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LOW ENERGY HOUSING FOR THE HOT HUMID CLIMATE OF VIETNAM: THE VALUE OF A PASSIVE HOUSE APPROACH

LOW ENERGY HOUSING
FOR THE HOT HUMID CLIMATE OF VIETNAM:
THE VALUE OF A PASSIVE HOUSE APPROACH

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Abstract

In Vietnam, the climate is such that creating thermal comfort inside building consumes significant energy. Residential buildings are responsible for 35% of electricity consumption and 27% of total energy use in the country. Therefore, in the context of ongoing global warming and energy crises, there is an urgent need to use energy efficiently to create thermal comfort in Vietnamese housing. This study aims to identify a new approach, which is based on the Passive House methodology, as an alternative solution to conventional natural ventilation design and to support the development of more robust dwellings in Vietnam.

This study firstly carried out a thermal comfort investigation to supplement the modest thermal comfort database of Vietnam. The thermal comfort zone of Vietnamese people was found to range 23.7 – 29.6°C, and this was used as an important criterion to evaluate indoor thermal conditions of Vietnamese dwellings.

A field study was undertaken to examine existing conditions of Vietnamese housing. The results indicated a poor thermal performance of existing housing with houses failing to satisfy thermal comfort in the hot season. Based on the data collected from the field study and a complementary survey on household appliances and energy consumption, two typical terraced and detached houses were modelled. The simulations of whole-year thermal performance indicated that a significant amount of energy was required to maintain thermal comfort in the existing housing stock.

To improve the performance of existing housing, passive design techniques were applied. While these techniques significantly reduced the cooling demand, high indoor humidity was a continuing disadvantage of conventional naturally ventilated dwellings and added to other indoor air quality concerns in polluted high-density areas. Consequently, the Passive House approach was proposed as an advance alternative solution for low energy housing in Vietnam.

To investigate the potential of the Passive House approach, the housing models were improved to meet the Passive House standard. The standard was adapted to the hot humid climate of Vietnam with a higher thermal comfort zone, higher humidity limit and lower envelope air tightness. Substantial energy saving of the Passive House dwellings were demonstrated compared to the existing houses.

Subsequently, a parametric simulation, based on key influencing building parameters, was used to calculate opportunities for Passive House dwellings in Vietnam. Based on the simulation outcomes, design guidance for Passive House dwellings was proposed.

A questionnaire survey was carried out with 71 professionals to assess the value of the guidance. The results indicate that the Passive House approach should be further researched and developed in Vietnam, and that the proposed design guidance is a useful document to aid decision making at early stage design.

Publication list

Journal

Le, V. T., & Pitts, A. (2019). A survey on electrical appliance use and energy consumption in Vietnamese households: Case study of Tuy Hoa city. *Energy and Buildings*, *197*, 229–241. https://doi.org/10.1016/j.enbuild.2019.05.051

Conference proceeding

Le, V. T., & Pitts, A. (2020). Energy saving by adapting Passive House buildings in warm climates: A case study of Vietnamese housing. In *PLEA 2020- 35th International Conference on Passive and Low Energy Architecture*. A Coruna.

PGR conference

Le, V. T., & Pitts, A. (2018). Thermal acceptability of people in hot humid Vietnam and the potential of enery saving. In *LoLo Conference on Energy demand pathways*. London.

Le, V. T., & Pitts, A. (2019). Thermal performance and energy consumption of existing housing in Vietnam and the potential of enery saving. In *University of Huddersfield PGR conference 2019*. Huddersfield.

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List of Abbreviations

AC	Air conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREEAM	Building Research Establishment Environmental Assessment Method
CEN	Comité Européen de Normalisation
CIBSE	Chartered Institution of Building Services Engineers
CPHCSC	Central Population and Housing Census Steering Committee
DOE	U.S. Department of Energy
ET	Effective temperature
GBI	Green Building Index
HCMC	Ho Chi Minh city
IECC	International Energy Conservation Code
LEED	Leadership in Energy and Environmental Design
MOC	Ministry of Construction
MOET	Ministry of Education and Training
MOST	Ministry of Science and Technology
MVHR	Mechanical ventilation with heat recovery
NUCE	National University of Civil Engineering
NV	Natural ventialtion
OTTV	Overall thermal transfer value
PHI	Passive House Institute
PHPP	Passive House Planning Package
PMV	Predicted mean vote
PPD	Predicted percentage dissatisfied
RETV	Residential envelope transmittance value
RH	Relative humidity
RTTV	Roof thermal transfer value
SEER	Seasonal energy efficiency ratio
SET	Standard effective temperature
SHGC	Solar heat gain coefficient
TCH	Total comfort hours
TSV	Thermal sensation vote
UIA	Union of International Architects
USGBC	U.S. Green Building Council
VACEE	Vietnam Association of Civil Engineering Environment
VIAP	Vietnam Institute of Architecture, Urban and Rural Planning
VIUP	Vietnam Institute for Urban and Rural Planning
WHO	World Health Organisation

List of Symbols

A_{Du}	Dubois skin surface area
C	Convective heat loss from the clothed body
C_{res}	Convective heat loss from respiration
E_d	Heat loss by water vapour diffusion through the skin
$E_{d\ comf}$	Heat loss by water vapour diffusion through the skin in comfort condition
E_{sw}	Heat loss by evaporation of sweat from the surface of the skin
$E_{sw\ comf}$	Heat loss by evaporation of sweat from the surface of the skin in comfort condition
h_c	Convective heat transfer coefficient
L	Thermal load of the body
M	Metabolic rate
η	Mechanical efficiency
p_a	Water vapour pressure
R	Radiative heat loss from the clothed body
T_a	Air temperature
T_{cl}	surface temperature of clothed body
T_{comf}	Comfort temperature
T_g	Black globe temperature
T_{mrt}	Mean radiant temperature
T_{op}	Operative temperature
T_{out}	Prevailing outdoor air temperature
T_{rm}	Exponentially weighted running mean of outdoor temperature
U-value	Thermal transmittance
v	Air velocity
W	Mechanical work done

Chapter 1 Introduction

This chapter describes the background of the research, and firstly provides an overview of the Vietnam climate which is one of the most influencing factors in sustainable building design. Secondly it describes the Vietnamese housing issues including housing status quo, housing typologies and energy consumption. The disadvantages of existing housing are then highlighted and indicate the need for climate sensitive and low energy housing in Vietnam. In order to look for appropriate solutions for Vietnamese housing, sustainable technologies in architecture are discussed. Based on that background, the research hypothesis and objectives are outlined and graphically presented by a workflow diagram of the research. The end of this chapter gives the thesis structure providing comprehensive summaries of the 8 chapters of this thesis.

1.1 Background

1.1.1 An overview of the Vietnam climate

Buildings have been strongly affected by the surrounding environment, especially by the climate. Building structures and properties, therefore, have to correspond to the characteristics of the climate zone they belong to. Utilising the advantages and mitigating the drawbacks of adverse climate conditions will enhance building performance, especially in terms of energy consumption. For instance, in temperate climates, passive solar design is a common technique to maximise the sunlight go into buildings in winter and provide proper shading in summer to avoid overheating. As a result, the diversity of architectural styles can be found in different climates all over the world. Since climate comprehension is essential for research in building design, this subsection provides an overview of the Vietnam climate for the understanding of the first and important input for low energy housing design in Vietnam.

Located in Southeast Asia, the area of Vietnam is 331,212km^2 of which two thirds are mountains and highlands. The narrow plain strip runs along the 3,200km long coastline. Extending from 9° to 23° North latitude and from 102° to 110° East longitude, Vietnam's territory is located entirely within the tropics (between the Tropic of Cancer (23.5° North latitude) and the Tropic of Capricorn (23.5° South latitude)). As a result, Vietnam has a high number of sunny hours (around 2,000 hours per year) and large amount of solar radiation (around 1,628 kWh/m^2 per year). The annual rainfall is relatively large, averaging 1,100 - 4,800 mm. Rain is unevenly distributed and concentrates on rainy months. Across the territory, the relative humidity is high year-round, from 77 to 87%. In some places, during certain times the relative humidity can reach over 95%, sometimes saturated. Vietnam is located in the intersection of Asian monsoon systems. It is strongly influenced by the South Asian monsoon in summer and the Northeast Asian monsoon in the winter, which causes cold winter in the North of the country.

With the long ‘S’ shape stretching along the meridian, Vietnam consists of different climate types. Therefore, it is necessary to divide the country into different climate zones. According to the Vietnam Building Code for Natural Physical & Climatic Data for Construction (QCVN02: 2009/BXD), Vietnam generally has a tropical monsoon climate. However, it is divided into North and South regions with clearly different climates by the line of 16° North latitude:

- The North region has subtropical climate with cold winter. The annual average temperature is less than 25°C and average temperature in winter is from 10° to 15°C.
- The South region has a year-round high temperature. There are only two distinct seasons, the rainy season from May to October and the dry season from November to April of the next year.

Figure 1.1 shows the significant difference between the North and the South part of Vietnam especially in terms of temperature and solar radiation. To achieve more precise climate information for building constructions, the Vietnam building code QCVN02: 2009/BXD divided the North and South climate regions into 4 and 3 sub-regions respectively and each sub-region has differently specific climate conditions.

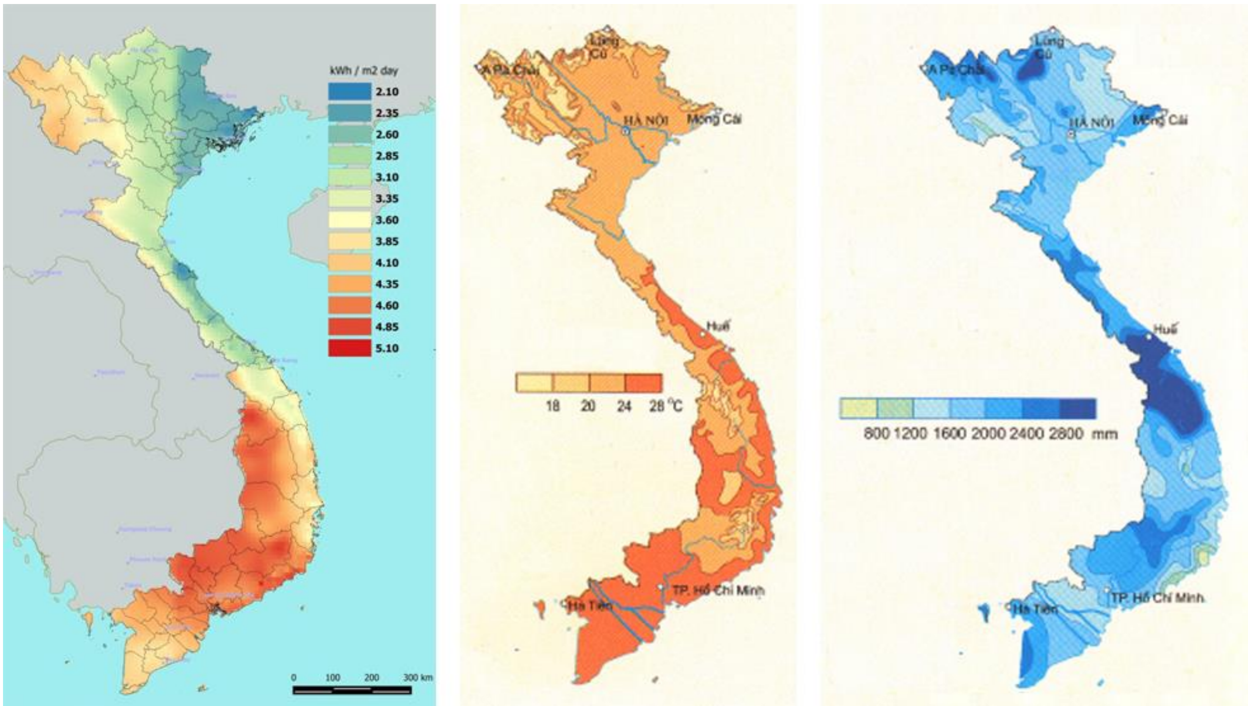

Figure 1.1: Map of annual average of solar radiation, temperature and rainfall of Vietnam. (Polo et al., 2015), (MOET, 2018)

According to the updated version of the Köppen - Geiger climate classification (D. Chen & Chen, 2013), Vietnam involves 3 types of climate: Cwa (mild temperate, dry winter and hot summer), Am (tropical monsoon climate), Aw (tropical, dry winter). As it can be seen in Figure 1.2, while Cwa is the prevailing climate of the Northern Vietnam, Aw and Am are the distinct climate types in the South. This indicated the similarity of Vietnam climate classifications between the two references.

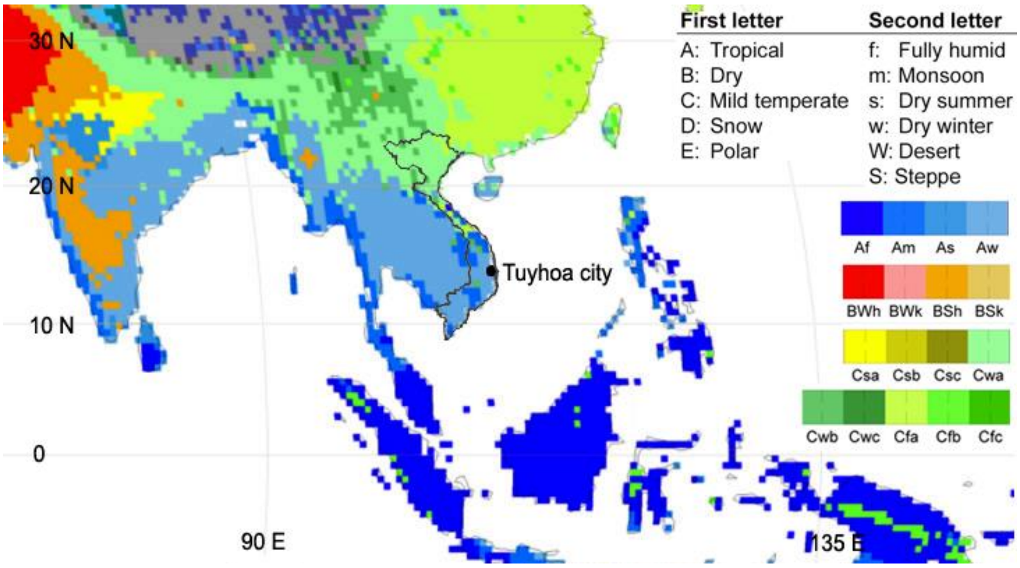

Figure 1.2: Köppen - Geiger climate classification for Southeast Asia (Chen & Chen, 2013)

In accordance with the initially established scope of this study, that is a focus on housing in hot humid climates. Hence, Southern dwellings in Vietnam are appropriate to be considered. In this study, Tuy Hoa city, which is located in the South Central Coast (see Figure 1.2), is selected as a typical site for the hot humid regions in Vietnam. The selection of a representative location facilitates the understanding of the climate data in more detail.

Figure 1.3 shows the statistical data of Tuy Hoa city climate obtained from the Vietnam Building Code QCVN02: 2009/BXD. This Building Code summarised the data from long-term monitoring records of national meteorological stations across Vietnam. Basically, Tuy Hoa city has a tropical monsoon climate which is strongly influenced by the ocean. High number of sunny days, along with a significant amount of solar radiation, keeps the monthly average temperature relatively high, between 23.1 and 29.3°C. The monthly average maximum temperature is 34.2°C in July while the monthly average minimum temperature is 21.1°C in January. The absolute lowest temperature has never dropped under 15°C, therefore protection from the cold is not necessary. Due to the effect of the sea, average relative humidity of Tuy Hoa city is considerably high all year round, from 74.4% to 86%. The rainy season happens from September to December with the yearly rainfall of approximately 1800mm. Main wind directions are North, Northeast in winter (cool period) and West, Southwest in summer.

According to the above climate features, it is necessary to outline corresponding needs for buildings in the hot humid climate of Vietnam as follows:

- The buildings need cooling in most time of the year, especially in hot summer, whilst heating demand is neglectable. Thermal insulation is needed to protect the buildings from high outdoor temperature.
- Intensive solar radiation required proper shading for buildings, focusing on West, East and South facades since the sun mainly moves in the South sky.
- High relative humidity needs to be paid attention to ensure indoor air quality.

- The frequency 36.7% of calm winds per year alongside environmental pollution are major obstacles for natural ventilation approach.

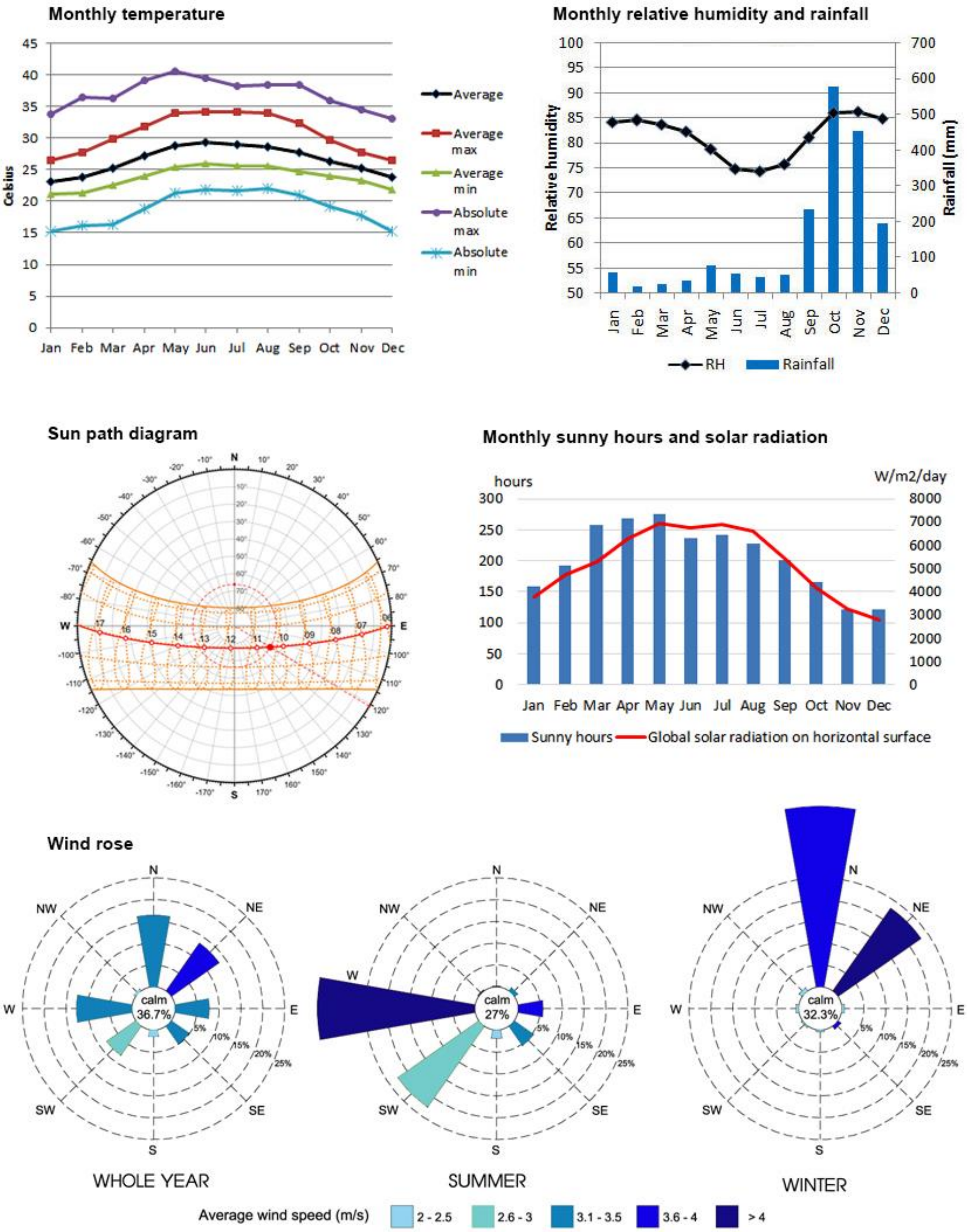

Figure 1.3 : Statistical climate data of Tuy Hoa city: Monthly temperature, Relative humidity, Rainfall, Global solar radiation, Sun path diagram and Wind rose

(Source: Adapted from Vietnam Building Code QCVN02: 2009/BXD
Sun path diagram was created by an online tool available at
http://andrewmarsh.com/apps/releases/sunpath2d.html)

1.1.2 Vietnamese housing issues

This subsection briefly reports the current status of housing stock, typologies, and energy consumption of Vietnamese dwellings. This investigation into the conditions of existing housing is absolutely necessary to understand the challenges and opportunities for low energy housing design in Vietnam, and thereby confirming the need of this research.

1.1.2.1 Housing status

Vietnam has 54 ethnic groups living in 63 cities and provinces in which the Kinh ethnic group accounts for 85.3% of the total population. According to the Vietnam Population and Housing Census which is conducted every 10 years by the Central Population and Housing Census Steering Committee (CPHCSC, 2019), Vietnam has 96.2 million people, ranked third in Southeast Asia and fifteenth in the world. Vietnam population increased by 1.14% per year from 2009 to 2019, equal to an increase of approximately 1 million people per year. The high population in a small territory of 331,212km^2 has put considerable pressure on the infrastructure of this developing country, especially in urban areas where 34.4% of the total population reside. The proportion of urban residents is lower than other Southeast Asian countries. However, this number has rapidly increased by 2.64% (1.2 million people) per year over the last decade, mainly due to the migration from rural to urban areas and the urbanisation across the country. However, 43% of the migrants are living in rented houses or apartments.

The last 30 years have seen a significant development of the Vietnamese housing market. From 98 housing projects in the first 5 years of the 1990s, the number of residential projects reached 1,100 in 2002. Until 2010, there were 22,616,405 houses in the whole country including 6,945,594 houses in the urban areas (CPHCSC, 2010). This total number of houses has gradually increased due to the new residential projects developed every year. The expansion of the housing market has mostly satisfied the need of dwellings for the residents. By 2019, there were 88.1% of the total 26,870,079 households living in their own houses while only 11.7% lived in rented accommodation. This proportion was 21.8% for urban areas (CPHCSC, 2019) which revealed the high demand for home ownership of urban residents.

Table 1.1: The proportion of Vietnamese households by housing area per capita (CPHCSC, 2019)

	Total	< 8m2	8-9 m2	10-14 m2	15-19 m2	20-24 m2	25-29 m2	> 30m2
Whole country	100	6.9	3.3	15.7	15.6	14.7	9.4	34.4
Urban	100	10.6	3.6	14.4	14.1	12.9	8.6	35.8
Rural	100	4.9	3.2	16.3	16.4	15.7	9.8	33.7

Although the accommodation demand was basically addressed, housing quality is still a big challenge for Vietnam. In 2019, the average floor area per capita, an important indicator of housing quality, was only 23.2m^2. Despite an increase of 6.5m^2 compared to the 2019 value, this number is relatively modest compared to 42.6m^2 of the European average (2011)[1], 36.9m^2 of China (2017)[2], 35.2m^2 of Japan, 30m^2 of Thailand or 27.3m^2 of Malaysia (2017)[3]. Table 1.1 shows the proportion of households in terms of floor area per person. It is noted that there was 10.2% of households living in very small dwellings (less than 10m^2/person).

Regarding housing sturdiness, based on main construction materials for columns, walls and roof, the 2019 Census classified Vietnamese dwellings into two categories: permanent and semi-permanent (93.1%); temporary and simple (6.9%). The combination of permanent and semi-permanent houses into one category gave a sense of positive result since most of households reside in sturdy houses. It is a fact that the semi-permanent house was the dominant type, accounting for 54.1% of the total (Vietnam General Statistics Office, 2015a). In another field study, Parkes and Burrage (2013) summarised common construction materials of 1394 houses as shown in Figure 1.4. In line with the 2019 Census result, the dominant materials for walls and roof were brickwork and corrugated iron which constitute the semi-permanent housing type. In the context of a developing country with a low GDP per capita income, which was 2985 USD in 2019 (General Statistics Office of Vietnam), a permanent house is hardly affordable for the majority of the residents. It requires much effort and a long-term saving from the owners. As a result, a high proportion of semi-permanent, temporary and simple houses indicated a high demand for sturdy dwellings in Vietnam.

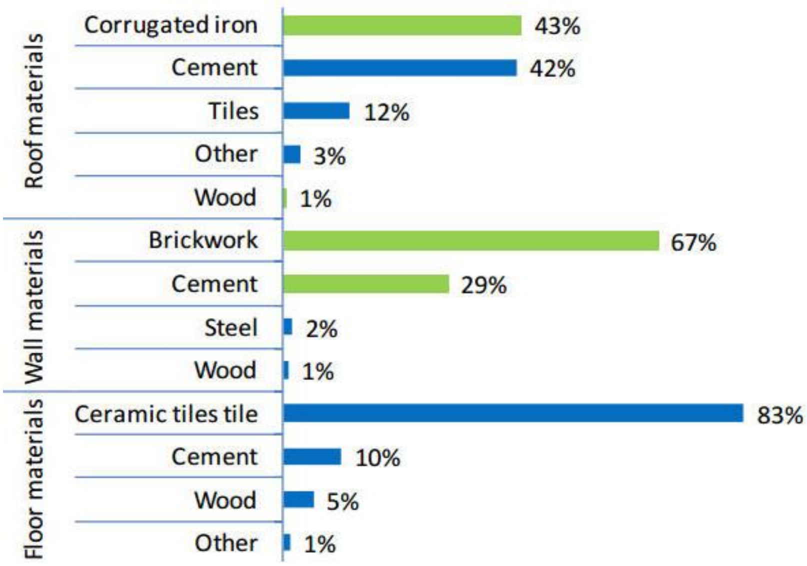

Figure 1.4: Common construction materials of Vietnamese housing (Parkes & Burrage, 2013)

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[1] Retrieved from https://ec.europa.eu/energy/content/housing-space-person_en [Date accessed 08 April 2020]

[2] Retrieved from https://www.ceicdata.com/en/china/residential-area-per-capita/floor-area-of-residential-building-per-capita-urban [Date accessed 08 April 2020]

[3] Retrieved from https://www.edgeprop.my/content/1471152/five-things-you-probably-did-not-know-about-size-malaysian-homes [Date accessed 08 April 2020]

1.1.2.2 Typical housing typologies in Vietnam

As specified by the Vietnam Building Code QCVN 03:2012/BXD, residential buildings are classified into two categories, apartments and single-family houses. Among them, single-family housing can be divided into villas and row houses (also called terraced houses, shop houses or street houses), and traditional rural houses. According to T.A. Nguyen (2013), there are 3 common housing types in Vietnam which are row houses, detached houses and apartments. The same classification is found in another study of Parkes and Burrage (2013) as shown in Figure 1.5. It is not difficult to recognise these 3 types of dwellings in urban areas owing to their particular characteristics.

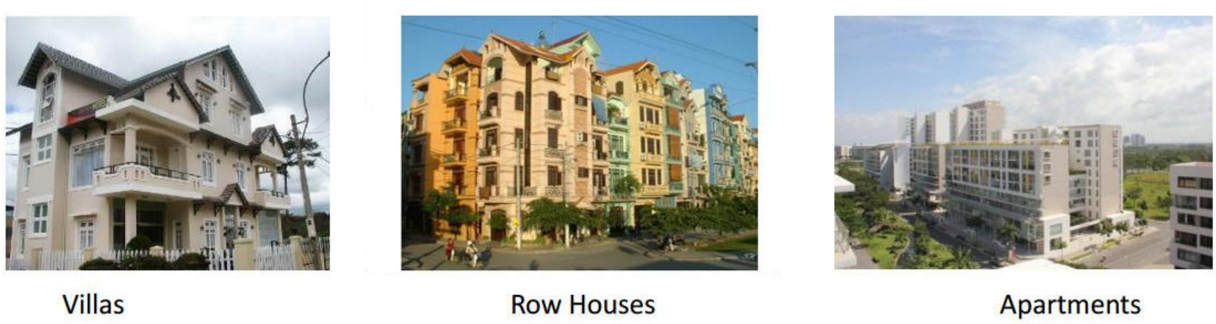


Figure 1.5: Three housing types in Vietnam (Parkes & Burrage, 2013)

A row house (shophouse or terraced house) is situated in a small area of land with a narrow and long shape as a tube. It is therefore also called the tube house. While the width of the facade is from 3 to 6 metres, the depth of row house is quite long, popular from 15 to 25 metres. The number of stories commonly fluctuates from 2 to 5. Such houses are built side by side and create a row of houses along the street. Due to the long-standing development from the 17th century and the considerable advantages of row houses, they are so far the most dominant housing type in Vietnam which makes up 75 percent of the total houses (T. A. Nguyen, 2013).

A villa or a detached house is built on a relatively large parcel of land. It is surrounded by the garden and the percentage of land coverage is from 40 to 60 percent in urban areas. Generally, the number of storeys is between 2 and 4. Another common form of villa is semi-detached house which share one common wall with the adjacent house. Detached and semi-detached houses are normally located in new residential areas in suburban regions. These kinds of dwellings provide the occupants with a high living standard. However, due to the significantly high cost of land and construction, a villa is only affordable to the minority of wealthy urban citizens.

An apartment building is composed of many apartment or flat units and each unit is possessed by a household. There are two types of apartment, low-rise and high-rise one. High-rise apartments can supply much affordable accommodation to the residents. Besides, they help to save much of the land and considerably contribute to the urban landscape. Hence, this type of housing is expected to solve the housing shortage issue in big cities.

Due to the great advantages of apartments for efficient use of land, the Vietnamese Government has released a number of policies to restrict single-family housing and to increase the ratio of apartments in new residential projects. For instance, this ratio must be 80% for Hanoi and Ho Chi Minh City and lower for other cities in the country. The aim was that until 2020 the proportion of apartments will reach the target of 15% of the total housing stock (The Prime Minister of Vietnam, 2011). Nevertheless, based on the statistics in the 2019 Census, apartments merely accounted for 5.8% of the total number of houses in urban areas (Table 1.2). Many cities in the country do not even have any apartment buildings. The 2020 target therefore was not achieved.

It is the fact that single-family housing still dominates the Vietnamese housing market so far and for a few more decades. Although the last ten years has seen the boom of apartment buildings in big cities such as Hanoi, Ho Chi Minh and Da Nang, the proportion of apartments in these cities is only 12.9%, 8.2%, and 4.5% respectively. In other cities and provinces, due to the low population density and the low level of urbanisation, most dwellings are terraced housing and detached housing (CPHCSC, 2019). This phenomenon can be clearly seen in the South Central Coast of Vietnam, including Tuy Hoa city. For that reason, with the aim of looking for an appropriate architectural solution for low energy housing that can meet the demand of the majority of urban citizens, this study pays attention to single-family housing as the research object.

Table 1.2: The proportion of housing types and average floor area per capita (CPHCSC, 2019)

	Ratio of housing types (%)			Average floor area (m^2/person)		
	Total	Apartments	Single-family houses	Total average	Apartments	Single-family houses
Whole country	100	2.2	97.8	23.2	20.1	23.3
Urban	100	5.8	94.2	24.5	20.1	24.8
Rural	100	0.3	99.7	22.5	20.2	22.5

1.1.2.3 Energy use in housing

According to Vietnam Electricity, a state-owned corporation, in 2015, the residential sector was responsible for 35% of the total electricity consumption and 27% of the total energy use (Figure 1.6). This proportion is comparable to the average energy use in the domestic sector in other countries. The energy demand for housing of Vietnam is projected to grow 3.1% per year in the period 2016-2035 (Danish Energy Agency, 2017). One of the main reasons for this growth is the improvement of living standard. The number of household facilities significantly increased compared to 10 years ago. The percentage of households owning fridges sharply rose by 48.9%, from 31.6% in 2009 to 80.5% in 2019. The increases of washing machine and air conditioner ownership were 37.3% and 25.5% respectively over the same period (Table 1.3).

