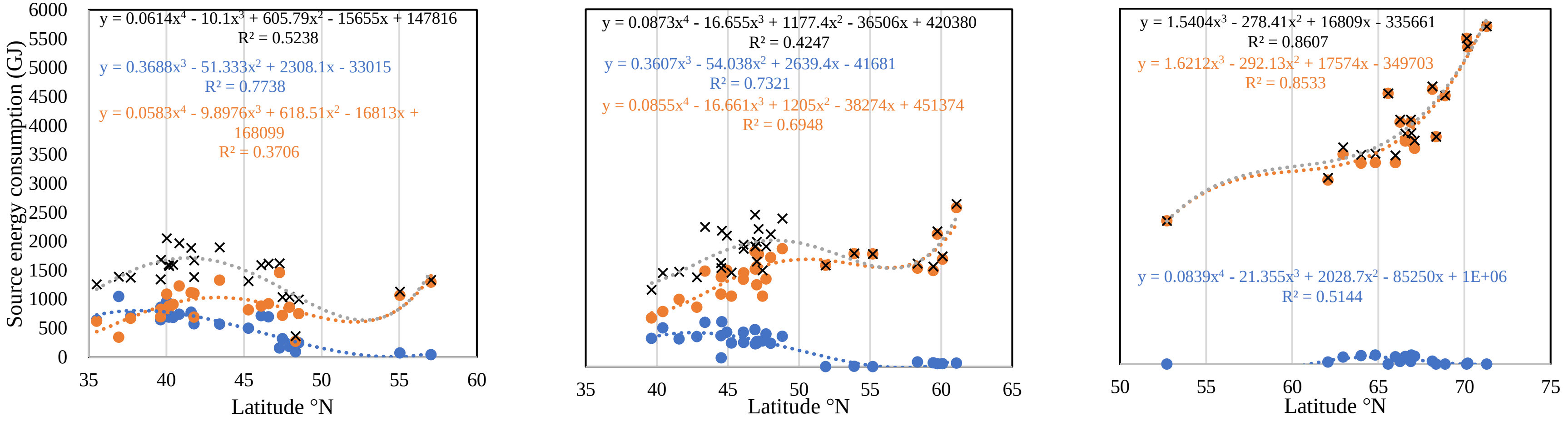
Figure 5.10 shows fitting analysis result of energy consumption and latitude distribution of different climate zones. It reveals a relative high correlation between energy consumption and latitude gradient in every climate zone. The fitting degree is from 0.6 to 0.9.



a. Climate 1-2 (A, B)

b. Climate 3 (A, B, C)

c. Climate 4 (A, B, C)



d. Climate 5 (A, B, C)

e. Climate 6 (A, B)-7

f. Climate 8

Figure 5.10. Fitting analysis of energy consumption and latitude distribution of different climate zone

5.3.2. Energy consumption distribution rules with latitude gradient

The area of U.S. distributed between north latitude of 15 degrees and 75 degrees. Figure 5.11 illustrates the latitude distribution of 8 climate zones. The United States locations and climate zones cited from ASHRAE 169-2013 Climate Data for Building Design Standard. Zone 4 mainly distributes in 35-40 latitude region. 35-45 latitude region include the most kinds of climate zone. There is no obvious correlation between climatic zoning and latitude.

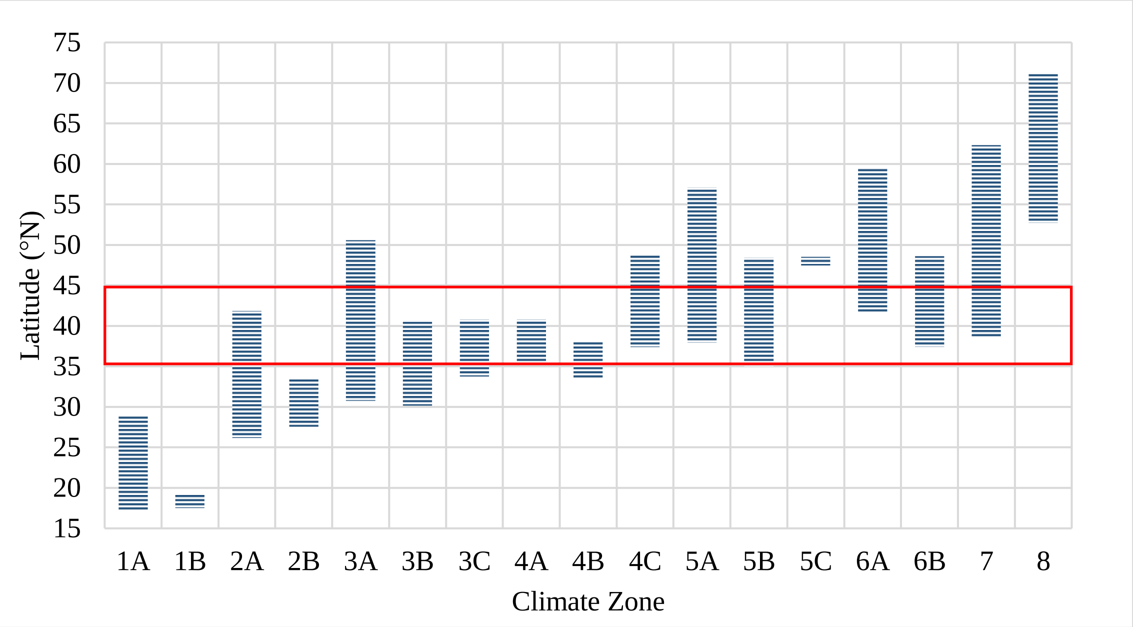
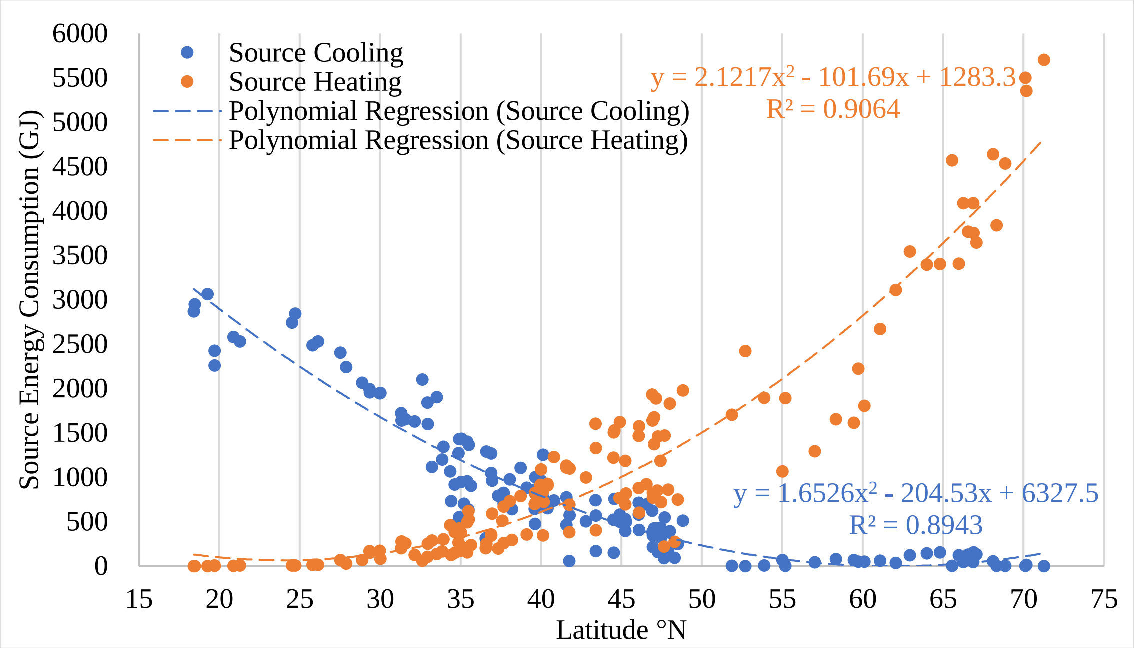
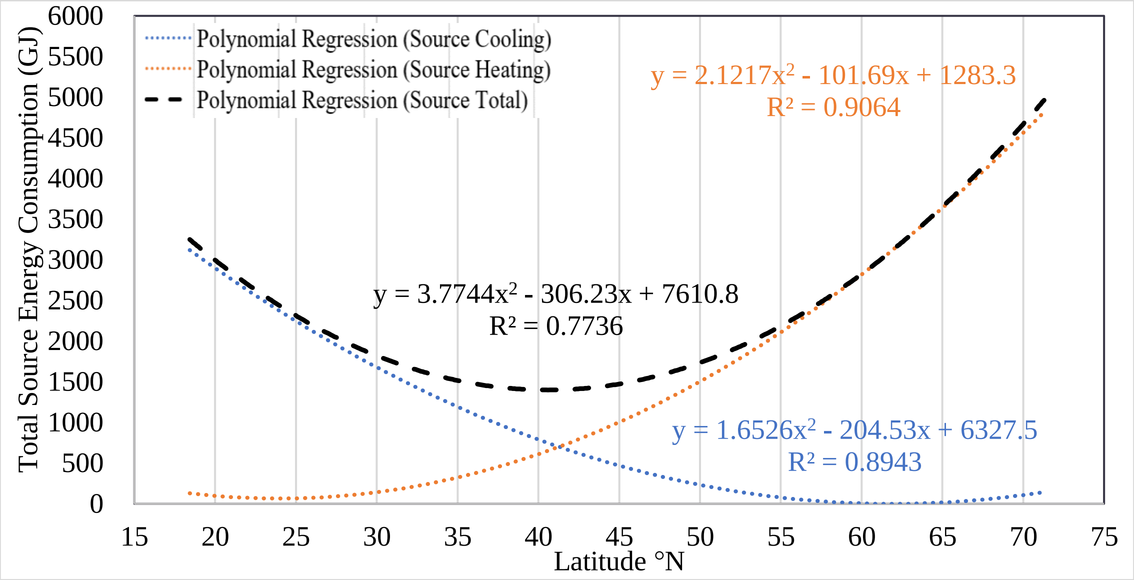


Figure 5.11.Latitude distribution of different climate zones

Figure 5.12 shows the fit relationship between building energy consumption and latitude changes. Obviously, there is a strong correlation between cooling and heating energy consumption and latitude. The fitting degree of both heating and cooling energy consumption with latitude is closed to 0.9 through the fitting test. In terms of the total energy consumption, the lowest consumption of total energy consumption appears in the mid-latitude range between 35 to 45 degree. Then it gradually increases when changing to higher latitudes and lower latitudes area. The fitting degree of total energy consumption is 0.77 with latitude gradient. Higher latitude area consumes more energy than other places. The highest latitude zone of 70-75 degree consumes approximately 2 times than the consumption in the lowest zone of 15-20 degree, which mainly driven by the heating energy consumption.



a. Heating and Cooling source energy consumption distribution with latitude gradient



b. Total and heating and cooling source energy consumption polynomial regression

Figure 5.12. Fitting analysis of energy consumption with latitude gradient in U.S.

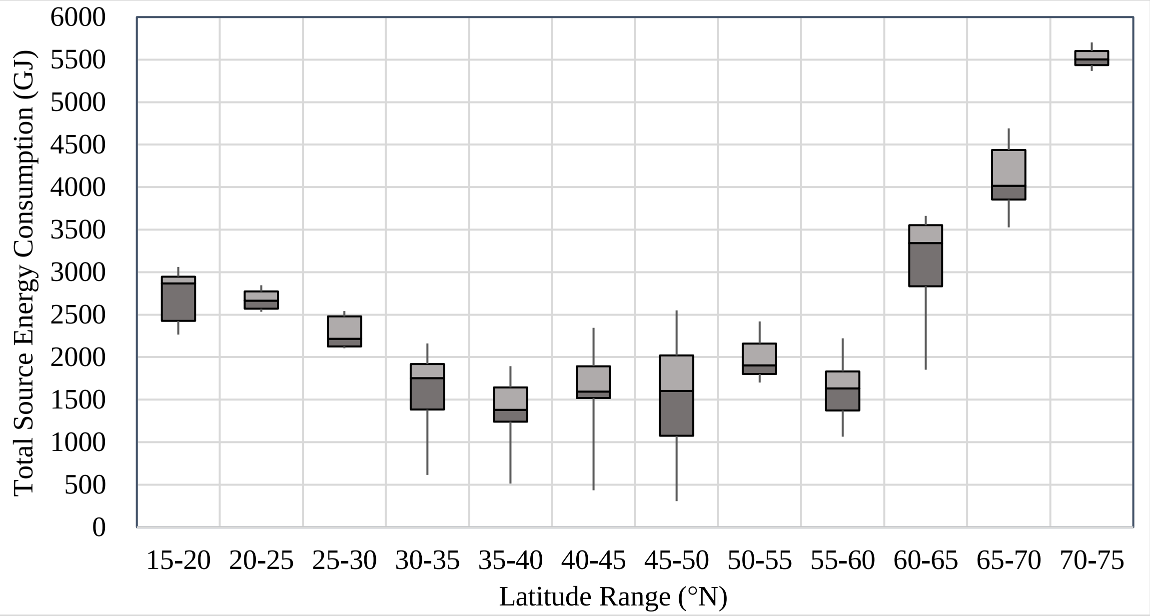


Figure 5.13. Energy consumption range in different latitude division

The area of the United States was divided into 12 intervals based on a 5-degree latitude, and the annual energy consumption of the same building in different intervals is counted. Figure 5.13 shows that in the middle latitude area, the relationship between energy consumption and latitude is not obvious. Moving to lower and higher latitude, the total energy consumption increased generally. Higher latitude area consumes more energy than other places. The highest latitude zone of 70-75 degree consumes approximately 2 times than the consumption in the lowest zone of 15-20 degree.

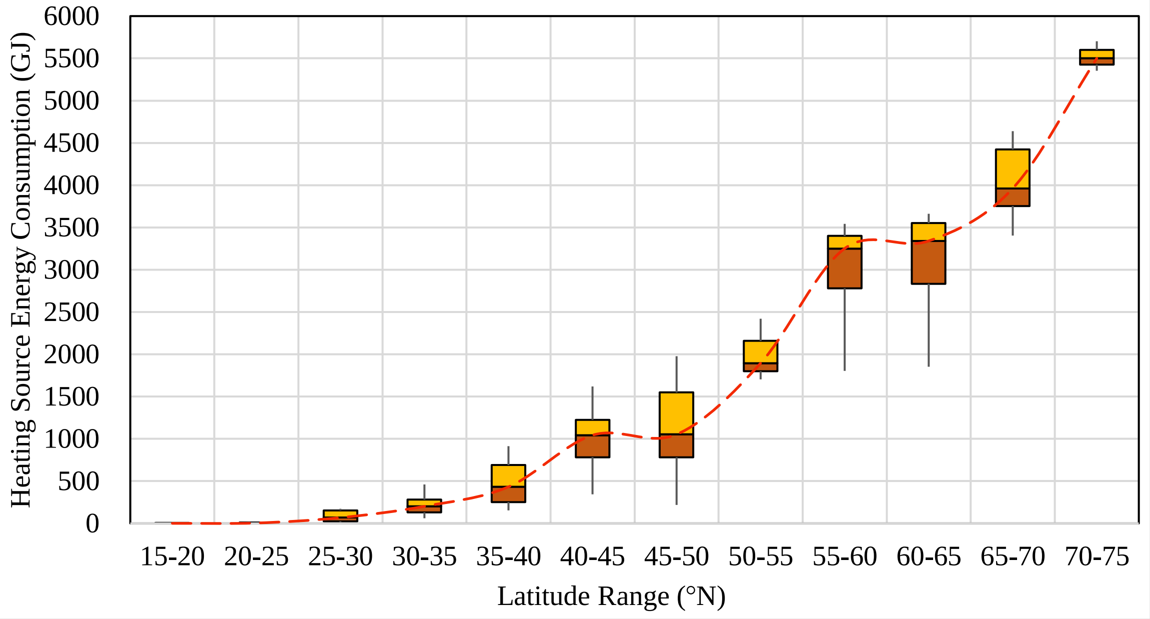


Figure 5.14.Heating energy consumption range in different latitude division

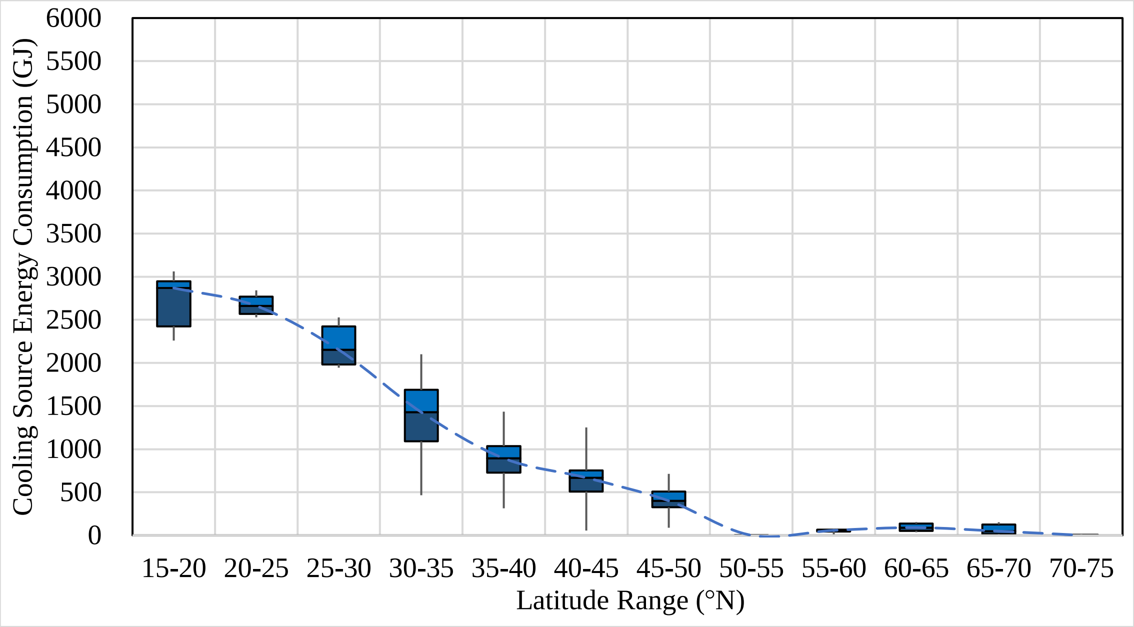


Figure 5.15. Cooling energy consumption range in different latitude division

The heating energy consumption in the high latitudes is strongly affected by the latitude changes, resulting in a significant increase in total energy consumption throughout the year. Optimizing the insulation performance of building envelopes is one of the main design strategies to achieve building energy efficiency, but its energy-saving effect in various latitudes lacks quantitative comparative research. Therefore, the contribution of the performance of the thermal insulation material to the energy saving in each latitude interval will be analyzed.

5.4. Discussion

5.4.1.Suggestion for building energy standard

In the study of the relationship between energy consumption and climatic zones, it is found that there is a clear correlation between energy consumption and humid climate zones (Letter number). Buildings in humid climate type area (Zone A) consume the most amount of energy, followed in the dry climate type area (Zone B), and in the marine climate type (Zone C) consume least energy. However, in the current ASHRAE design standards, there is no distinction among humid climate types in the thermal performance requirements of the envelope structure, which was set only according to different thermal climatic zones (Numeric number). The design requirements of the three humid climate types in a same thermal climatic zone are uniform. Based on the results of this study, it is recommended to subdivide the design requirements for humid climate types specifically.