In terms of air conditioner use, in a report of Vietnamese residential energy consumption undertaken by Parkes and Burrage through a survey on 1394 houses in 2013, the percentage of households having one air conditioner accounted for 28% of the total while 20% was the proportion of families having two or more air conditioners (Parkes & Burrage, 2013). In the context of global warming, the use of air conditioners in hot humid regions in general and Vietnam in particular, is predicted to increase. Hence, it can be stated that alongside the rapid expansion of the housing stock, the increase of household appliances has led to the increase of energy consumption in the residential sector.

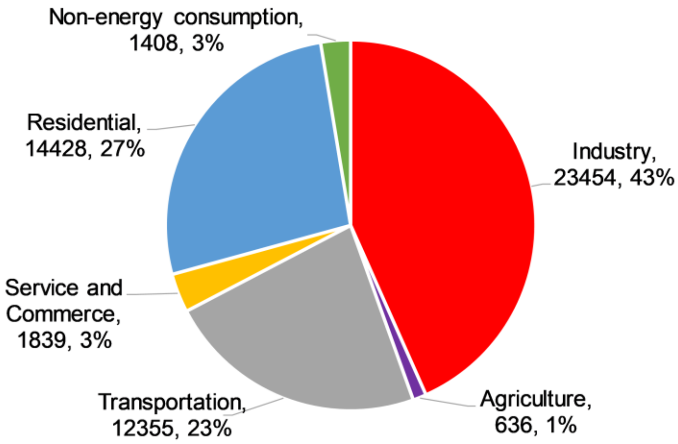


Figure 1.6: Share of final energy consumption by sectors in Vietnam in 2015 (million TOE, %) (Danish Energy Agency, 2017)

Table 1.3: The percentage of household appliance ownership in 2019 (CPHCSC, 2019)

	Television	Computer	Phone	Fridge	Washing machine	Water heater	Air conditioner
Whole country 2019	91.9	30.7	91.7	80.5	52.2	39.6	31.4
Whole country 2009	86.9	13.5	45.7	31.6	14.9	13.3	5.9
Urban 2019	91.4	51.5	94.5	86.2	69.2	51.8	49.6
Rural 2019	92.1	19.2	90.1	77.4	42.8	32.9	21.4

The increasing trend of using mechanical equipment for cooling arouses a deep concern about the efficiency of housing design and construction in Vietnam. Due to the major concern of high construction cost and the lack of professional consultation, housing design and construction in Vietnam so far has mainly focussed on the function and the stability of houses. Inadequate attention has been paid to energy saving and the thermal comfort issue. It can be seen from Figure 1.4 that the prevailing construction materials in Vietnamese housing are corrugated iron and concrete for roof, brickwork for walls with no insulation layer. These building components have high thermal conductivity. This results in the heat gain of internal spaces during hot weather which causes thermal discomfort for the occupants. Therefore, most households in Vietnam have to use fans and air conditioners for cooling, particularly in the hot time of a year when natural ventilation cannot satisfy the thermal comfort requirement. Besides, the poor thermal insulation of such building components cannot prevent energy transfer (heat gains) during the use of air conditioners.

In summary, in the 55 years from the end of the Vietnam war, along with the growth of the economy, the Vietnamese housing market has rapidly developed and provided accommodation for most residents. The majority of households are living in permanent or semi-permanent houses. The floor area per capita has gradually increased. Living conditions of households has significantly improved. However, as a developing country with low-middle income, the rapid growth in the number of residential buildings has not been accompanied with adequate technical design quality. There is still a high demand for sturdy houses. The floor area per capita is still low. Housing design and construction have mainly focussed on the durability, aesthetics and the low cost, ignoring the quality of indoor environment and energy saving issue.

Therefore, questions still remain to what extent the Vietnamese existing houses can provide thermal comfort for the occupants and how much energy they consume. Looking for the answer for these concerns, an investigation into the current condition of housing in terms of design techniques, construction materials, thermal performance and energy use is necessary. In the context of ongoing energy crisis, there is an urgent need to use energy efficiently to provide indoor comfort for housing in the hot humid climate of Vietnam. Therefore, it is essential to look for a sustainable design approach for housing in Vietnam that meets this demand.

1.1.3 Sustainable architecture tendency and opportunities for Vietnamese housing

Since the last decades of the 20th century, humanity has faced many global risks including environmental degradation, depletion of resources, energy crisis and especially the global climate change. These are serious concerns for the natural ecosystems and urban environment, threatening the development in present and even in the future. In this context, the need to mitigate the damage and protect the environment in parallel with seeking a sustainable development scheme is therefore extremely urgent.

In a conference of the United Nations Environment Programme (UNEP) held in 1972 in Stockholm, environmental degradation was identified as one of three main problems of the current world along with population explosion and resource depletion (as cited in Szokolay, 2008). In 1987, the Brundtland report, named Our Common Future, of the World Commission on Environment and Development (WCED) provided the terms and definition of “sustainable development: “Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.” (WCED, 1987).

The Earth Summit (1992) held in Rio de Janeiro with the participation of a large number of countries and organisations all over the world was an important milestone for the evolution of the sustainable development movement. The summit achieved important agreements among developing and developed countries on complex environmental issues. As a result, Rio Declaration including 27 principles was enacted as an instruction for attaining global sustainability (as cited in Williamson, Radford, & Bennetts, 2003). Afterwards, sustainable development has become a priority goal of many countries in the world as an indispensable tendency of the development.

Architecture is one of the areas strongly affected by the sustainable development concept since buildings are a complex connection between human and environment. However, the relationship between sustainability and architecture is not only one-way. Architecture is a key factor determining the success of the general sustainable development because buildings are responsible for around 40% of the total energy consumption in many countries in the world (Mihai, Tanasiev, Dinca, Badea, & Vidu, 2017). Besides, an intelligent design has the ability to raise community awareness about the need of sustainable development. In this context, sustainability becomes an essential requirement of building design.

In 1973, the Royal Institute of British Architects (RIBA) originated the LL/LF/LE (long life, loose fit, low energy) tendency. Its three principles were: the longer the buildings last, the more they benefit the environment; buildings should be designed for flexible changes of using purposes; and buildings should consume a small amount of energy during their life circle. Although the term "sustainable development" did not mentioned, it was an initial programme towards sustainability in architecture (Szokolay, 2008).

Architecture actually joined the sustainable movement in 1993 when the Union of International Architects (UIA) held the World Congress in Chicago. Its Declaration of Interdependence for a Sustainable Future endorsed all architectural and building-design professionals to place the sustainability at the core of their work and bring all components of the built environment to sustainable design standards (UIA, 1993). This declaration was adopted by many countries and architectural organisations and they enacted their own sustainable policies and standards.

The earliest standard was the Building Research Establishment Environmental Assessment Method (BREEAM) of the United Kingdom launched in 1990. In 1993, the U.S. Green Building Council (USGBC) started to develop the Leadership in Energy and Environment Design (LEED) standard and released the first version in 1998. So far, LEED is the most common rating system for sustainable buildings not only used worldwide but also adopted to national standards of other countries in the world. Besides, some countries developed their own building standards such as GBTool (now SBTool) of Canada, Environment Policy of Royal Australian Institute of Architects (RAIA) or Green Mark of Singapore. While some countries encourage sustainable architecture, it is a compulsory requirement in some other countries through design regulations and standards.

Sustainable architecture is not only of high aesthetic quality, but also minimises the impact on the environment, saves energy and natural resources, encourages the use of renewable energy, and provides healthy life both physically and mentally for occupants. With such significant advantages, sustainable architecture has become an indispensable trend and a smart choice for building owners and designers in the 21st century. Many sustainable architectural design trends have been initiated under various names such as Green architecture, Bioclimatic architecture, Zero energy building, Zero carbon building, Eco house or Passive House.

In Vietnam, until 2005, the professionals in architecture and the built environment started to approach the Green building movement. Afterwards, the Vietnam Green Building Council was established in 2007 with the mission of developing a Green building rating system for Vietnam and promoting the adoption in practice. However sustainable architecture or green buildings is not totally new to Vietnam. Vietnamese traditional buildings have shown great adaptation to the native tropical climate over centuries. It is the preliminary indication of climate responsive design, an important element of sustainable architecture. Since the 1960s and 1970s, Vietnam has promoted research and development of tropical architecture by applying passive design techniques such as: use insulated roof, increase surface reflection, design sunshades for building envelope, organise natural ventilation, plant trees around the building and on the roofs (D.N. Pham & H.H. Pham, 2015). By taking the advantages of natural conditions, buildings in the 1960 and 1970 decades provided good indoor microclimate in the absence of mechanical ventilation devices at that time. More details were described in section 2.2.

Although inheriting valuable experiences from traditional architecture, most of current Vietnamese buildings in general and housing in particular have not utilised those advantages under the negative effects of urbanisation. In addition to the economic constraints, the formalism has driven Vietnamese architecture away from the sustainable route for a long time. The past 10 years have seen efforts to pursue sustainable architecture again with the establishment of sustainable design regulations of the Government, the Vietnam Green Architecture Criteria and the LOTUS Green Building standard (based on LEED standard).

These sustainable architectural standards cover many aspects of sustainability such as energy efficiency, water efficiency, indoor environment quality, materials and resources, and also the social aspects. Due to the complexity of those standards, the application is still limited, and the number of certificated buildings is still modest. Another reason is the lack of knowledge about architectural and the built environment science of building designers. This leads to the difficulty in combining architectural design and sustainable solutions. Therefore, there is a need for a simpler standard that easier to apply widely. Despite the slight differences in the ultimate aims, it can be seen that contemporary sustainably architectural trends in the world mainly rely on the foundation of low energy buildings. Therefore, in the current conditions of Vietnam, the first and most fundamental step towards a comprehensive sustainable architecture could be the focus on energy efficiency of buildings.

In order to enhance the energy efficiency of buildings in general and dwellings in particular, the Passive House approach is an advance solution because it helps to maintain indoor temperature at a comfortable level year-round with minimal energy inputs. Due to great advantages, the Passive House standard which was originally developed in Germany has gradually become a desirable target for building design in many countries.

Over the last decades, considerable research on the Passive House approach has been conducted in the world. However, those studies have mainly concentrated on the temperate and cold zones and inadequate attention has been paid so far to warm climate regions, particularly in Southeast Asia in which Vietnam is located. Thus, there is a need to reconsider what "Passive House" means in practice and what design strategies are corresponding to the climate of Vietnam.

1.2 Research hypothesis

The global hypothesis of this research is that through examination of the Passive House approach in its broadest sense alongside gaining an understanding of design, construction and operation of housing in Vietnam, this will permit the identification of Passive House design techniques for use in Vietnam to improve energy efficiency in housing. The specific hypotheses forming this research are as follows:

i. The first hypothesis is that existing housing in Vietnam has not paid adequate attention to sustainable issues including building designs and material use. As a result, they have showed limitations on thermal performance, energy efficiency and failed in providing desired indoor thermal environment for occupants. Therefore, both construction materials and design solutions need to be improved.

ii. Thermal comfort research indicated that people living in different climates have different thermal comfort expectations. Hence, it is unconvincing to apply a single thermal comfort range to all regions in the world. Therefore, this study hypothesises that the Vietnamese people (who have long-term expose to the hot humid climate) have a specific thermal comfort range which is higher than those in current international standards. The use of appropriate modified temperature setpoints enhances building energy efficiency.

iii. The Passive House concept originated in Central Europe. Although, it has been widely developed in temperate climates, its efficiency for warm regions requires further investigations. Therefore, the third hypothesis is that Passive House methodology can be adapted to the hot humid climate of Vietnam. Low energy housing can be achieved by using the adapted Passive House principles and techniques to alter or adjust existing housing design and construction.

1.3 Research objectives

Aim of the research

This research aims to look for a new approach for the sustainable development of the Vietnamese housing in the context of ongoing climate change and energy crisis. This approach requires the combination of key features which are Passive House techniques, thermal comfort and energy efficiency in the harmony with the characteristics of climate and housing in Vietnam. Every feature is an essential part of the research that will be considered in the specific studies.

Objectives of the research

To meet the aim outlined above, the detailed objectives need to be carried out as follows.

i. To investigate the housing status quo and the need for climate sensitive and low energy housing in Vietnam.

ii. To review background knowledge of thermal comfort and low energy building design, focusing on warm climates.

iii. To review the Passive House Standard, design techniques and example buildings in different climates, particularly in warm regions.

iv. To examine the typical conditions and the limits of housing in Vietnam through field studies; to identify typical contemporary housing in Vietnam to act as case studies with the details of design and construction techniques.

v. To investigate the comfort temperature range for the Vietnamese to use for the setting of temperatures not to be exceeded in Passive Houses in the hot humid climate of Vietnam.

vi. To propose methods and techniques adapted from Passive House to alter or adjust housing design and construction in the hot humid climate of Vietnam, then analysing these proposals to identify the opportunities. Proposing a design guideline for Passive House residential buildings in Vietnam.

vii. To validate the design guideline in discussion with experts, designers and construction professionals, then enacting the final outcome of the research process in the form of general recommendations and a reference design guideline for low energy housing in Vietnam using Passive House approach.

1.4 Workflow of the study and structure of the thesis

Figure 1.7 demonstrates the workflow of this study. It shows a consistent sequence of major steps undertaken to achieve the above-mentioned objectives. The first step was background study and literature review which indicated the gaps in knowledge and formed the content of the research. The following step was data collection through the field studies in Vietnam including thermal comfort experiments and intensive housing surveys. Data analysis along with simulation step were then carried out and from which the results of proposed Passive House techniques and design guidelines for low energy housing in Vietnam were derived. Thereafter, these findings were validated through discussion with experts before being enacted as the final outcome of the research process.

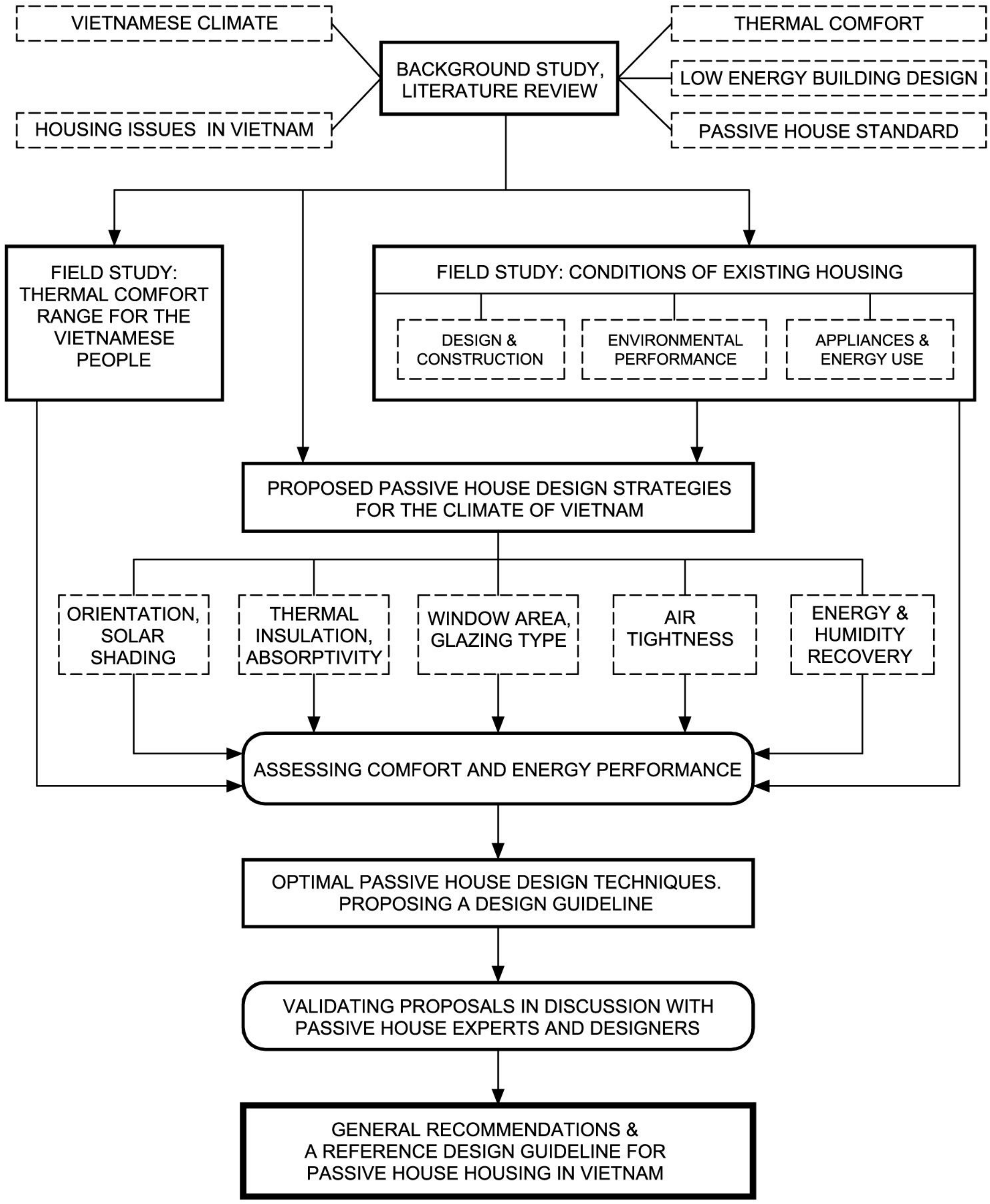


Figure 1.7: The workflow of the research

Structure of the thesis

This thesis consists of 8 chapters. The first chapter is Introduction described above. The contents of remaining chapters are summarised as follows:

Chapter 2 Literature review: this chapter reports up-to-date knowledge about thermal comfort theories and studies, design strategies and standards for low energy buildings in warm climates, and the principles of Passive House approach. Through the literature review, the gaps in knowledge were revealed and from which the research methodology was established.

Chapter 3 Research methodology: this chapter describes the selection of a research methodology model for this study among the 'Onion' model, 'Nested' model and 'Modified' model. Based on the selected model, research philosophy, research approach (including research modes, research strategies, research choices and time horizons) and research techniques (including data collection and analysis techniques) were described in detail. This chapter also mentions ethical issues relating to the research.

Chapter 4 An experiment on thermal acceptability of Vietnamese people: This chapter describes the procedure of an experiment in a semi-controlled room to investigate the appropriate thermal comfort range for the hot humid climate of Vietnam. The results were reported in comparison with comfort studies in Vietnam and other countries in warm regions.

Chapter 5 Household appliance use and energy consumption in existing housing: This chapter describes the detailed method of a survey on Vietnamese households in terms of electrical appliance use and energy consumption. The results indicated common household appliances and the breakdown of the actual energy consumption in a Vietnamese family. Challenges and recommendations for energy conservation in Vietnamese households were also highlighted.

Chapter 6 Thermal performance of existing housing in Vietnam and potential of energy saving: This chapter firstly reports the results of a field study on environmental performance of existing housing in Vietnam in hot and cool seasons. The EnergyPlus simulation programme was then employed to simulate the whole-year thermal performance and energy consumption of the typical housing models. Afterward, the potential of energy saving for Vietnamese housing was indicated by applying passive design strategies to improve existing housing.

Chapter 7 Passive House approach for Vietnam: This chapter describes the adaptation of Passive House standard to the hot humid climate of Vietnam. The effect of main Passive House parameters on energy consumption was investigated through a sensitivity analysis. Afterward, this chapter presented the results of the parametric simulation using the Passive House Planning Package. From these results, a reference design guideline for Passive House housing in Vietnam was generated. At the end of this chapter, the validity of the design guideline in discussion with experts using a questionnaire method is described.

Chapter 8 Conclusions and further work: This chapter summarises the main conclusions based on the objectives of the research. The contributions to knowledge were then highlighted, following by the limitations and the possible extension of the research.

Chapter 2 Literature review

This chapter reviews key issues related to low energy buildings in warm climates. The first section reviews the theories, previous studies and existing standards of thermal comfort, a factor closely related to energy consumption in buildings. Thereby, it highlights the need for further research on thermal comfort condition for buildings in Vietnam. The second section summarises low energy design strategies for buildings in hot humid climates including both passive and active techniques. Additionally, the existing low energy building standards and rating systems in the world are outlined. This section also describes achievements and limitations of research and practice on low energy buildings in Vietnam in which the traditional architecture is included. A review on low energy building design techniques and standards reveals opportunities for achieving low energy housing in Vietnam both by applying conventional natural ventilation strategies and by adopting the Passive House concept as an alternative approach. Therefore, the third section describes the Passive House approach in detail including its development history, principles, benefits, and research as well as applications of Passive House buildings in warm climates.

2.1 Thermal comfort theories, studies and standards

It is no doubt that providing safe and comfortable shelters is the most important function of buildings. After making sure the building stands, the designers need to provide an indoor environment that satisfies the occupants in which thermal satisfaction is a curial requirement. It is a fact that buildings and their indoor spaces are strongly influenced by the outdoor environment and the climate where the buildings are located. Therefore, understanding the thermal comfort condition corresponding to the climate is essential in design and operation of buildings in any location in the world.

This section provides a comprehensive review on the theories, previous studies and existing standard of thermal comfort, focusing on hot humid climates, then highlights the potential gaps of thermal comfort studies and the applications in Vietnam. The first subsection outlines the principles of thermal comfort including the definition, human thermoregulation, heat balance mechanism, and emphasises the role of thermal comfort in the built environment. The second subsection briefly describes two approaches of thermal comfort research, the heat balance model and the adaptive model, and discusses their applicability for Passive House buildings in Vietnam. The third and fourth subsections review previous work on thermal comfort in hot humid climates and in Vietnam in particular. The last subsection shows a summary of existing international thermal comfort standards as well as the available standards in Vietnam, then assesses the appropriateness of these standards in the built environment of Vietnam.

2.1.1 Thermal comfort principles and the role in the built environment

2.1.1.1 Thermal comfort definitions

Thermal comfort is defined as "*the condition of mind which expresses satisfaction with the thermal environment*" (ASHRAE, 2017). Thermal comfort includes two major concepts: thermal neutrality and thermal acceptability. Thermal neutrality is the condition in which human sensation is not warm or cool. People in a neutral thermal condition are completely satisfied with the surrounding thermal environment (Fanger, 1970). The temperature in this condition is defined as neutral or comfort temperature. Additionally, people can also be thermally satisfied within a relatively narrow range around the neutral temperature due to a special adjustment mechanism in human body (Szokolay, 2008). This range can be expanded due to the influence of thermal adaptations including behavioural, physiological and psychological adaptations (being discussed later). This comfort range reflects the thermal satisfaction or acceptability of people that stretches from 'slightly cool' to 'slightly warm'. Conversely, the dissatisfaction with the thermal environment, when people start to feel cold or hot, is called thermal discomfort.

Thermal sensation is obtained from the complex interactions of many factors including environmental and personal variables (Szokolay, 2008). According to Fanger (1970), the condition of thermal comfort is influenced by six important variables, including two occupant parameters (activity level, thermal resistance of the clothing) and four environmental parameters (air temperature, mean radiant temperature, air velocity and air humidity). These factors influence the thermal sensation of people through the effects on the heat balance mechanism. In addition, because thermal sensation is a condition of mind which is subjective, it is different from person to person albeit they are in the same space and expose to the same thermal environment condition. These different thermal perceptions are caused by the differences in gender, age, ethnic group, culture, geographic location, climate, thermal experience, and other factors (Nicol, 2011).

2.1.1.2 Human thermoregulation

Human body has a special thermoregulation mechanism. It maintains the core temperature in a healthy human body at a stable temperature of around 37°C. Any small change in core temperature will cause the reactions of the body and might lead to health problems. The hypothalamus of brain controls this thermoregulatory system. When the internal temperature rises above or drops below the equilibrium state, the hypothalamus will send signals to the relevant organs in the body and they will react physiologically to bring the core temperature to normal. (Koob, Moal, & Thompson, 2010)

When the internal body temperature rises, the thermoregulation reduces heat in the body through vasodilation: more blood flows and transfer the internal heat to the skin and consequently increases the diffusion of heat to the surrounding. Sweating happen if the core temperature further increases: the evaporation of sweat causes heat loss from the body skin. On the contrary, when the core temperature drops, human body initiates vasoconstriction to limit the blood flow to the skin and consequently conserves the internal heat. Further decrease in the core temperature results in muscular tensions and shivering to produce more body heat by the metabolic processes (Koob et al., 2010; Nicol, Humphreys, & Roaf, 2012). The thermoregulation in human body is an effective system. It can maintain a constant core temperature under the influences of wide ranges of environmental variables, even if comfort does not exist (Fanger, 1970).

2.1.1.3 Heat balance

Human always creates heat through the metabolic processes inside the body and different activities will produce the corresponding amount of heat. When reclining, the metabolic rate is about 46 W per m^2 body surface area (a total of $1.7m^2$ in a normal adult). This rate raises to 70 W/m^2 when seating and working, and to 110 W/m^2 when walking at 2 km/h (ISO, 2005). Meanwhile, the heat exchanges between the human body and the ambient space happen all the time through four ways: radiation, evaporation, convection and conduction. Consequently, to keep the core temperature stable, the heat production has to be equal the heat loss from the body. The heat balance mechanism is expressed by the following equation (Fanger, 1970):

$$M - W = R + C + E_d + E_{sw} + C_{res} + E_{res} \quad (2.1)$$

Where M: the metabolic rate

W: mechanical work done

C: convective heat loss from the clothed body

R: radiative heat loss from the clothed body

E_d: the heat loss by water vapour diffusion through the skin

E_{sw}: the heat loss by evaporation of sweat from the surface of the skin

C_{res}: convective heat loss from respiration

E_{res}: evaporative heat loss from respiration

Fanger (1970) based on this heat balance mechanism to create a model predicting human thermal sensation in a given environmental condition. This heat balance model is discussed later in subsection 2.1.2.

2.1.1.4 The role of thermal comfort in the built environment

Griffiths (1990) carried out a number of surveys on occupants' satisfaction and found that the most important requirement of a building was the 'right temperature' be provided. Having the 'right temperature' not only makes the occupant comfortable, but also improves productivity. A number of field studies as well as laboratory experiments have been conducted to investigate the effect of thermal environment on the occupants. They showed a clear tendency that hot and cold discomfort reduces the occupants' performance. People's manual and intellectual performance achieve the highest level in a thermal comfort condition (Fanger, 1970).

While thermal comfort makes people satisfied, thermal discomfort might cause harmful medical problems, even death, especially when thermal stress (extreme hot or cold discomfort) happens. For instance, the 2003 heatwave in Europe with temperature of more than 40°C killed about 35,000 people (Bhattacharya, 2003), meanwhile, UK winter deaths in 2017-2018 exceeded 50,000 (Campbell, 2018). The ongoing climate change and fuel poverty put further pressure on the need to improve thermal condition in buildings to protect occupants from extreme weather.

In addition to the effects on human's health, satisfaction and performance, the maintenance of thermal comfort strongly influences the energy consumption in buildings. There is no doubt that a large amount of energy consumption in buildings is for cooling demand in warm regions, and for heating demand in other regions in the world. In mechanically ventilated buildings, energy is used to maintain the indoor temperature within a comfort zone that satisfies the majority of the occupants. A number of studies showed that a change of every 1°C of indoor temperature can increase or decrease roughly 10% of the energy use for heating or cooling purpose (Kimura & Tanabe, 1993; Nicol et al., 2012). Therefore, the determination of a correct thermal comfort zone can save a substantial amount of energy by avoiding excessive cooling or heating of buildings.

It is worth mentioning that heating or cooling demand could be reduced significantly by using passive design techniques to improve thermal performance of buildings. The thermal comfort zone is an important input to determine building design and materials such as solar shading, size and type of windows, level of thermal insulation, thermal mass, and natural ventilation schedules.

In short, it can be seen that thermal comfort plays an important role in building science. It considerably influences the way buildings are built and operated, the energy use and the quality of indoor environment (de Dear & Brager, 1998).

Due to the importance of thermal comfort outlined above, it is necessary to correctly determine the suitable comfort zone of the occupants. There are two common approaches to predict comfort temperature and the corresponding acceptable range including the heat balance model (based on laboratory experiments) and the adaptive model (based on field studies).

2.1.2 Heat balance and adaptive approach

2.1.2.1 Heat balance approach

A number of researchers have created thermal comfort models based on physics and physiology. It is assumed that to maintain the stable internal temperature, a heat balance has to exist in human body where the heat production equals the heat dissipation. Based on this assumption, these researchers focus on analysing the heat flow in human body to build comfort models. They are often called 'heat balance' models and the most common models are the Predicted Mean Vote (PMV) and the Standard Effective Temperature (SET) model (Nicol et al., 2012). This thesis only introduces the PMV model due to its particular importance to most national and international comfort standards.

The PMV model was developed by P.O. Fanger based on the heat balance theory. To expand the heat balance equation (Equation 2.1) in more detail, Fanger (1970) compiled and analysed numerous data from the literature as well as inherited formulae from other researchers for the calculation of internal heat production and heat loss from human body. He found that at a given activity level, only mean skin temperature and sweat secretion are the physiological variables that influence the heat balance. He then carried out climate chamber experiments to investigate the skin temperature and sweat rates of American college-age subjects who were in thermal comfort at different activity levels. A regression analyses of the data acquired gave two formulae expressing the relationship between skin temperature and activity level and between sweat secretion and activity level in comfort condition. Inserting these two formulae into the heat balance equation 2.1, Fanger derived an equation for determining thermal comfort condition as follows (the detailed equation is relatively complex and can be found in Fanger (1970)):

$$M - W = C + R + E_{d\ comf} + E_{sw\ comf} + C_{res} + E_{res} \qquad (2.2)$$

where $E_{d\ comf}$ is the heat loss by water vapour diffusion through the skin in the comfort condition; $E_{sw\ comf}$ is the heat loss by evaporation of sweat from the surface of the skin in the comfort condition.

When thermal discomfort occurs, there is a thermal load the thermoregulatory system needs to resolve to maintain the body heat balance. Fanger defined the thermal load L of the body as the difference between the internal heat production and the heat loss to surroundings (in which the mean skin temperature and the sweat secretion are the comfort values at a given activity level) as follows:

$$L = (M - W) - (C + R + E_{d\ comf} + E_{sw\ comf} + C_{res} + E_{res}) \quad (W/m^2) \qquad (2.3)$$

In the comfort condition, L = 0, whilst in other conditions, L ≠ 0 and the skin temperature and sweat rate will be changed to preserve the body core temperature. Fanger considered the thermal load as a physiological strain and assumed that the thermal sensation is related to this strain. Therefore, he concluded "*the thermal sensation at a given activity level is a function of the thermal load L of the body*" (Fanger, 1970) as follows:

$$Y = f(L,M) \qquad (2.4)$$

where Y is the thermal sensation expressed by the mean vote on the seven-point scale of ASHRAE: hot (3), warm (2), slight warm (1), neutral (0), slightly cool (-1), cool (-2), and cold (-3).

For the quantification of Equation 2.4, Fanger analysed the data acquired from climate chamber experiments conducted in the U.S. and Denmark. He then arrived at:

$$Y = \left(0.352e^{-0.042(M/A_{Du})} + 0.032\right) L \qquad (2.5)$$

where A_{Du} is the body surface area of the subject (DuBois area), m²

Fanger referred Y as the 'Predicted Mean Vote' (PMV). By combining Equation 2.3 and Equation 2.5, he eventually obtained a prediction model as follows:

$$PMV = \left(0.352e^{-0.042(M/A_{Du})} + 0.032\right)\Big[\frac{M}{A_{Du}}(1-\eta) - 0.35\left[43 - 0.061\frac{M}{A_{Du}}(1-\eta) - p_a\right] - 0.42\left[\frac{M}{A_{Du}}(1-\eta) - 50\right] - 0.0023\frac{M}{A_{Du}}(44 - p_a) - 0.0014\frac{M}{A_{Du}}(34 - t_a) - 3.4 * 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_{mrt} + 273)^4] - f_{cl}h_c(t_{cl} - t_a)\Big] \qquad (2.6)$$

Where M: metabolic rate

A_{Du}: body surface area

η: mechanical efficiency

p_a: water vapour pressure

h_c: convective heat transfer coefficient

t_a: air temperature

t_{mrt}: mean radiant temperature

t_{cl}: surface temperature of clothed body

f_{cl}: clothing area factor

Equation 2.6 established a thermal sensation index (PMV index) to predict the mean vote of a large group of people to a given thermal environment on the ASHRAE seven-point scale. However, it is obviously people are not alike. In the same thermal environment, some people feel comfortable whilst the others may feel uncomfortable. Therefore, it is more meaningful to know the percentage of people who feel dissatisfied with the environment.

In order to predict the proportion of individuals who feel too warm (vote +2 or +3) or too cool (vote -2 or -3), Fanger introduced the “Predicted Percentage of Dissatisfied” (PPD) index which is a function of the PMV index. To investigate the relationship between the two indices, he analysed the votes of 1296 Danish and American subjects from the experiments mentioned above. A probit analysis of the percentages of dissatisfied votes showed the relationship between the PMV and the PPD index as follows:

$$PPD = 100 - 95e^{(-0.03353\, PMV^4 - 0.2179\, PMV^2)} \qquad (2.7)$$

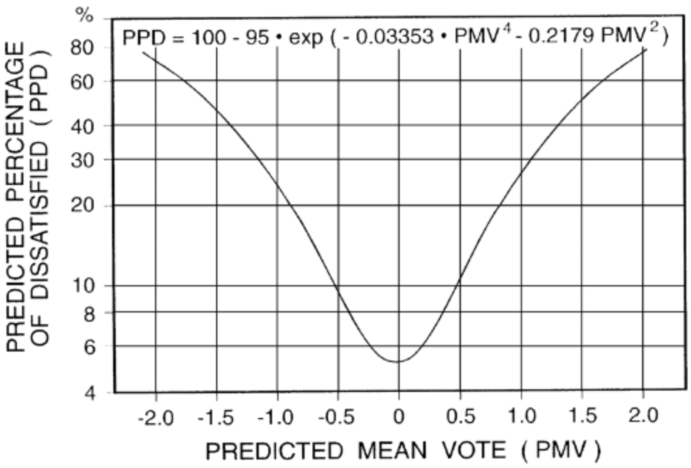


Figure 2.1: PPD as a function of PMV (Fanger, 1970)

Figure 2.1 shows that there is a minimum 5% of people who feel dissatisfied with a certain environment. If the PMV ranges from -0.5 to 0.5, less than 10% people feel thermal uncomfortable. Fanger claimed that the PPD index should be used as a basis for evaluating a given thermal environment.

Fanger carried out many experiments in climate chamber to investigate the influences on thermal comfort of a number of factors including national geographic location, ethnic group, gender, and age. He found that the influences of these factors on thermal comfort are neglectable and the PMV model could be used widely in practice without modifications (Fanger, 1970).

The PMV and PPD indices are used in some international standards such as ISO 7730, ASHRAE Standard 55 and CEN EN15251. It is noted that two latter standards only use these indices for mechanically ventilated buildings. Many researchers have validated that the thermal comfort predictions of the PMV model are accurate in steady state environments with low or sedentary activity level of air conditioned office buildings (de Dear & Brager, 1998; de Dear, Leow, & Ameen, 1991b; S. Tanabe, Kimura, & Hara, 1987; L. Yang, Yan, & Lam, 2014). It could be explained by the fact that the PMV and PPD indices were derived from experiments in climate chambers where environmental variables were set and strictly controlled, similar to those in air-conditioned buildings.

In naturally ventilated buildings, the indoor environment is changeable corresponding to the fluctuations within a wide range of outdoor temperatures, humidity and air speeds. Moreover, the occupants in practice interact more with the surroundings than in climate chamber experiments. For example, they can open windows or change clothing to seek thermal comfort, consequently, they could be able to accept a higher amplitude of temperature than the PMV prediction (Nicol et al., 2012). Field studies showed that the PMV-PPD model predicted differently from the actual thermal sensation vote of the occupants in free running buildings (De Dear & Brager, 2002; T. A. Nguyen, Singh, & Reiter, 2012). Therefore, the adaptive comfort approach was developed to overcome the disadvantages of the PMV model.

2.1.2.2 Adaptive approach

The origin of the adaptive approach can be traced back to a field study conducted by Charles Webb on thermal comfort in office buildings at the Building Research Establishment in 1965. Humphreys and Nicol subsequently took over this project when Webb retired. When analysing the collected data, they found that existing methods were not entirely appropriate to analyse such types of data. They developed their own method which was first presented in 1972. In the following years, Humphreys confirmed and introduced an approach subsequently known as the adaptive approach in thermal comfort research. Over the last 40 years, this approach has been researched and developed by Andres Auliciems, Richard de Dear, Gail Brager, Susan Roaf and other researchers around the world (Nicol et al., 2012).

In practice, it is no doubt that people can adjust themselves or influence the building to adapt to the surrounding environment. This adaptation significantly affects their thermal perception. Therefore, the theoretical PMV model for static conditions cannot accurately predict human thermal sensations in an ever-changing environment. The adaptative approach takes into account the complex interactions between the occupants, the building, and the climate. It is based on the adaptive principle: "*if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort"* (Humphreys & Nicol, 1998).

Humphreys and Nicol provided a list of the reactions people may take to respond to cold or hot discomforts. These reactions were classified into five basic types: adjusting the internal heat generation rate; adjusting the body heat loss rate; adjusting the thermal environment; selecting a different thermal environment; and modifying the body's physiological comfort conditions (Humphreys & Nicol, 1998). According to Brager & de Dear (1998), there are three categories of adaptive actions including behavioural adjustments, physiological and psychological adaptation as follows:

- Behavioural adjustments: including adjusting clothing, level of activities, moving to another location, adjusting window openings or shades, adjusting heating or cooling equipment, scheduling activities. Behavioural adjustments are considered the best opportunities for occupants to maintain thermal comfort.
- Physiological adaptation: (known as acclimatisation) including physiological changes in human body which result from long-term exposure to certain climatic condition. These changes help to gradually decrease the strain caused by such exposure. For example, physiological acclimatisation to hot climates leads to an increased sweating capacity for a given heat load.
- Psychological adaptation: including the influences of cognitive and cultural factors on thermal sensation. The past and current thermal experiences of people in different conditions of climate, culture, building type, heating/cooling type establish their own awareness of the optimal comfort levels that work as 'benchmarks' for environmental assessments. Thermal experiences can directly affect people's thermal sensations, satisfaction and expectation.

In order to encompass all variables of thermal adaptation described above, field survey is considered as the most appropriate method. Humphreys stated that field survey is the basic tool of the adaptive approach. Field surveys have been conducted to establish empirical indices of thermal comfort. Therefore, the adaptive approach is also called the empirical model which is different from the theoretical PMV model.

In 1976, Humphreys compiled data from many field studies on thermal comfort around the world. Using meta analyses, he found the high correlation between the comfort temperature and the mean operative temperature (Humphreys, 1976). He also recognised indoor comfort temperature is closely related to the outdoor temperature. In 1978, Humphreys showed this relationship in the well-known graph (Figure 2.2). As shown in the graph, the comfort temperature in naturally ventilated buildings has a linear correlation with the outdoor temperature while this relationship is more complex in air-conditioned buildings. In 2010, Humphreys analysed data from comfort field studies conducted since 1978 which involved more studies in hot climates. He reaffirmed the general shape of the 1978 graph. However, the new regression lines have translated up 2°C compared to the previous ones. This means for any given outdoor temperature, the comfort temperature has increased by about 2°C during the period 1978 to 2010 (Humphreys, Rijal, & Nicol, 2010). This increase is possibly caused by the adaptation of people to warmer buildings (Nicol et al., 2012).

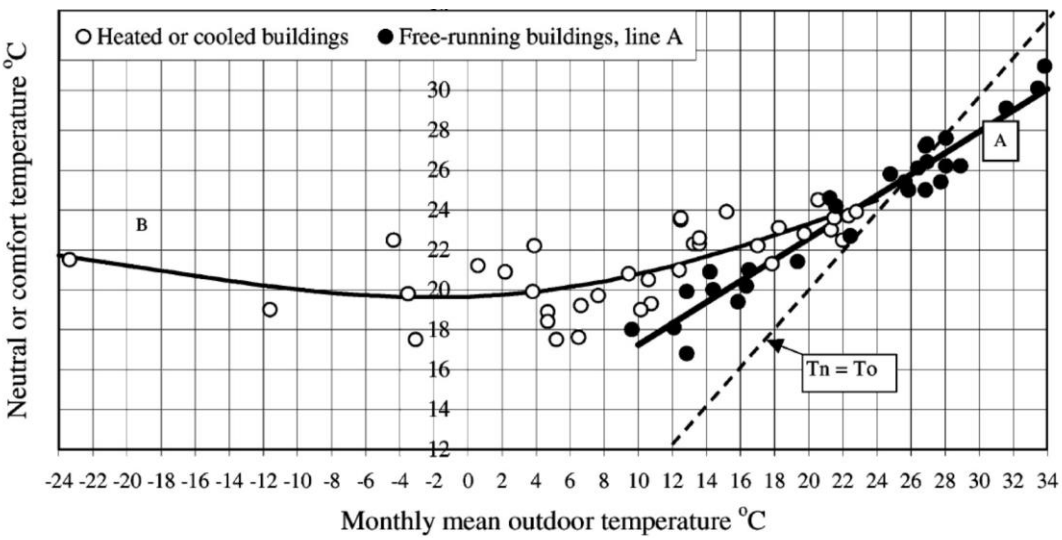


Figure 2.2: The relationship between comfort temperature and outdoor temperature (Humphreys, 1978)

The strong relationship between indoor comfort temperature and outdoor temperature is the basis of the adaptive approach (Nicol et al., 2012). Indoor comfort temperatures can be predicted based on outdoor temperatures, especially in naturally ventilated buildings where a linear correlation between those variables was observed. The general comfort equation (or adaptive comfort model) for free-running buildings is as follows:

$$T_{comf} = A \cdot T_{out} + B \tag{2.8}$$

Where T_{comf} is the comfort temperature; T_{out} is the prevailing outdoor air temperature (or monthly mean outdoor air temperature); A, B are constants.

The exclusion of other environmental parameters (mean radiant temperature, humidity, air speed) and occupant parameters (clothing insulation, activity level) in the calculation of comfort temperature is claimed as an imperfection of the adaptive model (Fanger & Toftum, 2002). However, it is clear that four environmental parameters (air temperature, mean radiant temperature, air speed and humidity) directly influence on thermal sensation votes of the occupants from which the adaptive model is built. Therefore, the adaptive model does take into account the effects of these environmental parameters (Halawa & Hoof, 2012; Nicol & Humphreys, 2002). In addition, participants in comfort field studies can be in diverse activities and clothing, therefore, their thermal sensations are already a function of these factors. The adaptive model uses outdoor temperature as an aggregate index which embraces the effects of all environmental and occupant parameters (Nicol et al., 2012).

The adaptive approach has been developed and widely applied in practice during the last four decades around the world, especially in naturally ventilated buildings. By taking into account the occupants' ability to adapt to a particular environment, the adaptive approach can provide designers with a more appropriate comfort temperature for the corresponding climate, which is an important criterion in building design. Based on that criterion, suitable passive design techniques have been selected to reduce energy consumption in buildings as much as possible whilst satisfying the thermal comfort requirement. Due to its practical significance, the adaptive model has been applied in a number of international standards including ASHRAE Standard 55 (2010) and CEN Standard EN15251 (2007).

2.1.2.3 Discussion

The heat balance approach and adaptive approach coexist in thermal comfort studies. The two approaches are used separately to evaluate different thermal environments. The PMV model can precisely predict the thermal comfort conditions in indoor conditioned environments that exist independently of the outdoor environments. However, it fails to predict comfort temperature in free-running buildings where the indoor environment is constantly changing and the occupants can interact with the buildings to adapt themselves to those changes (Nicol, 2004). The adaptive model is more suitable to predict comfort condition in non-air-conditioned buildings, especially in warm and hot climates (De Dear & Brager, 2002; Nicol et al., 2012). Therefore, both models are included in international comfort standards such as ASHRAE 55 and EN15251.

Although the PMV and adaptive model have been applied widely around the world, it is necessary to have further studies to revise or complement these models. It is a fact that these comfort models have not derived from the comfort studies for every location in the world. Hence, the application for any location needs to be carefully considered. Any particular region has specific climate, buildings and culture which influence the thermal sensations and expectations of the local residents (Nicol et al., 2012). Therefore, studies on their own comfort condition need to be carried out and the results are useful to assist with the local building design. For the adaptive approach that takes into account the complex interactions between occupants and buildings along with human adaptability on three aspects of physiology, psychology and behaviour, studies on thermal comfort for each specific area is necessary.

The heat balance approach creates a theoretical model. However, most constants in the formula for PMV calculation (Equation 2.6) are derived from the experiments on American and European subjects. Fanger subsequently conducted laboratory experiments and to investigate the effect of national-geographic location on thermal comfort condition. In addition, he compared the comfort equation with the results from field studies in the tropics. Fanger concluded that the difference was not significant and the comfort equation (or the PMV model) can be used in most locations without modifications (Fanger, 1970). However, a number of studies both in climate chamber experiments and field studies showed that acclimatisation and long-term thermal history have influences on thermal comfort condition and thermal acceptability (Dang & Pitts, 2018; De Dear & Brager, 2002; Du et al., 2018; Jowkar, de Dear, & Brusey, 2020; B. Li, Du, Yao, Yu, & Costanzo, 2018; Nicol & Humphreys, 2010; Ning, Wang, & Ji, 2016; Wang et al., 2018; Zhang, Chen, Wang, & Meng, 2016). In other words, people living in warm climates could have higher neutral temperature and comfort zone than people living in cool climates. Consequently, the PMV model may give wrong predictions even in mechanically ventilated spaces, especially in hot humid climates.

Due to the ongoing climate change and global warming, the increase of temperature in many areas around the world has been observed. People have adapted to warmer environments and this has affected their thermal expectations. As mentioned above, according to Humphreys et al. (2010) the comfort temperature has increased by about 2°C during the period 1978 to 2010. Therefore, further comfort studies are necessary to contribute to the worldwide databases and to the upgrade of existing comfort models, particularly for the PMV model which was built from the research conducted 50 years ago.

Despite some limitations outlined above, the heat balance approach (PMV model) and adaptive approach (adaptive models) have been used in international standards as major methods to predict thermal comfort conditions. The next subsection introduces three well-known international standards and the applications of the PMV and adaptive comfort models.

2.1.3 International thermal comfort standards

Thermal comfort standards play an extremely important role in building science. They help to define appropriate comfort conditions for the occupants based on which buildings will be designed and operated to ensure those recommended comfort conditions in buildings. There are three widely used international thermal comfort standards including ISO Standard 7730, ASHRAE Standard 55, and CEN Standard EN16798-1 (the updated version of EN15251:2007). These standards use various thermal comfort models for naturally ventilated buildings and air-conditioned buildings. Brief summaries of these standards are as follows.

ISO Standard 7730 was first released in 1984 by the International Standard Organisation (ISO). It was then revised in 1994 and 2005. ISO 7730 involves the calculation and application of the PMV and PPD indices based on the heat balance model developed by Fanger (1970). The standard presents the necessary data for the PMV calculations including a table of thermal insulation values of clothing and a table of metabolic rates of various activity levels. ISO 7730 also provides methods to evaluate local thermal discomfort. This standard classifies buildings into three categories based on their indoor thermal conditions as shown in Table 2.1 (ISO, 2005). It is noted that until the latest version in 2005, ISO 7730 has not included any adaptive comfort models.

Table 2.1: Specifications of building categories in ISO 7730:2005

Category	PPD (Predicted percentage discomfort)	DR (Draft rating)	Local discomfort	PMV (Predicted mean vote)
A	< 6%	< 10%	< 3 – 10%	-0.2 < PMV < +0.2
B	< 10%	< 20%	< 5 – 10%	-0.5 < PMV < +0.5
C	< 15%	< 30%	< 10 – 15%	-0.7 < PMV < +0.7

ASHRAE Standard 55 was developed by the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE). The standard was first enacted in 1966, and subsequently updated several times before the latest version in 2017. There are three major milestones: the 1992 version first included the PMV/PPD method; the 2004 version first included the adaptive method; and the 2013 version replaced the monthly mean outdoor temperature in the comfort equation by the prevailing mean outdoor temperature (Carlucci, Bai, de Dear, & Yang, 2018).

ASHRAE 55 is similar to ISO 7730 in terms of being based on the PMV method. In addition, an adaptive standard was embedded within ASHRAE 55 from the 2004 version onwards for use in free-running buildings. ASHRAE 55 is the first international standard including an adaptive method (Nicol et al., 2012). As shown in Figure 2.3, the standard classifies the comfort zones into two categories: the limits of 80% acceptability are for typical buildings, and the limits of 90% acceptability are for higher-standard buildings (ASHRAE, 2017). These comfort zones were obtained from the following adaptive comfort model which derived from the database of ASHRAE project RP884 (Nicol et al., 2012).

$$T_{comf} = 0.31\,T_o + 17.8 \qquad (2.9)$$

T_o was defined as the monthly mean outdoor temperature in the 2010 version backwards. From 2013, T_o has been defined as the prevailing mean outdoor temperature which is the average of the mean daily outdoor temperatures over a period that has to be "no fewer than seven and no more than 30 sequential days prior to the day in question" (ASHRAE, 2017). ASHRAE 55 adaptive model only applies to free-running buildings where the occupants have the metabolic rates ranging from 1 to 1.3 met (sedentary activities). If the prevailing mean outdoor temperature falls outside the range of 10 – 33.5°C, this adaptive standard may not be used.

The database of ASHRAE project RP884 includes 21000 sets of data from field studies in many locations with different climate types across four continents (de Dear & Brager, 1998). Therefore, although ASHRAE 55 is essentially a national standard of the US, it has been widely used around the world and is actually considered as an international standard.

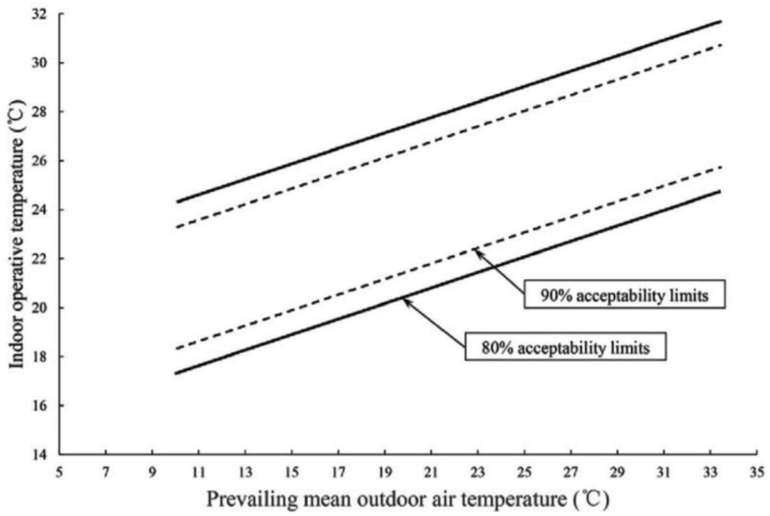


Figure 2.3: Acceptable ranges for naturally conditioned spaces in ASHRAE 55:2017

The European Standard EN16798-1:2019 was developed by the European Committee for Standardization (Comité Européen de Normalisation (CEN)) to replace the well-known CEN Standard EN15251:2007. This standard presents criteria for various aspects of indoor environment including indoor air quality, thermal condition, lighting and acoustics. Similar to ASHRAE 55:2017, EN16798-1:2019 includes the PMV/PPD model and an adaptive comfort model for mechanically ventilated and free-running buildings respectively. Table 2.2 shows that the specification of building categories based on the PMV/PPD indices in EN16798-1:2019 is identical to that in ISO 7730 (CEN, 2019). The category I with a high standard is recommended for special buildings serving vulnerable occupants. The category II is for normal new or retrofitted buildings whilst the lower category III may be applied to existing buildings. The adaptive model was derived from the Smart Controls and Thermal Comfort (SCATs) project that collected data from 26 office buildings in five European countries including France, Greece, Portugal, Sweden, and United Kingdom (McCartney & Nicol, 2002). The comfort equation is as follows:

$$T_{comf} = 0.33\, T_{rm} + 18.8 \tag{2.10}$$

Where T_{rm} is the exponentially weighted running mean of outdoor temperature.

The bandwidths of acceptable temperatures are shown in Table 2.2. It is noted that the thermal comfort zones for free-running buildings in EN16798-1:2019 have two changes compared to the previous version (EN15251:2007). The first change is the extension of the applicable range of outdoor running mean temperature from 15 - 30°C to 10 - 30°C. The second change is the extension of the thermal comfort zone where the new lower limit of indoor operative temperature is 1°C lower than the previous one. The comfort zones for three building categories in EN16798-1:2019 are graphically shown in Figure 2.4.

Similar to ASHRAE 55, the EN16798-1:2019 adaptive standard only applies to free-running buildings where the occupants engage in sedentary activities. If the outdoor running mean temperature falls outside the range of 10 – 30°C, this adaptive standard may not be used.

Table 2.2: Specification of building categories in EN16798-1:2019

Category	Description	PMV - PPD model		Adaptive model ΔT_{op} (°C)
		PPD (%)	PMV	
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons	≤ 6	- 0.2 ≤ PMV ≤ + 0.2	Upper limit: +2 Lower limit: -3
II	Normal level of expectation and should be used for new buildings and renovations	≤ 10	- 0.5 ≤ PMV ≤ + 0.5	Upper limit: +3 Lower limit: -4
III	An acceptable, moderate level of expectation and may be used for existing buildings	≤ 15	- 0.7 ≤ PMV ≤ + 0.7	Upper limit: +4 Lower limit: -5
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	> 15	PMV < - 0.7 or PMV > + 0.7	

PMV: predited mean vote; PPD: predicted percentage discomfort

ΔT_{op}: deviation from the neutral operative temperature

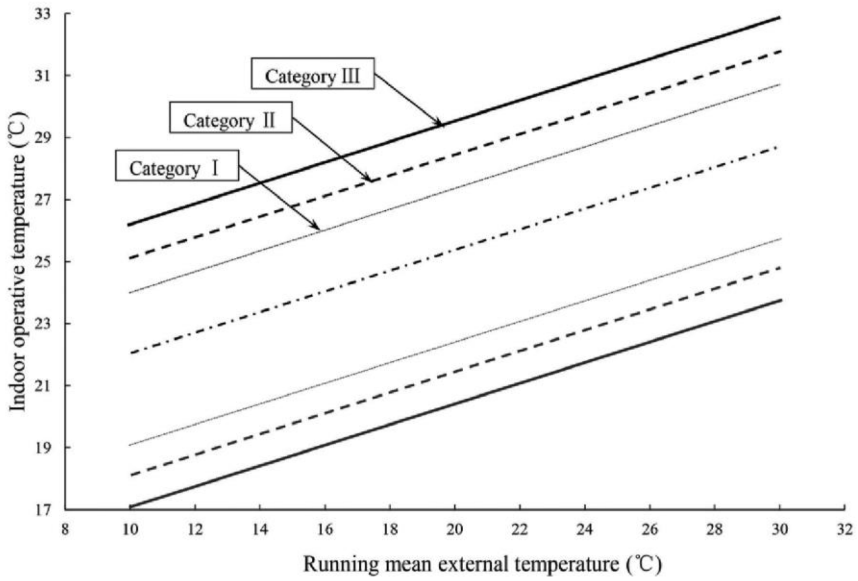


Figure 2.4: Acceptable ranges for free-running buildings in EN16798-1:2019

The above international standards provide reliable guidance for comfortable indoor environments based on the well-known PMV model and the results from numerous numbers of field studies around the world. As a result, those standards have been widely used not only in practice but also in research on thermal and energy performance of buildings. However, the application of those standards to every location in the world, especially in hot humid regions, should be carefully considered due to some limitations as follows.

ISO 7730:2005 specifies that the PMV model is only used when the indoor air temperature does not exceed 30°C and air speed is lower than 1 m/s (ISO, 2005). There is no doubt that indoor air temperature and air speed in naturally ventilated buildings in hot humid climates often exceed those values. Local residents in hot humid areas even feel satisfied at temperatures more than 30°C (Dang & Pitts, 2018; Djamila, Chu, & Kumaresan, 2013; Indraganti, 2010; Mishra & Ramgopal, 2014). Therefore, ISO 7730 is hardly applied to free-running buildings in hot humid climates. Moreover, in these climate zones, a number of studies found that the PMV model overestimated thermal sensation votes of occupants (Maiti, 2014; Nicol, 2004; Y. Yang, Li, Liu, Tan, & Yao, 2015). Therefore, the application of ISO 7730 to hot humid climates may show errors and lead to more energy consumption for cooling demand than necessary.

ASHRAE 55:2017 and EN16798-1:2019 also include the PMV model but it is recommended for use in air-conditioned buildings. These two standards adopt the adaptive theory to overcome the disadvantages of the PMV model in free-running buildings. However, the adaptive comfort models included in these standards show some drawbacks under hot humid conditions. Firstly, outdoor temperatures in hot humid climates often exceed the upper limits of the applicable ranges (33.5°C in ASHRAE 55:2017 and 30°C in EN16798-1:2019). Secondly, those adaptive models are based on the database collected from field studies on office buildings where the occupants experience a low level of behavioural adaptation (de Dear & Brager, 2002). Nicol (2011) pointed out that these standards have not satisfactorily encompassed the behavioural adaptability of occupants. A number of fieldwork projects in residential buildings found higher comfort temperatures than the values predicted by the adaptive models in ASHRAE 55:2017 and EN16798-1:2019 (de Dear, Leow, & Foo, 1991; Djamila et al., 2013; Feriadi et al., 2003; Indraganti, 2010).

In short, the three international standards show limitations when applying to buildings in hot humid climates. Note that these standards are under continuous review. Therefore, further studies in hot humid climates are necessary for the determination of appropriate thermal comfort conditions of local residents and for the update of these international standard in future.

2.1.4 Thermal comfort studies in hot humid climates

In the last three decades, along with the development of architectural and constructional technologies, research on thermal comfort has been carried out globally and in hot and humid climates in particular. Thermal comfort studies have been carried out in many different locations within the hot and humid belt, from Southeast Asian countries to India, Brazil, Mexico and the hot and humid parts of China. The studies have been conducted both by climatic chamber experiments and field studies. The types of surveyed buildings are diverse including offices, high-rise and low-rise residential buildings, educational buildings, and health care centres. The cooling modes of surveyed buildings are also different including natural ventilation and air conditioning.

Table 2.3: Climate chamber experiments on thermal comfort in hot humid climates

Authors	Year	Location	No. of subjects	Neutral temperature (°C) & Comfort zone (°C)
de Dear et al.	1991	Singapore	32	Preferred temperature: 25.4
de Dear et al.	1991	Singapore	98[b]	Upper limit: 27.6 (70% RH) (80% acceptance)
Abdulmalik & Young	1993	Malaysia	N/A	25.5 – 29.5
H.M. Nguyen et al.	2003	Hanoi, Vietnam	40	24 – 29 (90% acceptance)
Maiti	2014	Bangalore, India	40	24.8 23.3 – 26.3 (90% acceptance)
Y. Yang et al.	2015	Chongqing, China	80	Upper limit: 26.8 SET (90% acceptance)
Karyono et al.	2015	Jakarta, Indonesia	54 [b] 36 [c]	24.1 (22.6 – 25.7) (Untar students) 24.9 (23.6 – 26.1) (UMB students) (90% acceptance)
Zhang et al.	2016	Guangzhou, China	30[a] 30[b]	27.1 (24.5 – 29) SET (90% acceptance) 26.4 (24.5 – 28.1) SET (90% acceptance)
Jin et al.	2017	Guangdong, China	30[a]	25.3 (60%RH) Upper limit: 29 (69%RH) or 30 (55%RH) (90% acceptance)

[a] Subjects have long-term exposure to naturally ventilated environment
[b] Subjects have long-term exposure to mechanically ventilated environment
[c] 50% of subjects have long-term exposure to mechanically ventilated environment
RH: relative humidity; SET: standard effective temperature; N/A: not available

Table 2.4: Field studies on thermal comfort in hot humid climates

Authors	Year	Location	Building type	Ventilation mode	No. of subjects	Neutral temperature (°C) & Comfort zone (°C)
Busch	1990	Bangkok, Thailand	Office	NV AC	1100	28.5 ET 24.5 ET
de Dear et al.	1991	Singapore	Residential	NV AC	583 235	28.5 T_{op} 24.2 T_{op}
Karyono	2000	Indonesia	Office	NV AC	596	26.7 (23.5 – 29.9) T_{op}
Feriadi et al.	2003	Singapore	Residential	NV	538	28.6 T_{op}
Yamtraipat et al.	2005	Thailand	Office & education	AC	1520	24 – 26 T_a (Chiang Mai) 24.5 – 27.4 T_a (Bangkok) 23.7 – 26.4 T_a (Prachuabkirikhan)
Rangsiraksa	2006	Bangkok, Thailand	Residential & office	NV AC	691 686	26.7 T_a 24.4 T_a
Hussein et al.	2009	Joho Bahru, Malaysia	Education	NV AC	375 184	28.4 (26 – 30.7) T_{op} 24.4 (23.1 – 25.6) T_{op}
Cândido et al.	2010	Maceio, Brazil	Education	NV	2075	Neutral temp.:26 – 31 T_{op} with air velocity: 0.4 – 0.7 m/s
Indraganti	2010	Hyderabad, India	Residential	NV	100	29.2 (26 – 32.5) T_g
T.A. Nguyen	2013	Danang, Vietnam	Education	NV	1198	27.8 T_{op}
Djamila et al.	2013	Kota Kinabalu, Malaysia	Residential	NV	890	30 (27 – 32.5) T_{op}
Mishra & Ramgopal	2014	Kharagpur, India	Laboratory	NV	121	26.4 (21 – 31.9) T_{op}
Yau & Chew	2014	Malaysia	Hospital	AC	293	26.4 (23.7 – 27.7) T_{op}
Damiati et al.	2016	Singapore Indonesia Malaysia	Office	AC	14 16 90	26.4 T_{op} 26.3 T_{op} 25.6 T_{op}
Dang & Pitts	2018	Ho Chi Minh, Vietnam	Residential	NV	117	28.5 (25.5 – 31.5) T_{op}

NV: natural ventilation; AC: air conditioning; ET: effective temperature
T_a: air temperature; T_g: globe temperature; T_{op}: operative temperature

Table 2.3 and Table 2.4 show major findings from numerous climate chamber experiments and field studies on thermal comfort in hot humid climates. It is observed that the number of field studies dominates the total number of thermal comfort research activities. Note that Table 2.4 only presents some notable research using field study method whilst Table 2.3: Climate chamber experiments on thermal comfort in hot humid climates shows all climate chamber studies that can be found from literature by the author. It could be due to some constraints of the laboratory-based method including the high cost of establishing a climate chamber, the complex and time-consuming experiment procedure and the difficulty in finding participants. As a result, sample sizes in such experiments are generally small. Conversely, field studies are carried out in actual buildings and the subjects are surveyed in their normal working or living environments. Therefore, sample sizes in field studies on thermal comfort are usually much larger and more diverse compared to that of climate chamber experiments (de Dear, 2004). A comparison among the thermal comfort studies in hot humid climates derived some conclusion as follows:

Firstly, although the studies were all conducted in hot and humid climates, it is clear that the results differed significantly. The differences of results can be found between different countries, and between different cities within the same country. For example, in a field study on naturally ventilated buildings in Danang city, Viet Nam, T. A. Nguyen (2013) found the neutral temperature of the Vietnamese was 27.8°C whilst Indraganti (2010) found that of people in Hyderabad, India was 29.2°C. A similar study in Kota Kinabalu, Malaysia reported a neutral temperature of 30°C (Djamila et al., 2013). Considering comfort studies in the same country, another field studies in India showed the comfort temperature in Kharagpur city was 26.4°C which is 2.8°C lower than the value found in Hyderabad city. The discrepancy between neutral temperatures in different cities within a country is also found in the studies of T. A. Nguyen (2013) and Dang & Pitts (2018).