At present, the green building evaluation system has encouraged to implement many energy- saving design strategies. However, many strategies many technologies do not detail the climatic regions where they are suitable. This will lead to mismatched building technologies, which cannot effectively achieve the goal of saving energy, and even bring additional energy consumption. There is an urgent need to study the adaptability of building technology and the energy-saving potential according to the energy consumption distribution characteristics of buildings in different latitudes. Regional applicability evaluations and recommendations for all technologies in building energy efficiency standards or green building standards is also important as well.

5.4.2. Guidance of Builidng design strategies implementation

It is necessary to put forward different design strategies for different latitude area. The distribution rule indicates that the area in higher than latitude of 35 degrees should considered more about decreased the heating energy. Because the energy for heating increased significantly with the latitude of locations rising, which lead to higher total energy consumption obviously. Building envelope thermal performance improvement is one of suggested design strategies to achieve the objective in these areas. The influence of the performance improvement of the insulation materials in different latitudes on the energy-saving effect is analyzed. The conclusion is that the building energy-saving effect is not obvious in the area with the latitude below 35 degrees but contributed significantly to realizing energy saving in higher latitude area, which verified the design suggestion. In the areas of latitude lower than 35 degrees, cooling energy consumption accounts larger partition of total energy. One of proper design strategies introducing outdoor ventilation. that most obvious energy-saving effect due to natural ventilation appears in the latitude of 20 to 25 degree, reaching 52%. The amount of total energy saving appears in this area.

5.4.3.Limitation of the study

The above study only provides a distribution rule of energy consumption in the United States. However, both climate and latitude are global indicators. The relationship between building energy consumption and their changes needs to be further expanded in order to make their regular conclusions more accurate. In the process of studying the characteristics of energy consumption distribution, the influences of terrain, ocean, and radiation were ignored. Its main purpose is to obtain the distribution characteristics of building energy consumption in the region, so as to guide the designation of energy conservation policies in different regions at the national level and the determination of the types and scope of indicators in design standards. For the selection of building energy-saving technologies in the same latitude area, it is still necessary to take these factors into consideration and further analyze their energy-saving effects.

5.5. Summaries

In this research, an effort has been made to summarize a distribution rule of energy consumption with the change of climate zone and latitude gradient. The article first studies the distribution characteristics of building energy consumption in different climate zones. Based on its conclusions, the architectural design requirements of different climatic zones were verified, and suggestions for improvement were put forward. Next, the energy consumption distribution in different latitudes is analyzed, and appropriate design strategies for different latitudes are proposed. Two kinds of these design strategies, improving structural thermal insulation performance and introducing natural ventilation, were used as case studies to investigate the energy saving potential of in different latitudes.

138 selected locations in the United States and their total source energy consumption were simulated. Clear differences in energy consumption are observed in hot climate zone (Zone 1 and 2) and subarctic climate zone (Zone 8), where consume more energy than the others. There is no significant difference in warm (Zone 3), mixed (Zone 4) and cold (Zone 5 and 6) climate zone area. However, there is a clear correlation between energy consumption and humid climate zones (Letter number). Buildings in humid climate type area (Zone A) consume the most amount of energy, followed in the dry climate type area (Zone B), and in the marine climate type (Zone C) consume least energy. There is a strong correlation between cooling and heating energy consumption and latitude. The fitting degree of both heating and cooling energy consumption with latitude is closed to 0.9 through the fitting test. The lowest consumption of total energy consumption appears in the mid-latitude range between 35 to 45 degree. Then it gradually increases when changing to higher latitudes and lower latitudes area. The fitting degree of total energy consumption is 0.77 with latitude gradient. Higher latitude area consumes more energy than other places. The highest latitude zone of 70-75 degree consumes approximately 2 times than the consumption in the lowest zone of 15-20 degree, which mainly driven by the heating energy consumption.

In areas with a latitude below 35 degrees, the optimization of the insulation layer on the building energy-saving effect is not obvious. Energy saving from 3% to 15% improvement of insulation only increase less than 20GJ. More than 35 degrees is suitable for optimizing the insulation performance of the envelope structure. With the increase of latitude degree and R-value, the amount of energy saving rises dramatically. The most obvious energy-saving effect due to natural ventilation appears in the latitude of 20 to 25 degree, reaching 52%. The amount of total energy saving appears in this area. This research needs to be further expanded in the following studies. The applicability of the rules drawn in this article to other countries will require further analysis. Due to the limitation of the number of simulation location samples at the initial stage. a large number of case data need to be added to support the distribution rule requires. Additionally, more building energy-saving technologies need to be evaluated based on this distribution rules in the further study to draw a distribution map of the applicability of regional energy-saving technologies and provide a simple and applicable technical guidance for architects and engineers in the initial design phase.

Appendix A. Source energy consumption simulation result of simulated cities in the United States (with latitude distribution order from low to high)

Country/LOCATION	WMO#	Lat	Long	CZ	Source Heating	Source Cooling	Source Total
SAN JUAN L M MARIN INTL AP	785263	18.43	–66.00	1A	0.15835	2869.04864	2869.20699
AGUADILLA/BORINQUEN	785140	18.5	–67.13	1A	0.34837	2948.12863	2948.477
WAKE ISLAND	912450	19.28	166.64	1A	0.09501	3061.47556	3061.57057
HILO INTERNATIONAL AP	912850	19.72	–155.05	1A	6.36567	2259.30613	2265.6718
KONA INTL AT KEAHOL	911975	19.73	–156.03	1A	0.85509	2424.81355	2425.66864
KAHULUI AIRPORT	911900	20.9	–156.43	1A	2.09022	2580.37659	2582.46681
BARBERS POINT NAS	911780	21.3	–158.07	1A	4.72116	2529.26121	2533.98237
KEY WEST INTL ARPT	722010	24.55	–81.75	1A	5.22555	2742.27363	2747.49918
MARATHON AIRPORT	722016	24.73	–81.05	1A	4.40213	2841.7491	2846.15123
MIAMI INTL AP	722020	25.82	–80.30	1A	11.87625	2486.47504	2498.35129
NAPLES MUNICIPAL	722038	26.15	–81.78	2A	14.69488	2527.86773	2542.56261
LAREDO INTL AIRPORT	722520	27.55	–99.47	2B	67.21564	2404.35473	2471.57037
ST PETERSBURG CLEAR	722116	27.9	–82.68	2A	28.34805	2242.33101	2270.67906
SOUTHWEST PASS	994010	28.9	–89.43	2A	68.79084	2062.63543	2131.42627
HONDO MUNICIPAL AP	722533	29.36	–99.17	2B	167.56633	1992.61306	2160.17939
DEL RIO INTERNATIONAL AP	722610	29.37	–100.92	2B	150.08559	1954.76741	2104.853
HOUSTON BUSH INTERCONTINENTAL	722430	29.99	–95.36	2A	172.72491	1944.63301	2117.35792
NEW ORLEANS LAKEFRONT AP	722315	30.04	–90.03	2A	80.12573	1949.19349	2029.31922
ALEXANDRIA INTERNATIONAL	747540	31.33	–92.55	2A	202.13786	1721.29617	1923.43403

SAN ANGELO MATHIS FIELD	722630	31.35	–100.49	3B	276.1487	1638.03574	1914.18444
NACOGDOCHES (AWOS)	722499	31.58	–94.72	3A	255.24642	1652.63561	1907.88203
DAVIS-MONTHAN AFB	722745	32.17	–110.88	2B	124.27839	1629.64319	1753.92158
YUMA INTL AIRPORT	722800	32.65	–114.60	2B	60.94477	2100.60776	2161.55253
CASA GRANDA (AWOS)	722748	32.95	–111.77	2B	101.68556	1840.12201	1941.80757
FORT WORTH ALLIANCE	722594	32.98	–97.32	2A	252.57558	1599.49335	1852.06893
TRUTH OR CONSEQUENCES MUNI AP	722710	33.24	–107.27	3B	285.92266	1115.67076	1401.59342
LUKE AFB/PHOENIX	722785	33.53	–112.38	2B	137.11494	1902.13187	2039.24681
MARCH AFB/RIVERSIDE	722860	33.88	–117.27	3B	164.95839	1200.48302	1365.44141
ATHENS BEN EPPS AP	723110	33.95	–83.33	3A	301.74125	1342.71299	1644.45424
CANNON AFB/CLOVIS	722686	34.38	–103.32	4B	460.60126	1065.63216	1526.23342
SANTA BARBARA MUNICIPAL AP	723925	34.43	–119.84	3C	124.8731	730.37354	855.24664
PRESCOTT LOVE FIELD	723723	34.65	–112.42	4B	383.00838	917.66992	1300.6783
LOMPOC (AWOS)	722895	34.67	–120.47	3C	149.46641	465.42232	614.88873
EDWARDS AFB	723810	34.9	–117.88	3B	265.16329	1272.34225	1537.50554
LITTLE ROCK AFB	723405	34.92	–92.15	3A	422.5785	1428.12698	1850.70548
SANTA MARIA PUBLIC ARPT	723940	34.92	–120.47	3C	168.15854	550.17124	718.32978
ALBUQUERQUE INTL ARPT	723650	35.04	–106.62	4B	372.5564	945.88789	1318.44429
NEW BERN CRAVEN CO REGL AP	723095	35.07	–77.05	3A	218.08589	1434.74601	1652.8319
SAN LUIS CO RGNL	722897	35.23	–120.63	3C	175.78358	700.44539	876.22897
BAKERSFIELD MEADOWS FIELD	723840	35.43	–119.06	3B	154.08729	1401.87255	1555.95984
ASHEVILLE REGIONAL ARPT	723150	35.43	–82.54	4A	492.5309	954.15376	1446.68466

GALLUP SEN CLARKE FLD	723627	35.51	–108.79	5B	620.44091	636.91537	1257.35628
OKLAHOMA CITY/WILEY	723544	35.53	–97.65	3A	524.25161	1364.09024	1888.34185
PASO ROBLES MUNICIPAL ARPT	723965	35.67	–120.63	3C	236.02582	903.67178	1139.6976
MONTEREY PENINSULA	724915	36.58	–121.85	3C	199.87892	313.91304	513.79196
MERCURY DESERT ROCK AP	723870	36.62	–116.03	4B	249.66287	1290.74252	1540.40539
NORFOLK NAS	723085	36.93	–76.28	3A	354.80917	1266.54664	1621.35581
PAGE MUNI (AMOS)	723710	36.93	–111.45	5B	341.90351	1047.23189	1389.1354
WISE/LONESOME PINE	724117	36.98	–82.53	4A	590.94349	960.96281	1551.9063
SAN JOSE INTL AP	724945	37.36	–121.93	3C	196.09999	793.30183	989.40182
CALIENTE (AMOS)	724870	37.62	–114.52	4B	509.95706	805.08307	1315.04013
LIVERMORE MUNICIPAL	724927	37.69	–121.82	3C	259.64082	822.4699	1082.11072
CEDAR CITY MUNICIPAL AP	724755	37.7	–113.10	5B	668.72997	703.83408	1372.56405
LAMAR MUNICIPAL	724636	38.07	–102.68	4B	728.81188	976.03773	1704.84961
NAPA CO. AIRPORT	724955	38.21	–122.28	3C	293.902	641.47585	935.37785
ST LOUIS LAMBERT INT'L ARPT	724340	38.75	–90.37	4A	788.69608	1105.47302	1894.1691
UKIAH MUNICIPAL AP	725905	39.13	–123.20	3C	354.42294	883.46632	1237.88926
PRICE/CARBON COUNTY	724700	39.62	–110.75	5B	697.14455	645.30792	1342.45247
MORGANTOWN HART FIELD	724176	39.64	–79.92	5A	823.92146	858.85873	1682.78019
EAGLE COUNTY AP	724675	39.64	–106.92	6B	815.86957	474.89165	1290.76122
WILMINGTON NEW CASTLE CNTY AP	724089	39.67	–75.60	4A	704.71725	1001.05703	1705.77428
COLUMBUS PORT COLUMBUS INTL A	724280	39.99	–82.88	4A	913.21658	820.03131	1733.24789
UNIV OF ILLINOIS WI	725315	40.03	–88.27	5A	1088.94707	961.15283	2050.0999

WASHINGTON (AWOS)	725117	40.13	–80.28	5A	836.59035	758.30648	1594.89683
RED BLUFF MUNICIPAL ARPT	725910	40.15	–122.25	3B	344.02498	1251.75675	1595.78173
AKRON WASHINGTON CO AP	724698	40.17	–103.23	5B	883.00305	690.62769	1573.63074
BELMAR-FARMINGDALE	724084	40.18	–74.13	4A	721.79915	764.29211	1486.09126
GREELEY/WELD (AWOS)	724768	40.43	–104.63	5B	908.50639	686.16222	1594.66861
VERNAL	725705	40.43	–109.52	6B	926.17921	649.90007	1576.07928
MANSFIELD LAHM MUNICIPAL ARPT	725246	40.82	–82.52	5A	1227.11222	739.30448	1966.4167
TOLEDO EXPRESS AIRPORT	725360	41.59	–83.80	5A	1109.61788	774.58486	1884.20274
ROCK SPRINGS ARPT	725744	41.59	–109.07	6B	1129.59373	465.13729	1594.73102
CRESCENT CITY FAA AI	725946	41.78	–124.24	4C	379.15369	55.48584	434.63953
MONTAGUE SISKIYOU COUNTY AP	725955	41.78	–122.47	5B	690.6403	692.11618	1382.75648
LOGAN-CACHE AIRPORT	724796	41.79	–111.85	5B	1099.85265	572.05521	1671.90786
LANDER HUNT FIELD	725760	42.82	–108.73	6B	997.69066	503.67968	1501.37034
ESTHERVILLE MUNI	726499	43.4	–94.75	6A	1602.44402	743.04154	2345.48556
NORTH BEND MUNI AIRPORT	726917	43.42	–124.25	4C	401.80534	169.08613	570.89147
JUNEAU/DODGE CO	726509	43.43	–88.70	5A	1330.44624	566.67131	1897.11755
WATERVILLE (AWOS)	726073	44.53	–69.68	6A	1219.01618	520.0214	1739.03758
YELLOWSTONE LAKE (RAMOS)	726664	44.54	–110.42	7A	1505.93268	149.89411	1655.82679
RED WING	726564	44.58	–92.48	6A	1526.30833	755.45618	2281.76451
SALEM MCNARY FIELD	726940	44.91	–123.00	4C	765.54624	500.19598	1265.74222
WAUSAU MUNICIPAL ARPT	726463	44.93	–89.63	6A	1619.64097	577.94583	2197.5868
AURORA STATE	726959	45.25	–122.77	4C	694.84618	529.61741	1224.46359

DILLON AIRPORT	726796	45.26	–112.55	6B	1185.58002	395.27327	1580.85329
LA GRANDE MUNI AP	726884	45.29	–118.01	5B	817.69148	496.64894	1314.34042
WALLA WALLA CITY COUNTY AP	727846	46.1	–118.29	5B	878.55512	713.11339	1591.66851
LIDGERWOOD (RAMOS)	727534	46.1	–97.15	6A	1467.22891	578.89593	2046.12484
KELSO WB AP	727924	46.12	–122.89	4C	601.30546	406.0094	1007.31486
HOULTON INTL ARPT	727033	46.12	–67.79	7A	1574.29717	405.18598	1979.48315
HANFORD	727840	46.57	–119.60	5B	919.81286	693.63634	1613.4492
FARGO HECTOR INTERNATIONAL AP	727530	46.93	–96.81	6A	1929.75642	620.92202	2550.67844
LORING AFB/LIMESTON	727125	46.95	–67.88	7A	1637.85896	383.207	2021.06596
HOQUIAM AP	727923	46.97	–123.94	4C	769.61302	215.07097	984.68399
OLYMPIA AIRPORT	727920	46.97	–122.90	4C	824.17137	344.60127	1168.77264
LEWISTOWN MUNICIPAL ARPT	726776	47.05	–109.47	6B	1372.4819	392.20128	1764.68318
TWO HARBORS	727444	47.05	–91.75	7A	1675.66974	422.95285	2098.62259
HANCOCK HOUGHTON CO AP	727440	47.17	–88.51	6A	1887.50467	425.04307	2312.54774
SHELTON/SANDERSON	727925	47.24	–123.15	4C	849.46	355.81245	1205.27245
STAMPEDE PASS	727815	47.29	–121.34	5B	1460.22655	157.74827	1617.97482
GREAT FALLS	727760	47.45	–111.38	6B	1185.21839	430.52198	1615.74037
BREMERTON NATIONAL	727928	47.48	–122.75	5C	721.10123	317.74511	1038.84634
DESTRUCTION ISLAND	994070	47.67	–124.48	4C	218.33673	88.48598	306.82271
SIDNEY-RICHLAND	727687	47.7	–104.20	6B	1470.02399	547.44762	2017.47161
QUILLAYUTE STATE AIRPORT	727970	47.93	–124.56	5C	858.46646	184.16105	1042.62751
ORR	726544	48.02	–92.87	7A	1831.78541	393.08804	2224.87345

SMITH ISLAND	994180	48.32	–122.83	5C	272.24298	92.69809	364.94107
FRIDAY HARBOR	727985	48.52	–123.02	5C	748.22335	248.07111	996.29446
ROSEAU MUNI (AWOS)	727477	48.85	–95.70	7A	1977.41181	511.02712	2488.43893
ADAK NAS	704540	51.88	–176.65	7A	1702.1063	1.45682	1703.56312
SHEMYA AFB	704140	52.72	174.12	8A	2420.50063	0.12668	2420.62731
DUTCH HARBOR	704890	53.9	–166.55	7A	1895.22833	6.99907	1902.2274
ANNETTE ISLAND AP	703980	55.04	–131.57	5A	1064.73578	68.50221	1133.23799
COLD BAY ARPT	703160	55.21	–162.72	7A	1893.04782	1.07678	1894.1246
SITKA JAPONSKI AP	703710	57.05	–135.36	5A	1292.48773	42.4378	1334.92553
JUNEAU INT'L ARPT	703810	58.36	–134.58	6A	1653.95898	78.09822	1732.0572
SKAGWAY AIRPORT	703620	59.46	–135.31	6A	1614.84573	66.34865	1681.19438
ILIAMNA ARPT	703400	59.75	–154.92	7A	2221.71117	49.56355	2271.27472
SEWARD	702770	60.12	–149.45	7A	1803.77102	48.80347	1852.57449
SPARREVOHN AFS	702350	61.1	–155.57	7A	2670.60825	60.77473	2731.38298
SAINT MARY`S (AWOS)	702005	62.07	–163.30	8A	3108.64436	35.7871	3144.43146
NORTHWAY AIRPORT	702910	62.96	–141.95	8A	3542.36747	119.49091	3661.85838
BIG DELTA ALLEN AAF	702670	64	–145.72	8A	3393.9252	142.41999	3536.34519
FAIRBANKS INTL ARPT	702610	64.82	–147.86	8A	3401.6142	154.73962	3556.35382
TIN CITY AFS (AWOS)	701170	65.57	–167.92	8A	4571.27877	1.52016	4572.79893
INDIAN MTN AFS AWOS	701730	66	–153.70	8A	3403.97945	122.94294	3526.92239
SHISHMAREF (AWOS)	701195	66.27	–166.05	8A	4086.65736	44.36967	4131.02703
FORT YUKON	701940	66.57	–145.27	8A	3765.47806	128.16849	3893.64655

KOTZEBUE RALPH WEIN MEMORIAL	701330	66.89	–162.60	8A	4086.65736	44.36967	4131.02703
BETTLES FIELD	701740	66.92	–151.51	8A	3750.04312	152.3327	3902.37582
AMBLER	701718	67.1	–157.85	8A	3643.10973	133.20402	3776.31375
ANAKTUVUK PASS	701625	68.13	–151.73	8A	4639.04363	52.31884	4691.36247
POINT HOPE (AWOS)	701043	68.35	–166.80	8A	3837.94334	1.9002	3839.84354
CAPE LISBURNE(AWOS)	701040	68.88	–166.13	8A	4534.51135	3.167	4537.67835
BARTER ISLAND (DEW)	700860	70.13	–143.63	8A	5500.47305	1.17179	5501.64484
DEADHORSE	700637	70.19	–148.48	8A	5353.47897	13.45975	5366.93872
BARROW W POST-W ROGERS ARPT	700260	71.29	–156.76	8A	5702.34728	0.12668	5702.47396

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Chapter 6. Study on the Thermal Insulation of Building Envelope Opaque Area Impact on Energy Consumption

6.1. Introduction

Energy consumption for heating and cooling of office buildings is growing. In particular, there is an increase in the demand for electricity for cooling in the summer and heating in the winter. Optimizing the insulation performance of building envelopes is one of the main design strategies to achieve building energy efficiency, but its energy-saving effect in various latitudes lacks quantitative comparative research. Therefore, the contribution of the performance of the thermal insulation properties to the energy saving in each latitude interval will be analyzed.