The differences of results between thermal comfort studies are observed not only in field studies but also in laboratory experiments. In comfort research using climate chamber, de Dear (1991) found the upper limit of the comfort zone for Singapore was 27.6°C whilst Maiti (2014) found that value was 26.3°C for Bangalore city in India. In different cities in China, Y. Yang (2015) and Zhang (2016) found those values for Chongqing and Guangzhou city in China were 26.8°C and 29°C respectively.

The discrepancy of the thermal comfort results in different locations could be explained by the effects of people's adaptation to the local climates on their thermal sensations and preferences (De Dear & Brager, 2002; Nicol & Humphreys, 2010). Long-term exposures to warmer climates result in higher neutral temperatures and thermal comfort zones (Ning et al., 2016). In addition, the discrepancy of the above results might be due to the different periods of conducting research in a year when the outdoor temperatures differ. For example, Dang & Pitts (2018) only carried out the field study in summer whilst T. A. Nguyen (2013) conducted the study in both summer and spring.

Secondly, there is a significant difference of 2-5°C between neutral temperatures in air-conditioned buildings and those in naturally ventilated buildings. In a field study in Thailand, Busch (1990) showed that the neutral temperatures for air-conditioned buildings and non-air-conditioned buildings were 24.5°C and 28.5°C respectively. Similarly, these values were 24.4°C and 28.4°C in Malaysia (Hussein, Rahman, & Maria, 2009). De Dear et al. (1991) also found the similar result with 24.2°C and 28.5°C in a field study in Singapore. However, in recent studies, Yau & Chew (2014) found that the neutral temperature in air-conditioned buildings in Malaysia was 26.4°C which is around 2°C higher than those of previous studies. Damiati et al. (2016) also found the identical values of 26.4°C and 26.3°C respectively for Indonesia and Singapore. Moreover, it can be seen in the Table 2.4 that the magnitude of comfort zones in naturally ventilated buildings are larger than those in air-conditioned buildings.

The discrepancy of thermal comfort conditions between air-conditioned buildings and free-running buildings is possibly caused by two major factors. The first one is the influence of occupants' thermal history on their thermal perception. People in air-conditioned buildings adapt themselves to cool indoor environments in which the temperature setpoints are usually set at their defined comfort temperature or even lower. This makes their expected temperatures significantly lower than those of people in free-running buildings. The second factor is the interactive ability between occupants and the surroundings. The occupants in air-conditioned buildings "are removed from the thermal control loop" whilst the occupants in free-running buildings can adjust their behaviours or control the building properties to make them comfortable under various thermal conditions (de Dear, 2004). Therefore, they can accept a higher limit of temperature in hot humid climates.

Thirdly, the thermal comfort conditions are different between field studies and experimental research. In general, the neutral temperatures and comfort ranges from the empirical studies on free-running buildings are considerably higher than those from the experiments. Meanwhile, the filed studies on air-conditioned buildings showed that the results were closer to those of climate chamber experiments. For example, in a field study in 1991, de Dear found that the comfort temperatures for Singapore were 28.5°C and 24.2°C for free-running and air-conditioned buildings respectively, while the preferred temperature of the Singaporean residents he derived from a climate chamber experiment in the same year, was 25.4°C.

Similar to the condition in mechanically ventilated buildings, the strict control of environmental and human parameters in climate chamber experiments limit the behaviours of the occupants to seek thermal comfort. This reason helps to explain the similarities of the comfort conditions found in air-conditioned buildings and climate chambers. As a result, a number of studies claimed that the comfort models based on experimental studies such as the PMV model work well in mechanically ventilated buildings (de Dear & Brager, 1998; S. Tanabe et al., 1987; L. Yang et al., 2014). However, some researchers found the significant discrepancies between the predicted thermal sensations from the PMV model and the actual thermal sensations from their experiments. For example, the upper-limit temperature of 26.8°C from Y. Yang's (2015) experiment is 1.6°C higher than the predicted value of 25.2°C. Similarly, Maiti (2014) found that difference was around 1°C in the context of Bangalore city in India. Both authors argued that the PMV model overestimates thermal sensation votes of the occupants, therefore, the PMV model shows limitations in hot humid climates.

Finally, it is worth mentioning that the comfort conditions derived from climate chamber experiments differ between subjects who have long-term exposure to naturally ventilated environments ('NV' subjects) and subjects who familiarise with air-conditioned environments ('AC' subjects). Karyono et al. (2015) and Zhang et al. (2016) found that the comfort temperature of the

NV subjects is around 1°C higher than that of the AC subjects. Again, thermal history could be the major factor that caused different thermal expectations of the above groups.

In summary, a review on thermal comfort studies in hot humid climates showed that there are differences in terms of neutral temperatures and comfort zones. These discrepancies are observed between different locations, between air-conditioned and free-running buildings, between field studies and experimental research, and between NV subjects and AC subjects. Apart from the possible errors from measurements and analyses, the main reason for these differences could be the adaptations of people to their own local climates and prevailing indoor thermal environments. This reasoning strongly supports the adaptive theory in thermal comfort research, not only in field studies but also in laboratory-based experiments. Therefore, it is necessary to carry out thermal comfort studies on particular locations and subjects to determine the appropriate comfort conditions. Additionally, according to the ASHRAE Global Thermal Comfort Database II, the number of field studies in hot humid climates is relatively modest compared to other climate zones (Ličina et al., 2018). There are also few climate chamber experiments in hot humid regions. Consequently, there is a need for further studies on thermal comfort in hot and humid climates including Vietnam.

2.1.5 Thermal comfort studies and standards in Vietnam

2.1.5.1 Thermal comfort studies in Vietnam

Research on thermal comfort in Vietnam was initiated in the 1960s with pioneering researchers such as Pham Ngoc Dang and Pham Duc Nguyen. However, in the limited conditions of the Vietnam War and the underdevelopment of the country in general and of scientific research in particular, the implementation of thermal comfort studies requiring equipment for measurements and calculations seemed impossible. Therefore, the thermal comfort standard applied in building design needed to be based on foreign standards, such as the ISO 7730. However in 2002, Pham Duc Nguyen carried out a thermal comfort field study in a student accommodation building (N.D. Pham, 2002); and one year later, H.M. Nguyen et al. (2003) conducted a climate chamber experiment in Hanoi capital city which is the only laboratory-based research on thermal comfort in Vietnam so far. In 2004, the Ministry of Construction (MOC) enacted the building code TCXDVN 306:2004 “Dwellings and public buildings- Parameters for micro-climates in the room”. This building code was partly based on a thermal comfort research run by the MOC (MOC, 2004). However, the details of this research are not available. In 2012, T.A. Nguyen used the meta-analysis method to create an adaptive comfort model for Southeast Asia, afterwards, he validated that model by conducting a comfort field studies in a university in Danang city (T.A. Nguyen, 2013). The latest thermal comfort research in Vietnam is another field study on residential buildings in Ho Chi Minh city conducted by Dang & Pitts in 2018. These available thermal comfort studies in Vietnam are shown in Table 2.5 and their details are described in the following paragraphs.

Table 2.5: Thermal comfort studies in Vietnam

Authors	Year	Location	Building type	Ventilation mode	No. of subjects	Neutral temperature (°C) & Comfort zone (°C)
N.D. Pham	2002	Vinh	Student hall	NV	12	Upper limit: 28.5 – 29.2 T_a (RH 90%) 30.5 T_a (RH 80%)
H.M. Nguyen et al.	2003	Hanoi	Climate chamber	AC	40	24 – 29 T_a
MOC	2004	Northern Vietnam	N/A	N/A	1100	21.5 – 29.5 T_a (RH 80%)
T.A. Nguyen	2013	Danang	Education	NV	1198	27.8 T_{op}
Dang & Pitts	2018	Ho Chi Minh	Residential	NV	117	28.5 (25.5 – 31.5) T_{op}

NV: natural ventilation; AC: air conditioning; N/A: not available
T_a: air temperature; T_{op}: operative temperature

The field study conducted by N. D. Pham (2002) involved 12 college-aged students (6 males and 6 females). The surveyed building was a naturally ventilated student hall in Vinh city. This city has a hot summer and a cold winter. The average air temperature is 23.9°C, with the lowest monthly average of 15.6°C in January and the highest monthly average of 34.2°C in July (MOC, 2009). The study took place for 3 days with 2 hours per day. During the study, human parameters including clothing and activity were controlled at 0.5 clo (summer clothing) and 1 met (sedentary activity). The subjects voted their thermal sensations on the 7-point scale of ASHRAE. Meanwhile, the indoor environmental parameters were measured. The result indicated that with 80% satisfaction standard, the upper-limit temperature of the subjects was 29.2°C with 90% relative humidity or 30.5°C with 80% relative humidity. The author did not determine the neutral temperature. This study indicated that Vietnamese people can accept a much higher temperature than the upper limit of 26°C of the ISO 7730:1994 comfort standard which was applied in Vietnam at that time. However, N. D. Pham proposed that those outcomes need to be validated by further studies due to the small sample size and other limitations of the research method.

The only thermal comfort experiment using climate chamber in Vietnam so far was conducted in winter in Hanoi capital city (H. M. Nguyen et al., 2003). Hanoi city has a subtropical climate with a hot summer and a cold winter. The average air temperature is 23.6°C, with the lowest monthly average of 14.3°C in January and the highest monthly average of 33.1°C in July (MOC, 2009). 40 students (21 males and 19 females) participated in this experiment. During the test, each subject wearing T-shirt and thin trousers singly entered the chamber, sat on a chair and read books. The chamber was initially set at 22°C and 40% relative humidity. The temperature was increased 1°C after each 20 minutes until the subject felt warm. Before the change of temperature, subjects were required to vote their thermal sensation on the ASHRAE seven-point scale. Table 2.6 shows the numbers and percentages of subjects who felt comfortable at each set temperature. The result showed that over 90% of the participants accepted the temperature from 24 to 29°C.

Table 2.6: Number of participants who felt comfort in the experiment of H.M.Nguyen et al. (2003)

Room temperature (°C)	Number of participants who felt comfort							
	Male (n=21)			Female (n=19)			Total (n=40)	%
	Slightly cool	Neutral	Slightly warm	Slightly cool	Neutral	Slightly warm		
22	10	1	1	3	2	0	17	42.5
23	8	5	0	4	7	2	26	65
24	7	7	5	7	11	1	38	95
25	4	11	5	3	10	6	39	97.5
26	4	7	10	1	6	12	40	100
27	2	4	15	1	3	15	40	100
28	2	2	16	1	5	13	39	97.5
29	1	1	17	0	2	15	36	90
30	1	0	5	1	0	3	10	25

Despite the small sample size, the study of H.M. Nguyen et al. (2003) is a significant contribution to the modest number of comfort studies in Vietnam, especially in terms of the specific method employed. However, questions could be raised about the validity and applicability of the result as the authors did not mention the climate chamber properties, the measurements of environmental variables and the subjects' thermal history. Further analysis is necessary to determine the comfort zone for the precise 90% acceptance criterion rather than the "over 90%" value. Moreover, the sudden change in the percentage of subjects who felt comfortable from 90% at 29°C to 25% at 30°C is rarely observed in comfort research. Another controversial issue in that study is the time interval of 20 minutes for each temperature because this period could be not enough for human body to reach the thermal equilibrium. Therefore, the thermal sensation votes may not correspond to the set temperature.

The thermal comfort study mentioned in the building code TCXDVN 306:2004 (MOC, 2004) involved a large sample size with 1100 subjects. However, the details of that study are not available, including the research method, types of surveyed buildings, ventilation modes and subjects' characteristics. Therefore, it is impossible to assess the validity of findings and to compare to the results of other research.

T. A. Nguyen et al. (2012) conducted a meta-analysis on thermal comfort data collected from field studies around Southeast Asia. A total of 5176 thermal responses were analysed including 3430 samples in naturally ventilated buildings and 1746 samples in air-conditioned buildings. He found that the neutral operative temperature in naturally ventilated buildings and air-conditioned buildings were 27.9°C and 25.8°C respectively. The most important contribution of that study is the establishment of an adaptive model for free-running buildings in Southeast Asia as follows:

$$T_{comf} = 0.341\, T_{out} + 18.83 \qquad (2.10)$$

In order to validate the applicability of this model in the context of Vietnam, T. A. Nguyen (2013) carried out a comfort survey in Danang, a large city in the Centre Coast of Vietnam. The average air temperature in this city is 25.8°C, with the lowest monthly average of 19.1°C in

January and the highest monthly average of 34.4°C in July (MOC, 2009). The surveys were conducted in 6 days (2 days per month) in April, May and June with the monthly average temperature of 26.4°C, 28.3°C and 29.2°C respectively. 1200 university students were surveyed in naturally ventilated environments of their classrooms and the library. The participants voted their thermal sensations on the ASHRAE seven-point scale whilst the indoor environmental parameters were measured. An analysis of 1198 qualified responses showed that the neutral operative temperature was 27.8°C. This result is in line with the neutral temperature of 27.9°C found from the meta-analysis mentioned above. Consequently, the author concluded that Vietnamese people desire similar thermal comfort condition as other people in Southeast Asia (T. A. Nguyen, 2013). However, these neutral temperatures are 0.5 – 0.8°C lower than those of other studies in Southeast Asia which are summarised in Table 2.4.

To survey the thermal preference of people in their own living spaces, Dang & Pitts (2018) conducted a field study on 59 free-running shophouses with 117 participants in warm season of Ho Chi Minh city. The average air temperature in this city is 27.4°C with the lowest monthly average of 21.1°C in January and the highest monthly average of 34.6°C in April (MOC, 2009). The participants also based on the ASHRAE seven-point scale to vote their thermal sensations whilst indoor environmental variables were measured. The result showed that the neutral temperature of people in Ho Chi Minh city was 28.5°C and the comfort zone was 25.5 – 31.5°C. This neutral temperature is consistent with those of other field studies in Southeast Asia shown in Table 2.4. This study is significant since it is the only thermal comfort research in residential buildings in Vietnam so far. Moreover, this study involved a wide range of subjects' age, from 15 to 65, and ensured the highest adaptive level of the occupants in their daily living environments. However, because the survey was only carried out in warm season, the results cannot be used as a whole-year value. Further surveys in other seasons are needed.

In summary, a literature review on thermal comfort studies in Vietnam shows a modest number of 5 studies in total. It is worth mentioning that there could be other thermal comfort studies under the forms of national and local research projects have been conducted and accepted, but they have not been published. This situation is relatively common in Vietnam. Hence, this thesis only refers to the available comfort studies. It is clear from Table 2.5 that the studies were conducted in different cities from the North to the South of Vietnam and on various building types. Note that there is no comfort study on air-conditioned buildings and only one study using climate chamber so far. Although all studies found relatively high neutral temperatures and comfort zones for the Vietnamese, there are discrepancies among these values of the 5 studies. Therefore, further studies are necessary to supplement the modest thermal comfort database of Vietnam. Along with individual comfort studies, Vietnam government has enacted a few national standards to determine the thermal comfort conditions of Vietnamese people in different indoor environments. The details of these standard are presented in the next subsection.

2.1.5.2 Thermal comfort standards in Vietnam

There are 4 existing national building codes including thermal comfort standards for the Vietnamese, namely TCVN 7438:2004, TCXDVN 306:2004, TCVN 5687:2010, and TCVN 9411:2012. The details of thermal comfort standards in these building codes are as follows.

TCVN 7438:2004: "Ergonomics - Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for the comfort" is completely equivalent to ISO 7730:1994 (MOST, 2004). Therefore, TCVN 7438:2004 also presents the same thermal prediction method using the PMV/PPD indices along with additional information about thermal insulation values of clothing and metabolic rates of various activity levels. TCVN 7438:2004 aims to be mainly applicable to office buildings but it can also be used for other building types (MOST, 2004).

TCXDVN 306:2004: "Dwelling and public buildings – Parameters for micro-climates in the rooms" introduces thermal comfort conditions for use in residential and public buildings (MOC, 2004). This standard also includes methods of measuring environmental parameters and formulae for the determination of operative and mean radian temperature. Table 2.7 shows the specified thermal comfort and discomfort zones according to effective temperature and air temperature in both cool and warm season. Generally, the thermal comfort zone of the Vietnamese is specified from 21.5 to 29.5°C. Additionally, this standard also mentions the local comfort conditions in which the vertical differences of operative temperatures, air velocities and relative humidity do not exceed ±2°C, ±0.1 m/s, and ±15% respectively outside the comfort zone. The thermal comfort conditions in TCXDVN 306:2004 are based on the results of a comfort study with 1100 subjects in the Northern Delta of Vietnam.

Table 2.7: Thermal comfort conditions of the Vietnamese in TCXDVN 306:2004

Thermal zone	Thermal sensation	Effective temperature (°C)		Air temperature (°C) (80%RH, v = 0.3 - 0.5 m/s)	
		Cool season	Warm season	Cool season	Warm season
Cold	Cold	≤ 17.3	N/A	≤ 19.8	N/A
	Cool	18.5	N/A	N/A	N/A
Comfortable	Slightly cool	20	N/A	21.5	N/A
	Neutral	23.3	24.4	24.5	25.5
	Slightly warm	26.5	27	29	29.5
Hot	Warm	N/A	28.5	N/A	N/A
	Hot	N/A	≥ 29.2	N/A	≥ 31.5

RH: relative humidity; v: air speed; N/A: not available

TCVN 5687:2010: "Ventilation and air conditioning – Design standards" is applied to the design and installation of ventilation and air-conditioning systems for residential, public and industrial buildings (NUCE, 2010). Although this standard is not dedicated to the determination of thermal comfort conditions, it specifies the indoor environmental requirements for air-conditioned buildings as shown in Table 2.8. The criteria of temperature, relative humidity and air speed associated with various activity levels are defined for both cool and warm season. However, this building code does not mention the references used for those criteria.

Table 2.8: Thermal comfort requirements for air-conditioned buildings in TCVN 5687:2010

Activity level	Cool season			Warm season		
	Temperature (°C)	Relative humidity (%)	Air speed (m/s)	Temperature (°C)	Relative humidity (%)	Air speed (m/s)
Resting	22 – 24	60 – 70	0.1 – 0.2	25 – 28	60 – 70	0.5 – 0.6
Light	21 – 23		0.4 – 0.5	23 – 26		0.8 – 1
Medium	20 – 22		0.8 – 1	22 – 25		1.2 – 1.5
Heavy	18 – 20		1.2 – 1.5	20 – 23		2 – 2.5

TCVN 9411:2012: "Row houses – Design standards" determines criteria relating to planning, architecture and engineering of row houses (VIAP, 2012b). These criteria refer to other particular standards in the building code system of Vietnam. For example, designing ventilation and air-conditioning systems has to comply with the building code TCVN 5687:2010: "Ventilation and air conditioning – Design standards". Consequently, the comfort conditions of indoor environment in rowhouses, where the activity level is commonly sedentary, are derived from Table 2.8. In addition to the comfortable zone, TCVN 9411:2012 specifies the upper and lower acceptable limits of air temperature, relative humidity and air velocity as shown Table 2.9.

Table 2.9: Thermal comfort zones and limits for Vietnamese dwellings in TCVN 9411:2012

Season	Air temperature (°C)		Relative humidity (%)		Air speed (m/s)	
	Comfortable	Limit	Comfortable	Limit	Comfortable	Limit
Cool	22 – 24	20 – 22	70 – 75	75 – 80	0.2 – 0.3	0.5
Warm	25 – 28	29	75	80	0.5 – 1	1.5

In summary, Vietnam has 4 existing standards relating to thermal comfort which are based on domestic research or foreign standards. The application of these standard in Vietnam needs to be reconsidered due to the following reasons. Firstly, there are discrepancies between the thermal comfort zones specified in these standards. Moreover, these thermal comfort zones are lower than those of other studies in hot humid climates. This raises a concern about the validity of the existing thermal comfort standards of Vietnam. A consistent and appropriate thermal comfort zone of the Vietnamese is therefore necessary. Secondly, the existing comfort standards do not differentiate thermal comfort conditions for naturally ventilated and air-conditioned buildings which are significantly different. Thirdly, the territorial boundaries of Vietnam include various climate types in which the Northern subtropical climate is distinctly different from the Southern tropical climate. Therefore, the application of a fixed thermal comfort zone across the country could raise errors.

The above literature review on the existing thermal comfort standards and individual comfort studies in Vietnam shows a dissimilarity between the results and a shortage of database evidence for thermal comfort. Therefore, further comfort studies on free-running buildings, air-conditioned buildings and climate chambers are essential for the determination of appropriate thermal comfort zones for Vietnamese people in the corresponding spaces and climate conditions. Consequently, this research includes a thermal comfort study in Vietnam that is presented in Chapter 4. As discussed in Section 2.1.1, a precise comfort zone plays an important role in low energy building design since it directly influences the amount of energy consumed in buildings to maintain indoor comfort. Cooling and heating demand of buildings can be significantly reduced by applying low energy design techniques. Therefore, it is necessary to review potential design techniques for low energy buildings in hot humid climates. The details are discussed in the next section.

2.2 Design strategies and standards for low energy buildings in hot humid climates

This section firstly summarises low energy building design strategies for hot humid climates including both passive and active solutions. Secondly, common low energy building standards and green building rating systems are reviewed. Thirdly, this section describes achievements and limitations of research and practice on low energy buildings in Vietnam.

In hot and humid climates where cooling is the dominant demand, it is essential to prevent heat gains to satisfy thermal comfort requirement and minimise energy consumption of buildings. As shown in Figure 2.5, the heat gain sources can be classified into 5 categories including external solar gains, internal solar gains, conductive gains, ventilation gains, and internal gains (from occupants and equipment) (Baker & Steemers, 2005). Heat gains in buildings can be energy-efficiently reduced by the application of climate-responsive design strategies including both passive and active techniques. In order to synthesise low energy design techniques used in hot humid climates, a literature review was made on a number of notable books in the field, namely “Passive cooling of buildings” (Santamouris & Asimakopolou, 1996), “Climate responsive design: a study of buildings in moderate and hot humid climates” (Hyde, 2000), “Energy and environment in architecture: A technical design guide” (Baker & Steemers, 2005), “Ecodesign: a manual for ecological design” (Yeang, 2008), “Introduction to architectural science: A basis of sustainable design” (Szokolay, 2008), “Design primer for hot climates” (Konya, 2013), “Sustainable Asian house: Thailand, Malaysia, Singapore, Indonesia, Philippines” (McGillick & Kawana, 2013) “Design with climate: Bioclimatic approach to architectural regionalism - New and expanded edition” (Olgyay, 2015), “Building design, construction and performance in tropical climates” (Riley, Cotgrave, & Farragher, 2018). In addition, low energy design techniques mentioned in some design guidelines and a large number of journal articles have also been reviewed. Passive and active design strategies in hot humid climates are summarised in the following subsections.

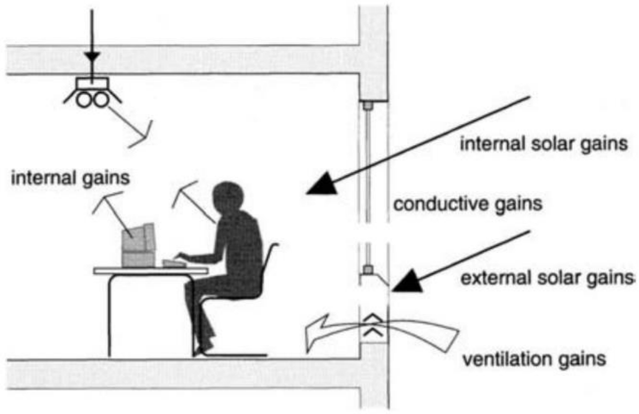


Figure 2.5: The sources of heat gains (Baker & Steemers, 2005)

2.2.1 Passive and active design strategies

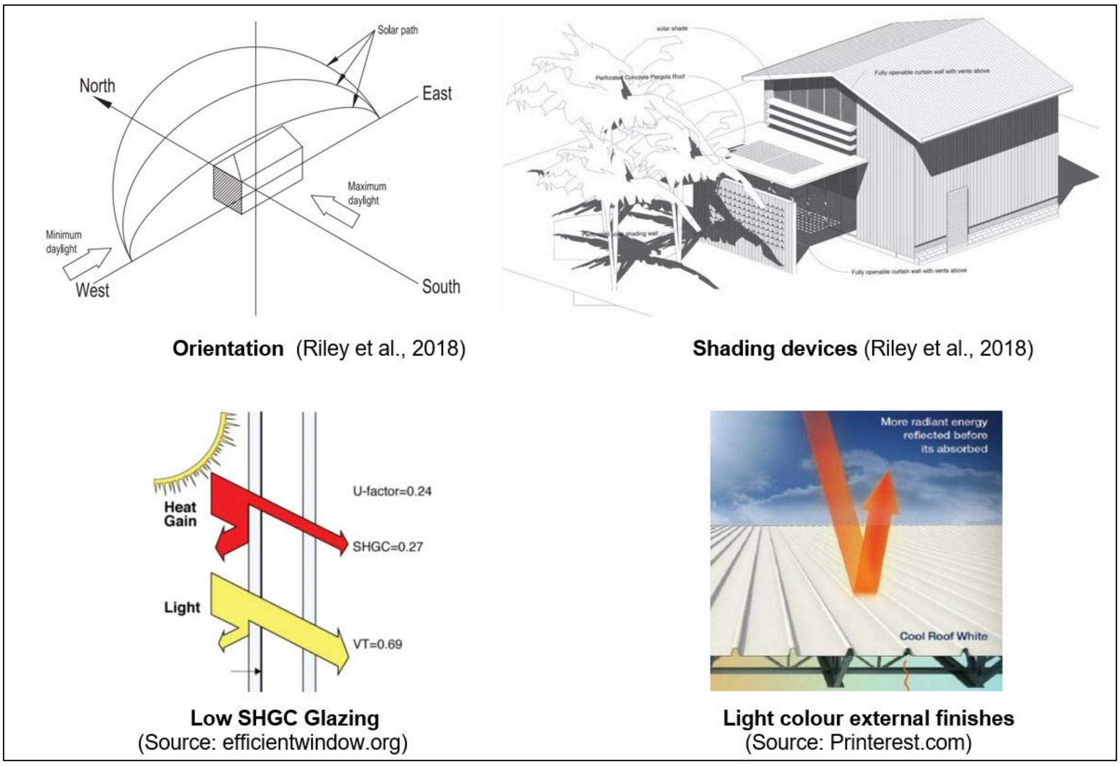
2.2.1.1 Passive design strategies

Passive design strategies employ techniques that maximise the advantages and minimise the disadvantage of the climate to maintain thermal comfort in buildings. These techniques are based on the natural interactions between architectural elements and the surrounding environment. Therefore, these energy-free techniques have been encouraged in most climate types. In hot humid climates, it is important to avoid heat gains in buildings, especially in hot daytime. Two principle strategies to avoid heat gains are heat prevention and heat release (Santamouris & Asimakopolou, 1996). The heat prevention strategies consist of solar control, thermal control, and thermal zoning whilst the heat release strategies include passive cooling techniques (Attia, 2012).

Solar control techniques (Figure 2.6): Building envelope including exterior walls, roofs, windows and doors expose to the sun. They absorb sunrays and their outer surface temperatures increase. The heat is then transferred to indoor spaces. Therefore, building design needs to control the solar absorption of the envelope. This task could be initially solved by a suitable building orientation and building form. In hot humid areas located around the equator, it is a rule of thumb that main façades face North and South and glazed areas (window to wall ratio) should be minimised on the West and East façades. Solar heat gain coefficient (SHGC) of glazing is an important factor to reduce solar gains. The next step is the use of fixed and movable shading devices to prevent direct sunrays from reaching the building. Shading devices may include diverse types of vertical and horizontal overhangs, louvres, venetian blinds, shading screens with various materials such as wood, concrete, or aluminium. Additionally, landscape factors including trees and ground cover with grass can limit direct sunrays and the reflectance. Moreover, solar absorptance of the envelope could be reduced by the use of light colours.

Thermal control techniques (Figure 2.7): Apart from solar heat gain avoidance, it is necessary to control the thermal conductance caused by the difference between indoor and outdoor temperatures. High outdoor temperatures in hot humid climates and the solar absorption of external building components lead to the transfer of heat to indoor spaces. These thermal exchanges depend on thermal properties of the building fabric including opaque and glazed components; hence, the thermal conduction could be prevented by the application of cavity walls, insulation layers, green roof, low solar absorptivity external finishes (e.g. light colour), and low-thermal-transmittance glazing (low U-value). Thermal mass is another solution to modulate the heat flow in buildings.

Thermal zoning techniques (Figure 2.8): Positioning building spaces corresponding to the sun paths and prevailing wind directions could improve thermal conditions. Auxiliary spaces such as toilets, corridors and courtyards act as buffering zones to absorb the heat and prevent solar gains in the main spaces. The spatial layout could also improve the effectiveness of natural ventilation and thereby enhance the heat release.