Office buildings represent a considerable rate of the building heritage. This kind of buildings is nowadays characterized by a significant rise of electrical energy consumption for summer air conditioning. This increase in energy requirement could generate a growth of over 50% of total electric energy demand for office buildings in just a few years[1]. Among the various passive solutions to decrease the energy demand in office buildings, the insertion of an insulation layer in the opaque building envelope is very common. However, a too high thickness of insulating material, even if complying with the current legislative requirements, can be disadvantageous, with reference to energy requirements, environmental impact and economic analysis. In particular, for buildings characterized by high values of internal thermal loads as office ones and/or buildings placed in climates with mild winters and hot summers, an excessive decrease of the U-value (stationary unitary thermal transmittance) of the opaque components could generate an increase of cooling energy demand in summer, higher than the reduction of heating energy requirement in winter. In fact, in some cases, the difficulty of a too insulated building envelope to expel excessive heat in the night during the hot season could eliminate the benefit related to the decrease of thermal loads during the cold periods[2].

The selection of insulation material is based on the thermal conductivity and price, the lower the thermal conductivity and price are, the higher the economic efficiency of insulation material is. The increase of insulation thermal resistance will decrease the energy consumption for cooling and heating, however, the investment for the insulation will increase as well, and then there must be an optimum point where the total investment cost for the insulation and energy consumption can be minimized over the lifetime. Therefore, the selection of proper insulation material, as well as the determination of optimum insulation thermal resistance is very critical for the economic analysis[3]. Generally, the increase of building envelope thermal resistance is achieved by increasing the thickness of insulation. When the insulation thickness is increased, the building thermal loads and the energy costs diminish, but the costs of the materials increase, so that the optimal thickness of thermal insulation commonly is limited.

6.2. Simulation model conditions

The simulation models are based on the previous study in Chapter 5. Cities are selected from every latitude range. Each climate zone type in every latitude range will have at least one city to present. Then the variable indicator is the thermal resistance (R-value) of thermal insulation. Increase the R-value from 3% to 15% of base model respectively, as show in Table 5.1. The other boundary conditions are shown in Table 5.2.

Table 5.1. R-value of Case Design

	Base model	3% R	6% R	9% R	12% R	15% R
wall	2.368	2.439	2.510	2.581	2.652	2.723
Floor	2.299	2.368	2.437	2.506	2.575	2.644
Roof	3.472	3.576	3.681	3.785	3.889	3.993

Table 5.2. Office prototype building parameters list

Categories	Parameters	Value
Construction	Exterior walls	Steel-Frame Walls 10.16mm. Stucco+15.88 mm. gypsum board + wall insulation+15.88 mm. gypsum board
	Roof	Built-up roof: Roof membrane + roof insulation + metal decking
	Window	Hypothetical window with weighted U-factor and SHGC
HVAC	System	MZ VAV (multizone variable air volume)
	Heating	Furnace
	Cooling	PACU (packaged air-conditioning unit)
	Thermostat Setpoint	23.8℃ cooling / 21℃ heating
	Thermostat Setback	26.7℃ cooling / 15.6℃ heating
Internal Loads	Occupancy	18.6 m2/person
	Outside air requirements	9.44L/s/person
	Lighting	9.69 W/ m2
	Service Water Heating	Storage tank Natural gas
	Water temperature setpoint	60 ℃

6.3. Energy saving potential of insulation improvement of opaque area

Figure 6.1 shows the relationship between thermal resistance and energy savings. The x-axis represents an increase in thermal resistance based on the base design, which is 3%-15% of the base model. The Y axis is total source energy saving. Lines of different colors represent latitude partitions. In areas with a latitude below 35 degrees, the optimization of the insulation layer on the building energy-saving effect is not obvious. Energy saving from 3% to 15% improvement of insulation only increase less than 20GJ. More than 35 degrees is suitable for optimizing the insulation performance of the envelope structure. With the increase of latitude degree and R-value, the amount of energy saving rises dramatically.

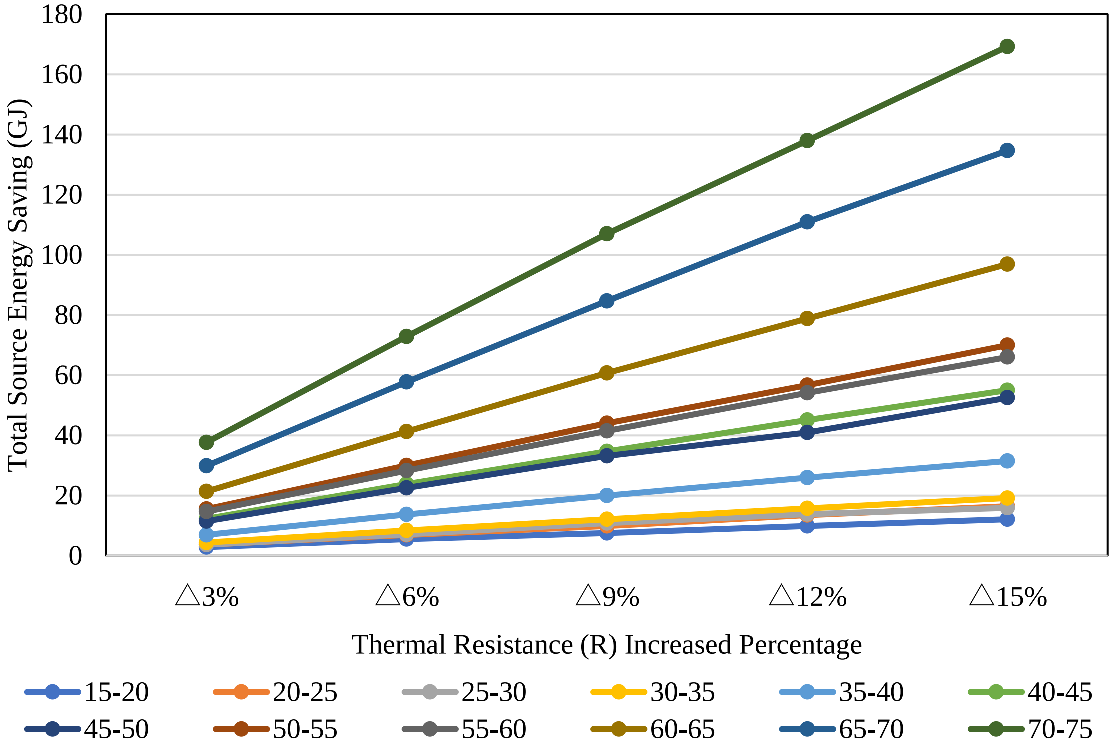


Figure 6.1 Total source energy saving with thermal resistance increase

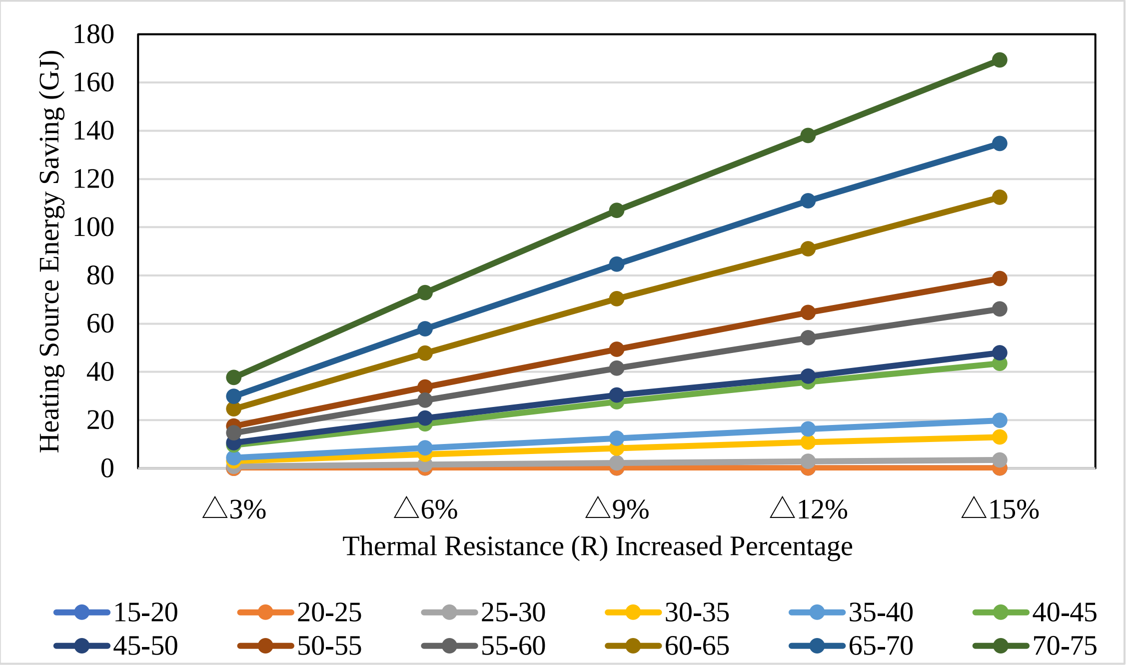


Figure 6.2 Heating source energy saving with thermal resistance increase

The change law of Heating is basically the same as the change law of total energy consumption, and the energy saving amount is also close to the total energy saving (Figure 6.2). It shows that the main saving of the optimized enclosure is the heating energy consumption. The energy consumption in all latitudes decreases with the increase of thermal resistance. However, in the latitudes below 35 degrees, the magnitude of the change is not obvious. The energy saving potential of improving the performance of the envelope structure is not high. The reason should be that the temperatures in these areas are warm relatively. More important design strategies should be natural ventilation and shading design rather than improving the insulation properties.

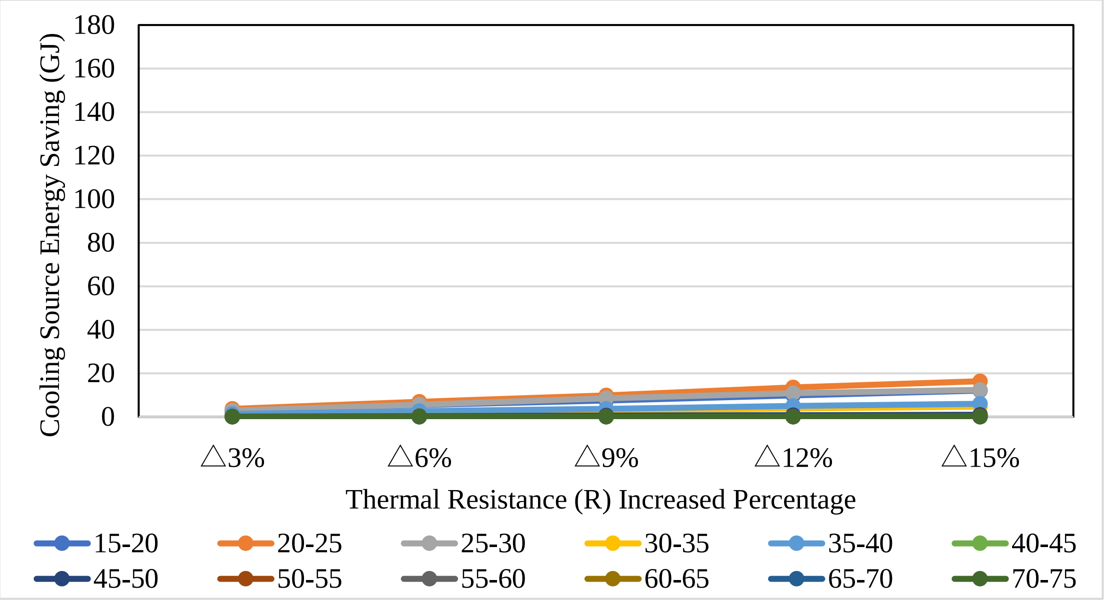
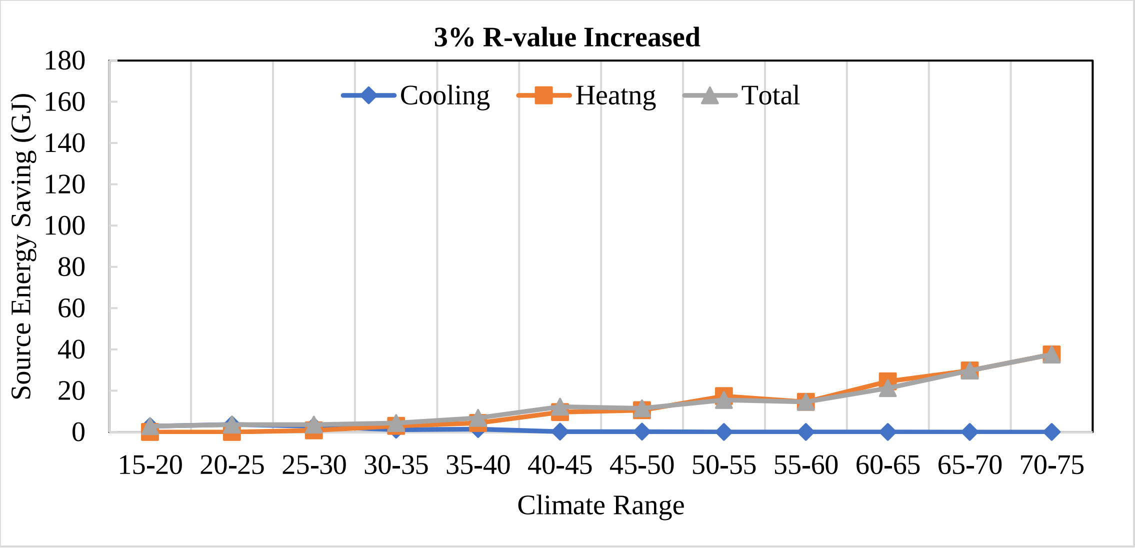
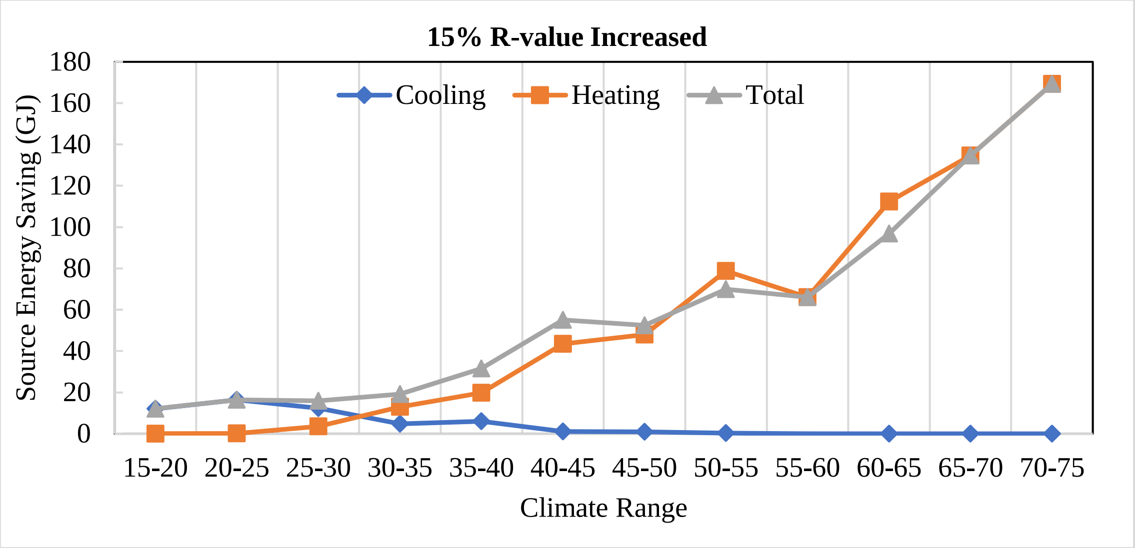


Figure 6.3 Cooling source energy saving with thermal resistance increase

Figure 6.3 shows the cooling source energy saving with the thermal resistance increase. The amount of cooling energy saving is small in all the latitude area, which also reveals that the improvement of thermal properties of building envelope do not influence the cooling energy consumption dramatically.



a. Source energy consumption with 3% thermal resistance increased



b. Source energy consumption with 15% thermal resistance increased

Figure 6.4 Comparison of source energy saving with 3% and 15% thermal resistance increased

Figure 6.4 compares the energy saving between 3% and 5% R-value increased. The insulation layer contributes very little to the energy saving of cooling. In places where the latitude is above 35 degrees, the contribution to energy saving for heating energy consumption increases significantly and increases with increasing latitude. The amount of energy saving in thermal resistance by 15% increase is significantly higher than that by 3%.

6.4.Green building standard for thermal performance of building envelope

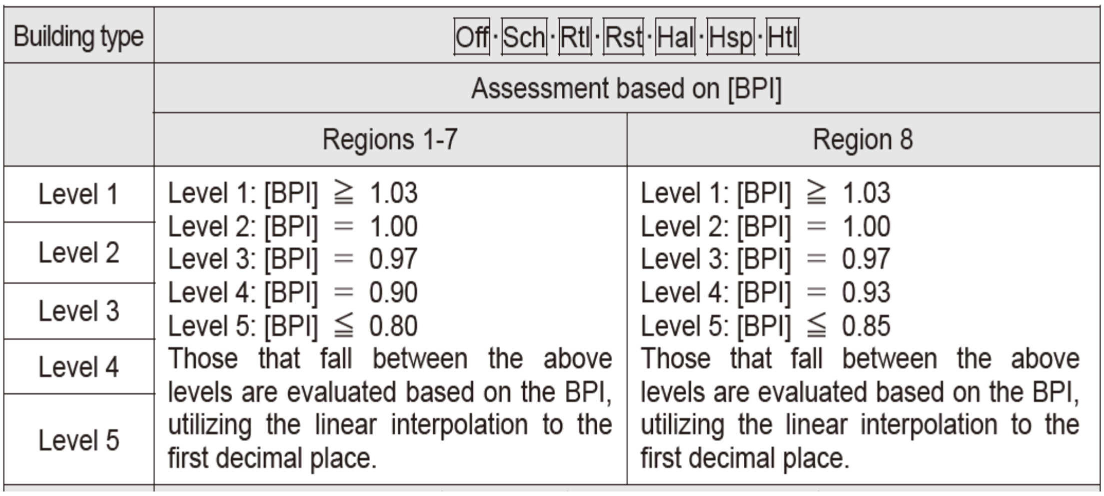
As introduced in chapter 4, The green building requirement in terms of energy saving related to the building envelope design is the credit of Thermal Performance Optimization of Envelope (section 7.2.4 of standard). The thermal performance of the envelope is required to be increased by 5%, 10% or 15% compared with GB50189-2015[4], with 5 points, 10 points and 15 points respectively. Based on the result of this study, this requirement should be considered seriously in the place where above latitude of 35 degree. Otherwise, for places with latitude lower than 35-degree, Overemphasis on increasing insulation layer and optimizing insulation performance not only brings little energy saving, but also increases the cost and recycling cycle. From the perspective of the whole life cycle of the building, the energy saving effect is not achieved.

LEED and CASBEE adopt composite indicators to evaluate the energy efficiency of the building including building envelopes contributes. CASBEE adopts envelope performance (PAL*) ， and primary energy consumption amount (ET) of equipment and plug load to evaluate the energy efficiency performance for non-residential buildings. CASBEE assessment of energy using the same assessment indicators based on methods in accordance with BEC2013 （Figure 6.5 and Figure 6.6）. GB50189-2019 has another evaluation option is similar with LEED and CASBEE that based on the whole building energy saving percentage by simulation. The requirement of green building rating systems in these three countries. These kinds of indicators will be more appropriate to evaluate the building energy saving correctly, rather than R-value or U-value of thermal insulation optimization directly. That is because the composite indicator will consider all aspects of energy consumption in the building.

Table 5.3. LEED Points for percentage improvement in energy performance

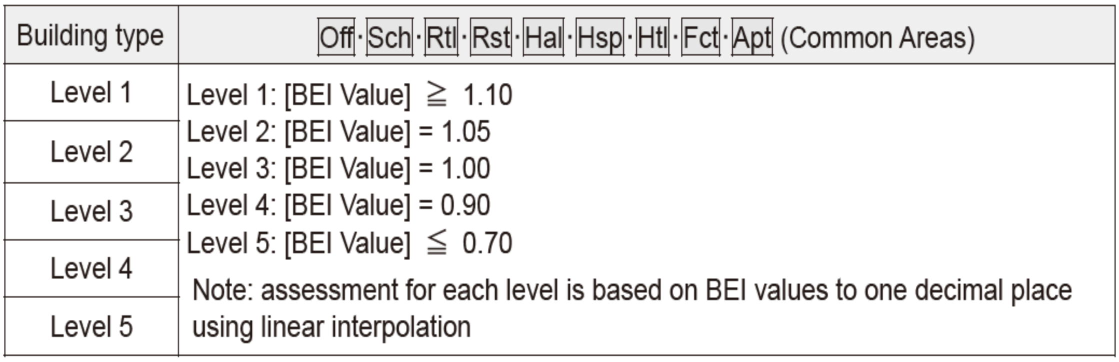
New Construction	Points (except schools, healthcare)
6%	1
8%	2
10%	3
12%	4
14%	5
16%	6
18%	7
20%	8
22%	9
24%	10
26%	11

29%	12
32%	13
35%	14
38%	15
42%	16
46%	17
50%	18



Building type	Off·Sch·Rtl·Rst·Hal·Hsp·Htl	
	Assessment based on [BPI]	
	Regions 1-7	Region 8
Level 1	Level 1: [BPI] ≧ 1.03 Level 2: [BPI] ＝ 1.00 Level 3: [BPI] ＝ 0.97 Level 4: [BPI] ＝ 0.90 Level 5: [BPI] ≦ 0.80 Those that fall between the above levels are evaluated based on the BPI, utilizing the linear interpolation to the first decimal place.	Level 1: [BPI] ≧ 1.03 Level 2: [BPI] ＝ 1.00 Level 3: [BPI] ＝ 0.97 Level 4: [BPI] ＝ 0.93 Level 5: [BPI] ≦ 0.85 Those that fall between the above levels are evaluated based on the BPI, utilizing the linear interpolation to the first decimal place.
Level 2		
Level 3		
Level 4		
Level 5		

Figure 6.5. Evaluation standard of heat load on the outer surface of buildings



Building type	Off·Sch·Rtl·Rst·Hal·Hsp·Htl·Fct·Apt (Common Areas)
Level 1	Level 1: [BEI Value] ≧ 1.10 Level 2: [BEI Value] = 1.05 Level 3: [BEI Value] = 1.00 Level 4: [BEI Value] = 0.90 Level 5: [BEI Value] ≦ 0.70 Note: assessment for each level is based on BEI values to one decimal place using linear interpolation
Level 2	
Level 3	
Level 4	
Level 5	

Figure 6.6. Evaluation standard of efficiency in building service system

6.5. Summary

At present, the green building evaluation system has requirements for the insulation properties of the building envelope structure. Therefore, the influence of the performance improvement of the insulation materials in different latitudes on the energy-saving effect is analyzed. The conclusion is that the building energy-saving effect is not obvious in the area with the latitude below 35 degrees. It is recommended to reconsider the setting of the score in the green building evaluation in areas below 35 degrees. Energy-saving effects such as natural ventilation and sunshade design are obvious in these areas, and it is considered to increase the proportion of the scores. The energy saving potential of natural ventilation is detailed in Chapter 7.

The insulation performance of the building envelope in the places where above 35 latitude degrees, the energy-saving effect is obviously improved. Therefore, this kind of green building strategies should be encouraged to apply in that area.

Appendix A1. Energy consumption with 3% and 6% increased R-value of thermal insulation of building envelope opaque area.

Country/LOCATION	Lat	Long	CZ	3% R-value increased			6% R-value increased		
				Source Heating	Source Cooling	Source Total	Source Heating	Source Cooling	Source Total
SAN JUAN L M MARIN INTL AP	18.43	–66.00	1A	0.16	2866.20	2866.36	0.13	2863.57	2863.70
KAHULUI AIRPORT	20.9	–156.43	1A	2.09	2576.70	2578.79	2.06	2573.50	2575.56
MIAMI INTL AP	25.82	–80.30	1A	11.78	2482.10	2493.89	11.69	2478.78	2490.47
ST PETERSBURG CLEAR	27.9	–82.68	2A	27.99	2240.49	2268.48	27.67	2237.71	2265.38
HONDO MUNICIPAL AP	29.36	–99.17	2B	165.66	1990.21	2155.87	163.69	1988.27	2151.96
DAVIS-MONTHAN AFB	32.17	–110.88	2B	122.87	1627.58	1750.46	121.49	1625.91	1747.40
FORT WORTH ALLIANCE	32.98	–97.32	2A	249.45	1597.56	1847.01	246.70	1596.17	1842.87
ATHENS BEN EPPS AP	33.95	–83.33	3A	298.04	1341.32	1639.36	294.45	1339.96	1634.41
CANNON AFB/CLOVIS	34.38	–103.32	4B	455.56	1064.78	1520.34	450.99	1064.11	1515.10
SANTA BARBARA MUNICIPAL AP	34.43	–119.84	3C	123.39	730.15	853.55	122.01	729.93	851.94
EDWARDS AFB	34.9	–117.88	3B	261.85	1270.13	1531.97	258.93	1267.94	1526.87
BAKERSFIELD MEADOWS FIELD	35.43	–119.06	3B	152.09	1399.91	1552.00	150.22	1397.53	1547.76
ASHEVILLE REGIONAL ARPT	35.43	–82.54	4A	486.62	953.68	1440.30	481.25	953.17	1434.42
PASO ROBLES MUNICIPAL ARPT	35.67	–120.63	3C	233.14	902.50	1135.64	231.55	902.21	1133.76
MERCURY DESERT ROCK AP	36.62	–116.03	4B	246.56	1288.21	1534.77	243.56	1286.06	1529.61
NORFOLK NAS	36.93	–76.28	3A	351.19	1264.42	1615.62	347.74	1262.65	1610.39
PAGE MUNI (AMOS)	36.93	–111.45	5B	337.31	1045.71	1383.02	332.77	1044.38	1377.15
MORGANTOWN HART FIELD	39.64	–79.92	5A	815.42	858.42	1673.83	807.00	857.78	1664.78

WASHINGTON (AWOS)	40.13	–80.28	5A	828.46	757.83	1586.29	824.79	757.42	1582.21
RED BLUFF MUNICIPAL ARPT	40.15	–122.25	3B	340.18	1249.79	1589.97	336.49	1247.86	1584.35
BELMAR-FARMINGDALE	40.18	–74.13	4A	714.29	763.31	1477.60	707.03	762.68	1469.70
GREELEY/WELD (AWOS)	40.43	–104.63	5B	898.83	685.47	1584.29	889.18	684.90	1574.07
ROCK SPRINGS ARPT	41.59	–109.07	6B	1117.65	464.79	1582.44	1106.18	464.41	1570.59
WATERVILLE (AWOS)	44.53	–69.68	6A	1207.92	519.70	1727.63	1197.27	519.55	1716.82
YELLOWSTONE LAKE (RAMOS)	44.54	–110.42	7A	1489.17	149.96	1639.13	1473.36	149.96	1623.32
SALEM MCNARY FIELD	44.91	–123.00	4C	757.37	499.72	1257.09	749.83	499.34	1249.17
AURORA STATE	45.25	–122.77	4C	687.42	529.05	1216.46	680.14	528.38	1208.52
WALLA WALLA CITY COUNTY AP	46.1	–118.29	5B	869.73	712.26	1581.99	861.20	711.53	1572.73
LIDGERWOOD (RAMOS)	46.1	–97.15	6A	1453.86	578.14	2031.99	1440.91	577.53	2018.44
HOULTON INTL ARPT	46.12	–67.79	7A	1560.49	405.19	1965.68	1547.06	405.19	1952.24
GREAT FALLS	47.45	–111.38	6B	1173.93	430.02	1603.95	1163.03	429.60	1592.63
QUILLAYUTE STATE AIRPORT	47.93	–124.56	5C	849.59	184.22	1033.81	841.21	184.07	1025.27
SHEMYA AFB	52.72	174.12	8A	2400.36	0.13	2400.49	2381.69	0.13	2381.81
DUTCH HARBOR	53.9	–166.55	7A	1880.44	7.00	1887.43	1866.59	7.00	1873.58
COLD BAY ARPT	55.21	–162.72	7A	1877.29	1.08	1878.36	1862.23	1.08	1863.31
SITKA JAPONSKI AP	57.05	–135.36	5A	1279.66	42.44	1322.09	1267.91	42.47	1310.38
JUNEAU INT'L ARPT	58.36	–134.58	6A	1638.63	78.07	1716.70	1624.63	78.07	1702.70
SPARREVOHN AFS	61.1	–155.57	7A	2647.27	60.74	2708.01	2625.91	60.77	2686.68
BIG DELTA ALLEN AAF	64	–145.72	8A	3368.08	142.32	3510.40	3343.13	142.32	3485.46
KOTZEBUE RALPH WEIN MEMORIAL	66.89	–162.60	8A	4056.82	44.37	4101.19	4028.86	44.37	4073.23

BARTER ISLAND (DEW)	70.13	–143.63	8A	5462.84	1.17	5464.01	5427.63	1.17	5428.81

Appendix 2. Energy consumption with 9% and 12% increased R-value of thermal insulation of building envelope opaque area.

Country/LOCATION	Lat	Long	CZ	9% R-value increased			12% R-value increased		
				Source Heating	Source Cooling	Source Total	Source Heating	Source Cooling	Source Total
SAN JUAN L M MARIN INTL AP	18.43	–66.00	1A	0.13	2861.51	2861.64	0.13	2859.17	2859.29
KAHULUI AIRPORT	20.9	–156.43	1A	2.06	2570.50	2572.55	2.06	2566.89	2568.94
MIAMI INTL AP	25.82	–80.30	1A	11.62	2474.85	2486.48	11.53	2472.03	2483.56
ST PETERSBURG CLEAR	27.9	–82.68	2A	27.45	2235.84	2263.29	27.17	2233.69	2260.85
HONDO MUNICIPAL AP	29.36	–99.17	2B	162.05	1985.04	2147.09	160.51	1983.02	2143.53
DAVIS-MONTHAN AFB	32.17	–110.88	2B	120.18	1623.75	1743.93	118.97	1621.85	1740.82
FORT WORTH ALLIANCE	32.98	–97.32	2A	244.23	1594.08	1838.30	242.02	1592.11	1834.13
ATHENS BEN EPPS AP	33.95	–83.33	3A	291.24	1338.79	1630.02	288.14	1337.77	1625.91
CANNON AFB/CLOVIS	34.38	–103.32	4B	446.49	1063.76	1510.25	442.22	1063.07	1505.28
SANTA BARBARA MUNICIPAL AP	34.43	–119.84	3C	120.69	729.84	850.53	119.44	729.58	849.03
EDWARDS AFB	34.9	–117.88	3B	256.17	1265.82	1521.99	253.26	1264.17	1517.43
BAKERSFIELD MEADOWS FIELD	35.43	–119.06	3B	148.37	1395.29	1543.66	146.63	1393.10	1539.73
ASHEVILLE REGIONAL ARPT	35.43	–82.54	4A	475.85	953.08	1428.92	470.99	952.67	1423.66
PASO ROBLES MUNICIPAL ARPT	35.67	–120.63	3C	227.73	900.88	1128.62	225.33	899.90	1125.24
MERCURY DESERT ROCK AP	36.62	–116.03	4B	242.29	1284.98	1527.27	238.10	1281.68	1519.79
NORFOLK NAS	36.93	–76.28	3A	344.15	1260.97	1605.12	340.96	1259.17	1600.13

PAGE MUNI (AMOS)	36.93	–111.45	5B	328.61	1042.96	1371.56	324.55	1041.40	1365.95
MORGANTOWN HART FIELD	39.64	–79.92	5A	799.27	857.53	1656.80	792.21	857.12	1649.32
WASHINGTON (AWOS)	40.13	–80.28	5A	813.40	756.82	1570.21	806.65	756.28	1562.93
RED BLUFF MUNICIPAL ARPT	40.15	–122.25	3B	333.01	1245.77	1578.78	329.68	1244.25	1573.93
BELMAR-FARMINGDALE	40.18	–74.13	4A	700.15	761.76	1461.91	693.77	760.94	1454.70
GREELEY/WELD (AWOS)	40.43	–104.63	5B	880.19	684.20	1564.39	871.93	683.53	1555.46
ROCK SPRINGS ARPT	41.59	–109.07	6B	1095.26	464.09	1559.35	1085.50	463.84	1549.34
WATERVILLE (AWOS)	44.53	–69.68	6A	1187.27	519.17	1706.44	1177.63	518.94	1696.57
YELLOWSTONE LAKE (RAMOS)	44.54	–110.42	7A	1458.62	149.96	1608.58	1444.34	150.02	1594.36
SALEM MCNARY FIELD	44.91	–123.00	4C	742.47	498.99	1241.47	735.58	498.74	1234.32
AURORA STATE	45.25	–122.77	4C	673.22	528.03	1201.26	666.88	527.43	1194.31
WALLA WALLA CITY COUNTY AP	46.1	–118.29	5B	853.33	710.71	1564.03	845.99	709.85	1555.84
LIDGERWOOD (RAMOS)	46.1	–97.15	6A	1429.97	577.12	2007.09	1418.98	576.43	1995.41
HOULTON INTL ARPT	46.12	–67.79	7A	1534.13	405.09	1939.22	1529.01	404.96	1933.98
GREAT FALLS	47.45	–111.38	6B	1152.65	429.03	1581.68	1143.15	428.69	1571.83
QUILLAYUTE STATE AIRPORT	47.93	–124.56	5C	833.19	184.13	1017.32	825.23	184.10	1009.32
SHEMYA AFB	52.72	174.12	8A	2363.67	0.13	2363.80	2346.07	0.13	2346.20
DUTCH HARBOR	53.9	–166.55	7A	1853.27	7.00	1860.27	1840.43	7.00	1847.43
COLD BAY ARPT	55.21	–162.72	7A	1847.18	1.08	1848.26	1833.31	1.08	1834.39
SITKA JAPONSKI AP	57.05	–135.36	5A	1256.87	42.47	1299.34	1246.25	42.50	1288.75
JUNEAU INT'L ARPT	58.36	–134.58	6A	1611.09	78.10	1689.19	1597.62	78.10	1675.72
SPARREVOHN AFS	61.1	–155.57	7A	2605.29	60.77	2666.06	2585.71	60.81	2646.51

BIG DELTA ALLEN AAF	64	–145.72	8A	3318.67	142.32	3460.99	3296.70	142.26	3438.96
KOTZEBUE RALPH WEIN MEMORIAL	66.89	–162.60	8A	4002.06	44.34	4046.39	3975.73	44.34	4020.07
BARTER ISLAND (DEW)	70.13	–143.63	8A	5393.49	1.17	5394.66	5362.53	1.17	5363.70

Appendix 3. Energy consumption with 15% increased R-value of thermal insulation of building envelope opaque area.