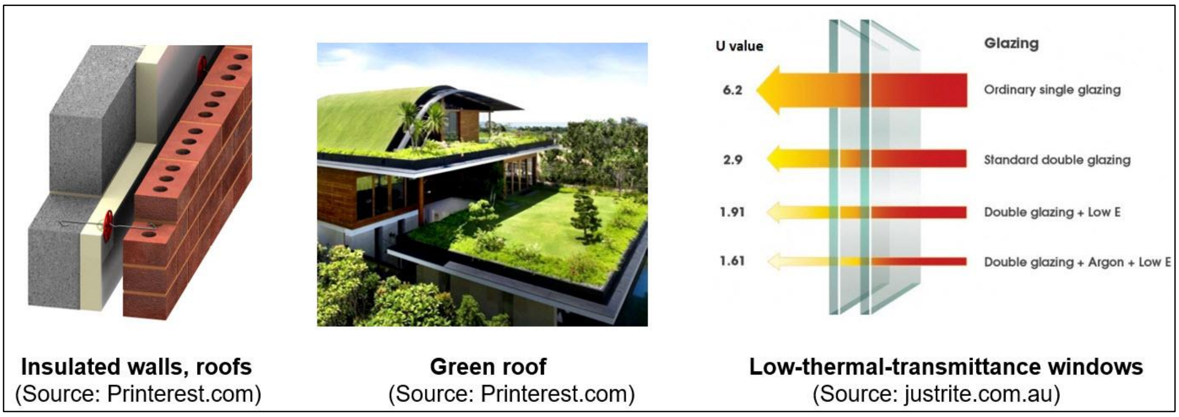
Orientation (Riley et al., 2018)

Shading devices (Riley et al., 2018)

Low SHGC Glazing (Source: efficientwindow.org)

Light colour external finishes (Source: Printerest.com)

Figure 2.6: Solar control techniques



Insulated walls, roofs (Source: Printerest.com)

Green roof (Source: Printerest.com)

Low-thermal-transmittance windows (Source: justrite.com.au)

Figure 2.7: Thermal control techniques

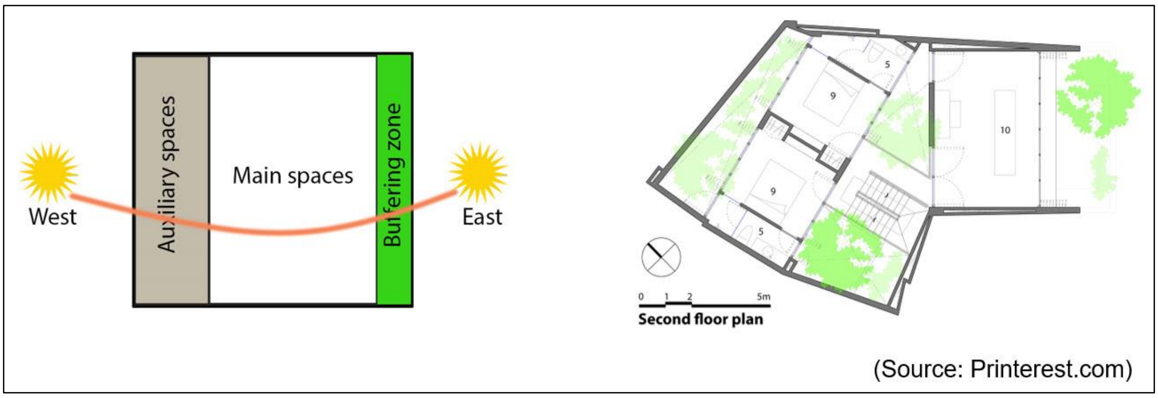


Figure 2.8: Thermal zoning techniques

Passive cooling techniques (Figure 2.9): In hot humid climates, passive cooling is a common and useful strategy to provide thermal comfort. Passive cooling strategy exploits natural heat sinks to release the heat in buildings to the surrounding environment. There are four main techniques of passive cooling including cooling with natural ventilation, radiative cooling, evaporative cooling and ground cooling (Santamouris & Asimakopolou, 1996).

- Natural ventilation is the use of natural air movements through building spaces to improve the thermal conditions. Natural ventilation strategy includes daytime ventilation (or comfort ventilation) and night ventilation (or nocturnal ventilation). Daytime ventilation exploits air velocity to enhance the rate of sweat evaporation of occupants, thereby providing thermal comfort even in high indoor temperature and high humidity conditions. During night time when the outdoor air temperature is low, night ventilation helps to decrease the temperature of indoor ambience and structures. The cool structural mass will absorb the heat next day. Night ventilation is recommended for climates with large swing of diurnal temperature (more than 15°C). Therefore, the low diurnal temperature swing and high humidity in hot humid climates are major obstacles to apply night ventilation techniques (Attia, 2012; Kubota, Chyee, & Ahmad, 2009).
- Radiative cooling is a technique where the roof acts as a radiator radiating towards the sky. For example, a roof pond system with a movable insulated cover absorbs the internal heat in daytime and radiates thermal energy to the sky at night (Figure 2.9). Radiative cooling technique is not effective in humid climates because humidity absorbs long-wave radiation (Santamouris & Asimakopolou, 1996).
- Evaporative cooling converts sensible heat from the air into latent heat through evaporation process. Evaporative cooling includes direct and indirect methods. Direct evaporative cooling cools the ventilation air when it passes wet areas such as ponds and fountains or fogging systems. This process increases the moisture of the air. On the contrary, in indirect evaporative cooling, the air is cooled by the surfaces that is cooled by the evaporation (e.g., roof pond and roof spray techniques). Subsequently, the

humidity of the cooled air is not changed. Therefore, indirect evaporative cooling is suitable for hot humid climates while direct evaporative cooling is effective in hot dry climates.

- Ground cooling (or earth cooling): the earth acts as a cooling source since the soil temperature at a certain depth is significantly lower than the air temperature in summer. Buildings can be built underground to utilise the earth cooling or can use underground pipe systems to cool the supply air (earth-to-air heat exchanger). Earth pipe systems often accompany fans to enhance the effectiveness.

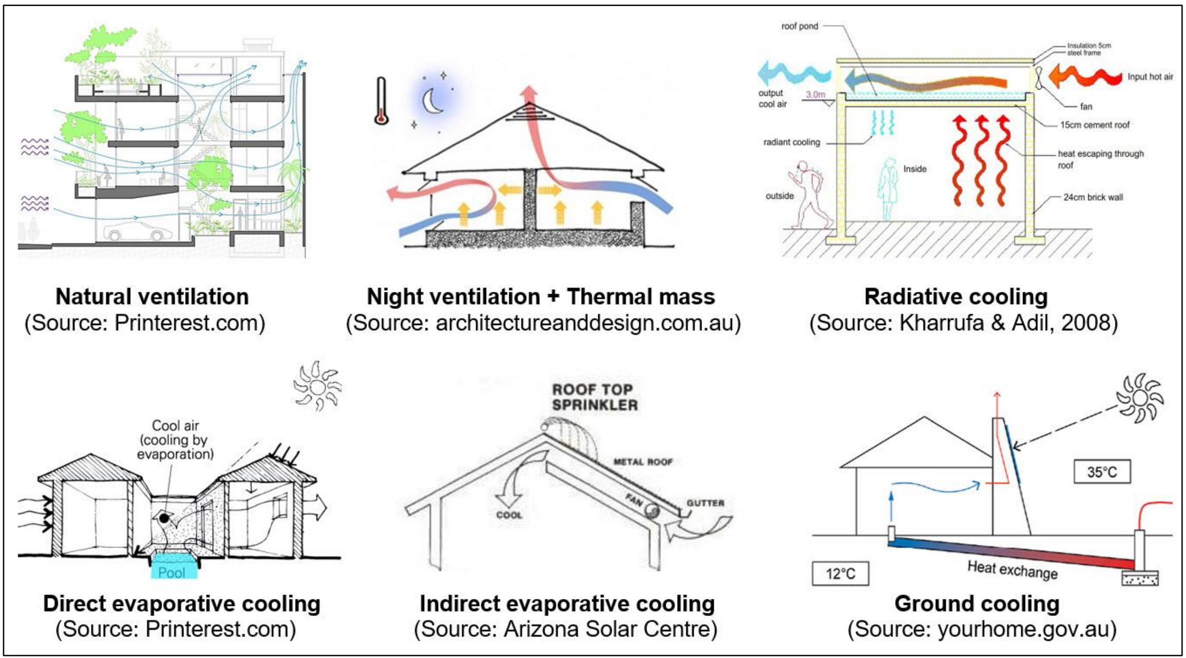


Figure 2.9: Passive cooling techniques

Natural lighting: is a passive technique to reduce energy consumption for artificial lighting. However, the use of natural lighting in hot humid climates must be carefully considered due to the high potential of solar heat gains through large glazing areas.

The integration of passive heat-prevention and passive cooling techniques into buildings in hot humid climates can significantly reduce the energy consumption. These techniques utilise natural phenomena to prevent heat gains and release heat back to the surrounding environment. As a result, the effectiveness of passive design strategies strongly depends on local climates. In hot humid climates where outdoor temperature often exceed 30°C, sole passive design strategies in some cases cannot provide thermal comfort for building occupants, especially in extreme climate conditions. Therefore, additional active techniques are necessary to satisfy cooling demands in such conditions. The next subsection presents active design strategies that can be used in buildings in hot humid climates.

2.2.1.2 Active design strategies

Buildings in hot humid climates need to be integrated active strategies to satisfy most cooling demand when passive techniques are not sufficient. Active design strategies employ energy-based mechanical and technological means to provide solar shading, mechanical ventilation, air conditioning, and renewable energy generation. The details of these techniques are as follows.

Active solar shading techniques use movable shading devices which are controlled mechanically and automatically. Depending on sun positions, control systems adjust the positions and the tilts of shading devices to maximise shading ability.

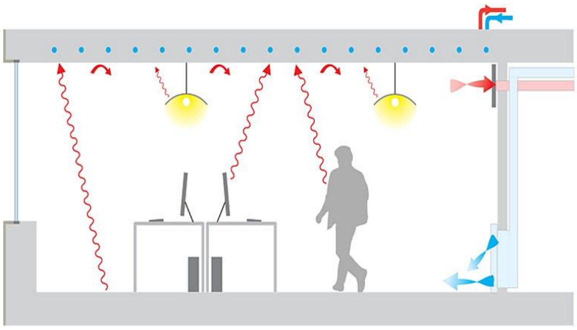
Active ventilation techniques include the use of electric fans and a duct system to supply fresh air into and exhaust stale air out of the buildings. This mechanical ventilation system helps to deliver desired air change rates in buildings that natural ventilation cannot provide. In addition, mechanical ventilation systems often include a filter component to remove pollutants from supply air. This is beneficial for buildings in polluted and high-density cities. In humid regions, outdoor air supply can increase indoor humidity that can be handled with separated dehumidifiers or a dehumidifying component integrated into the mechanical ventilation system. Moreover, hot outdoor air in hot humid climates causes indoor heat gains especially in summer, therefore, a mechanical ventilation system with energy recovery is necessary.

Another simple solution to improve the thermal condition is the use of electric fans (ceiling, wall-mounted and standing fans) to create air movement. This is the most common technique for cooling in residential buildings in warm climates. For example, a field study showed that 100% of households surveyed in a hot humid city in Vietnam used electric fans for cooling (V. T. Le & Pitts, 2019). However, in severe weather conditions, air conditioning is needed.

Air conditioning techniques include conventional and non-conventional techniques. Conventional air conditioning techniques are the use of window, split, packaged, or central air conditioners. Non-conventional air conditioning techniques including radiant slab cooling and evaporative cooling (Attia, 2012; Szokolay, 2008). Note that the components and operations of these systems are not necessarily described in this thesis.

Conventional window or split air conditioners are used for single rooms with small air conditioning capacities. Therefore, they are widely used in residential buildings. Due to the aesthetic design and the convenient installation, split air conditioners are the most popular in houses today. Packaged and central air conditioners have higher cooling capacities so that they are often used in big buildings such as restaurants, offices, and apartment buildings.

Radiant cooling is a non-conventional HVAC technology that cool the spaces by both convective and radiative means. The most common type is the radiant slab cooling system which deliver cooling to the conditioned spaces through building concrete slabs (Figure 2.10). High thermal mass concrete slabs support to maintain a stable thermal condition with less energy consumption. A research of the Lawrence Berkeley National Laboratory showed that radiant cooling systems in the US save a considerable amount of 30% of energy consumption compared to conventional air conditioning systems. Those values for cool, humid climates and hot, arid climates are 17% and 42% respectively (Stetiu, 1999). The application of radiant cooling in hot humid climates needs to be associated with a dehumidifier to prevent condensation on the cool slabs. Moreover, outdoor air infiltration and operable windows are necessarily controlled. Another concern about this technology is the high first cost. Therefore, it is relatively complicated to employ radiant slab cooling techniques in residential buildings.

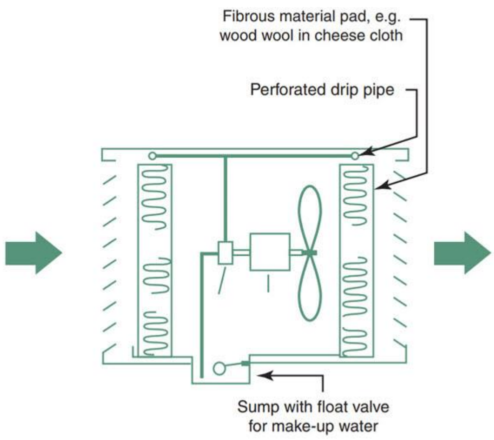


(Source: en.wikipedia.org)

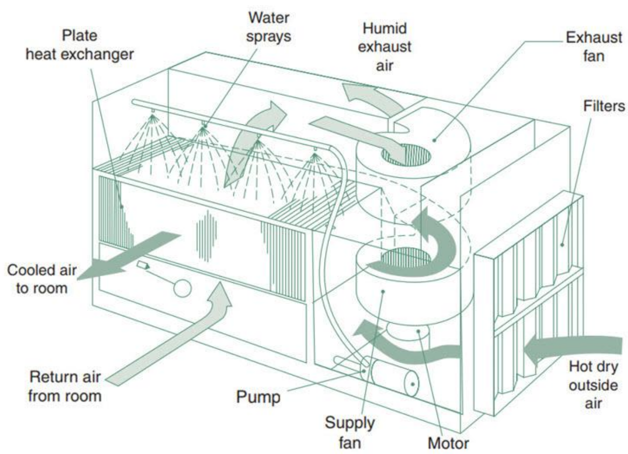
(Source: lemoniteur.fr)

Figure 2.10: Radiant slab cooling technique

Active evaporative cooling techniques have the same operating principle as passive evaporative cooling techniques where sensible heat from the air is converted into latent heat through evaporation process. However, the active techniques include the use of pumps, fans, and/or other electric components to enhance cooling effectiveness. The simple systems are fogging systems, direct and indirect evaporative coolers. The indirect systems include a heat exchanger to avoid the increase of moisture in supply air caused by evaporative process (Figure 2.11). Consequently, indirect evaporative cooling technique is suitable for hot humid climates. More sophisticated systems may include a desiccant wheel to remove humidity (Szokolay, 2008).



Direct evaporative cooler
(Source: Szokolay, 2008)



Indirect evaporative cooler
(Source: Szokolay, 2008)

Figure 2.11: Principles of direct and indirect evaporative coolers

Renewable energy production: The development of technologies allows the production of clean energy in individual buildings from exploiting renewable energy sources including solar radiation, natural wind and biomass (Attia, 2012). The energy from on-site production can partly or fully satisfy the energy demand of buildings or even be fed back into the grid. This helps to reduce the use of fossil energy and CO_2 emissions in buildings. Therefore, alongside energy-efficient building designs, on-site renewable energy production is of great importance to the environment.

The most common method of renewable energy production in individual buildings is the use of photovoltaics. Photovoltaic systems directly convert solar radiation into electricity. Photovoltaic panels are commonly integrated into the roofs of buildings. Some advanced technologies allow the installation of photovoltaic cells or films on building façades even on glazing areas. Another common method to generate energy from the solar source in buildings is the use of solar water heating systems. This technique significantly reduces the consumption of conventional energy (electricity, gas) for domestic hot water demand. Solar energy is also exploited to reduce energy consumption for air conditioning by using solar-assisted cooling systems. On-site solar energy production is beneficial in hot humid climates due to the great potential of solar radiation and the roughly identical phases of cooling load and solar energy availability.

Energy production from wind turbines is efficient in large scales. The application of wind turbines in individual buildings has some disadvantages including low effectiveness, building height restriction, structural problem, noise, and aesthetic issue (Kwok & Grondzik, 2007). Therefore, Wind energy production is not a appropriate technique for residential buildings.

Biomass is another source of renewable energy. Combusting biomass materials is the most common way to generate energy and widely used in rural areas. More sophisticated methods consist of gasification, pyrolysis, and anaerobic digestion (U.S. Department of Energy, 2016). The advantage of energy generation from biomass is the availability of these materials when needed, however, biomass materials are not free and need to be collected and stored. Furthermore, combusting biomass materials releases emissions that have to be strictly controlled. Therefore, energy generation from biomass source in urban buildings is limited.

Artificial lighting systems and appliances: Another active solution for low energy buildings is the use of energy-efficient artificial lighting systems and appliances to reduce internal heat gains and energy consumption.

In summary, passive and active design strategies for low energy buildings in hot humid climates are summarised in Table 2.10. In 20^{th} century, thermal comfort in buildings was mainly relied on mechanical systems run by fossil fuels or electricity (Nicol et al., 2012). Due to the depletion and expensiveness of these energy sources along with the increasing severity of the climate, building design today requires a more sustainable approach. A potential approach is the combination of traditional passive strategies and technological active strategies in building design and operation. While passive design strategies significantly reduce cooling demand, energy-efficient active techniques maintain thermal comfort and make the thermal performance of buildings more controllable. Consequently, this combination helps the buildings to consume less energy than the use of sole conventional active systems. Examples of low energy buildings employing both passive and active design strategies are presented in the next subsection.

Table 2.10: Passive and active design strategies for low energy buildings in hot humid climates

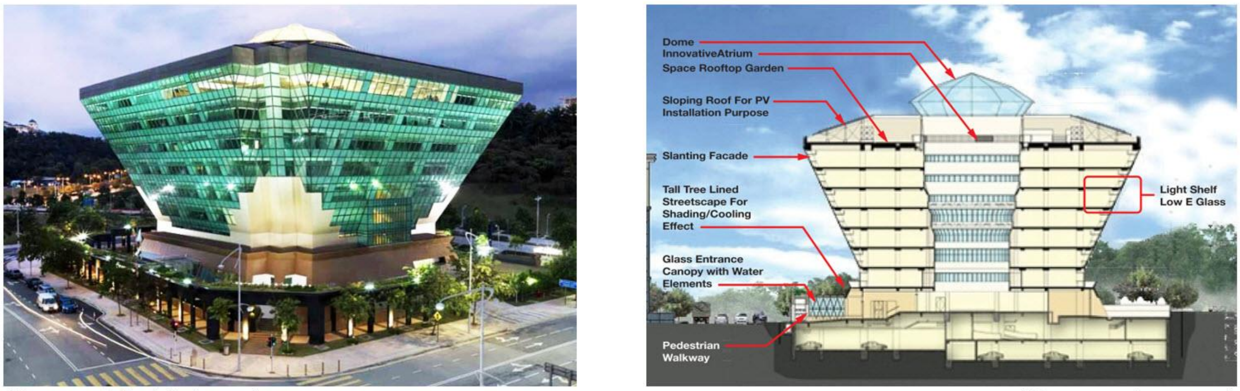
Low energy design strategies	
Passive strategies	Active strategies
Solar control: - Orientation, building form - Solar shading (shading devices, landscape) - Window to wall ratio, low SHGC glazing - Light colour external finishes **Thermal control**: - Insulated envelope - Green roof - Low thermal transmittance window - Thermal mass **Thermal zoning**: Spatial layout **Passive cooling**: - Natural ventilation - Night ventilation - Radiative cooing - Evaporative cooling (indirect) - Ground cooling **Natural lighting**	**Active shading:** Movable shading devices (automatically controlled) **Active ventilation**: - Mechanical ventilation systems - Electric fans **Air conditioning**: - Conventional AC systems (window, split, packaged, central) - Radiant slab cooling (with dehumidification) - Evaporative cooling (indirect cooler) **Renewable energy production**: - Solar: thermal and electrical energy - Wind - Biomass **Energy-efficient artificial lighting systems and appliances**

2.2.1.3 Examples of low energy buildings

Low energy design strategies for hot humid climates including both passive and active techniques can be recognised in successful low energy buildings such as the Diamond Building in Malaysia and the ZCB (Zero Carbon Building) in Hong Kong.

The Diamond office building in Putrajaya, Malaysia (completed in 2010) adopts both passive and active strategies to achieve the low energy consumption target. The passive techniques include building orientation, tilting facades, low-e glazing, and insulated concrete roof to avoid intensive solar radiance. A large atrium was designed for ventilation and daylighting which provide 50% of the lighting demand. The active techniques include automatic internal shading, rooftop solar panels (covers 10% of the energy need), radiant slab cooling, and artificial lighting with daylight sensors. These design strategies help the Diamond Building to achieve the building energy index of 85 kWh/m^2/a. The energy savings compared to typical office buildings and the

Malaysia energy standard MS1525 are 65% and 37% respectively (The Energy Commission, n.d.).



(Source: inhabitat.com) (Source: st.gov.my)

Figure 2.12: The Diamond Building in Malaysia (2010)

The ZCB Hong Kong (completed in 2012) is a multi-function building including exhibition, education, office and leisure spaces. The adoption of more than 80 climate-responsive design strategies and state-of-the-art technologies makes this building the first zero carbon building in Hong Kong. Firstly, various passive design techniques were used in this building including building form and orientation, solar shading, thermal insulation, high performance window, window positioning, natural ventilation, and natural lighting. These solutions help to save 20% energy consumption of the building. Secondly, the energy-efficient active techniques including radiant slab cooling, ventilation fans, dehumidification system, active skylights contribute to 25% energy saving. Finally, the on-site electricity generation systems using photovoltaic panels and waste cooling oil produce respectively 60% and 110% of the energy demand (G. Li, 2013).

(Source: archdaily.com) (Source: archdaily.com)

Figure 2.13: The ZCB in Hong Kong (2012)

The above examples indicate the great potential of energy saving in buildings using passive designs and low-energy active techniques. In the circumstance of ongoing climate change and fossil fuel depletion, low energy architecture becomes an inevitable trend. To guide and evaluate the practices of low energy buildings, a number of standards and benchmarks have been enacted around the world. The next section discusses these standards with a focus on hot humid climates.

2.2.2 Low energy building standards for warm climates

Towards the sustainable development in the built environment, many countries in the world have released their own standards, codes and rating systems for energy-efficient and green buildings. Some of them have been widely used and be considered as international standards. The notable existing international standards, codes and rating systems are as follows:

- The Leadership in Energy and Environmental Design (LEED) rating system developed by the U.S. Green Building Council (USGBC)
- The Building Research Establishment Environmental Method Assessment (BREEAM) developed in the UK by the Building Research Establishment
- ASHRAE Standard 189.1-2017 Standard for the design of high-performance green buildings
- ASHRAE Standard 90.2-2018 Energy-efficient design of low-rise residential buildings
- International Energy Conservation Code 2018 (IECC) of the International Code Council
- Passive House (Passivhaus) standard of the Passive House Institute

LEED and BREEAM are the most well-known green building rating systems. According to 2016 statistics of USGBC, there are nearly 80,000 LEED-certified projects in 162 nations (USGBC, 2016a). BREEAM has been applied in 88 nations with more than 592,000 certificates and 2,312,000 registered buildings (BREEAM, 2020). LEED rating system covers a significant number of building aspects including Integrative Process, Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, Innovation, and Regional Priority. BREEAM building topics include Management, Health and Wellbeing, Energy, Transport, Water, Waste, Land Use and Ecology, Pollution, and Innovation (optional). The topic weightings of these rating systems are shown in Figure 2.14. LEED-certified buildings are classified into 4 categories (Certified, Silver, Gold and Platinum) depending on their total number of credits whilst the BREEAM rating scale includes 6 categories: Unclassified, Pass, Good, Very Good, Excellent, and Outstanding.

It is noted that the above rating systems contain few performance and prescriptive requirements for green building practice that must be referred to other building codes and standards. For instance, regarding energy performance which is the focused topic in this work, the LEED performance path of annual energy consumption is based on the ENERGY STAR National Programme Requirements and the HERS Index (Home Energy Rating System). Meanwhile, the prescriptive path of building envelope components is based on the International Energy Conservation Code. Alongside the International Energy Conservation Code, ASHRAE Standard 189.1-2017 and ASHRAE Standard 90.2-2018 are also developed in code model, therefore, they provide minimum/maximum mandatory requirements for building components. For example, maximum solar heat gain coefficient (SHGC) and thermal transmittance (U-value) for walls, roof, floor, and fenestration of buildings in hot humid climates are presented in Table 2.11. These standards and codes are the necessary supplements to the voluntary rating systems.

Table 2.11: Prescriptive requirements of dwelling envelope components in hot humid climates

Standard, Code	Maximum U-factors (W/m^2K)							Maximum SHGC
	Frame walls	Mass walls	Basement walls	Ceilings	Floors	Skylights	Fenestration	Glazed Fenestration
ASHRAE 90.2-2018	0.47	1.12	2.04	0.2	0.36	4.26	6.82	0.3
IECC 2018	0.47	1.12	2.04	0.2	0.36	4.26	2.84	0.25

IECC: International Energy Conservation Code;
SHGC: Solar heat gain coefficient; U-factor: thermal transmittance

Compared to other standards and building rating systems, the Passive House standard much more focusses on energy and thermal performance of buildings, therefore, it is suitable for low energy building design. The criteria include maximum total primary energy demand (or renewable primary energy), heating and cooling load, air tightness, and frequency of overheating. This standard is described in more detail in Section 2.3.

In addition to international standards and rating systems, a significant number of national energy-efficient building standards and green building benchmarks have been developed in hot humid countries around the world. In Southeast Asia, the Green Mark of Singapore is the most influential rating system alongside the Green Building Index (GBI) of Malaysia, the GREENSHIP of Indonesia, the Thai's Rating of Energy and Environmental Sustainability (TREES) of Thailand. The category weightings of the two notable benchmarks, Green Mark and Green Building Index, are shown in Figure 2.14.

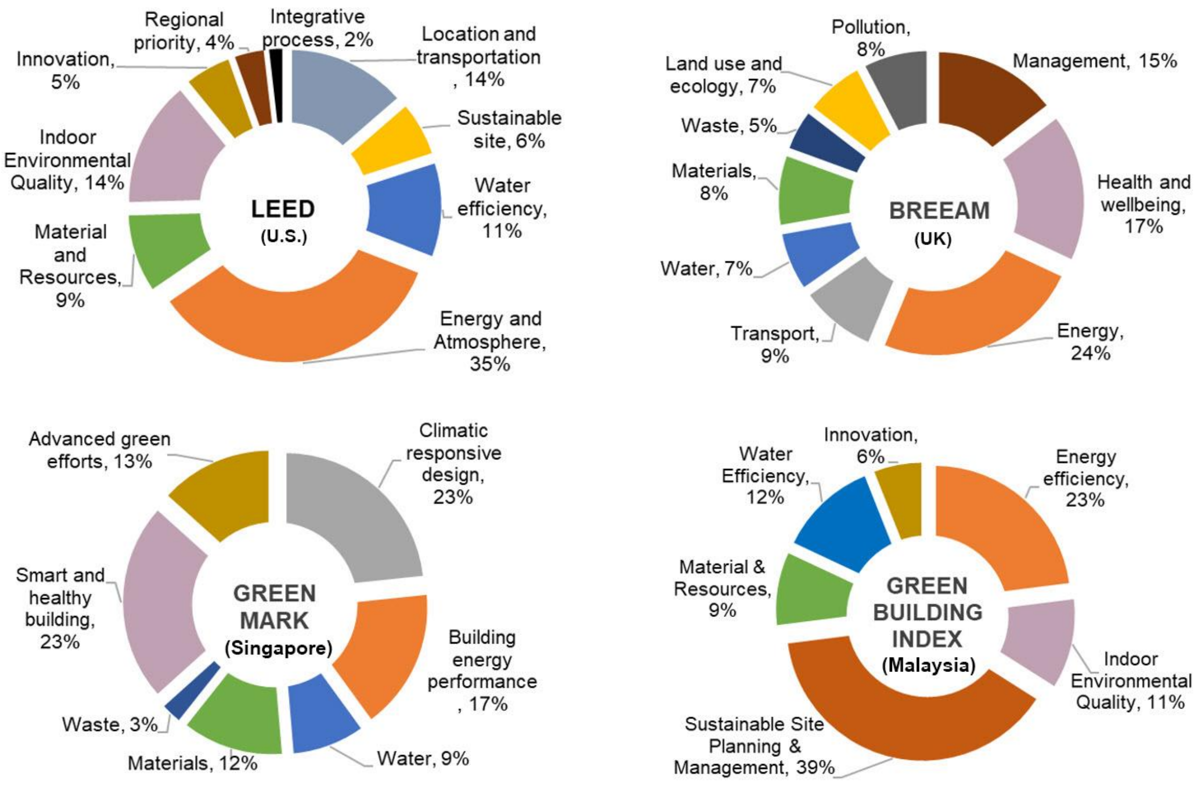


Figure 2.14: Category weightings of 4 green building rating systems

These building rating systems are based on international standards and national building codes and regulations. In terms of energy and envelope thermal performance in residential buildings, the Green Mark is based on the Code on Envelope Thermal Performance for Buildings which indicates prerequisite requirements for the Residential Envelope Transmittance Value (RETV) and the U-values for roof types. Green Mark is the only rating system including the climatic-responsive design section. The Green Building Index of Malaysia is based on the Code of Practice - Energy Efficiency and Use of Renewable Energy for Residential Buildings (MS 2680-2017) which define maximum numbers of the Overall Thermal Transfer Value (OTTV), the Roof Thermal Transfer Value (RTTV) and the roof U-values. The TREES of Thailand evaluates energy use in buildings based on the ASHRAE Standard 90.1 and the Thai Ministerial Regulation for Energy Saving Building Design B.E. 2552 (2009). Moreover, the maximum OTTV and RTTV are also defined. However, the regulation B.E. 2552 (2009) is only applied for the buildings with more than 2000 square metre of floor area. The prescriptive requirements mentioned above are listed in Table 2.12.

Table 2.12: Prerequisite requirements of building envelope in GM, GBI, and TREES rating systems

Green Mark (GM) (Singapore)	Green Building Index (GBI) (Malaysia)	TREES (Thailand)
RETV ≤ 25 W/m^2	OTTV ≤ 50 W/m^2	OTTV (W/m^2): Office, education: ≤ 50 Commercial buildings: ≤ 40 Hotel, condominium: ≤ 30
Roof U-value (W/m^{2}K): Light: ≤ 0.8 Medium: ≤ 1.1 Heavy: ≤ 1.5	RTTV ≤ 25 W/m^2 Roof U-value (W/m^{2}K): Light: ≤ 0.4 Heavy: ≤ 0.6	RTTV (W/m^2): Office, education: ≤ 15 Commercial buildings: ≤ 12 Hotel, condominium: ≤ 10

RETV: Residential Envelope Transmittance Value
OTTV: Overall Thermal Transfer Value; RTTV: Roof Thermal Transfer Value

Apart from standards for energy performance and building envelope, there are also standards for energy-efficient equipment rather than the standards for the building itself. Such product standards are not the focus of this study; therefore, they are not presented in the thesis.

A review on low energy building standards, codes and rating systems in hot humid climates leads to following conclusions:

Firstly, existing rating systems cover diverse topics of green buildings, hence, there may be some difficulties in applying these benchmarks to developing countries where economic, technological and informative barriers exist. Therefore, a simpler building assessment method may be necessary. It would be a potential opportunity to focus on the energy efficiency category since it accounts for the largest proportion of the total points of common rating systems. For instance, these weightings are 24%, 35%, and 40% for BREEAM, LEED, and Green Mark system (including climate-responsive design) respectively. Consequently, the Passive House standard would be an appropriate standard.

Secondly, evaluation methods vary among the standards and rating systems. They cover different building topics with different weightings and may evaluate annual energy use (performance method) or building component properties (prescriptive method). Moreover, the criteria are also differ. For example, maximum U-value of heavyweight roof in Singapore Green Mark is 1.5 W/m^2K whilst that of Malaysia Green Building Index is only 0.6 W/m^2K.

According to the above conclusions, the application of existing international energy efficiency standards, rating systems and those of neighbouring countries to the context of developing Vietnam could be difficult and inappropriate. Therefore, Vietnam needs its suitable low energy building standards and assessment methods. To fulfil this requirement, the understanding of Vietnam climate, cultural context and the sustainably architectural development is necessary. The next subsection covers these aspects and provides a summary of the existing standards and studies on low energy buildings in Vietnam.