Country/LOCATION	Lat	Long	CZ	15% R-value increased		
				Source Heating	Source Cooling	Source Total
SAN JUAN L M MARIN INTL AP	18.43	–66.00	1A	0.13	2856.98	2857.11
KAHULUI AIRPORT	20.9	–156.43	1A	2.03	2564.00	2566.03
MIAMI INTL AP	25.82	–80.30	1A	11.46	2471.08	2482.55
ST PETERSBURG CLEAR	27.9	–82.68	2A	26.91	2232.16	2259.08
HONDO MUNICIPAL AP	29.36	–99.17	2B	159.00	1980.93	2139.92
DAVIS-MONTHAN AFB	32.17	–110.88	2B	117.78	1620.43	1738.21
FORT WORTH ALLIANCE	32.98	–97.32	2A	239.58	1590.09	1829.66
ATHENS BEN EPPS AP	33.95	–83.33	3A	287.03	1337.23	1624.26
CANNON AFB/CLOVIS	34.38	–103.32	4B	438.25	1062.28	1500.53
SANTA BARBARA MUNICIPAL AP	34.43	–119.84	3C	118.19	729.52	847.71
EDWARDS AFB	34.9	–117.88	3B	250.82	1262.43	1513.25
BAKERSFIELD MEADOWS FIELD	35.43	–119.06	3B	144.98	1391.10	1536.09
ASHEVILLE REGIONAL ARPT	35.43	–82.54	4A	466.31	952.35	1418.66
PASO ROBLES MUNICIPAL ARPT	35.67	–120.63	3C	222.95	899.05	1121.99
MERCURY DESERT ROCK AP	36.62	–116.03	4B	235.60	1279.31	1514.91

NORFOLK NAS	36.93	–76.28	3A	338.06	1257.43	1595.48
PAGE MUNI (AMOS)	36.93	–111.45	5B	320.97	1040.39	1361.37
MORGANTOWN HART FIELD	39.64	–79.92	5A	785.25	856.77	1642.02
WASHINGTON (AWOS)	40.13	–80.28	5A	800.02	755.84	1555.85
RED BLUFF MUNICIPAL ARPT	40.15	–122.25	3B	326.58	1242.26	1568.84
BELMAR-FARMINGDALE	40.18	–74.13	4A	687.83	759.73	1447.57
GREELEY/WELD (AWOS)	40.43	–104.63	5B	864.32	682.81	1547.12
ROCK SPRINGS ARPT	41.59	–109.07	6B	1075.86	463.55	1539.41
WATERVILLE (AWOS)	44.53	–69.68	6A	1168.77	518.69	1687.46
YELLOWSTONE LAKE (RAMOS)	44.54	–110.42	7A	1430.84	150.02	1580.86
SALEM MCNARY FIELD	44.91	–123.00	4C	728.91	498.33	1227.24
AURORA STATE	45.25	–122.77	4C	660.76	527.12	1187.88
WALLA WALLA CITY COUNTY AP	46.1	–118.29	5B	838.78	709.15	1547.94
LIDGERWOOD (RAMOS)	46.1	–97.15	6A	1408.48	575.67	1984.14
HOULTON INTL ARPT	46.12	–67.79	7A	1511.28	405.06	1916.34
GREAT FALLS	47.45	–111.38	6B	1134.02	428.08	1562.10
QUILLAYUTE STATE AIRPORT	47.93	–124.56	5C	817.87	184.07	1001.93
SHEMYA AFB	52.72	174.12	8A	2329.77	0.13	2329.89
DUTCH HARBOR	53.9	–166.55	7A	1828.54	7.00	1835.54
COLD BAY ARPT	55.21	–162.72	7A	1820.37	1.08	1821.45
SITKA JAPONSKI AP	57.05	–135.36	5A	1235.80	42.50	1278.30
JUNEAU INT'L ARPT	58.36	–134.58	6A	1585.26	78.07	1663.33

SPARREVOHN AFS	61.1	–155.57	7A	2565.73	60.77	2626.50
BIG DELTA ALLEN AAF	64	–145.72	8A	3274.13	142.32	3416.46
KOTZEBUE RALPH WEIN MEMORIAL	66.89	–162.60	8A	3952.01	44.34	3996.35
BARTER ISLAND (DEW)	70.13	–143.63	8A	5331.20	1.17	5332.37

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Chapter 7. Study on the Energy Saving Potential Introducing Ventilation Design Strategies

7.1. Introduction

Ventilation that reduces building energy consumption and improves indoor environment has become a major method to achieving sustainability in the building industry. The potential for utilizing ventilation strategies depends greatly on the local climate, which varies widely from region to region in the world. According to the conclusion of previous study of this thesis, the building energy-saving effect is not obvious in the area with the latitude below 35 degrees. It is recommended to reconsider the setting of the score in the green building evaluation in areas below 35 degrees. Energy-saving effects such as introducing ventilation are obvious in these areas, and it is considered to increase the proportion of the scores. In this chapter, energy saving potential of several locations in America, Japan and China were calculated with Building Energy Simulation (BES). It demonstrated the ventilation time derived from outdoor meteorological data can measure maximum energy saving potential of ventilation without conduction detailed BES.

Studies have shown that the building sector account for 23% to 47% of total primary energy consumption in developed and developing counties worldwide[1–5]. Given this enormous energy consumption, lots of advanced technologies have been developed to achieve high building energy efficiency. Among them, introducing ventilation, which supplies and removes air to and from an indoor space using mechanical or natural forces of wind and buoyancy, shows great potential to reduce the energy required for cooking buildings while still provides acceptable indoor environmental quality[6–8].

The design strategy for buildings with ventilation systems relies heavily on the characteristics of local climate, which varies considerably from different latitude. Researches in the past have investigated various aspects with regard to ventilated buildings across different climate zones in the world. Yao et al. investigated the natural ventilation cooling potential of office buildings in five climate zones of China using the Thermal Resistance Ventilation model and demonstrated that the natural ventilation cooling potential depends on climate, building thermal characteristics and internal gains[9]. Tantasavasdi et al. conducted a study in Bangkok, Thailand, suggesting that natural ventilation can provide a thermally comfortable indoor environment for 20% of the year. The natural ventilation threshold for indoor air velocity was derived from the climate and thermal comfort analysis[10]. Existing studies focus largely on natural ventilation systems at a specific region in the world. The regional variations in ventilation potentials have rarely been investigated from a global perspective. Building ventilation strategies are highly dependent on climatic conditions at the location of interest. As climate varies from region to region in the world, it is critical to understand the variation between regions in order to utilize ventilation more effectively. The objective is to assist policy makers and architects in recognizing quantitatively the ventilation potentials at various regions and climates around the world, and in properly developing sustainable strategies considering local climatic characteristics.

7.2. Simulation model

The simulation model was adopted the same DOE model as introduced in Chapter 5. In order to obtain concise and definite results, when analyzing the thermal environment in this study, the calculation time in summer was assumed to be 1st June to 30th September, and 1st December to 30th March in winter. The other months are mild season. HVAC is not running in mild season. The World Health Organization's standard for comfortable warmth is 18 °C (64 °F) for normal, healthy adults who are appropriately dressed[11]. A series of psychological experiments by ASHRAE showed that people have been acculturated to believe that 22.2° C is the optimum comfortable room temperature. It also showed that “The preferred temperature range for occupants dressed in summer clothes is 22.5° C to 26° C”[12]. Therefore, this research set a ventilation boundary 18-26° C roughly.

- ✓ Summer season is from 1st June to 30th September. The room air temperature cooling setpoint is 24°C.
- ✓ Winter season is from 1st December to next year 30th March. The room air temperature heating setpoint is 21°C.
- ✓ Mild season with no HVAC system running.
- ✓ The boundary conditions of ventilation implementation are developed according to the seasons. In mild season, when outdoor temperature is 18°C to 26°C, the ventilation will be employed by 4 times per hour air change. When the outdoor temperature out the temperature range, the window will be closed, means there is no ventilation or air conditioning running. In summer daytime from 8 am to 10 pm, HVAC system will be running with 24°C setpoint. In nighttime, it will be employed ventilation by 4 times per hour air change as well based on the outdoor temperature (18°C to 26°C), while HVAC system will stop. There is no ventilation implementation in winter all the time.

The case for the evaluation of energy potential with implementation of ventilation choose the same cities in chapter 5 where located in the latitude lower than 35-degree area. After simulation with boundary conditions as introduced above, the energy consumption will be compared to the base model result in chapter 5.

The case selected cities for evaluate the applicability of ASHRAE in Japan and China are based on the result of chapter 4 where they are located in the same ASHRAE climate zone but in different climate zone of their own county.

- ✓ Selected simulation cities in Japan: Miyakojima, Hana, Fukuoka, Takayama, Kanazawa, Sendai.
- ✓ Selected simulation cities in China: Qionghai, Guangzhou, Zhaotong, Nanjing, Qingdao, Nanyang.

7.3.Comparison of introducing ventilation energy saving potential in U.S., Japan and China

The boundary condition was assumed that when the outdoor temperature is 18-26 degree, which means it is suitable to apply ventilation and stop the air-conditioning working. Then compared the energy consumption with the base model, which using air-conditioning for all year. Figure 5.1 shows that most obvious energy-saving effect due to introducing ventilation appears in the latitude of 20 to 25 degree, reaching 52%. The amount of total energy saving appears in this area.

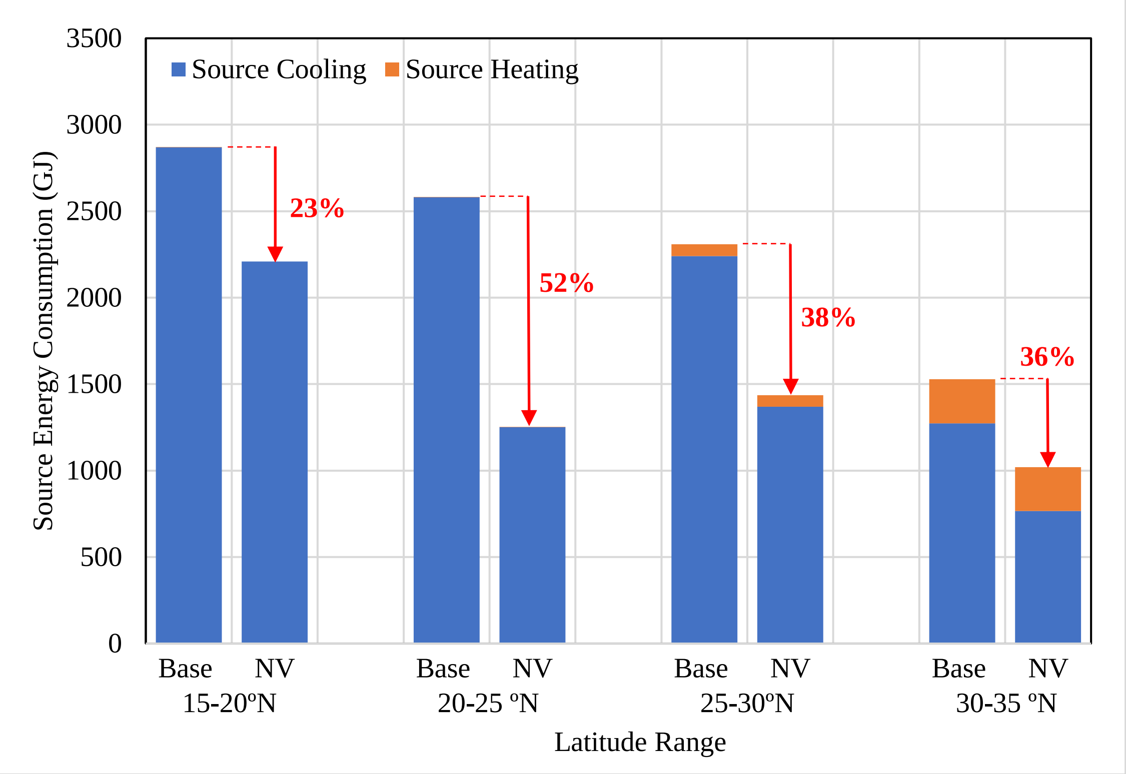


Figure 5.1. Energy saving with ventilation strategy in U.S.

The blue column stands for cooling energy consumption and orange column stands for heating. Introducing ventilation can effectively reduce the cooling energy.

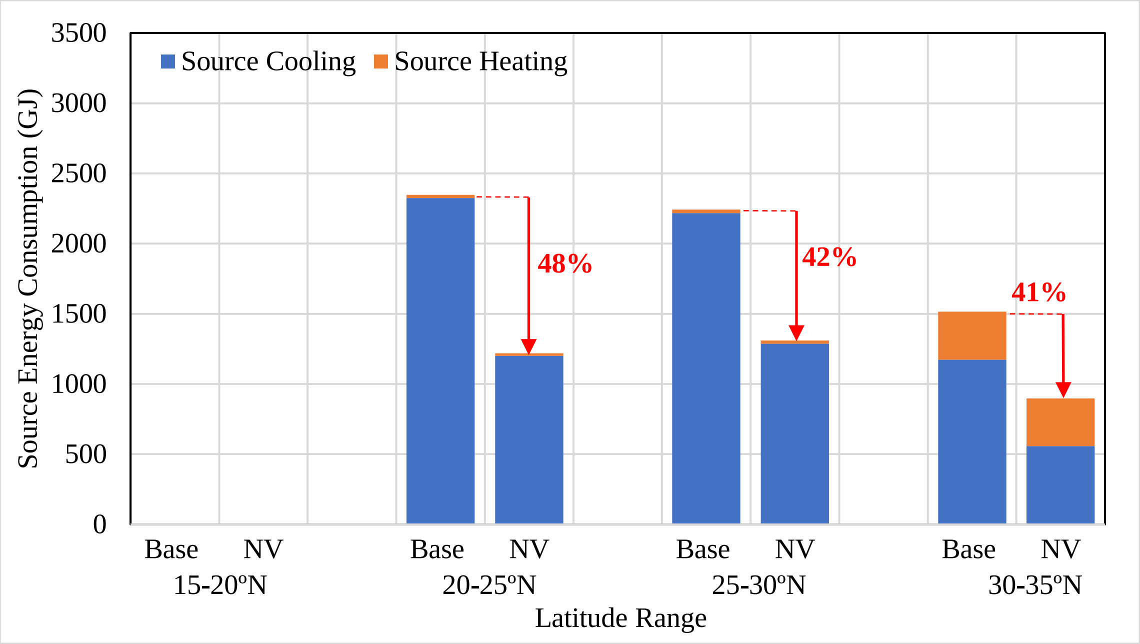


Figure 5.2.Energy saving with ventilation strategy in Japan

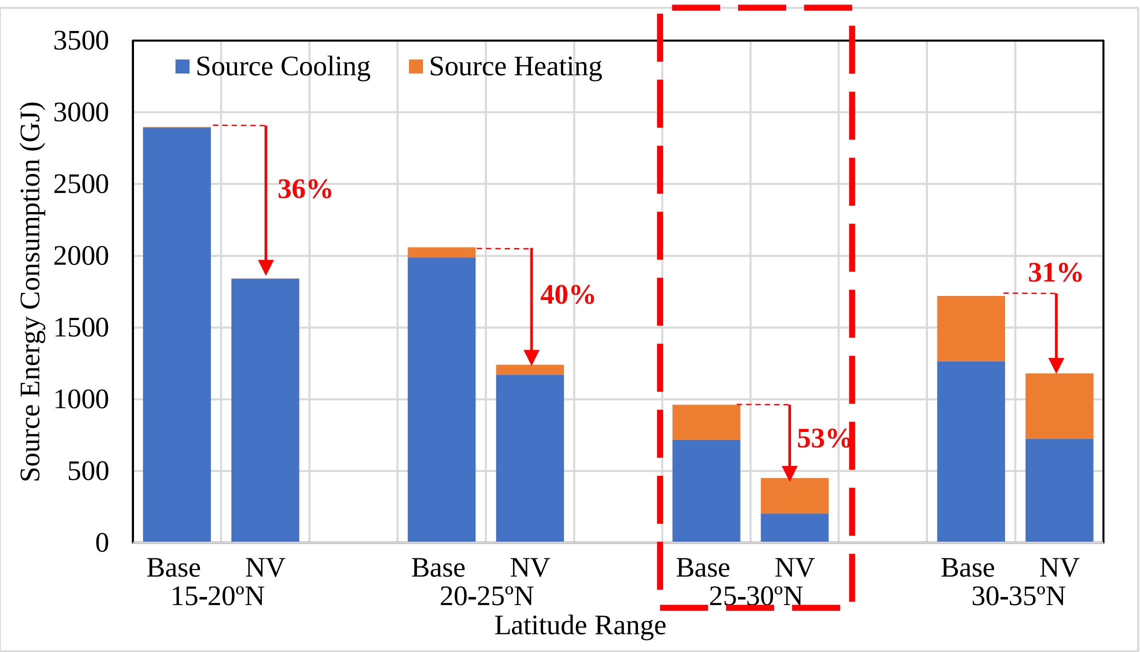


Figure 5.3.Energy saving with ventilation strategy in China

Figure 5.2 and Figure 5.3 respectively analyze the energy-saving potential of ventilation in buildings in areas below 35 degrees in Japan and China. Japan does not have a region of 15-20 degrees, and other regions have similar results with the United States. In the 20-25 latitude area, the energy-saving effect is the most obvious, reaching 48%. However, the most obvious area of energy conservation in

China is located at 25-30 degrees, reaching 53%. Moreover, the total energy consumption of the base building in this area is lower than that in the 30-35 area. It does not agree with the conclusions of Chapter 4 that the lowest consumption appears in the mid-latitude range of 35-45 degree. The reason is predicted that the climatic conditions in 25-30-degree latitudes of China are different from those in the United States. In the following part the applicability of the US global climate division in China and Japan will be verified.

7.4. Applicability of ASHRAE climate zone in Japan and China

7.4.1. Analysis of climate zone latitude distribution

Figure 5.4, Figure 5.6 and Figure 5.5 shows the climate zone distribution cited from ASHRAE 169. Japan has only Zone A under the ASHREA zoning method. Therefore, Japanese architectural design needs to focus on dehumidification and prevention of condensation; there are many places in China that are in Zone 6,7,8 which is relatively cold and should focus on building insulation design. Zone 3 and 4 should considered ventilation.

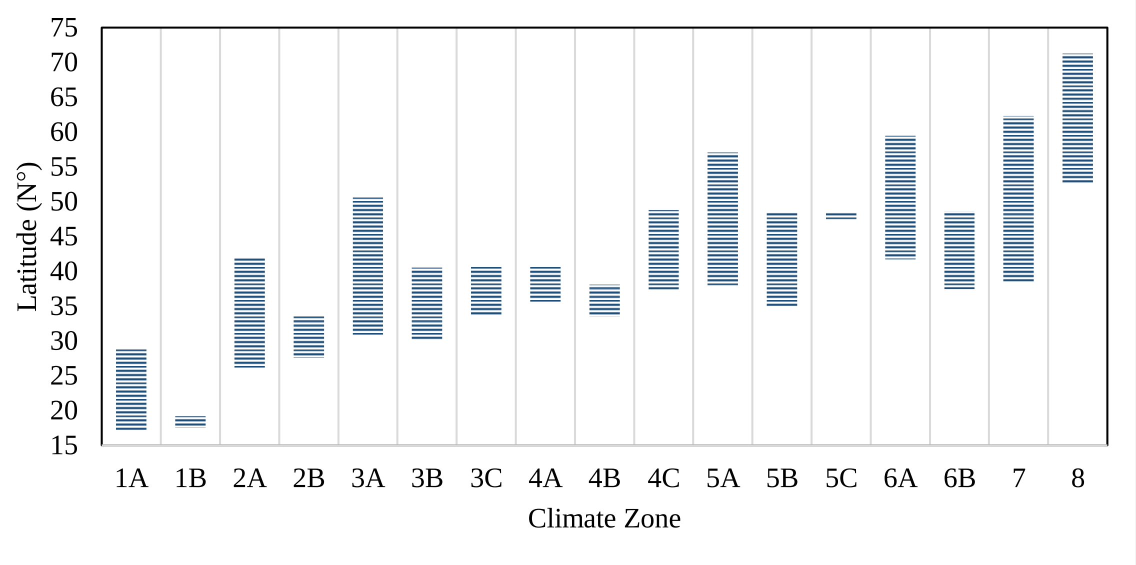


Figure 5.4. American climate zone latitude distribution based on ASHRAE 169

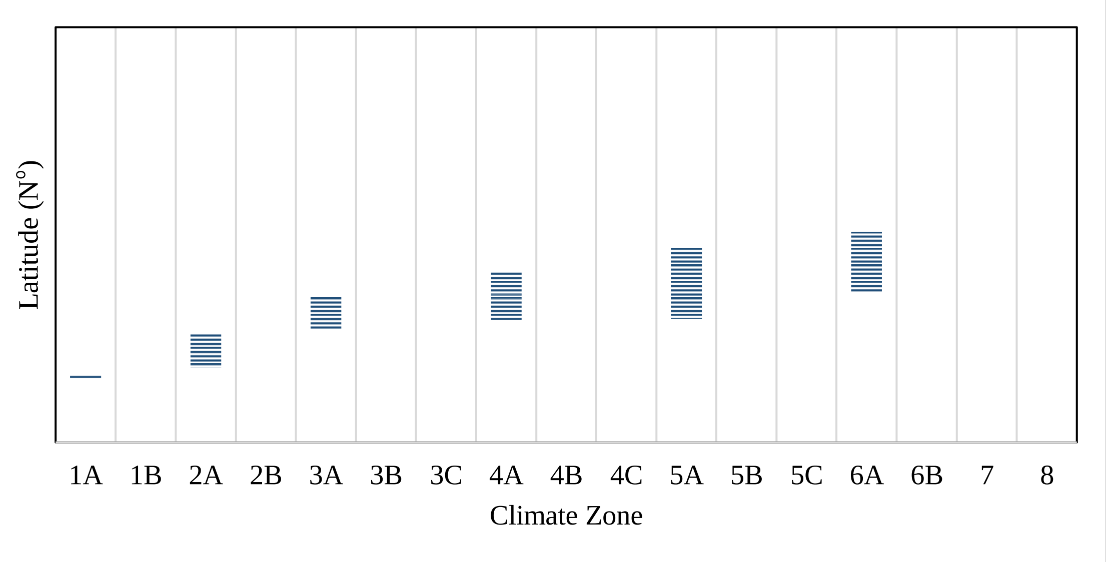


Figure 5.5. Japan climate zone latitude distribution based on ASHRAE 169

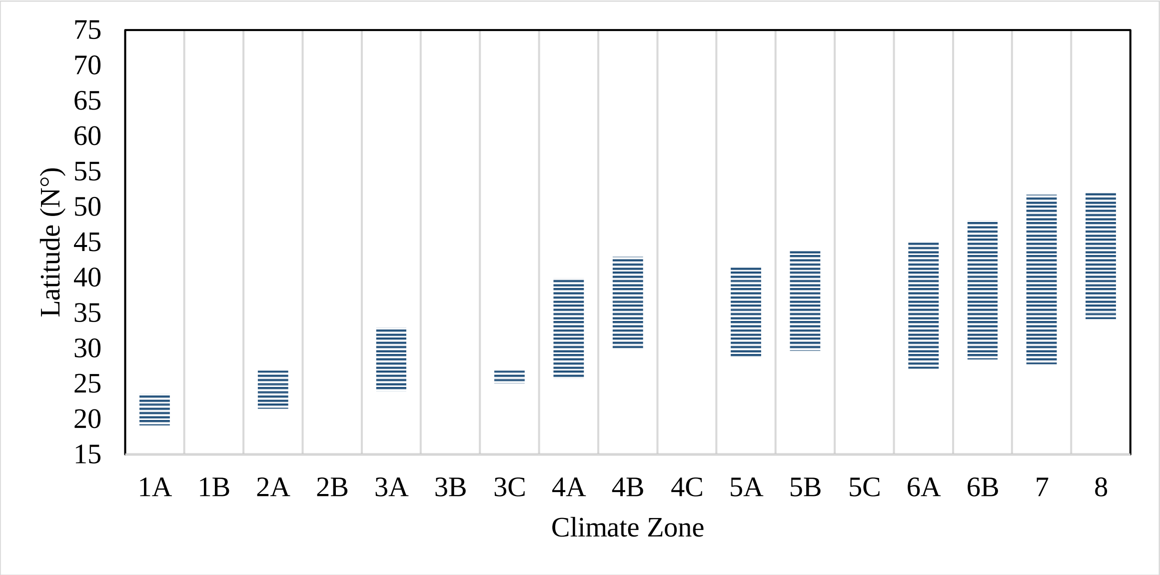


Figure 5.6. China climate zone latitude distribution based on ASHRAE 169

7.4.2. Analysis of applicability of ASHRAE climate zone

➢ Validation in Japan -Case 1

First validation chooses Fukuoka and Kagoshima in Japan, which located in Zone 6 and Zone 7 according to Japan climate zone division respectively (Figure 5.7). In ASHRAE climate zone, both of them are located in the same zone of 3A. The total source energy consumption agrees with the distribution rule of America.

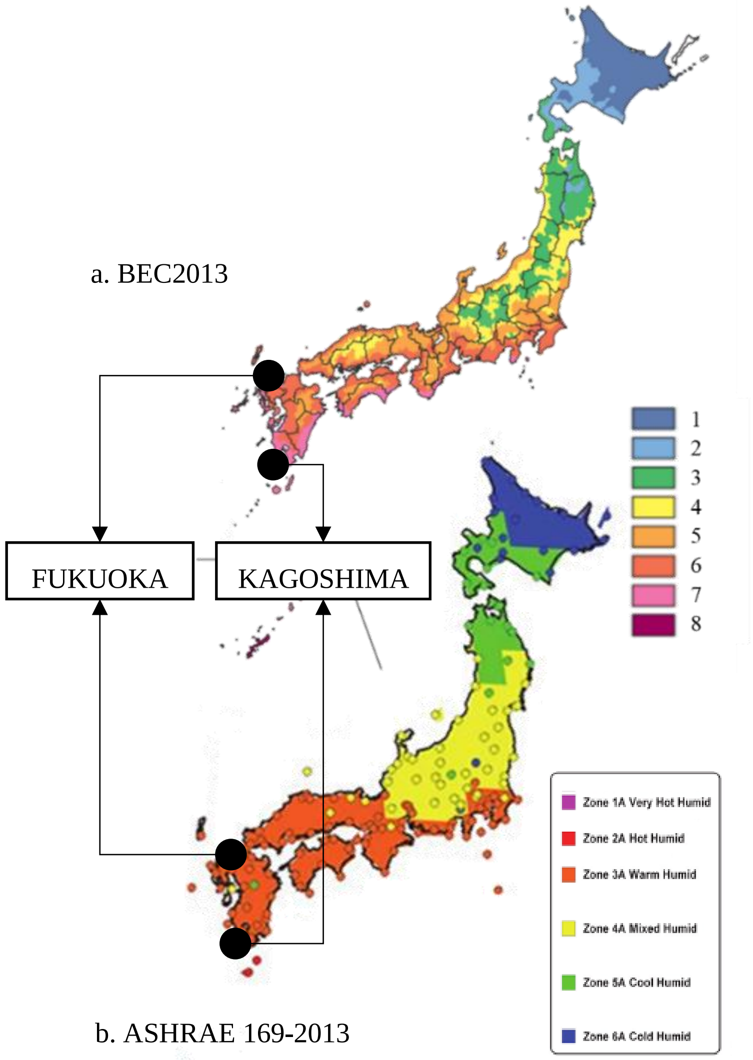


Figure 5.7. Selected city in Japan-Case 1

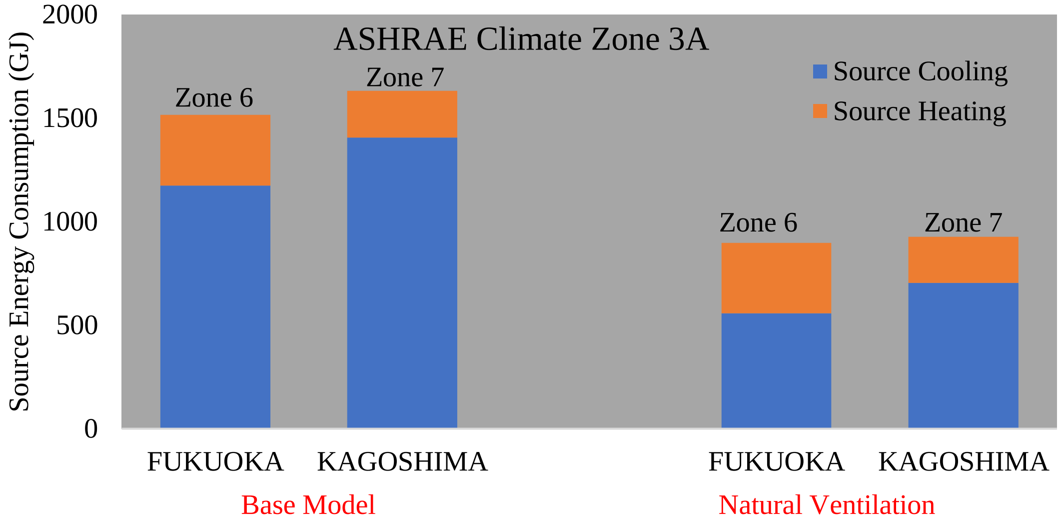


Figure 5.8. Japan climate zone map

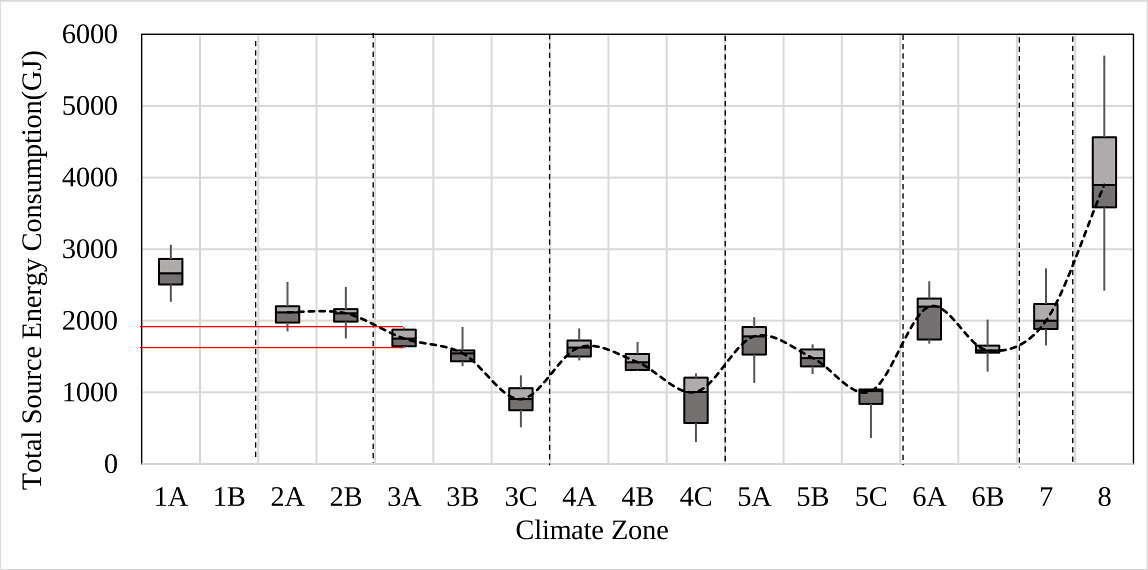
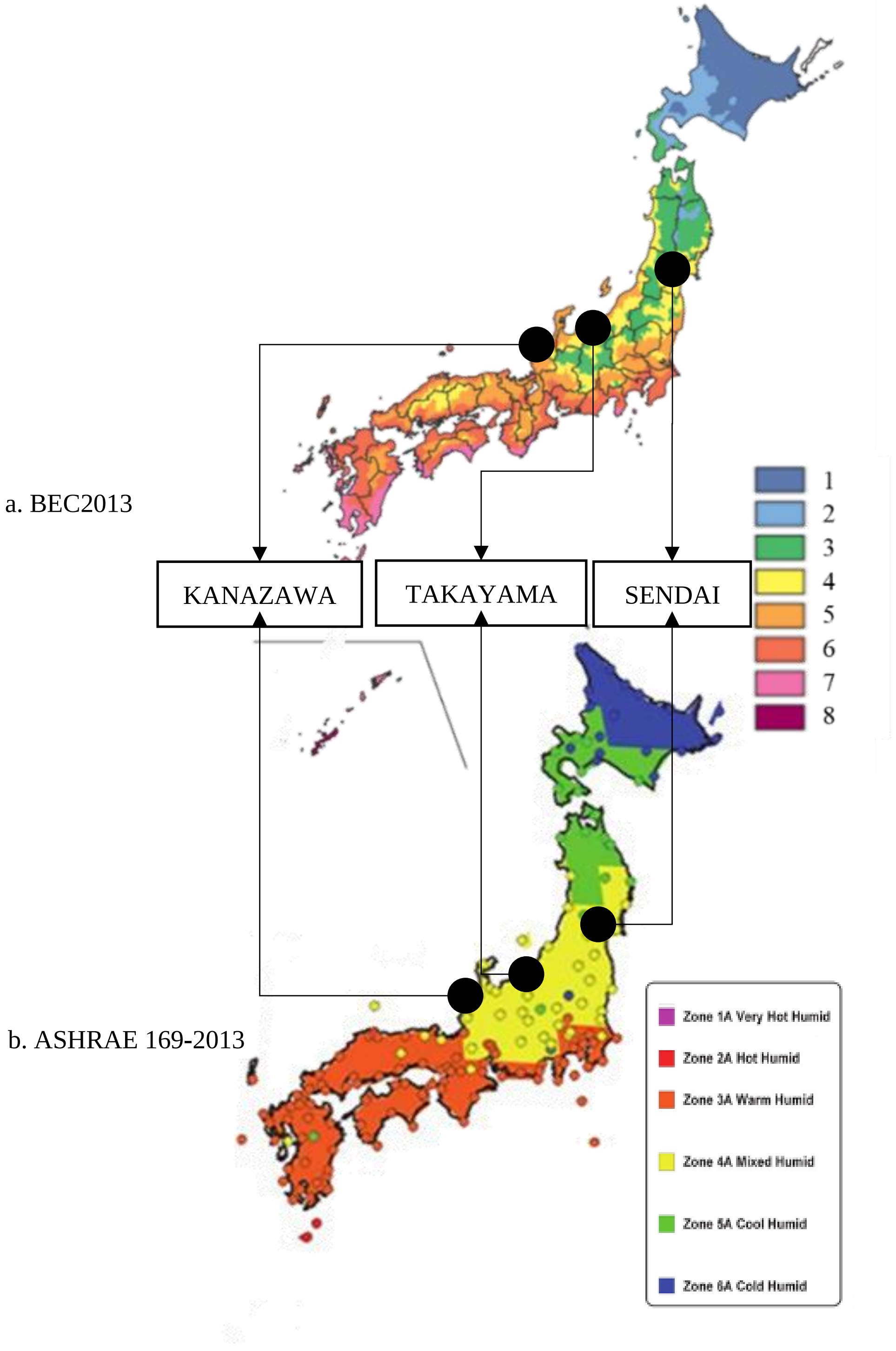


Figure 5.9. Comparison of Japan case 1 with the Zone 3A energy consumption distribution rude

- Validation in Japan -Case 2

The second validation choose three cities with different climate zone in Japan, which are Sendai, Takayama, and Kanazawa. according to Japan climate zone division, they belong to zone 3,4,5 respectively. In ASHRAE climate zone, all of them are located in the same zone of 4A. Similarly, the total source energy consumption also agrees with the distribution rule of America. Japan's climate division is more detailed than ASHRAE.

Because Japan is an island country, its geographical characteristics determine that humidity is a very important factor in the design of energy-efficient buildings. Japan's climate zoning takes full account of the distinction between coastal and inland areas. However, the United States classifies Japan only from the latitude. Although the simulation results have no obvious difference in the division method between the United States and Japan, the obvious difference between the two can still be seen from the partition map. And the US ASHRAE design standards do not require humidity design in different climatic zones, so it is not completely applicable to Japanese building energy-saving design.