2.2.3 Studies and practices of low energy buildings in Vietnam

2.2.3.1 Lessons from traditional architecture

Vietnamese traditional architecture contains valuable lessons from the ancestors in dealing with nature and climate. These are important theoretical and practical foundations for the research and development of Vietnamese sustainable architecture in general and low energy building in particular. In the past, building design adapting to the environment is the only choice since the technological development at that time did not allow people to control their living environment as they can do now. Throughout the centuries, people have created living spaces accumulating in which the experiences passed on. Traditional buildings using local construction materials and techniques were built to well adapt to the surrounding environment and to the lifestyle and culture of local residents. These buildings are considered as independent ecological units, do not consume much resources, nor create pressure on the environment. Thus, traditional architecture is the combination and synthesis of local materials and construction techniques, climate and socio-cultural characteristics (T. Q. Nguyen & Ho, 2017). Below are common climate-responsive design strategies of Vietnamese traditional architecture summarised from the studies of N. D. Pham, Nguyen, & Tran (1998), Hoang (2005), Khuat (2007),(T. A. Nguyen, Tran, Tran, & Reiter, 2011), T. Q. Nguyen & Ho (2017).

In terms of building orientation and spatial layout, most of buildings are orientated to the South or Southeast to avoid solar radiation from the East and West, and to catch the prevailing cool wind direction. Opening are limited on North façades to avoid cold wind. Buildings are always associated with trees and water areas to improve the microclimate (Figure 2.15). The porch is an indispensable part of traditional buildings in hot humid Vietnam. It acts as a transition space between inside and outside spaces. The porch is often combined with movable woven bamboo panels to prevent rain and sunrays (Figure 2.16). Traditional shophouses in Hanoi and Hoi An Old Quarters use courtyards to enhance natural ventilation and daylighting (Figure 2.17). With a semi-opened architectural style in harmony with trees and nature, traditional buildings in Vietnam can maintain cool spaces without the appearance of mechanical cooling equipment.

Traditional roof systems adapt to the hot humid climate of Vietnam by using high slope and deep eaves, and often covering porches. These designs help to shield the building from sunlight and rain, and to drain rainwater quickly. Roof systems of traditional houses are often covered with thick layers of straw to prevent heat. In some areas in the Central region, double-layered roofs (e.g., thatch roof above and clay mixture-bamboo frame roof below) are used for better thermal insulation. Thick yin-yang tile roofs also provide good heat flow control. In buildings with large roof areas, the roof is often designed in the form of multiple levels (clerestory roofs) to avoid a very large roof and to enhance natural ventilation (Figure 2.17).

Traditional walls often made of wooden frames, clay mixed with straw, or thick rustic brick have a good thermal insulation effect. ‘Trinh Tuong’ houses of some ethnic minorities have 50-60cm thickness compressed-soil walls (ramped earth wall) which well prevent thermal conductance (Figure 2.18). The use of very thick brick walls for insulation is also observed in later French buildings.

Regarding ventilation and cooling techniques, natural ventilation is the key solution to deal with hot humid conditions in traditional architecture. Large openings are orientated to the main cool wind direction (South, Southeast). ‘Lattice above - panel below’ doors and shutter windows are used to allow wind to pass through and block solar radiation (Figure 2.19). Stack ventilation is enhanced by the use of multi-level roofs (clerestory roofs) and gable vents.

The above design techniques, which were derived from the long-term adaptation to the local climate, help to improve thermal comfort condition in Vietnamese traditional buildings where mechanical ventilation and active cooling techniques were not available. Therefore, traditional architecture could be considered as a primitive form of green architecture which embraces design strategies for the sustainable development (C. V. Nguyen, 2013).

Thai Hoa Palace
(Source: vntrip.vn)

An Hien vernacular house, Hue city
(Source: vnexpress.net)

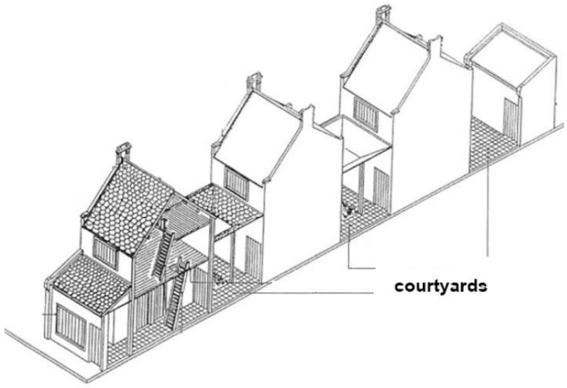
Figure 2.15: Harmony between traditional architecture and the environment

(Source: kienviet.net)

(Source: tapchikientruc.com.vn)

Figure 2.16: Wide porch with woven bamboo panels

Clerestory roofs of Tay Phuong pagoda
(Source: bmktcn.com)



Courtyards in a vernacular shophouse
(Source: tapchikientruc.com.vn)

Figure 2.17: Clerestory roof and courtyards in traditional architecture

A 'Trinh tuong' house
(Source: vnexpress.net)

Wall-making technique
(Source: tapchikientruc.com.vn)

Figure 2.18: 'Trinh tuong' house of minority ethnic groups

Shutter windows and doors in a Hoi An house
(Source: dulich24.com.vn)

'Lattice above – Panel below' door type
(Source: tapchikientruc.com.vn)

Figure 2.19: Shutter windows and 'lattice above-panel below' doors

In the 1960s and 1970s, the Modern architecture movement strongly influenced Vietnamese architecture. However, in addition to adopting the internationally Modern style, a Modern architectural trend suitable for the climate and indigenous culture of Vietnam was initiated. This architectural trend exploits traditional passive design solutions combined with new construction materials and techniques such as concrete and glass. Major solutions include designing insulated walls and roofs; increasing surface reflectivity; designing solar shading devices for windows; using wide corridors, deep eaves; employing natural ventilation; arranging ponds and trees around the building and even bring greenery to walls and roofs. These passive design solutions take advantage of favourably natural conditions to maintain thermal comfort for indoor spaces with a minimum use of mechanical cooling equipment (D. N. Pham & Pham, 2015). The most successful buildings include the Independence Palace, the General Sciences Library of Ho Chi Minh city (Figure 2.20).

Independence Palace (1966)
(Source: khamphadisan.com.vn)

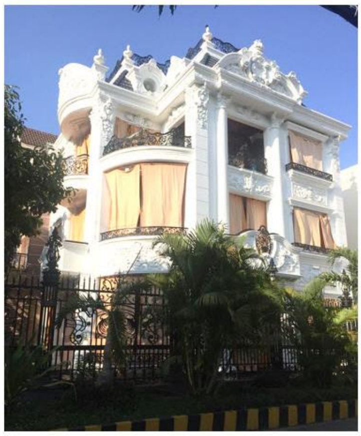
General Sciences Library (1972)
(Source: thuvientphcm.gov.vn)

Figure 2.20: The Independence Palace and the General Sciences Library of Ho Chi Minh city

Vietnamese traditional architecture contains valuable experiences in building designs for tropics that can be applied to modern architecture. This is evidenced by the success of the trend combining Modern and traditional architecture of the 1960s and 1970s. However, along with the economic and technological development, especially in the field of air conditioning, Vietnamese architecture for a long time did not reflect the local climatic characteristics and depended on mechanical equipment to maintain thermal comfort. The identical architectural styles found across the country blurred the identities of localities and regions.

Danang Administration Centre
(Source: baogialai.com.vn)

Modern shophouses
(Source: thuenhagiare.vn)



A new 'old-style' villa
(Source: Nguyen Thanh Tuan)

Figure 2.21: Examples of modern buildings regardless of the climate

Binh Thanh house
(Source: ashui.com)

Stacking green house
(Source: archdaily.com)

Figure 2.22: New terraced houses successful with passive design solutions

Today, when sustainable architecture has gradually become an inevitable trend in the world, Vietnamese architecture has made its first steps on the road towards sustainability. Some projects have been successful with the development of traditional architecture (Figure 2.22). However, the majority of buildings still focus on the appearance without adequate attention to local climatic conditions, leading to significant amounts of energy consumed (Figure 2.21). Therefore, it is essential to orientate architectural practice towards energy efficiency. This requires in-depth studies on low energy buildings to be able to enact regulations, standards and guidelines for Vietnamese conditions. The representative studies on low energy buildings in Vietnam are summarised in the next sub-section.

2.2.3.2 Low energy building studies in Vietnam

In Vietnam, it is observed that most research on low energy buildings has focussed on free running buildings through the bioclimatic approach. Building physics has been studied in Vietnam from 1960s by the Department of Building Physics, National University of Civil Engineering (D. N. Pham & Pham, 2002). The pioneering experts including Pham Ngoc Dang, Pham Duc Nguyen, Hoang Huy Thang, Nguyen Ngoc Gia,and Nguyen Van Muon based their work on bioclimatic charts to analyse the climate of Vietnam and to propose corresponding design strategies to achieve energy efficiency and thermal comfort in buildings. These proposed general strategies could be listed as: the harmony of building and nature, building orientation, external shading, opened and semi-opened spaces, external wall structure with multi layers and heat reflecting materials (D. N. Pham & Pham, 2002; N. D. Pham, 2002; N. D. Pham et al., 1998). However, quantitative assessments in terms of the energy efficiency of these design solutions were not conducted by the aforementioned studies due to the lack of support from computer-simulation tools at that time.

T. A. Nguyen (2013) re-examined the climate-responsive design principles for Vietnam by using a stronger, more reliable and more comprehensive approach. Using various modern techniques (numerical model calibration, parametric simulation and optimisation methods), he proposed optimal climate-responsive design strategies for housing in three main climatic regions of Vietnam. He pointed out that in Vietnam, naturally ventilated housing can achieve thermal comfort year-round without using mechanical cooling systems. However, the high humidity element in hot humid Vietnam was not paid sufficient attention in the research. He proposed night ventilation technique in the final design guides for dwellings in Vietnam which is not suitable for hot humid climates (Attia, 2012; Riley et al., 2018; Santamouris & Asimakopolou, 1996). For example, in Hanoi capital city, 46% of total hours per year see the relative humidity exceeds 90%, which causes mould growth and negative impacts on thermal sensation and health of occupants (N. D. Pham, 2017a).

Although cooling by natural ventilation can significantly reduce energy consumption in buildings, this strategy may be ineffective in some cases. It is obvious that natural wind flow is an uncontrollable factor. Wind always changes direction and speed. Moreover, the frequency of calm wind is relatively high (from 10-40%) and also strong winds can cause discomfort (N. D. Pham, 2017a). Spatial layout to achieve effective cross ventilation is difficult, especially in big buildings with large floor areas. Note that wind speeds from meteorological stations are measured at the height of 10m and with no obstructions around. Such a condition is completely different from that of low-rise residential buildings in urban areas, which leads to a difference between the simulated result of natural ventilation and actual measured data in the building. Furthermore, other environmental variables including air pollution, noise, and the urban heat island effect are also considerable disadvantages of natural ventilation strategy. Therefore, in order to achieve the desired ventilation effect, N. D. Pham (2017a) proposed a controllable natural-ventilation solution using a simple ventilation system which includes supply fans, exhaust fans, and ducts. This mechanical ventilation solution is not new for large projects but has not been applied to low-rise residential buildings in Vietnam. Therefore, the effectiveness of this solution for housing needs to be studied further.

Pham also proposed two approaches to energy-efficient building design: closed-space buildings using air conditioning (e.g., offices, hotels) and open-space buildings using natural ventilation (e.g., school, housing). Each of these approaches is closely related to solutions for building form, spatial layout, building envelope's structure and corresponding materials (N. D. Pham, 2016). In general, naturally ventilated housing is a suitable approach for Vietnam's climate. However, due to the above-mentioned disadvantages of the conventional natural ventilation approach, it is necessary to research and apply the closed-space design approach to housing as an alternative solution.

In recent years, the interest in Green architecture has been increasing in Vietnam. Alongside a number of studies on Green architecture of individual researchers (T. T. B. Le & Nguyen, 2015; N. D. Pham, 2017b), the Vietnam Green Building Council (VGBC), established in 2007, has researched and enacted the LOTUS, the first Green building rating system for Vietnam, in 2010. In another effort, the Vietnam Association of Architects issued "Criteria for Vietnamese green architecture" in 2014. These Green building rating system and criteria are described in the next subsection alongside the existing building energy codes of Vietnam.

2.2.3.3 Low energy building standards in Vietnam

Vietnam has two existing standards directly relating to low energy building design: TCVN 9258:2012 "Heat protection for residential buildings – Design guide" (VIAP, 2012a) and QCVN 09:2013/BXD "National technical regulation on energy efficiency buildings" (VACEE, 2013).

TCVN 9258:2012 is a voluntary standard providing guidance for overheating prevention and cooling in dwellings. The design guidelines include techniques for solar shading (shading devices and greenery), thermal insulation, and natural ventilation. However, the standard only introduced the principles of these techniques without any prescriptive requirement.

QCVN 09:2013/BXD is a mandatory code for low energy building design. This code specifies prescriptive requirements for energy-efficient building envelope and building equipment including ventilation and air conditioning, artificial lighting, hot water system and other appliances. For example, the maximum U-value of walls is 1.8 W/m^{2}K. Those of flat roofs and slope roofs are 1 and 1.18 W/m^{2}K respectively. The maximum OTTV of walls and roofs are 60 and 25 W/m^2 respectively. These requirements have similarities and differences compared to those of other Southeast Asia countries' standards shown in Table 2.12. The SHGC and VLT values (visible light transmittance) of glazing depends on the window-to-wall ratio and the orientation (Table 2.13). Note that the building code QCVN 09:2013/BXD is only applied for buildings with the total floor area larger than 2,500 m^2. Although this code is not mandatory for low-rise residential buildings, some elements are also recommended to be used in this building type. Nevertheless, energy efficiency building codes or standards dedicated for dwellings are necessary.

Table 2.13: Specifications of SHGC depending on WWR (VACEE, 2013)

WWR (%)	Maximum SHGC in 8 orientations				Minimum VLT
	North	East, West	NE, NW, SE, SW	South	
20	0.9	0.8	0.86	0.9	0.7
30	0.64	0.58	0.63	0.7	0.7
40	0.5	0.46	0.49	0.56	0.6
50	0.4	0.38	0.4	0.45	0.55
60	0.33	0.32	0.34	0.39	0.5
70	0.27	0.27	0.29	0.33	0.45
80	0.23	0.23	0.25	0.28	0.4
90	0.2	0.2	0.21	0.25	0.35
100	0.17	0.18	0.19	0.22	0.3

SHGC: solar heat gain coefficient; WWR: window-to-wall ratio; VLT: visible light transmittance

These above standards are the minimum legal bases that are used for designing energy-efficient buildings and used as a basis for the assessment and certification of green buildings in Vietnam. In 2010, the Vietnam Green Building Council released the pilot version of LOTUS, the first Green building rating system for Vietnam. The current version is LOTUS NC V3 enacted in 2019. The LOTUS rating system include 6 assessment tools for 6 categories, namely new construction buildings with total floor area from 2,500 m^2 and above, small non-housing buildings with total floor area less than 2,500 m^2, existing buildings, homes, interior and small interior projects. The LOTUS is a harmonious combination between the international green building rating systems and the Vietnamese standards (VGBC, n.d.). Figure 2.23 shows the LOTUS Homes categories with the corresponding weightings (VGBC, 2017).

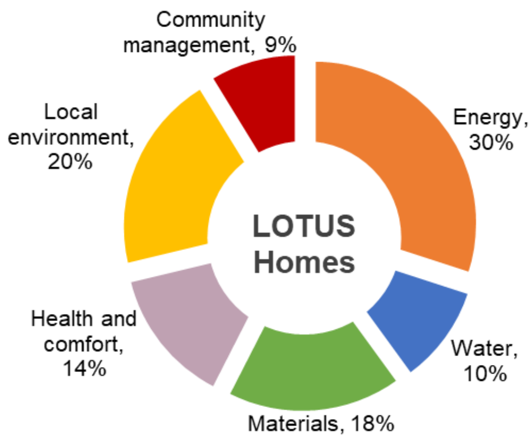


Figure 2.23: Category weightings of the LOTUS Homes

Regarding the energy category, LOTUS V1 Homes technical manual (2017) specifies prescriptive requirements for building orientation, walls and roofs, window-to-wall ratio, solar shading, glazing types. U-values of building envelope components are not specified but detailed requirements of materials are provided. For example, external walls may include one of following materials: autoclaved aerated concrete (AAC) blocks, lightweight hollow blocks, 40mm insulation layer, or equivalent (VGBC, 2017). This type of requirements facilitates the application of the LOTUS Homes in practice. However, so far only 31 green buildings in all types of LOTUS system were certificated and 39 buildings are in progress (VGBC, n.d.).

Green One UN house (LOTUS platinum)
(Source: vgbc.vn)

Sky house (LOTUS Homes Silver)
(Source: kienviet.net)

Figure 2.24: Examples of LOTUS certified buildings

In another effort, the Vietnam Association of Architects issued the "Criteria for Vietnamese Green Architecture" in 2014 to promote the development of sustainable architecture that is suitable for the environment and culture of Vietnam. The 5 criteria include sustainable location; resources and energy efficiency; indoor environmental quality; advanced architecture with Vietnamese identities; sustainably social and humanistic characteristics. These criteria are qualitative since they do not contain any prescriptive requirement. Therefore, the titles of 'Green Building' are recognised via the Green Architecture Competition organised by the Vietnam Association of Architects according to the criteria set out.

It can be observed that both the LOTUS rating system and the Criteria for Vietnamese Green Architecture have not yet been applied widely. It could be due to various barriers in this developing country. The first one is a financial issue since green buildings currently require higher first cost whilst the supports from the Government are insufficient. The second barrier relates to the production technology and supply of green construction materials. The third barrier is the lack of green building knowledge and sustainable behaviours of stakeholders including building owners and designers. Therefore, training and education on sustainable architecture are essential. The LOTUS is similar to other green building rating systems in terms of the diverse categories that could be another difficulty for its application in developing Vietnam.

A questionnaire survey conducted by the author in 2019 showed that 45% of the total of 71 surveyed professionals in building design were unsatisfied with the existing energy efficiency standards of Vietnam (Figure 2.25). 100% of the surveyed people think that an energy efficiency design guidance for Vietnamese housing is necessary (Figure 2.26).

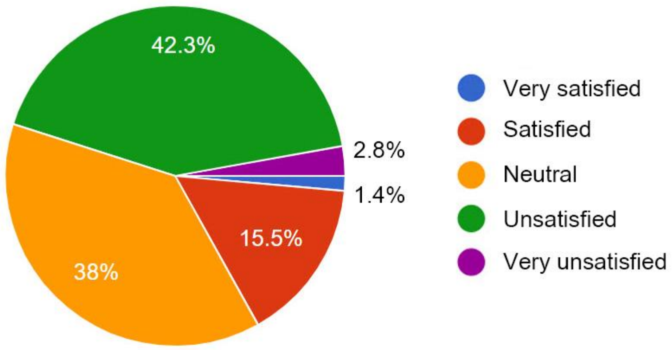


Figure 2.25: Satisfaction levels of people about current building energy standards of Vietnam

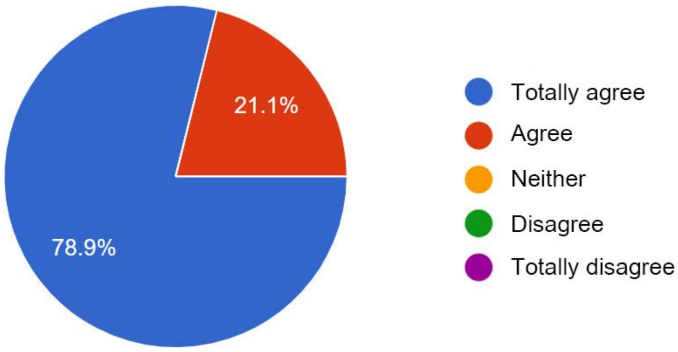


Figure 2.26: The necessity of an energy efficiency design guidance for Vietnamese housing

In summary, Vietnamese traditional architecture contains valuable lessons about climate-responsive design solutions that can be used in modern low energy buildings. Along with continuing to promote the values of traditional architectural heritage, it is essential to research and apply high-tech energy-efficient architecture, including the closed-building design approach. The diversification of architectural design methods enhances the ability to provide optimal design solutions for different situations, including for buildings in high-density urban areas and for extreme climatic conditions, especially in the ongoing climate change. However, studies on low energy housing in Vietnam so far has mainly focussed on passive solutions for open buildings using natural ventilation. It is, therefore, necessary to investigate alternative solutions for low energy housing in Vietnam.

The existing green building standards cover many fields of building design, including energy efficiency, water efficiency, materials, social community and so on. This requires significant efforts from the stakeholders, and it seems to be relatively complicated to apply, especially to single-family housing. Thus, there is a need to investigate a simpler approach for housing in Vietnam focussing on energy efficiency, the most important factor of sustainable architecture.

A technique much more focussing on low energy consumption in sealed buildings is the use of the Passive House standard (PHI, n.d.). This standard has rapidly developed throughout Europe and now is beginning to be used in a variety of climate types all over the world. Hence, Passive House could be a new potential approach for low energy housing in Vietnam and therefore needs to be examined through in-depth studies.

2.3 Passive House approach

A literature review on low energy design strategies showed that in hot and humid regions, maximising cooling airflows and minimising heat gain are the common principles. However, in the adverse cases mentioned above, particularly in extreme hot weather, the natural ventilation approach shows limitations. This leads to the excessive use of energy for mechanical systems in order to maintain thermal comfort for occupants. In an attempt to look for alternative solutions for Vietnamese housing, Passive House, a closed-building approach much more focusing on low energy consumption, was considered. This section firstly gives an overview on the development, principles, and benefits of the Passive House approach. Subsequently, studies and practical applications of Passive House in hot and hot humid climates are summarised.

2.3.1 History and development of the Passive House concept

The origin of Passive House can be traced back to centuries ago. After the timber crisis in Europe in the 17th century, Icelandic people built their turf-roofed houses with very thick turf walls for stability. These houses then revealed the high level of insulation, and reduction in firewood burnt for heating. In other regions in the world, for example in China, Portugal, traditional houses were also built with good insulating qualities, and these houses are the simple forms of Passive Houses (PHI, 2019b). The foundation of the Passive House concept was formally laid in the 1980s by Wolfgang Feist, a German who emerged as the father of the Passive House movement. In 1989, Dr Feist built the first Passive House project in Darmstadt, Germany. This pilot Passive House apartment block involving four dwellings showed an outstanding result. The annual heating energy saving was 90% compared to the German Building Code in 1995, while the building maintained stable thermal comfort and healthy living conditions year-round (Figure 2.27).

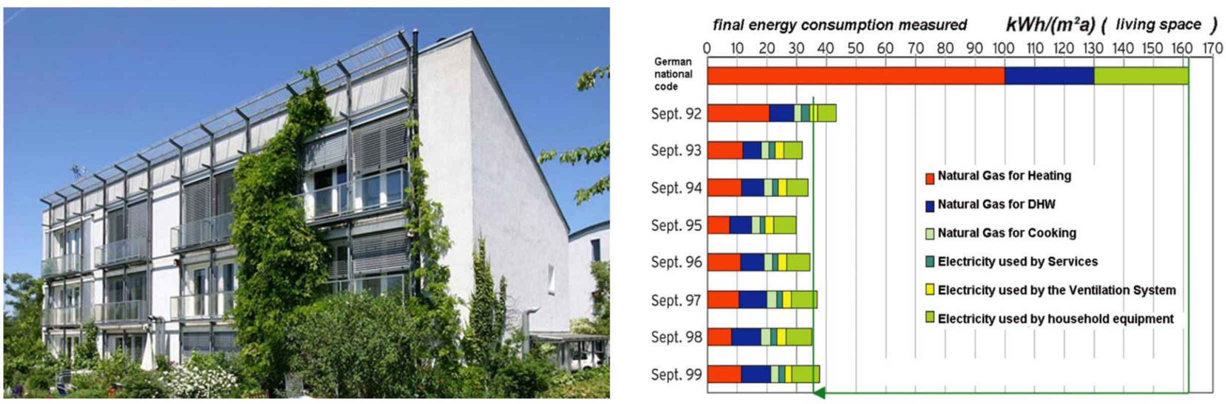


Figure 2.27: Energy efficiency of the first Passive House in the world (Darmstadt, Germany) (Source: passivehouse-international.org, passipedia.org)

To proceed from the success of the pilot project, Dr Feist established the Passive House Institute (PHI) in 1996 to research on Passive House. A design tool called the Passive House Planning Package (PHPP) was also developed and has been continually upgraded. This spreadsheet-based simulation tool includes necessary elements to design a Passive House building such as calculation tools of cooling/heating load and annual energy demand. In addition, another tool called designPH was developed to support the PHPP. DesignPH is a SketchUp plugin that is used to create building model and export building information into the PHPP tool.

Along with the development of the Passive House movement, many countries have established their own Passive House organisation such as the UK Passivhaus Trust, the Australian Passive House Association, the North American Passive House Network. They are part of the International Passive House Association (iPHA), which currently has 19 affiliates worldwide (iPHA, n.d.-a). It is noted that some countries retain the German name 'Passivhaus' such as the UK, Austria, and Portugal whilst the iPHA and other countries translate this name into English. In this study, the name 'Passive House' is chosen.

To promote research and practice of Passive House, an international conference is held annually by the Passive House Institute presenting numerous studies on Passive House around the world. Up to 2020, there were 24 international Passive House conferences that took place in different countries. With approximately 60,000 certificated Passive House buildings (2016 statistics) located in different climate zones, the Passive House standard is seen the fastest growing sustainable building standard in the world (PHI, 2018a).

2.3.2 Principles and benefits of Passive House

The Passive House Institute defined Passive House as follows: "*A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air*." (PHI, n.d.)

This definition aims to emphasise the outstanding advantage of Passive House buildings which is able to supply sufficient fresh air for occupants with a small amount of energy use. Conventional air conditioners with the recirculation of air seem to be obsolete and are not used alone in Passive House buildings. A Passive House building has to meet strict criteria of energy consumption and indoor comfort as shown in Table 2.14 (iPHA, n.d.-b).

Originating from a standard for buildings in the temperate climate of Centre Europe, the Passive House standard has been upgraded to be applied for all different climates in the world. The new classification of Passive Houses as Classic, Plus or Premium was introduced in 2015, which is based on renewable energy demand and generation as an alternative for primary energy demand. This reflects the development of Passive House in terms of renewable energy towards a leading sustainable building standard. It is a fact that satisfying such a strict standard is not easy due to various reasons. The Passive House Institute, therefore, released the PHI Low

Energy Building Standard for buildings that cannot meet the high requirements of the Passive House Standard.

Table 2.14: Passive House certification criteria

(Source: www.passivehouse-international.org)

Space heating demand	Not to exceed 15kWh annually OR 10W (peak demand) per square metre of usable living space
Space cooling demand	Roughly matches the heat demand with an additional, climate-dependent allowance for dehumidification
Primary energy demand	Not to exceed 120kWh annually for all domestic applications (heating, cooling, hot water and domestic electricity) per square metre of usable living space
Airtightness	Maximum of 0.6 air changes per hour at 50 Pascals pressure (as verified with an onsite pressure test in both pressurised and depressurised states)
Thermal comfort	Thermal comfort must be met for all living areas year-round with not more than 10% of the hours in any given year over 25^{0}C

The Passive House approach has many outstanding benefits. According to the statement of the Passive House Institute, the Passive House standard is "*A building standard that is truly energy efficient, comfortable, affordable and ecological at the same time*". This statement has been verified through numerous research projects on actual constructed buildings. Many quantitative studies showed that Passive Houses can save up to 90% of heating energy consumption in comparison with conventional buildings. This rate is over 75% compared to new buildings (PHI, n.d.). Energy efficiency is the key factor of the Passive House concept to considerably reduce carbon emissions into the environment. Indoor environment in Passive House buildings is excellent since the spaces are provided with clean fresh air; the indoor temperature is maintained between 20 and 25°C; and the relative humidity is controlled in the range of 30-60%. The additional cost for building a Passive House is between 5 and 10% (Schnieders, Feist, & Rongen, 2015), but due to low energy consumption, the life-cycle cost of a Passive House building is affordable (Bere, 2013).

In order to satisfy the high requirements of the Passive House standard and obtain the significant benefits mentioned above, a building has to comply with the following basic principles, which are graphically described in Figure 2.28:

- Extra high level of insulation
- High performance window frames and glazing
- Thermal-bridge-free design and construction
- Extra high level of airtightness for building envelope
- Mechanical ventilation with highly efficient heat (or energy) recovery

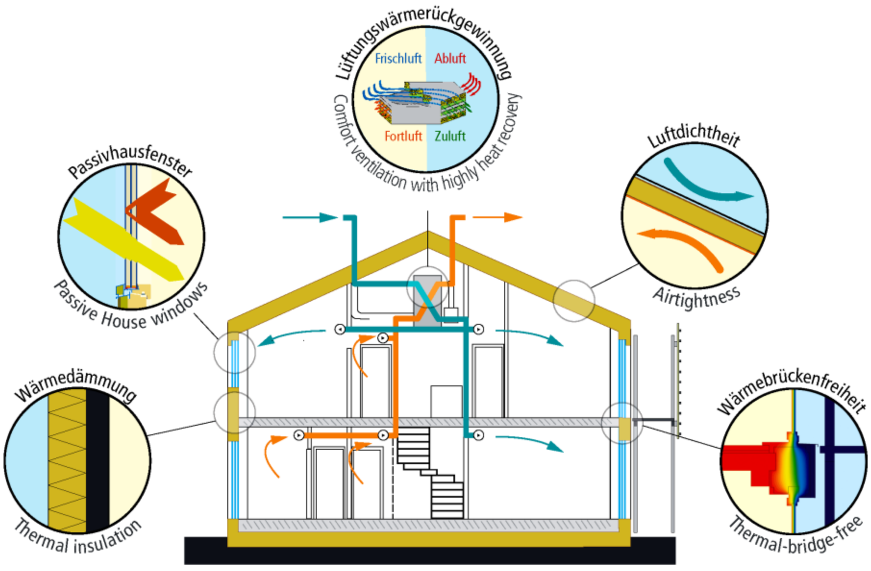


Figure 2.28: Five principles of Passive House
(Source: passipedia.org)

Generally, Passive House buildings require a high level of thermal insulation by applying high-performance windows and doors as well as well-insulated walls, ground floor and roofs. This helps to prevent heat (or energy) loss from the building. An airtight envelope with thermal-bridge-free construction helps to eliminate thermal transfers and draughts and keeps the indoor temperature at a stably comfortable state. Dealing with ventilation issues in such an airtight building fabric, a heat-recovery ventilation system (or energy recovery for warm regions) is used to supply fresh air which is heated by the heat from the extracted stale air. This system can operate all year round if necessary with a minimum amount of energy consumption. These basic principles remain for Passive House buildings in all climates, however depending on the local climate characteristics, the detailed techniques would be adapted (Bere, 2013).

2.3.3 Passive House applications in warm climates

The past 20 years have seen a significant development of the Passive House standard. With almost 60,000 certificated buildings realised, Passive House has become a promising low energy building standard in the world (Passive House Institute, 2016). It can be seen that the majority of Passive Houses are situated in the Temperate Zone of Europe. Over the last decade, the interest in the Passive House standard has spread to warmer regions such as Southern Europe, China and America (Figure 2.29). Inadequate attention has been paid so far to Passive House in hot and hot humid climates, particularly in Southeast Asia. However, it can be seen in Figure 2.29 that the number of certified Passive House buildings in warm countries has increased between 2016 and 2020. This subsection reviews Passive House applications in warm climates under two perspectives: practical applications and theoretical studies.