a. BEC2013

b. ASHRAE 169-2013

Figure 5.10. Selected city in Japan-Case 2

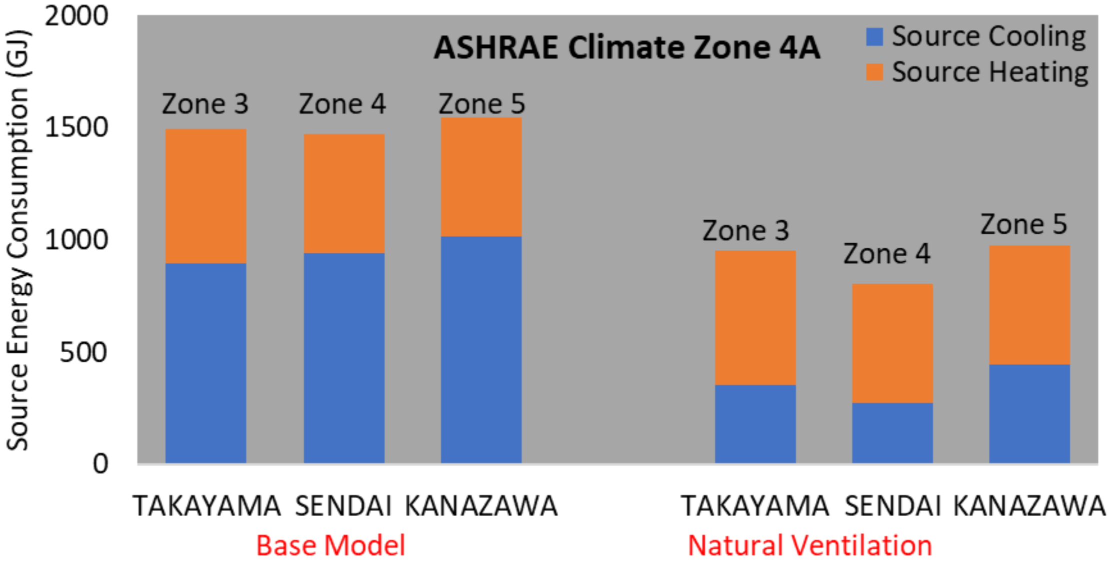


Figure 5.11. Japan climate zone map

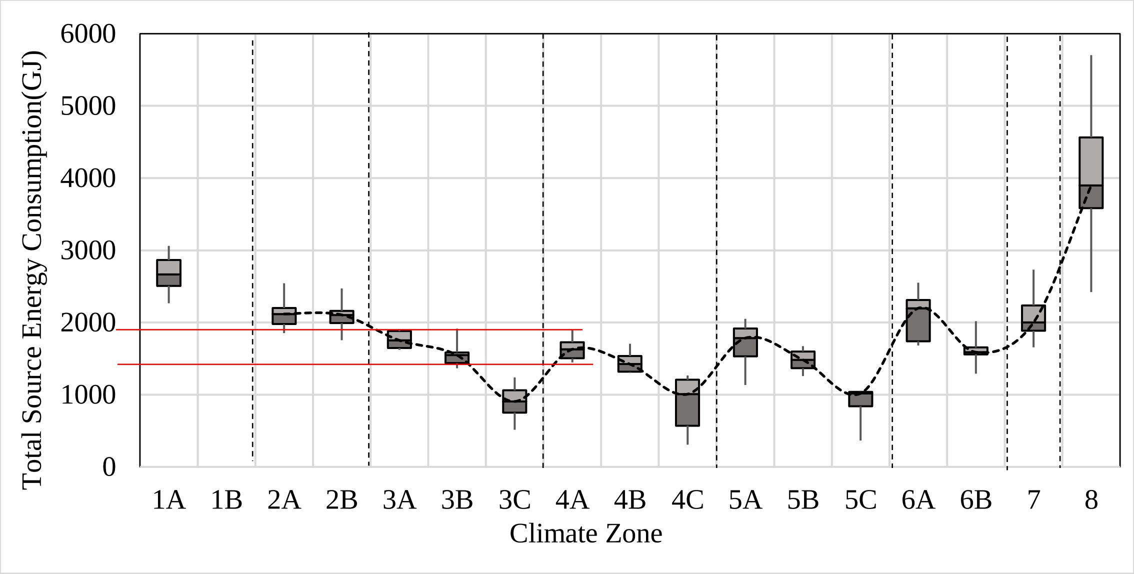
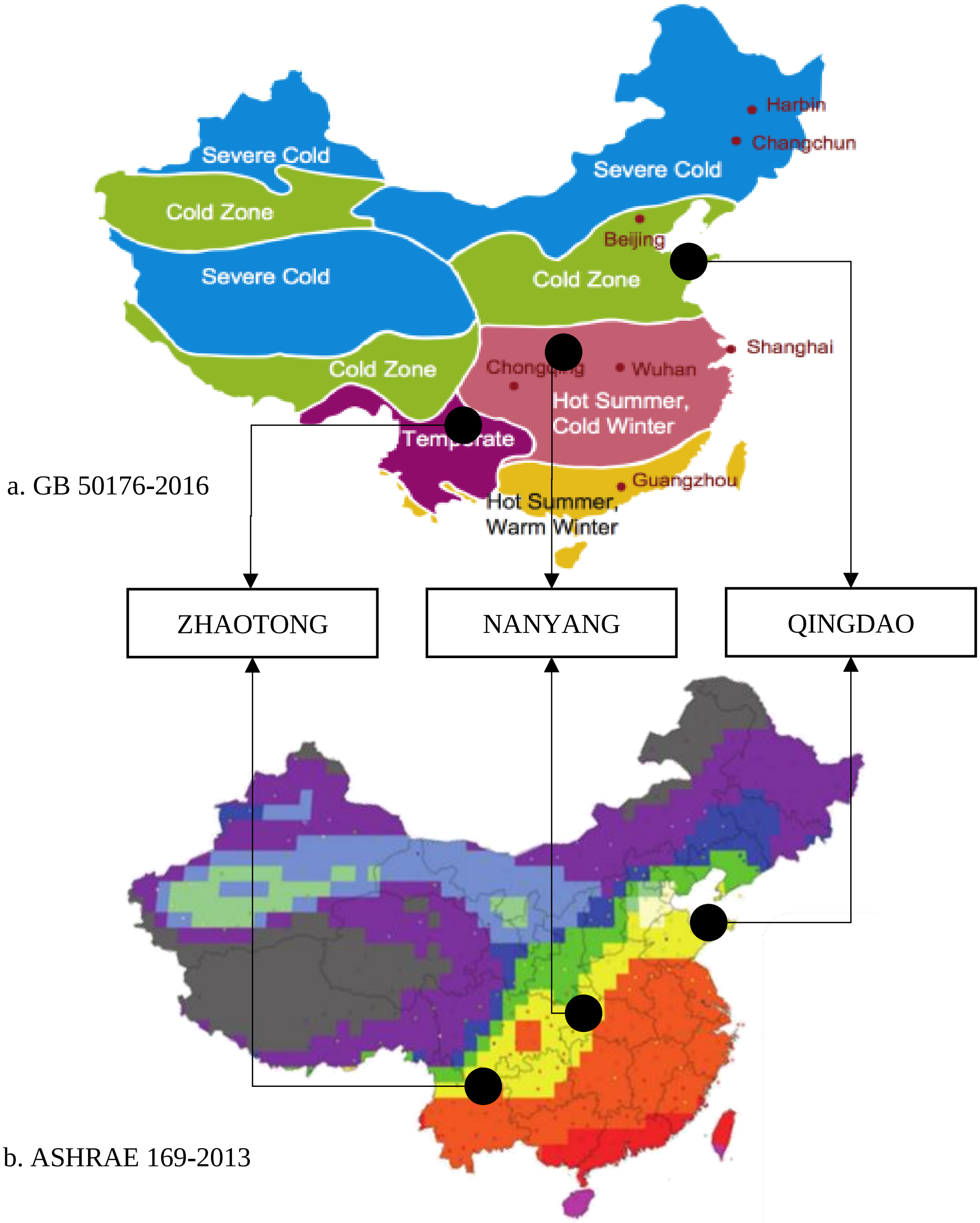


Figure 5.12. Comparison of Japan case 2 with the Zone 4A energy consumption distribution rude

- Validation in China

The cities selected in China for validation is Qingdao, Nanyang, Zhaotong, which located in cold zone, hot summer and cold winter zone, and temperature zone respectively. They all belong to Zone 4A in ASHRAE standard. The column chart shows that there is obvious different feature among these three cities. Qingdao and Nanyang have the similar total source energy consumption. However, the heating consumption in Qingdao is larger than Nanyang, the cooling condition is opposite. Zhaotong consume less energy than the other because its mild climate. ASHRAE climate zoning method is not applicable in several area of China.



a. GB 50176-2016

b. ASHRAE 169-2013

Figure 5.13. Selected city in China

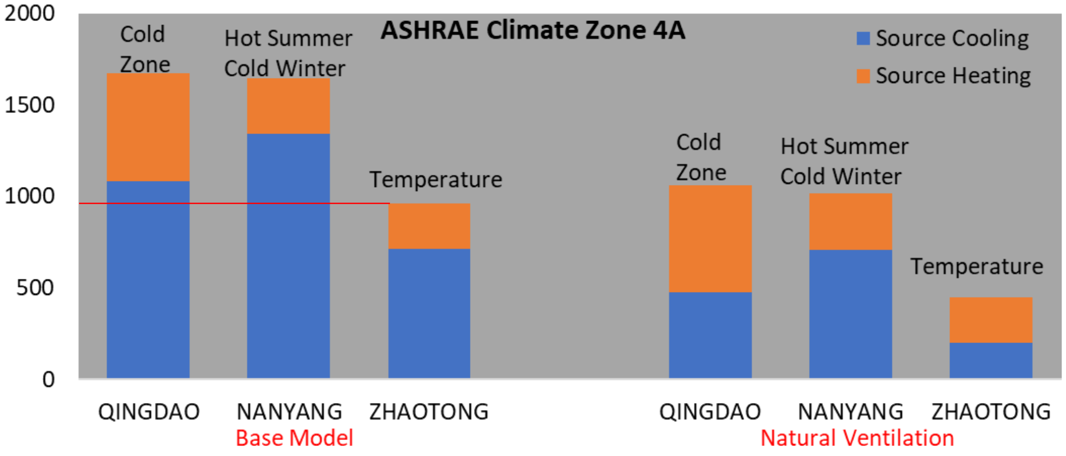


Figure 5.14. China climate zone map

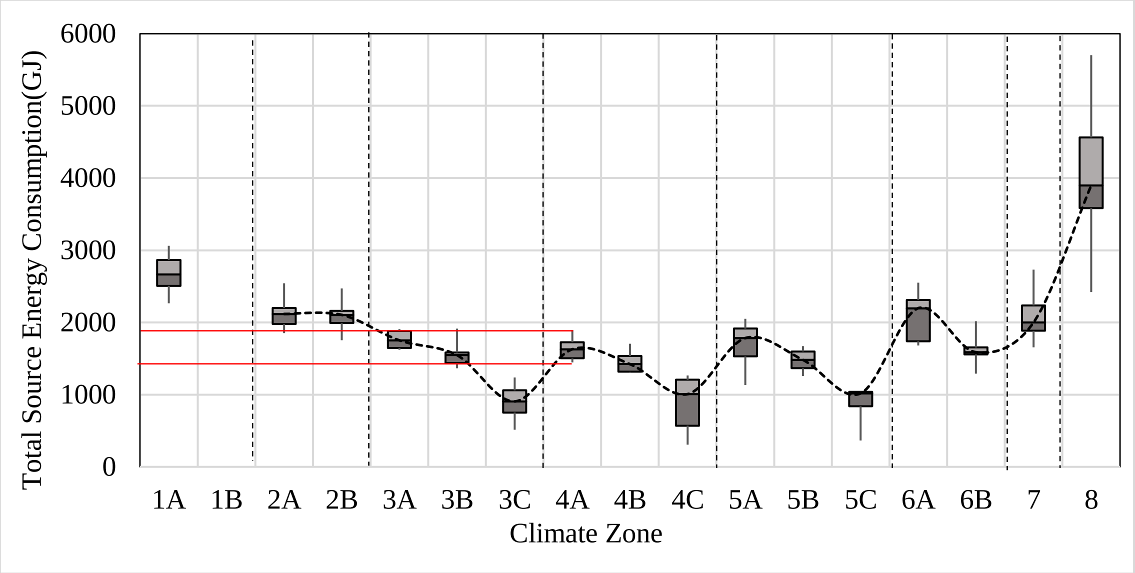


Figure 5.15. Comparison of China case with the Zone 4A energy consumption distribution rude

7.5. Introducing ventilation impact on the indoor thermal environment

Energy saving potential with ventilation is obvious after evaluation above. Meanwhile, the indoor thermal environment is also import with this strategy. Take a case in Fukuoka for example. The heat map of outdoor and indoor were plot. Figure 5.16 shows that the outdoor temperature for whole year in Fukuoka. Obviously, in summer daytime, the temperature is around 30℃, which means HVAC systems should be employed during that time. During December to next year March, the temperature is lower than 13℃ that the heating is necessary. When the outdoor temperature is between 18℃ to 26℃, it is better to apply ventilation. Figure 5.17 show when apply ventilation, the room air temperature will change greater than that with air-conditioning. However, most of time the temperature still in a comfort range which is still acceptable for occupants.

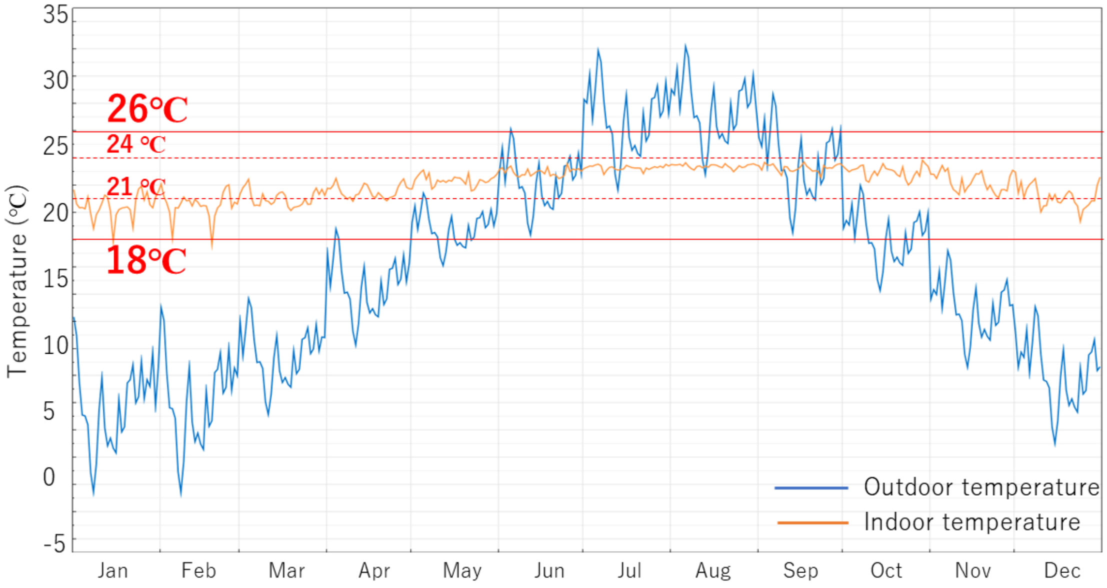


Figure 5.16. Outdoor and indoor temperature of base model in Fukuoka

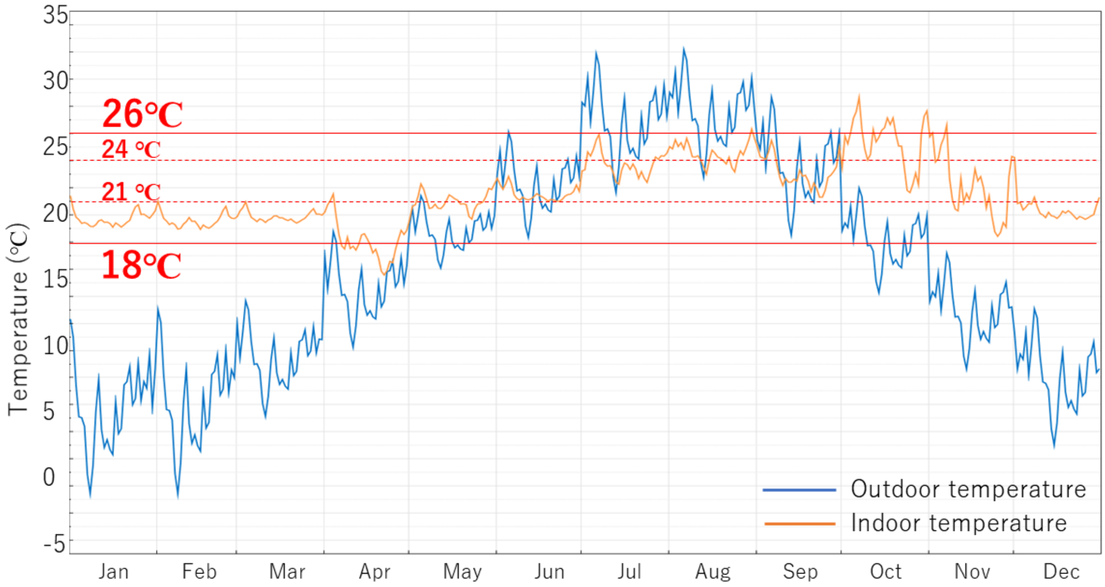


Figure 5.17. Outdoor and indoor temperature with ventilation strategy in Fukuoka

The ASHRAE Standard 55-2013 Thermal Environmental Conditions for Human Occupancy uses a graphic comfort zone method that takes into account the factors of relative humidity, humidity ratio, operative temperature, and wet bulb temperature with notes on clothing, metabolic rate, radiant temperature, and air speeds (Figure 5.18). In Appendix F, ASHRAE states "there are no established lower humidity limits for thermal comfort; consequently, this standard does not specify a minimum humidity level."

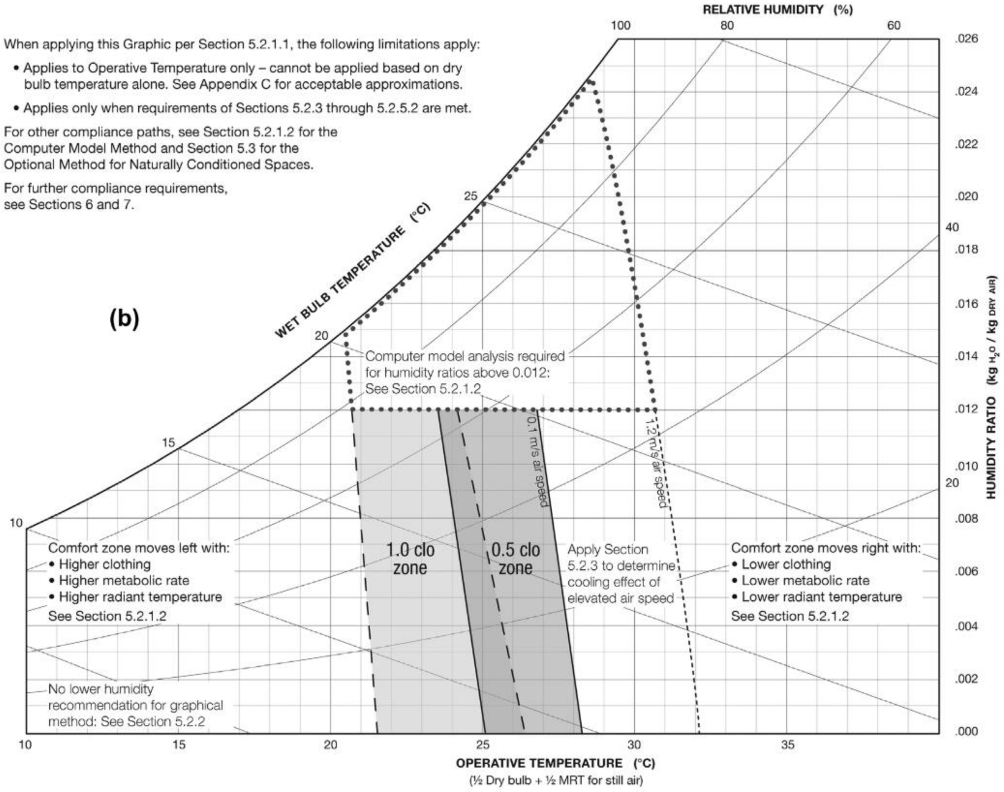


Figure 5.18. Graphic Comfort Zone Method: Acceptable range of operative temperature and humidity for spaces

With regard to humidity, if it is too high this will cause discomfort (excessive perspiration, exacerbation of the effects of high temperature, feelings of 'closeness', etc.) and if it's too low it can cause respiratory problems. Relative humidity levels below 20% can cause discomfort through drying of the eyes and mucous membranes and skin. Low relative humidity levels may also cause static electricity build-up and negatively affect the operations of some office equipment such as printers and computers. Relative humidity levels above 70% may lead to the development of condensation on surfaces and within the interior of equipment and building structures. Left alone, these areas may develop mound and fungi. Higher humidity also makes the area feel stuffy. The Health and Safety Executive (UK) states that a relative humidity between 40% and 70% does not have a major impact on thermal comfort[13].

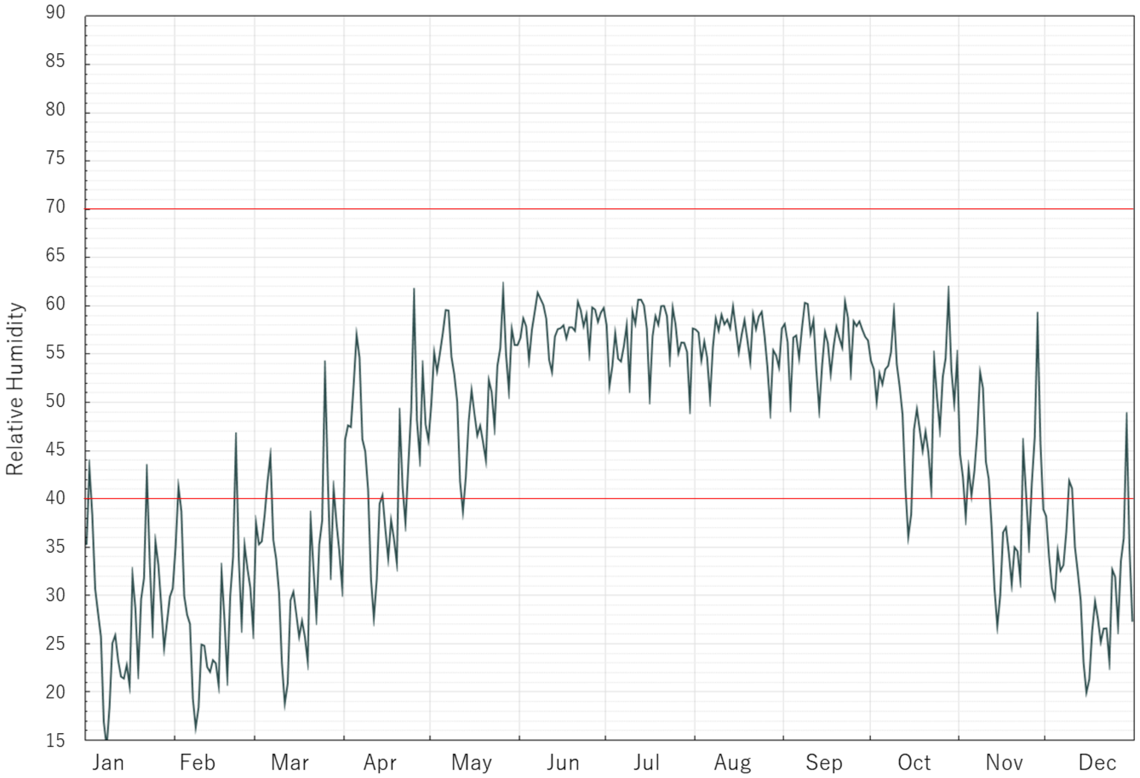


Figure 5.19. Indoor relative humidity of base model in Fukuoka

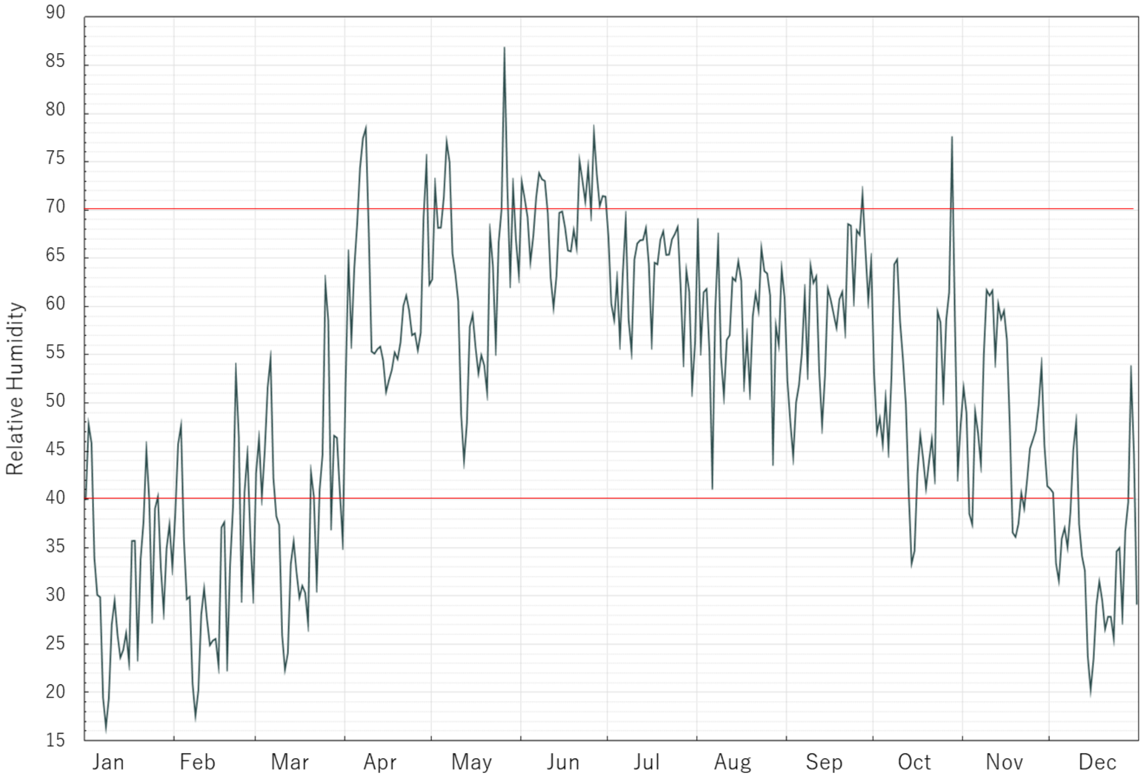


Figure 5.20. Indoor relative humidity with ventilation strategy in Fukuoka

Figure 5.19 and Figure 5.20 shows the indoor relative humidity of base model and introducing ventilation in Fukuoka, respectively. The reference model uses air conditioning throughout the year. During the summer months from June to September, the indoor humidity is strictly controlled between 50% and 60%. In winter, from December to March, the indoor humidity is between 15% and 40%. Humidity fluctuates between 30% and 60% during the transition season. The year-round air-conditioning mode controls the indoor temperature and humidity more strictly to ensure that the room is always within the comfortable range. At the same time, it will bring relatively high energy consumption. Figure 5.20 shows the indoor relative humidity fluctuations after the ventilation system is introduced. After the introduction of the ventilation system, the indoor relative humidity fluctuations are significantly greater than the year-round air conditioning, especially in summer. From June to September in summer, the indoor humidity can reach a maximum of about 85% and a minimum of 40%. The indoor humidity in winter is basically consistent with the performance under the condition of using year-round air conditioning. Relative humidity above 70% may cause discomfort. However, based on the whole year, the indoor relative humidity exceeds 70% only in a small part of the transition season and summer. After using the ventilation system, the indoor humidity can still be controlled within the comfort range most of the time. The energy-saving effect it brings is considerable. It can be concluded that when the outdoor environment is suitable, the indoor environment can be optimized by introducing ventilation, and the purpose of energy saving can be achieved at the same time.

7.6. Summary

This chapter analyzed the energy saving potential with the application of ventilation. In America, the most obvious energy-saving effect due to introducing ventilation appears in the latitude of 20-25 degree, reaching 52%. The amount of total energy saving appears in this area. Main contribution of ventilation is to reduce cooling energy consumption. Japan and America have similar conclusions, while China's most energy-efficient regions are located at 25-30 degrees. When the latitude is above 35 degrees, the natural ventilation energy-saving effect is obvious. Therefore, the application of this technology should be considered in the green building design process, and the rating ratio should be increased in the green building evaluation process. Introducing ventilation into indoor space will make the temperature and relative humidity more fluctuating than that of whole year air-conditioning condition. However, the temperature and relative humidity still in the acceptable range for occupants' comfort.

Verification of the applicability of the ASHRAE global climate zoning approach shows that it is not fully applicable. The validation chose cities in different climate zone in Japan and China but in the same climate zone with ASHRAE classification. Then compare the energy consumption of base model in these cities. The result shows that there is obvious difference of building energy consumption in the selected cities located in different climate zones in China. ASHRAE global climate zoning approach is not suitable for China. Because Japan is an island country, its geographical characteristics determine that humidity is a very important factor in the design of energy-efficient buildings. Japan's climate zoning takes full account of the distinction between coastal and inland areas. However, the United States classifies Japan only from the latitude. Although the simulation results have no obvious difference in the division method between the United States and Japan, the obvious difference between the two can still be seen from the partition map. And the US ASHRAE design standards do not require humidity design in different climatic zones, so it is not completely applicable to Japanese building energy-saving design.

Appendix A. Source energy consumption with ventilation strategies of selected cities of America

Country/LOCATION	Lat	Long	CZ	Electricity [GJ]		Natural Gas [GJ]	Source Heating [GJ]	Source Cooling [GJ]	Source Total [GJ]
SAN JUAN L M MARIN INTL AP	18.43	–66.00	1A	0	697.52	0	0.00	2209.05	2209.05
KAHULUI AIRPORT	20.9	–156.43	1A	0.37	395.1	0	1.17	1251.28	1252.45
MIAMI INTL AP	25.82	–80.30	1A	3.32	478.08	0.004	10.52	1514.08	1524.60
ST PETERSBURG CLEAR	27.9	–82.68	2A	7.94	433.08	0.12	25.28	1371.56	1396.84
HONDO MUNICIPAL AP	29.36	–99.17	2B	48.78	385.37	9.7	165.00	1220.47	1385.47
DAVIS-MONTHAN AFB	32.17	–110.88	2B	38.52	366.3	0.56	122.60	1160.07	1282.67
FORT WORTH ALLIANCE	32.98	–97.32	2A	73.38	353.12	16.28	250.04	1118.33	1368.37
ATHENS BEN EPPS AP	33.95	–83.33	3A	89.88	214.1	14.16	300.00	678.05	978.05
CANNON AFB/CLOVIS	34.38	–103.32	4B	134.72	188.21	30.67	459.90	596.06	1055.97
SANTA BARBARA MUNICIPAL AP	34.43	–119.84	3C	38.78	40.21	1.43	124.37	127.35	251.71
EDWARDS AFB	34.9	–117.88	3B	80.75	289.68	8.23	264.66	917.42	1182.07

Appendix B. Source energy consumption of base model of selected cities of Japan

Country/LOCATION	Lat	Long	CZ	Japan CZ	Electricity [GJ]		Natural Gas [GJ]	Source Heating [GJ]	Source Cooling [GJ]	Source Total [GJ]
MIYAKOJIMA	24.8	125.28	1A	8	7.09	733.84	0	22.45	2324.07	2346.53
NAHA	26.2	127.68	2A	7	7.76	699.91	0	24.58	2216.61	2241.19
FUKUOKA	33.58	130.38	3A	6	98.83	370.58	26.19	341.38	1173.63	1515.01
KAGOSHIMA	31.55	130.55	3A	7	65.04	444.02	17.52	224.97	1406.21	1631.18

TAKAYAMA	36.15	137.25	4A	3	155.46	283.17	98.84	599.48	896.80	1496.28
SENDAI	38.27	140.9	4A	4	141.37	297.05	73.93	527.86	940.76	1468.62
KANAZAWA	36.58	136.63	4A	5	148.18	319.93	60.27	534.62	1013.22	1547.84

Appendix C. Source energy consumption with ventilation strategies of selected cities of Japan

Country/LOCATION	Lat	Long	CZ	Japan CZ	Electricity [GJ]		Natural Gas [GJ]	Source Heating [GJ]	Source Cooling [GJ]	Source Total [GJ]
MIYAKOJIMA	24.8	125.28	1A	8	6.1	378.9	0	19.32	1199.98	1219.30
NAHA	26.2	127.68	2A	7	6.95	406.61	0	22.01	1287.73	1309.74
FUKUOKA	33.58	130.38	3A	6	98.63	175.94	26.19	340.75	557.20	897.95
KAGOSHIMA	31.55	130.55	3A	7	64.67	222.13	17.52	223.80	703.49	927.29
TAKAYAMA	36.15	137.25	4A	3	155.45	111.29	98.84	599.45	352.46	951.91
SENDAI	38.27	140.9	4A	4	141.35	87.06	73.93	527.80	275.72	803.51
KANAZAWA	36.58	136.63	4A	5	148.01	139.62	60.27	534.08	442.18	976.26

Appendix D. Source energy consumption of base model of selected cities of China

Country/LOCATION	Lat	Long	CZ	China CZ	Electricity [GJ]		Natural Gas [GJ]	Source Heating [GJ]	Source Cooling [GJ]	Source Total [GJ]
QIONGHAI	19.23	110.47	1A	HSWW	1.21	914.03	0	3.83	2894.73	2898.57
GUANGZHOU	23.17	113.33	2A	HSWW	22.46	627.62	0	71.13	1987.67	2058.80
ZHAOTONG	27.33	103.75	4A	Temp	73.74	225.86	12.41	246.99	715.30	962.29
NANJING	32	118.8	3A	HSCW	122.9	399.71	60.81	455.14	1265.88	1721.02

NANYANG	33.03	112.58	4A	HSCW	78.98	423.5	50.09	304.43	1341.22	1645.65
QINGDAO	36.07	120.33	4A	CZ	151.02	341.45	102.07	588.92	1081.37	1670.30

Appendix E. Source energy consumption with ventilation strategies of selected cities of China

Country/LOCATION	Lat	Long	CZ	China CZ	Electricity [GJ]		Natural Gas [GJ]	Source Heating [GJ]	Source Cooling [GJ]	Source Total [GJ]
QIONGHAI	19.23	110.47	1A	HSWW	0.86	581.37	0	2.72	1841.20	1843.92
GUANGZHOU	23.17	113.33	2A	HSWW	21.69	370.16	0	68.69	1172.30	1240.99
ZHAOTONG	27.33	103.75	4A	Temp	73.73	64.27	12.41	246.96	203.54	450.50
NANJING	32	118.8	3A	HSCW	122.79	229.31	60.81	454.79	726.22	1181.02
NANYANG	33.03	112.58	4A	HSCW	78.95	224.32	50.09	304.33	710.42	1014.75
QINGDAO	36.07	120.33	4A	CZ	150.94	149.81	102.07	588.67	474.45	1063.12

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Chapter 8. Conclusions

Green building, as a solution to address the current energy and environment issues, has developed twenty years. It has a majority of achievement, but still facing many barriers and challenges. This paper analyzes the shortcomings and misunderstandings in the development of green building and puts forward some reasonable suggestions. The influencing factors were divided into two categories, internal and external. The external factor refers to development status of green building which include policy support, economic benefits, and certification scheme. The internal factor refers to fundamental characteristics of green building which include technologies implementation, building management, and occupants' behavior. This research aims to provide a development roadmap for government, companies and other stakeholders. As for the internal factors, this paper focus on the aspects of energy saving and indoor thermal environment improvement, in terms of building envelope design and natural ventilation design strategies based on climate characteristics. The objectives include pointing out the shortcomings of green building design standard and misunderstanding of the implementation of air-conditioning, give suggestion of regional suitable green building design strategies. The conclusions of this research are summarized as follows.

In chapter one, **Background and Purpose of This Study,** introduced the today's global issues like climate change, energy shortages, increasing environmental pollution, rising population, and rapid urbanization present tremendous challenges to the sustainable development of human society. Among those various causes of these problems, the building construction industry has been criticized as being a leading exploiter of a large proportion of primary energy and natural resources. The global buildings sector consumed 30% of total final energy use. Accounting for upstream power generation, buildings represented 28% of global energy-related CO_2 emissions. To address these issues, the concept of Green building comes up. It is an integrative process that focuses on the relationship between the built environment and the natural environment. Building can have both positive and negative impacts on their surroundings as well as people who inhabit them every day, reduced energy and water use, healthy indoor environment quality, smart material selection and the building 's effects on its site are key considerations of a green building.

In chapter two, **Survey on the Status and Challenges of Green Building Development in Various Countries,** provided a comprehensive survey of the historical and current development of GB worldwide. It clearly identifies the key influencing factors related to different stakeholders in the development of green buildings, which were divided into two categories - the external and internal. The purpose of this division is to clearly identify the key influencing factors related to different stakeholders in the development of green buildings. The external factor refers to development status of green building which include policy support, economic benefits, and certification scheme. The internal factor refers to fundamental characteristics of green building which include technologies implementation, building management, and occupants' behavior.

Green building development situations in various countries were introduced. In the United States, the GB policies include mandate and incentive-based policies. LEED was developed by third party, as incentive based policies. In California, it was instituted as mandatory policy. In Japan, there are two authorization systems. One is the certification system, and another is the local governments' reporting system, with the purpose to encourage building owners to carry out voluntary efforts to reduce environmental load. In UK, BREEAM is widely applied, due to the fact that professional organizations and the construction industry have been a great effort to progressively make it compulsory to all new buildings and renovation projects. China emphasizes the development of GBs through a combination of mandates and incentives.

49 rating systems summarized specifically for GB design and certification all over the world. Since the first green building assessment BREEAM issued in 1990, the development of green building aligns with the development of the green building rating system. There are 49 rating systems summarized specifically for GB design and certification all over the world. A GBRS defines the attributes of GBs, provides tools to assess the environmental effects of buildings, and identifies specific interventions intended to promote the green building market. 11 standards are applied other countries except their own country. BREEAM has been carried out in 77 countries for nearly 30 years, with a total of nearly 60 thousand certification programs accumulated, ranking the first in the world, accounting for 80% of the total certificated green building projects in the world (Figure 5). LEED was most popular one applied in 167 countries. For better green building rating system implementation, many professionals who conduct auditing for achieving credits were certified. Sometimes they also can help to implement the international application of the standards to which the professionals belong. They work closely with the design team and the developers during the entire building construction process.

The fundamental characteristics includes technologies implementation, building management and occupants behavior. the technology field related to GBs is quite broad, encompassing land, energy, water resources, materials, building structure, indoor environment to construction technology, and more. The well-developed GB technology is not only the study of a single technology but also the ability to integrate multiple technologies and enable various stakeholders to continually participate in the process of GB construction. Second, an integrated management methodology is necessary to handle all aspects of GBs. From the occupants' perspective, enhancing their feedback is essential, because they directly impact the successful implementation of GBs. In the operation phase, successful building performance mainly depends on occupants who contribute to achieving the initial ecological objective by correctly using devices if they have a better understanding of GBs.

In chapter three, **Theories and Methodology of the Study,** introduced the research methodology and simulation theories. The simulation models are detailed introduce in this chapter as well. The climate data in this study are mainly employed TMY3 files which are derive from Integrated Surface Database (ISD) of US National Oceanic and Atmospheric Administrations (NOAA) with hourly data through 2017. The building energy consumption simulation among the 138 stations in U.S. were estimated using EnergyPlus, a validated and physics-based BES program developed by the U.S. Department of Energy (DOE).

In chapter four, **Comparison on Climate Zoning and Thermal Standard of Green Building Design**, summarized the relationship among climate, building energy standard and green building standard. The impact of climate is mainly reflected in the climate division in the energy standard for buildings. The energy-saving indicators of green buildings are generally based on building standards to further enhance the requirements. The climate zone division are roughly coinciding with the topographic trend in America, Japan and China. Only in America, the climate zone is consistent with administrative division. Japan has a more detailed classification of its own climate than ARSHRAE. ASHRAE shows a similar division for the north China. But in the middle area is quite different. Zone 4A across China's three climate zones of hot summer and cold winter, mild, and cold zone areas.

In chapter five, **Evaluation of Climate Impact on Building Energy Consumption,** evaluate the distribution rules of energy consumption with climate zone and latitude. Taking U.S. for example, there is no obvious distribution rules of total source energy consumption change with climate zone. The humidity zone ABC has significant differences in energy consumption, but the US design standards only require temperature partitioning and there is no distinction between humidity ABC zone. Questioned the classification of climate zones in the United States (the energy distribution map of the climate zone shows that the energy consumption in the 3th, 4th, and 5th zones is close, and the law is not obvious). Based on the rules, this chapter gives green building design strategies suggestion for different latitude area. Suitable Strategies for lower than latitude of 35-degree area is natural ventilation and shading design. Suitable Strategies for higher than 35 degrees area: optimizing insulation performance.

In chapter six, **Study on the Thermal Insulation of Building Envelope Opaque Area impact on Energy Consumption**, evaluate the energy saving potential in different latitude with the increase of building envelope opaque area. In areas with a latitude below 35 degrees, the optimization of the insulation layer on the building energy-saving effect is not obvious. Energy saving from 3% to 15% improvement of insulation only increase less than 20GJ. Higher than 35-degree areas are suitable to optimize the insulation performance of the envelope structure. With the increase of latitude degree and

R-value, the amount of energy saving rises dramatically.

In chapter seven, **Study on the Energy Saving Potential with Ventilation Design Strategies**, analyzed the energy saving potential with the application of ventilation. In America, the most obvious energy-saving effect due to introducing ventilation appears in the latitude of 20-25 degree, reaching 52%. The amount of total energy saving appears in this area. Main contribution of natural ventilation is to reduce cooling energy consumption. Japan and America have similar conclusions, while China's most energy-efficient regions are located at 25-30 degrees. When the latitude is above 35 degrees, the natural ventilation energy-saving effect is obvious. Therefore, the application of this technology should be considered in the green building design process, and the rating ratio should be increased in the green building evaluation process. Introducing ventilation not only achieves energy saving, but also keep the indoor environment in the acceptable comfort range for occupants. Verification of the applicability of the ASHRAE global climate zoning approach shows that it is not fully applicable.