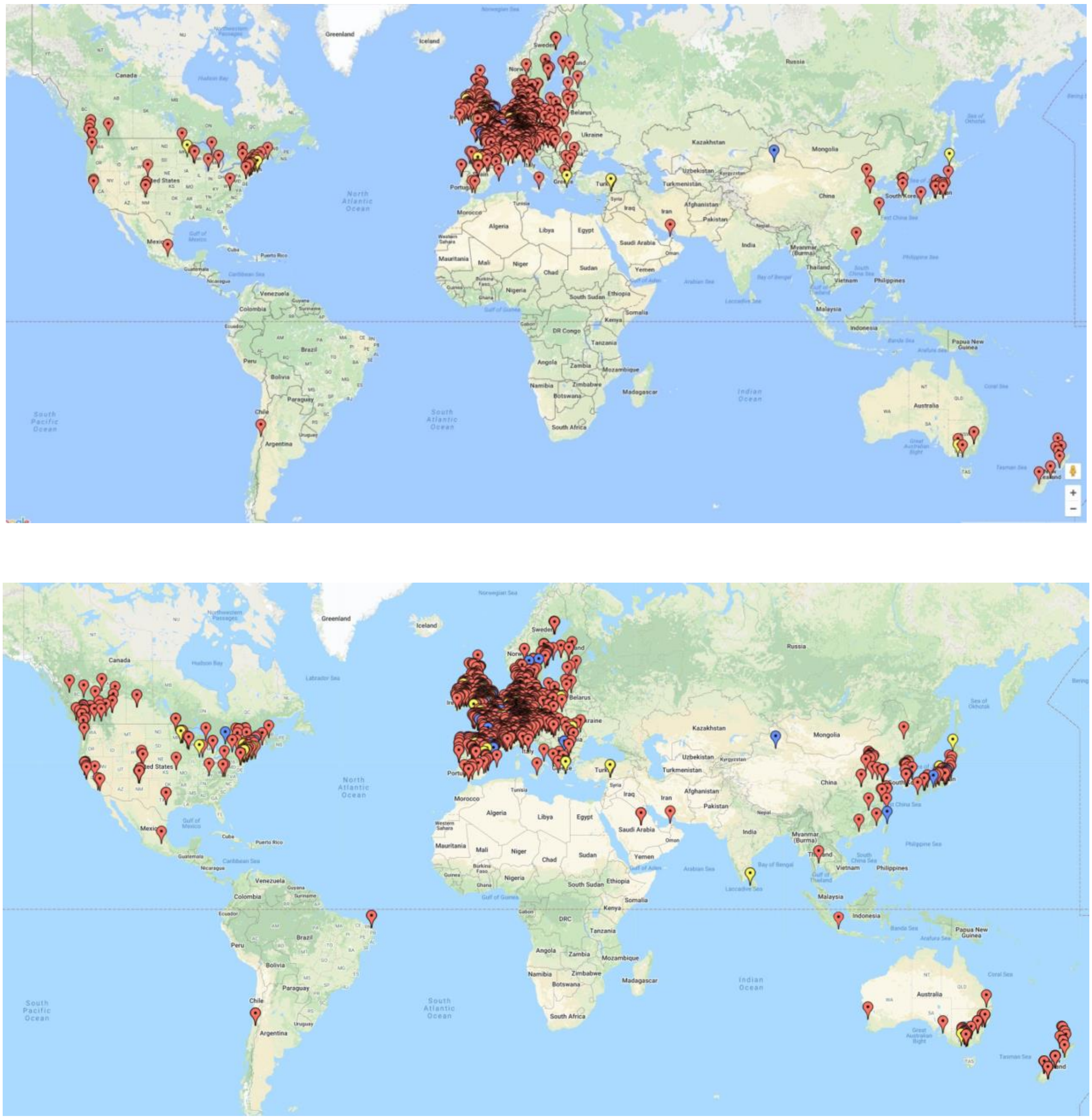


Figure 2.29: Map of certified Passive House buildings in 2016 (above) and 2020 (Source: passivehouse-international.org)

Regarding practical applications, to date, there are only few attempts at Passive House constructions in warm regions. In hot climates, two Passive House buildings were constructed in Dubai (2016) and Saudi Arabia (2018). Another Passive House project was built in Qatar in 2014, however, it could not meet the Passive House standard. In hot humid climates, there is a retrofitted Passive House in Sri Lanka (2016) and three new-built Passive Houses respectively in Indonesia (2011), Brazil (2017), and Thailand (2019). All of them are the first and unique Passive House projects in their countries. The technical information of these buildings can be found on the website the Passive House Database.

A PH office building in Dubai (2016)
(Source: passivehouse-database.org)

A PH project in Qatar (2014)
(Source: globalconstructionreview.com)

Figure 2.30: Passive House buildings in hot climates of Dubai (UAE) and Qatar

A PH office building in Indonesia (2011)
(Source: passivehouse-database.org)

A PH home in Thailand (2019)
(Source: passivehouse-database.org)

Figure 2.31: Passive House buildings in hot humid climates of Indonesia and Thailand

In hot humid climates, the Passive House building in Jakarta, Indonesia is the first one in Southeast Asia. This is the office of the Austrian Embassy and was designed by an architectural company situated in Vienna. The building with no conventional air conditioning offers a comfortable indoor environment with the stable temperature of 25°C and 60% relative humidity. The energy consumption and the CO2 emission have been significantly decreased 85.2% and 85% respectively compared to those of a conventional building in Jakarta (Oettl, 2014). To achieve these positive results, alongside the use of an energy recovery system as usual, this building employed the concrete core temperature control as a radiant cooling system. This system circulates cold water through a dense grid of pipes put in concrete slabs for cooling. Obviously, this system would raise the construction cost and makes the construction more complicated. Thus, there is a need to look for further appropriate solutions for Passive House in Southeast Asia, especially for residential buildings.

In 2019, the second Passive House building in Southeast Asia was completed in Bangkok, Thailand. It is a detached single-family house consulted by BWK Green Architecture Company located in Taipei, Taiwan. This concrete building achieved an air tightness level of 0.6 ACH. U-values for walls, roof, and glazing are 0.16, 0.2 and 1.3 W/(m^2K) respectively. SHGC of glazing is 0.26. The cooling load is 9 W/m^2 and the cooling and dehumidification demand is 88 kWh/(m^2a) (iPHA, 2020). The success of this first Passive House residential building in Southeast Asia is a valuable reference for Passive House studies in other countries in the region, including Vietnam.

The first Passive House project in Qatar failed to meet the strict requirements of the Passive House standard. In order to keep the indoor temperature under the maximum of 25°C all year round, the annual total energy use of the Passive House villa is over 200 kWh/(m^2a), exceeding the criterion of 120 kWh/(m^2a) (Khalfan & Sharples, 2016). Questions still remain as if the maximum indoor temperature setpoint of the Passive House standard should be higher 25°C for buildings in hot and hot humid climates.

Regarding the theoretical studies, although there are existing standards and numerous research projects on Passive House in mild climates, it would be a risk to apply these solutions to other different regions because of the particular constructional traditions and the specific climate conditions (PHI, 2018b). Thus, in recent years, Passive House experts and researchers have paid much attention to Passive House in warm climates. This can be seen in recent international Passive House conferences where there was always a specific session for Passive House in this type of climate. However, so far there has been little discussion about Passive House in hot humid regions, especially in Southeast Asia.

Schnieders J., Feist W. and Rongen L., in their research on Passive House for different climate zones in 2015, showed that it is possible to achieve Passive House residential buildings in the context of Singapore. This could be the motivation for the development of Passive House in Southeast Asia. However, in that research, the authors solely used one building model based on the end-terraced house in Hannover for many countries such as the U.S., Japan, China, or Singapore regardless the differences in the culture and housing characteristics between these countries. In addition, the comfort temperature range between 20 and 25°C used for thermal comfort assessment is the same for all places from cold to hot regions. As mentioned above, this issue needs to be reconsidered, particularly in hot and hot humid climates.

Figure 2.32: Hannover building model
(Source: Schnieders et al., (2015); passiv.de)

Based on the above study and the study on Passive House in tropical climates including Singapore, Salvador da Bahia and Mumbai, the Passive House Institute has enacted some recommendations for Passive House buildings in hot and humid climates. These findings can be found on the website of The Passive House Resource (passipedia.org). Despite playing an important role as the initial findings, these general remarks need to be verified and adapted to the context of each country in hot humid regions.

Indonesia, besides the success of the first Passive House in Southeast Asia, is paying attention to seek for a Passive House standard for the country. Santy, Matsumoto, Tsuzuki, & Susanti (2017) employed bioclimatic analysis methods to examine the characteristics of Indonesia climate. This examination is considered the primary step for forming a Passive House standard for housing in Indonesia. However, the 'passive house' concept stated in this research, which is "*a house that does not need the application of a mechanical HVAC system for heating or cooling purposes*" (Santy et al., 2017, pp.8), is not really the same as the Passive House definition of the Passive House Institute. This could lead to the ambiguousness between an authentic Passive House building and a free-running building purely using passive design techniques.

Recently, Sigalingging, Chow, & Sharples (2020) applied the Passive House approach to a conventional terraced house in Jakarta, Indonesia. The authors identified the benefits of the Passive House approach in terms of energy saving and thermal comfort in the tropical climate of Indonesia. It is noted that the upper limit of comfort range was set at 27.6°C for Jakarta rather than the 25°C criterion of the Passive House standard. In addition, the simulation result showed that the Passive House model only reduced about 28% of annual energy consumption for cooling compared to the original model. This percentage of energy saving is relatively modest in comparison to the energy-saving potential of Passive House buildings (up to 90%). Therefore, the value of the Passive House approach in hot humid climates needs to be further examined.

In Vietnam, although passive design techniques are common both in traditional and in current architecture, it seems that Passive House is a new concept. Most researchers have mainly focussed on improving naturally ventilated buildings, particularly housing, as a common way for buildings in hot humid climates. Consequently, with the outstanding benefits outlined above, Passive House is a potential new approach for low energy housing in Vietnam. However, further studies are essential to capitalise on the conventional Passive House techniques and develop appropriate solutions for Passive House residential buildings in the hot humid climate of Vietnam.

2.4 Chapter conclusion

This chapter gives a comprehensive literature review on thermal comfort in buildings, low energy design strategies and existing standards, and the Passive House approach's history, principles and applications in warm climates. The key remarks are as follows:

Thermal comfort plays an important role in building science. Two major methods to predict thermal comfort condition are heat balance and adaptive approach. They are recognised in three well-known international standards. These standards show limitations when applying to buildings in hot humid climates, mainly due to the adaptation of people to their own local climate. Therefore, further studies in hot humid climates are necessary for the determination of appropriate thermal comfort conditions of local residents. A review on thermal comfort studies in hot humid climates showed that there are differences in terms of neutral temperatures and comfort zones between different countries and locations. The review on the existing thermal comfort standards and individual comfort studies in Vietnam also shows a shortage of database on thermal comfort and a dissimilarity between the results. Therefore, further comfort studies on free-running buildings, air-conditioned buildings and climate chambers are essential to identify a suitable thermal comfort zone for Vietnamese people.

A review on low energy design techniques in hot humid climates gives a summary of passive and active solutions. Passive solutions include solar control, thermal control, passive cooling, and natural lighting. Active solutions include active shading, active ventilation, air conditioning, renewable energy production, and energy-efficient artificial lighting system and appliances. In order to assess building quality and energy efficiency in particular, there are a number of standards established around the world. However, evaluation methods vary among the standards and rating systems. They cover different building topics with different weightings. They may set limits for annual energy use (performance method) or building component properties (prescriptive method). Moreover, these criteria are also differ. Consequently, the application of existing international energy efficiency standards, rating systems and those of neighbouring countries to the context of developing Vietnam could be difficult and inappropriate. Vietnam needs its suitable low energy building standards and assessment methods. It is observed that studies on low energy housing in Vietnam so far mainly focussed on passive solutions for free-running buildings. However, in extreme climates, natural ventilation in buildings is inefficient, especially in the context of globe warming. Therefore, it is essential to diversify architecture solutions by researching and applying high-tech energy-efficient architecture, including the closed-building design approach. A building technology much more focusing on low energy consumption in sealed building is the Passive House approach that could be beneficial in hot humid climates.

Despite the significant development of the Passive House standard with around 60,000 certificated buildings realised so far, inadequate attention has been paid to Passive House in warm climates, particularly in Southeast Asia, in both theoretical study and practical construction. Only few attempts on Passive House construction in hot humid regions had been carried out, for instance in Brazil, Indonesia, and Thailand. These projects showed a remarkable efficiency in energy saving. However, the strictness of the Passive House Standard needs to be revised when applying to hot humid climates, especially in terms of the thermal comfort criterion that requires the indoor temperature does not exceed the maximum of 25°C.

Chapter 3 Research methods

This chapter describes the aspects of the overarching methodology governing this research from philosophical assumptions to detailed research methods, and it is these methods which form the main components of this chapter. First section gives the selection of a research methodology model for this study between the ‘Research Onion’, ‘Nested’ model and ‘Modified’ model. According to the selected model, research philosophy, research approach (including research modes, research strategies, research choices and time horizons) and research techniques (including data collection and analysis techniques) are described in detail. The final section of this chapter mentions ethical issues relating to the research.

3.1 The selection of research methodology model

In order to organise the research in a systematic and logical process, it is necessary to specify a methodological model for the study. There are a number of existing research frameworks which support researchers in making their methodological decisions. Kagioglou (1998) proposed the ‘Nested’ model (Figure 3.1) that shows a hierarchical relationship between research philosophy, research approach and research techniques. The choice of research philosophy will govern the choice of research approach and in turn the research approach will determine the corresponding research techniques.

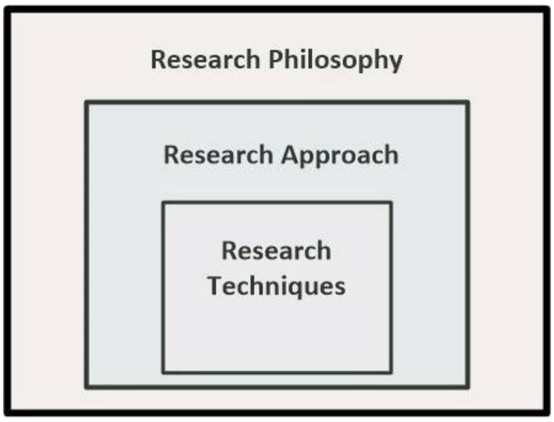


Figure 3.1: The ‘Nested’ model (Kagioglou, 1998)

The ‘Research Onion’ model proposed by Saunders, Thornhill, & Lewis in 2007 also describes research frameworks in a form of sequential layers, but extends further components. Methodological choice, research strategy and time horizon layers are added between research approach and research techniques layers. In addition, specific options within each layer are provided. Therefore, the ‘Research Onion’, as shown in Figure 3.2, sufficiently informs researchers of potentially methodological choices which can be employed to establish their research frameworks. Due to those advantages, the ‘Research Onion’ is one of the most common-used methodology models in different research disciplines.

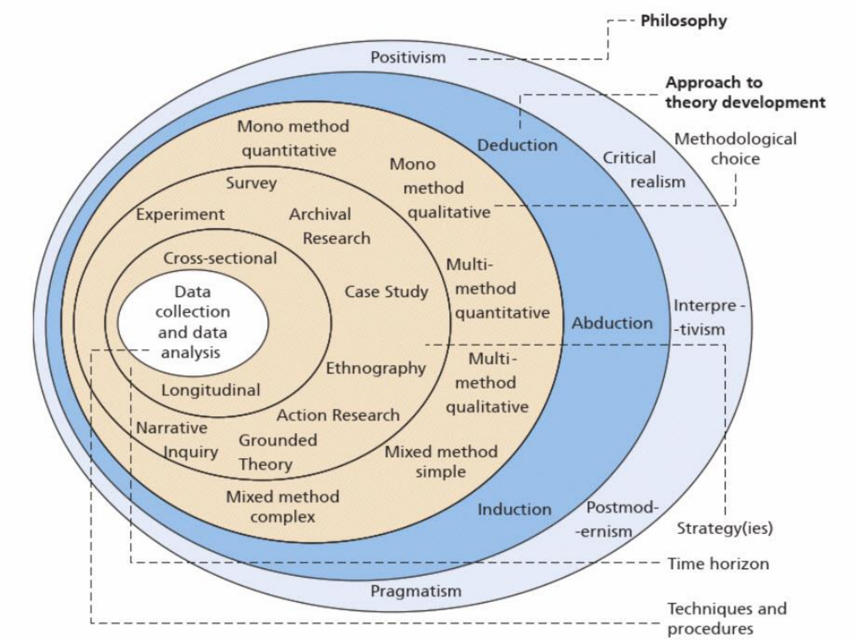


Figure 3.2: The 'Research Onion' model (Saunders et al., 2019)

Keraminiyage (2013) argued that the 'Research Onion' layers give a sense of sequence while some layers might not depend on the outer layers. For example, time horizon selection is not really controlled by the selection of methodological choices. Therefore, he suggested a 'Modified" model based on the combination of the 'Nested' model and the "Research Onion'. As shown in Figure 3.3, he used 'research approach' as an umbrella term covering four components: research strategies, research choices, research modes (research approach in the 'Research Onion') and time horizons. The subcategories remain the same as in the 'Research Onion'.

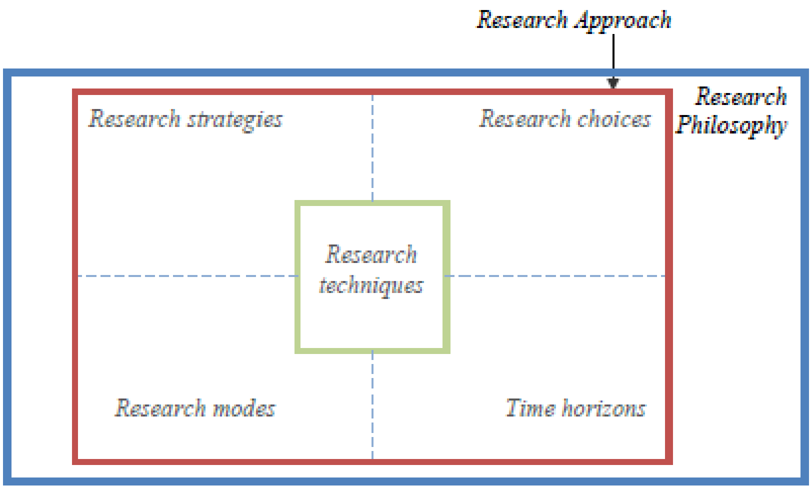


Figure 3.3: The 'Modified' model (Keraminiyage, 2013)

This study adopted the above 'Modified' model to illustrate the interconnection of key elements constituting the research methodology. The specific selections of research philosophy, research approach and research techniques for this study are listed in the model shown in Figure 3.4 and described in further sections.

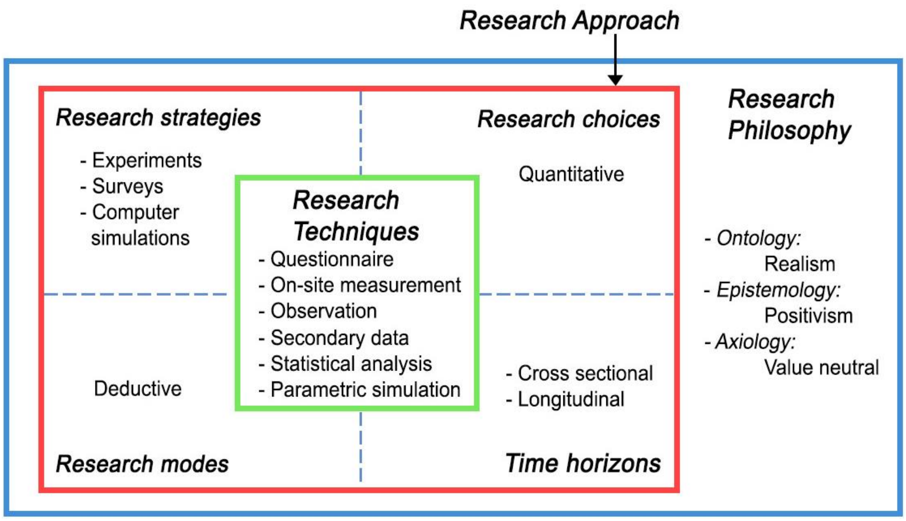


Figure 3.4: The research methodology model of this study (Adapted from the 'Modified' model)

3.2 Research philosophy

Research philosophy contains researcher's beliefs and assumptions about worldviews and the nature of research (Saunders et al., 2019). Despite of remaining mostly invisible in research, philosophical ideas still strongly affect the practice of research. This system of beliefs orientates the selections of research approach, strategies and specific methods (Creswell & Creswell, 2018). This ensures a coherent research with a logical procedure. Therefore, research philosophy needs to be clarified at an early stage of the study.

A research philosophy consists of three type of assumptions: ontology, epistemology and axiology. Ontology describes assumptions about the nature of reality and indicates the way researchers see their research objects. Two sides of ontology are realism and idealism. Realism considers the nature of reality to be a commonly experienced external reality with predetermined nature and structure. Idealism considers the nature of reality to be an unknowable reality perceived in different ways by individuals. Epistemology describes assumptions about knowledge, how acceptable, valid knowledge is constituted. Two sides of epistemology are positivism and interpretivism. Positivism involves the search for general laws and cause-effect relationships by rational means. Interpretivism involves the search for explanations of human action by understanding the way in which the world is understood by individuals. Axiology refers to value system and researchers' value position in their study. Two sides of axiology are value-neutral and value-biased. Value neutral means research is value free and objective while value-biased means research is value laden and subjective. (Keraminiyage, 2013; Saunders et al., 2019; Sexton, 2003)Based on the global aim of this research, which is to seek design solutions for low energy housing in Vietnam through the Passive House approach, it can be seen that the major research objects are houses, climate and energy consumption. From the researcher's viewpoint, all of them are objective and external realities. Therefore, the ontological assumption in this study is realism. Secondly, the above objective research objects need to be carefully surveyed and measured to rationally assess and refine the knowledge of housing performance and Passive House techniques in hot humid climates. By using rational and unbiased means in these investigations to acquire knowledge, the epistemology assumption in this study is positivism. Thirdly, during the research process, the researcher avoided to bring any personal value into the research to keep it objective and value-free. Therefore, the axiology assumption in this study is value neutral. In summary, the philosophical stand of this research comprises three assumptions which are realism, positivism and value neutral.

3.3 Research approach

According to the 'Modified' model, research approach comprises 4 components: research modes, research choices, research strategies and time horizons. The details of each component are as follows.

3.3.1 Research modes

Research modes (so called 'research approach' in the 'Research Onion' model) describe the reasoning the researchers adopt in designing their research. There are two contrasting approaches: deductive and inductive. Inductive reasoning is often used in research concerning theory building whilst deductive reasoning is often adopted in theory-testing research. In deductive approach, the research conclusion is logically acquired from testing and confirming the hypotheses derived from theories. Therefore, deductive approach is often used in positivists' research (Saunders et al., 2019). With a philosophical stand of positivism, this study adopted deductive as the main reasoning to design the research procedure in which the hypothesis about the effectiveness of Passive House approach in Vietnam was tested and confirmed. It is noted that apart from the main reasoning, inductive reasoning was also included in detailed pieces of the research.

3.3.2 Research choices

Research choices refer to the selections of quantitative, qualitative or mixed-methods research design. These selections are influenced by the philosophical stand of researchers. Quantitative research design is more likely to be used in positivism-influenced studies while qualitative research design is generally associated with interpretivism (Saunders et al., 2019). Because the philosophical assumptions of this study were based on realism, positivism and value neutral, the research choice was therefore determined as quantitative research.

An effective way to distinguish quantitative research and qualitative research is the classification of the data types which are numeric or non-numeric (Saunders et al., 2019). In quantitative research, the variables of research objects can be measured to generate numbered data which are then analysed using statistical procedures (Creswell & Creswell, 2018). Researching on the area of low energy housing, this study dealt with the major objects embracing housing characteristics, thermal comfort conditions and energy consumption. Data of these objects' variables including housing components' properties, indoor and outdoor temperature, humidity, air velocity and monthly amount of energy use were quantitatively collected. Subsequently, these numeric data were analysed using statistical techniques to examine their relationships and thereby proved the proposed hypothesis objectively. Consequently, quantitative approach was an appropriate selection for this research. This shows a consistency with the predefined philosophical worldview. In more detail, this research choice was multi-method quantitative research due to the use of various strategies in collecting and analysing data as described in the next subsection.

3.3.3 Research strategies

Research strategies can be in the form of experiments, surveys, archival research, case study, ethnography, action research, grounded theory and so on. The former strategies are generally associated with quantitative research while the latter ones are principally used in qualitative research (Creswell & Creswell, 2018) (Saunders et al., 2019). Adopting a multi-method quantitative research choice, this study employed different strategies including experiments, surveys and computer simulations to fulfil the corresponding principal research objectives. The details are as follows.

(i) Research objective: investigate the thermal comfort range for the Vietnamese. In thermal comfort studies, survey and experiment are the two main methods. The authors therefore adopted an experiment strategy for achieving this objective. Basically, experiment research is used to seek the impact of a specific treatment on the outcome (Creswell & Creswell, 2018). This study used experiment to investigate thermal sensation of the participants under a range of given temperature levels. Data on participants' thermal sensation and indoor environmental conditions were collected and analysed to find out a suitable thermal comfort range for Vietnamese people. This range is an important finding as it was used as a crucial criterion to assess thermal performance and energy consumption in dwellings.

(ii) Research objective: examine building characteristics and thermal performance of existing housing in Vietnam. To achieve this objective, this study conducted a field study using survey as a main research strategy. The survey strategy with on-site measurement and observation methods provided a numerical description of indoor and outdoor environmental variables along with building components and the corresponding construction materials. An analysis of these data provided understanding about the current conditions and limits of Vietnamese housing.

(iii) Research objective: examine energy consumption in existing housing. To fulfil this objective, a survey was carried out to collect data on household appliances and actual monthly energy consumption in a number of houses. This survey was a supplement to the above survey to acquire a comprehensive understanding about existing conditions of housing in Vietnam. In addition, this survey revealed a typical pattern of appliance usage in a household that was used in the next housing modelling and simulation steps.

(iv) Research objective: propose and assess Passive House design techniques for Vietnamese housing. These proposals were derived from the understanding of existing housing conditions alongside Passive House and low energy building design techniques from literature. To identify the optimal opportunities, this study employed a computer simulation strategy. Basically, computer simulation provides an environment where researchers can establish virtual experiments to predict the impact of components on the outcome. Different tests are allowed by modifying model's properties and by activating or deactivating desired parameters (Mollona, 2015). Based on the outcome of computer simulations, design guidelines for Passive House residential buildings in Vietnam were proposed.

(v) Research objective: validate the design guidelines. Outcome validation is an essential step for ensuring the feasibility and applicability of the design guidelines in practice. To fulfil this objective, it is important to gather assessments of building professionals and designers on the proposed design guidelines for which survey was an appropriate strategy.

3.3.4 Time horizons

Depending on research objectives, researchers are able to use cross-sectional study or longitudinal study or combining both. Cross-sectional time horizon is associated with studies of phenomena at a specific time whilst longitudinal study can be used to investigate the changes and development of research objects over a period of time (Saunders et al., 2019).

Because the relationship between human and the thermal environment is essentially dynamic (Nicol et al., 2012), the use of longitudinal study is a good choice for research in this area. However, it requires sufficient time and considerable effort from researchers and participants. Due to the time constraint and the requirement for data collection, this study adopted a cross-sectional approach to all fieldwork conducted. This included experiments on thermal perception of the Vietnamese and surveys on thermal performance of existing housing, household appliances and the outcome validation. However, to take into account the impact on buildings of weather changes and the adaptation of occupants over different seasons in a year, cross-sectional surveys on thermal performance of existing housing and experiments on thermal perception of Vietnamese people were carried out both in the hottest (June – August) and coolest period (December – February). Each field study lasted two months. The schedules are as follows:

- First field study: July – August 2017 (hot season)
- Second field study: January – February 2018 (cool season)

Longitudinal studies were used indirectly through secondary data collection of monthly electricity consumption in households for one year. These data indicated the relationship of climatic conditions, occupants' behaviour and energy consumption. Another longitudinal element in this study is the use of hourly simulation-based data on indoor environmental variables to assess thermal comfort conditions in buildings during a year.

3.4 Research techniques

Research techniques (or research methods) refer to specific techniques used to collect and analyse data. Therefore, research techniques can be divided into two categories: data collection techniques and data analysis techniques. It is noted that this chapter only provides a brief summary of research techniques employed in this study. To maintain the coherence of the thesis, the details of each technique will be described in corresponding chapters which follow later.

3.4.1 Data collection techniques

The data collection techniques used in this research were questionnaires, on-site measurements, observations, and secondary data. The specific roles of these research techniques used in the corresponding surveys or experiments are as follows:

- The thermal comfort experiments (i) employed questionnaire and on-site measurement techniques. During an experiment in a controlled room, questionnaires were used to collect data on participants' personal information and their thermal sensation votes at a given temperature. A sample of the questionnaire is shown in Appendix A. Meanwhile, indoor environmental variables including air temperature, black globe temperature, and relative humidity were measured by using appropriate instruments (Table 4.2). The detailed procedure is fully presented in Section 4.1. There were 128 college-aged subjects including 73 males and 55 females participating in the experiments. Eight experiments with each set air temperature from 23°C to 30°C were undertaken for each group of 16 subjects in both hot and cool seasons. Each participant filled 5 questionnaires during a 2.5 hour experiment, therefore, a total of 640 responses were collected.
- The survey on building characteristics and thermal performance of existing housing (ii) used observation and on-site measurement techniques. This survey involved 12 terraced houses in Tuy Hoa city. Observation technique was used to collect data on housing design and construction materials. When visiting a surveyed house, the author observed and recorded housing characteristics including building type, size, orientation, design features and materials of main structure, façades, and roof. Tools including sketching and redrawing, measurement, photography were employed to collect data from observations. On-site spot measurement was used to collect data on environmental variables in surveyed houses including air temperature, black globe temperature, relative humidity, natural daylight level, and air velocity. Five environmental variables were measured by handheld instruments (Table 6.2). The measurements were taken room by room, both indoor and outdoor. Air temperature, black globe temperature and relative humidity were measured at the centre point in each room at the height of 1.1m above the floor level. Air velocities were also measured at the height 1.1m and the data were recorded under the form of 2D mesh (Figure 6.3). Daylight data on the same grid were collected at 0.8m above the floor. Further explanation of the survey methods is provided in Subsection 6.1.1.
- The survey on energy consumption in existing housing (iii) used questionnaire method to collect data on the possession and the frequency of use of household appliances. A sample of

the questionnaire is shown in Appendix A. Face-to-face interviews were carried out in 13 households in combination with the in-situ measurements of environmental variables; other 57 households were asked to respond the questionnaire via email. Among them, 3 households did not respond, and 7 responses were insufficient. In total, there are 60 responses considered in the analysis. Secondary data on monthly electricity consumption in each surveyed house were obtained from the website of the state-owned electricity company. More detailed information is presented in Section 5.1.

- The design guidelines validation step (v) employed questionnaire method to gather responses of building professionals. The questionnaire shown in Appendix C is divided into three sections. The first section includes questions about the application of existing design guidelines and standards for energy efficiency in residential buildings. The second section discusses the feasibility of the Passive House approach in the context of Vietnam. The final section investigates the applicability of the proposed design guidelines for Passive House residential buildings in Vietnam. This questionnaire was converted to an online version using the Google Forms tool to facilitate the data collection and analysis. A representative sample of 10 professionals were sent the pilot questionnaire to gather their feedback. Subsequently, the official survey was carried out, and a total of 71 professionals in the field of architecture and construction responded to the survey.

3.4.2 Data analysis techniques

Statistical analysis and computational simulation are the two major data analysis techniques used in this research. The specific roles of these research techniques are as follows:

- Statistical analysis techniques were employed to analyse the data collected from field studies. For data management, calculations, and result presentations, this study used two widely available software products: the spreadsheet software Microsoft Excel (Office 365) and a more advanced data analysis software IBM SPSS Statistics (version 24). Depending on particular purposes, different analysis techniques were adopted. Descriptive statistics were used to describe basic characteristics of the collected data including the frequency; mean, median values; extreme values and standard deviations. For instance, descriptive statistics analyses were carried out to understand the distributions of environmental variables and energy consumption in the surveyed houses. More sophisticated analysis including linear and nonlinear regressions were used to examine the relationship between thermal conditions and occupants' thermal sensation votes. Based on these regressions, the neutral temperature and the thermal comfort range for Vietnamese people were identified. In addition, T-test analyses were employed to compare thermal sensation votes between male and female subjects and examine the differences between indoor and outdoor environmental variables in the surveyed houses. To ensure reliable results, all collected data were tested for error or bias problems before analysing.

- Computational simulation techniques were used in this research for two objectives. The first objective is to obtain the whole-year thermal performance and energy consumption of the existing housing models using EnergyPlus software (version 8.7). This dynamic simulation software provided hourly temperature of all main spaces in the houses during a year that on-site measurement methods could hardly fulfil. Based on these data, the thermal performance of existing housing was evaluated. Furthermore, the amount of energy used to maintain thermal comfort for the occupants throughout a year was calculated. The second objective is to assess energy efficiency of the proposed design solutions for Vietnamese housing based on a Passive House approach. These parametric simulations were carried out using the Passive House Planning Package (version 9.6), an essential piece of software for Passive House building design. With a given temperature setpoint, energy consumption was predicted under the changes of seven key influencing building parameters. Based on the outcome of these computational simulations, design guidelines for Passive House residential buildings in Vietnam were proposed.

3.5 Ethical issues

This research strictly complied with the University Policy on Research Ethics and Integrity. An ethics form was approved by the University's Research Ethics and Integrity Committee before carrying out the field studies. The major ethical issues of this research are as follows.

The risk level of this research was classified as limited (not significant). No particular ethical issues identified but contact with human subjects was part of thermal comfort experiments, existing housing surveys and questionnaires. However, this research did not involve any vulnerable groups since all participants were 'ordinary' adults (verified in advance). The researcher directly contacted with potential participants for their permissions to survey. Information sheets about the study were provided along with a clear explanation. Subsequently, the consent forms were collected before conducting any field studies.

The data collection and storage in this research complied with the Data Protection Act. This research did not include any security sensitive information. The authors highly ensured the confidentiality and anonymity of personal data relating to the participants. No physical harm or psychological stress were identified for the participants. The collected data were securely stored and only accessed by the researcher and the supervisors.

During the research process, the collected data and analysis results were honestly reported. Secondary data and material from other researchers were carefully used and fully referenced to ensure intellectual property rights and avoid plagiarism. The authors declare there is no conflicts of interest in this study.

3.6 Chapter conclusion

This chapter provides a logical process of the research from a broad worldview to specific research techniques to achieve the defined research objectives. Based on a philosophical stand of positivism, this study employed multi-method quantitative research to prove a hypothesis that the Passive House approach can be adopted in Vietnamese housing to achieve the goal of low energy consumption. Depending on particular research objectives, different research strategies were used including experiments, surveys and computer simulations. This study employed experiments to investigate the thermal comfort range for Vietnamese people. Surveys were used to examine building characteristics, thermal performance, energy consumption of existing housing in Vietnam and validate the proposed design guidelines. Computer simulations were an essential strategy to propose and assess energy efficiency of Passive House design techniques for Vietnamese housing. The particular techniques for the corresponding research objectives are summarised in Table 3.1.

Regarding time horizons, this research mainly focused on the cross-sectional studies which were repeated in both hot and cool seasons. The longitudinal elements were recognised in the use of secondary data on monthly actual electricity consumption in households and hourly simulation-based data on indoor environmental variables during a year.

Table 3.1: A summary of research methods used in this study

No.	Studies	Research strategies	Number of samples	Time horizons	Data collection techniques	Data analysis techniques
(i)	Thermal comfort	Experiment	128 participants (640 responses)	Cross sectional (repeated)	Questionnaire, Measurement	Statistical analysis
(ii)	Building characteristics and thermal performance	Survey	12 houses	Cross sectional (repeated)	Observation, Measurement	Statistical analysis
(iii)	Household appliances & energy consumption	Survey	60 households	Cross sectional, Longitudinal	Questionnaire, Secondary data	Statistical analysis
(iv)	Assess Passive House design techniques	Computer simulation	3888 cases of terraced house, 5184 cases of detached house	Cross sectional Longitudinal	-	Parametric simulation
(v)	Outcome validation	Survey	71 professionals	Cross sectional	Questionnaire	Statistical analysis

Chapter 4 An experiment on thermal acceptability of Vietnamese people

A review on thermal comfort in Chapter 2 highlighted the importance of thermal comfort to occupants' satisfaction, their work performance, health, and for energy consumption in buildings. Therefore, research on low energy housing in Vietnam requires an understanding on thermal perception of Vietnamese people. Since the Passive House methodology (which has been defined as a low energy approach to design) aims to build sealed buildings with mechanical ventilation and air conditioning (if necessary), research involving thermal comfort surveys in air-conditioned buildings and climate chamber experiments are suitable approaches alongside the use of the PMV-PPD model.

As discussed in chapter 2, the PMV-PPD model developed by Fanger based on experiments on North American and European subjects may lead to error when applying to other regions, especially in hot humid climates. Other comfort studies using surveys or experiment methods in hot humid countries showed discrepancies in results. The main reason could be due to the adaptation of local residents to their own climate. Consequently, thermal comfort studies for specific locations are necessary. In Vietnam so far, there have been no comfort surveys on air-conditioned buildings, and the only study using a climate chamber showed a number of limitations. The question still remains as to what neutral temperature and comfort range are suitable for Vietnamese people. Therefore, an investigation to determine the thermal comfort condition for use in Passive House buildings in Vietnam is necessary.

Regarding comfort study methods, it is observed that field surveys in air-conditioned buildings lacked data on high temperature situations since occupants tend to set indoor temperature at their most preferred level or even at lower temperatures. As a result, the determination of the comfort zone upper limit may be inaccurate. In contrast, experiments can test a wider range of temperatures, such as up to 30°C that is rarely observed in air-conditioned buildings. Therefore, to investigate the thermal acceptability of Vietnamese people, a comfort experiment was conducted and is presented in this chapter. The results of the upper and lower limits of the comfort zone will be used later as the set point temperatures in the simulation step. In addition, the comfort zone will be used as a criterion to evaluate the effectiveness of housing design techniques in terms of thermal performance.

It is noted that part of this chapter's content involves re-presentation from the Passive and Low Energy Architecture (PLEA) conference paper (V. T. Le & Pitts, 2020) written by the author of this thesis, with all data collected by him, and reviewed by the supervisor.

4.1 Experimental design

This section presents subject characteristics, experimental facilities, and experimental procedure. The details are as follows.

4.1.1 Subjects

The experiments were carried out with the participation of 128 college-aged subjects including 73 males and 55 females. All of them are volunteers although they were paid a small amount of money for expenses as an encouragement for their participation. All subjects were born and raised in the hot humid climate of Vietnam. They were in healthy condition and did not use alcohol or caffeine for 12 hours prior to the experiments.

The number of subjects in this study is significant compared to the average number of 25.2 ± 20.7 subjects taking part in more than 200 thermal comfort experiments around the world (Van Craenendonck, Lauriks, Vuye, & Kampen, 2018). College-aged subjects are common in comfort experiments because they are easy to be employed and are willing to participate in time-consuming comfort experiments. The average subject age of above-mentioned experiments is 23.7 ± 5.7. Table 4.1 shows the anthropometric data of 128 subjects in this study.

During the tests, the subjects were clothed in underpants, (and bra for women), short-sleeve shirts or T-shirts, thin long trousers and sandals. This clothing ensemble could be specified as light summer clothing, for which the thermal resistance value is assumed to be 0.5 clo.

Table 4.1: Anthropometric data of 128 subjects

Sex	Number	Age	Height (m)	Weight (kg)	DuBois area* (m^2)
Male	73	21.9 ± 1.8	1.69 ± 0.05	60.9 ± 9.1	1.69 ± 0.13
Female	55	21.5 ± 1.5	1.57 ± 0.05	47.9 ± 5.2	1.45 ± 0.08
All	128	21.7 ± 1.7	1.64 ± 0.08	55.2 ± 10	1.59 ± 0.16

* DuBois area = 0.202 * $(\text{weight})^{0.425}$ * $(\text{height})^{0.725}$

4.1.2 Experimental facilities

The experiments were conducted at MienTrung University of Civil Engineering, which is situated in Tuy Hoa city, South Central Coast of Vietnam. An air-conditioned classroom was employed and retrofitted for experiments. The dimensions of the classroom are 6m wide, 8m long and 3.8m high. The windows face North and South. The wide surrounding corridors of the upper floor and the inside curtains ensure the participants were not exposed to direct sunlight. Thermal comfort experiment in existing rooms equipped with air conditioners is a common method, accounting for 22% of more than 200 experiments recently summarised (Van Craenendonck et al., 2018).

Four environmental parameters, which are air temperature, globe temperature, relative humidity and wind velocity, were carefully measured during the experiments. Table 4.2 shows the properties of the measuring instruments used in this thermal comfort experiment. The accuracy of these instruments was validated by comparison with other measuring devices before being used in on-site measurements.

Table 4.2: Measuring instruments' properties

Instrument	Measuring variables	Manufacturer and code	Accuracy
Heat Index WBGT meter 	Air temperature, black globe temperature, relative humidity	PCE WB – 20 SD	Temperature: ± 0.6°C Humidity: ± 3% RH
Mini thermo anemometer 	Air velocity	Testo 425	Wind velocity: ± 0.03 m/s

In a pilot test, wind velocities were measured at three levels of height, 0.1m, 0.6m and 1.1m above the floor, at 27 sample points in the room. The result showed that the mean air velocity was 0.08 m/s with standard deviation of ±0.04 m/s. The maximum air velocity did not exceed 0.2 m/s (a value which can cause draught sensations). Therefore, the effect of air movement on thermal sensations is negligible. In addition, air temperature, globe temperature and relative humidity were measured at 4 sample points in the room in order to investigate the differences of these environmental variables at the three levels of height. The data indicated that there is no significant difference since the standard deviations were only ±0.1°C and ±2% for temperature and humidity respectively. Therefore, the measured data were collected at 0.6m above the floor, which is suitable for seated occupants, throughout the experiments.

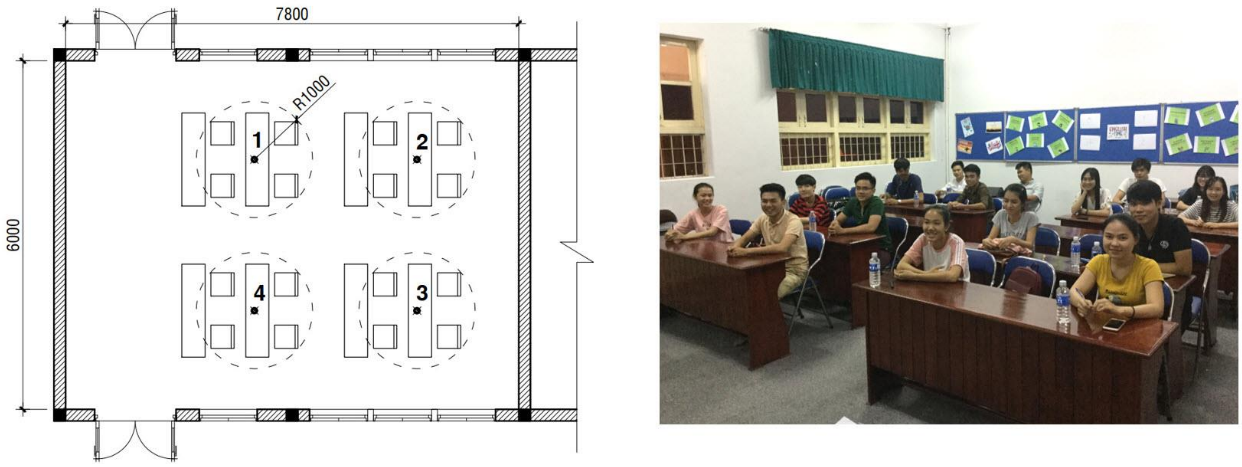


Figure 4.1: Layout and image of the experimental room

4.1.3 Experimental procedure

Eight experiments with set air temperatures from 23°C to 30°C were undertaken for each group of 16 subjects during 8 - 11 am or 2 - 5 pm in both hot and cool seasons. To take into account seasonal acclimatisation, the experiments on high temperatures from 26°C to 30°C were conducted in summer (August 2017) while the rest was conducted in cool season (January 2018).

The experimental procedure follows that of the comfort experiments conducted by Nevins, Rohles, Springer, & Feyerherm (1966); Fanger (1970); and de Dear et al. (1991). Before each experiment, the subjects sitting in a pre-test room next to the experimental room for half an hour completed the consent form and were informed of how to complete the questionnaire (shown in Appendix A). After entering the experimental room, 16 subjects were required to sit sedentarily for 2 hours in the room. They were allowed to study, read or quiet discussion. After every half an hour, subjects were asked to vote their thermal sensations based on the ASHRAE seven-point scale. Meanwhile, air temperature, globe temperature, relative humidity and air velocity were carefully measured at a point within radius 1m from the subject. Consequently, 5 data sets per participant per experiment were collected, including the one obtained at the beginning of the experiment. The experimental procedure is graphically illustrated in Figure 4.2.

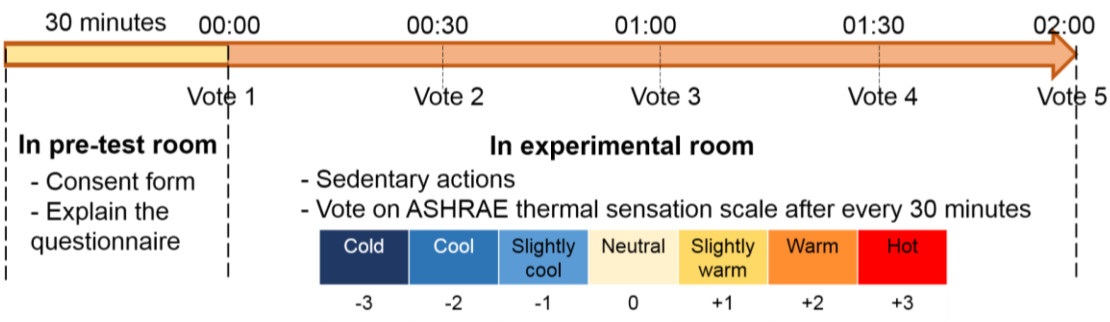


Figure 4.2: Experimental procedure

4.2 Results and discussion

This section presents an analysis on the collected thermal sensation votes to identify thermal comfort temperature and thermal acceptability of Vietnamese people. These results were then compared to those derived from the PMV-PPD model. The comfort temperature was also compared to the prefer temperature proposed by subjects at the beginning of the experiments. In addition, the influences of gender and seasonal factors on thermal sensation were determined.

4.2.1 Thermal acceptability of Vietnamese people

A total of 640 responses were collected from the experiments. However, only the last three thermal sensation ballots per subject, corresponding to 384 ballots for the 8 experiments, were used for the following analysis. This is based on the assumption that the subject had achieved thermal equilibrium after an exposure of one hour. The time period needed for acclimatising to the room temperature is a controversial issue since it has been applied differently across 147 experiment studies with the average time of 26.9 ± 11.8 minutes (Van Craenendonck et al., 2018). Table 4.3 shows the frequency distribution of thermal sensation votes in each of 8 experiments.

Table 4.3: Distribution of thermal sensation votes

Season	Air temperature (°C)	Mean radiant temperature (°C)	Operative temperature (°C)	Relative humidity (%)	Thermal Sensation Vote							Mean Vote	Percent of -1 to 1 Votes
					-3	-2	-1	0	1	2	3		
Cool	23 ± 0.2	22.6 – 22.9	22.7 – 23.0	58.1 – 66.1	1	25	18	4	0	0	0	-1.48	45.8
	24 ± 0.2	23.4 – 23.9	23.7 – 24.0	76.3 – 79.3	0	7	27	14	0	0	0	-0.85	85.4
	25 ± 0.4	24.2 – 24.8	24.4 – 25.0	75.1 – 78.6	0	5	15	28	0	0	0	-0.52	89.6
Hot	26 ± 0.4	25.9 – 26.4	25.9 – 26.4	45.2 – 48.8	1	11	25	12	0	0	0	-0.98	77.1
	27 ± 0.2	27.0 – 27.3	26.9 – 27.2	48.0 – 52.5	0	6	18	24	0	0	0	-0.63	87.5
	28 ± 0.4	27.6 – 28.3	27.6 – 28.3	48.3 – 50.7	0	2	9	29	7	1	0	-0.08	93.7
	29 ± 0.3	28.9 – 29.3	28.9 – 29.3	47.5 – 54.4	0	0	1	24	18	5	0	0.56	89.6
	30 ± 0.3	30.0 – 30.5	29.9 – 30.4	60.5 – 64.2	0	0	1	10	21	16	0	1.08	66.7

Among 4 environmental variables influencing human thermal sensations, apart from air movement which was negligible as mentioned above, relative humidity (RH) is an uncontrolled variable in this study due to the limitation of the experimental room. Therefore, the influence of RH on thermal sensation needs to be considered. de Dear, Leow, & Ameen (1991b) found that the difference of thermal acceptability between 35%RH and 70%RH of Singaporean subjects was only 0.3°C. In addition, Jin et al. (2017) found that in hot humid climates the influence of RH on thermal sensation is not significant if RH is less than 70%. Above the 70% threshold, RH significantly impacts on thermal sensation of occupants in hot humid conditions. Table 4.3 shows that in the 5 experiments in hot season, RH is always below 70%. Consequently, the effect of RH on thermal sensation in these experiments could be considered homogeneous. As a result, the determination of subjects' thermal acceptability depends on the remaining environmental variables, namely air temperature and mean radiant temperature. Air temperatures were directly measured by the measuring instrument whilst mean radiant temperatures were calculated from the measured air temperatures and globe temperatures. The values of these variables in the experiments are shown in Table 4.3.

Air temperature and mean radiant temperature are combined into one index, which is operative temperature. Since the air speeds in the experimental room were below 0.1 m/s, operative temperature was determined by the average value of air temperature and mean radian temperature. Operative temperature is often used to evaluate thermal performance of indoor environments (Nicol et al., 2012). Therefore, operative temperature is used as the main index for further thermal analyses in this thesis.

To determine relationship between actual thermal sensation and indoor temperature, all thermal sensation votes or mean thermal sensation votes were plotted against operative temperature by using the SPSS statistical package. Figure 4.3 shows the distribution of thermal sensation votes at 23, 24, 25°C in cool season and the votes at 26 - 30°C in hot season. Meanwhile, Figure 4.4 shows the mean votes distribution for both seasons.

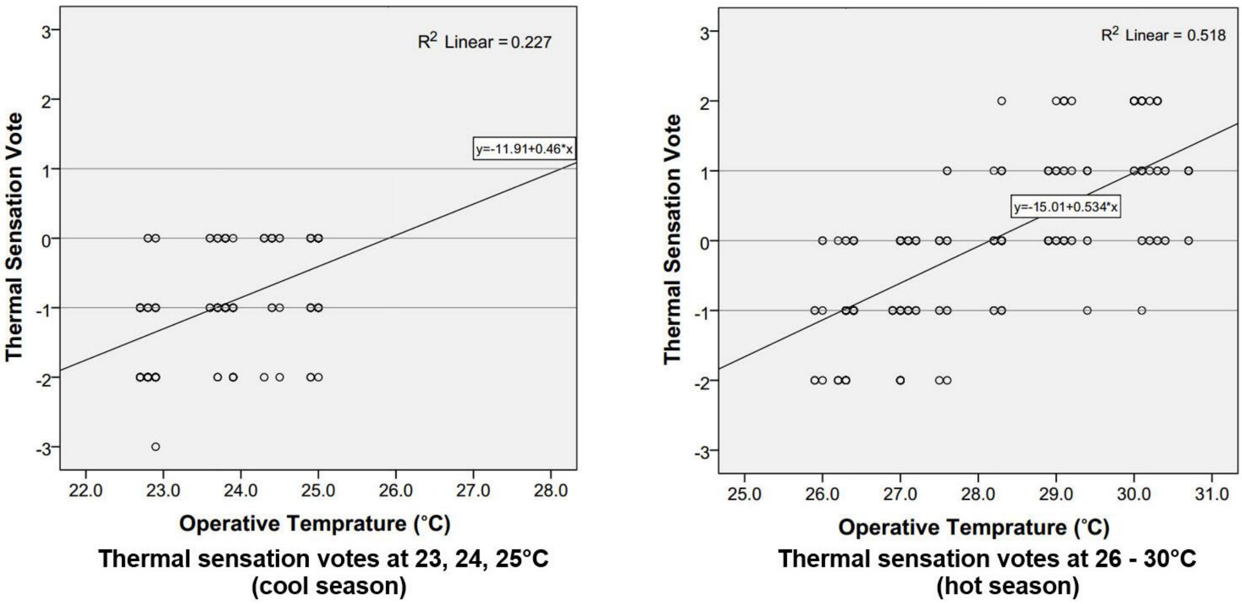


Figure 4.3: Scatter plot charts of thermal sensation votes in cool and hot seasons

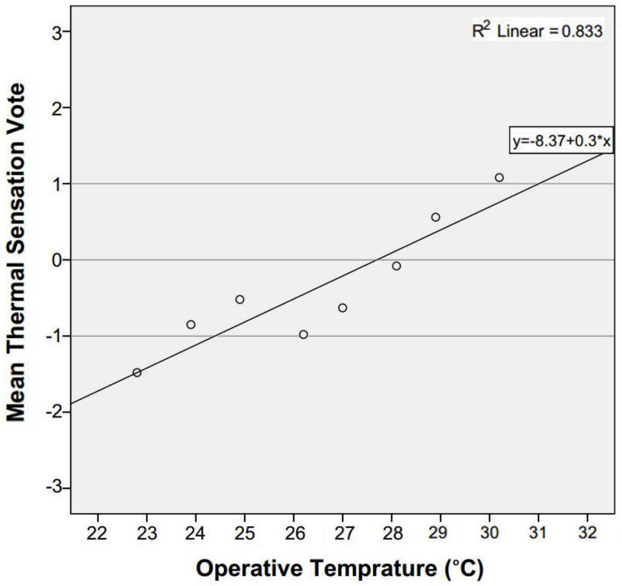


Figure 4.4: Scatter plot chart of mean thermal sensation votes in both seasons

Linear regression analyses showed the relationship between thermal sensation vote (TSV) and operative temperature (T_{op}) as follows:

- Cool season: $TSV = 0.46\ T_{op} – 11.91$ (4.1)
- Hot season: $TSV = 0.534\ T_{op} – 15.01$ (4.2)
- Both seasons: $TSV = 0.3\ T_{op} – 8.37$ (4.3)

From the above equations, neutral temperature and comfort range were calculated by putting thermal sensation vote value equal to 0 (neutral), -1 (slightly cool) and +1 (slightly warm). In cool season, neutral temperature is 25.9°C and the comfort range is 23.7 – 28.1°C. These numbers are 28.1°C and 26.2 – 30°C respectively for hot season. A combination of the two seasons showed the neutral temperature is 27.9°C and the comfort range is 24.5 – 31.2°C.

It is observed that the correlation between TSV and T_{op} in cool and hot season is similar since the slopes of the regression lines are not significantly different. However, the y-intercept in the hot season regression line is much smaller than that of cool season. This difference can be recognised in Figure 4.5 where the regression lines of mean TSV in cool and hot seasons were plotted together. It can be seen that the mean vote at 25°C or even at 24°C is higher than that value at 26°C. That means people felt warmer at 25°C in cool season than at 26°C in hot season. The gap 2.2°C between comfort temperatures in hot and cold season shows a significant difference of thermal sensations between 2 seasons. The discrepancy of thermal sensations between different seasons was also reported by Bae & Chun (2009), Maiti (2014), and (Liu, Wu, Li, Cheng, & Yao, 2017).

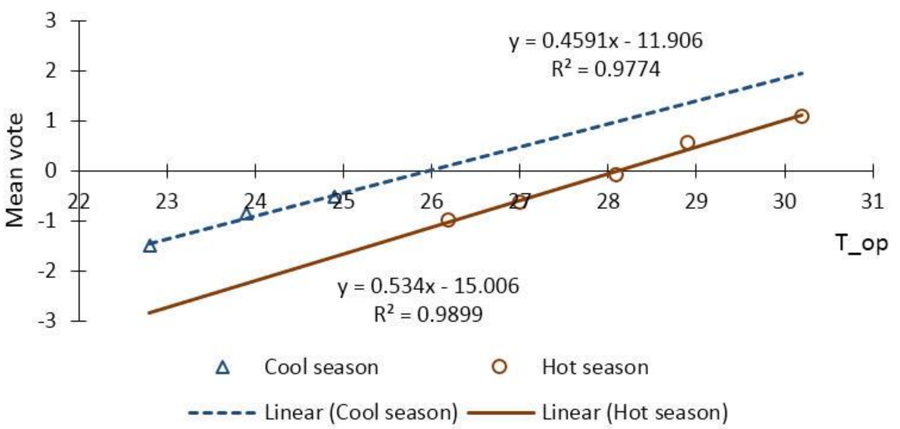


Figure 4.5: Mean Thermal Sensation Votes in cool and hot season

This difference means the linear regression based on the combination of data of both seasons may lead to the lack of reliability in determination of thermal comfort conditions. For example, the lower slope of the Equation 4.3 (for both seasons) resulted in a higher upper limit temperature at 31.2°C compared to the 30°C value for the hot season, which is unreasonable. Therefore, it is rational to determine temperature acceptable range of Vietnamese people based on the upper limit in hot season and the lower limit in cool season. Although comfort temperature is not identified using this method, it is more significant to determine the thermal acceptability of occupants since this is closely related to the energy consumption for cooling in hot and humid climates (Arens, Humphreys, de Dear, & Zhang, 2010; Nicol et al., 2012).

According to Fanger (1970), it is very difficult to set thermal conditions that can satisfy everyone: there is always a minimum of 5% of people who feel dissatisfied with a certain temperature. In comfort studies the boundaries are often extended to a criterion of 80% or 90% of people satisfied in order to determine the thermal acceptability of the group of people. The percentages of subjects who felt satisfied in this experiment, (i.e., voting from -1 to +1), were then plotted against the operative temperature. The percentage values of satisfied votes in the hot season experiments are shown in Figure 4.6. In the cool season, the thermal acceptability to low temperatures was determined by interpolation.

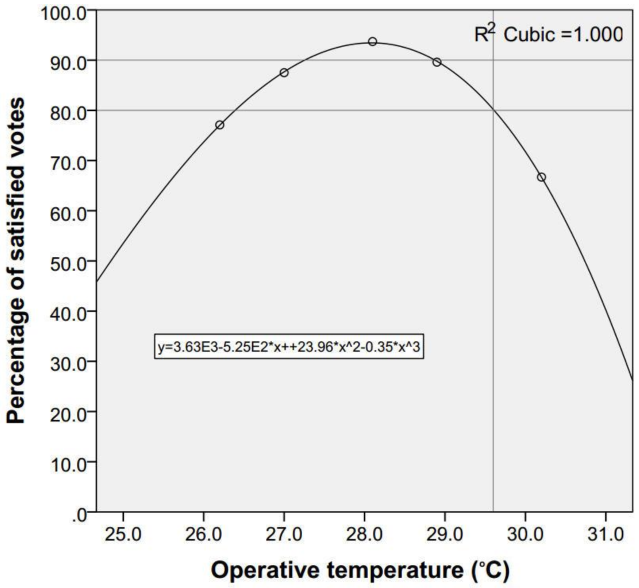


Figure 4.6: Percentage of satisfied votes in hot season experiments

In the cool season, the lower-limit temperature for 80% satisfaction was found at 23.7°C whilst the upper-limit temperature was found at 29.6°C in the hot season. The values for 90% satisfaction criterion are 24.8 and 28.8°C. The upper limit temperatures are in line with Vietnam's thermal comfort standards TCVN 9411:2012 and TCXDVN 306:2004 where these values are 29°C and 29.5°C respectively. Table 4.4 shows the finding of this study alongside the results of other comfort experiments in hot humid climates. The acceptable range of temperature found in this study is comparable to those of experiments carried out by: H. M. Nguyen et al. (2003) in Hanoi, Vietnam; Abdulmalik & Young (1993) in Malaysia; Zhang et al. (2016) and Jin et al. (2017) in Guangdong, China. However, the upper thresholds of temperature of this study are much higher than those in research conducted by: de Dear, Leow, & Ameen (1991b) in Singapore; Maiti (2014) in India; and Karyono et al. (2015) in Indonesia. This significant difference indicated that further experiments on thermal comfort in hot humid climates are necessary.

The application of thermal comfort zone with the criterion of 80% or 90% acceptance to Vietnamese housing needs to be identified. The ASHRAE defines an acceptable thermal environment as the one accepted by 80% of the occupants. This standard classifies the comfort zones into two categories: the limits of 80% acceptance are for typical buildings, and the limits of 90% acceptance are for higher-standard buildings (ASHRAE, 2017). There is no doubt that maintaining a broad range of acceptable temperatures requires less energy for cooling (and/or heating) than maintaining a narrow range (Arens et al., 2010; Nicol & Humphreys, 2002). Therefore, since residential buildings do not necessarily require high-standard thermal environment, the acceptable range of temperatures from 23.7°C to 29.6°C (80% acceptance) was selected for Vietnamese people.

A concern that arises is whether the thermal comfort zone taking in the lower limit in cool season and the upper limit in hot season could satisfy occupants at anytime since the upper limit in cool season is 28.1°C and the lower limit in hot season is 26.2°C. A climate analysis was carried out to investigate the possible thermal discomfort. The result showed that the number of hours in 3 months of cool season when outdoor temperature exceeds 28.1°C is only 72 hours with the average temperature of 28.7°C. As dwellings can provide cooler indoor temperatures in hot weather, which was proved by the on-site measurements shown in Chapter 6, it is safe to state that hot discomfort is negligible in short cool season.

In hot season, there are 174 hours when outdoor temperature falls below 26.2°C with the average temperature of 25.7°C. Again, the on-site measurement showed that indoor temperatures are higher than the outdoors in cold weather. In addition, low temperatures occur at late night when occupants are asleep, hence, the possible cold could be solved easily by a thin blanket. Therefore, cold discomfort is negligible in hot season.

Based on the above analyses, it is reasonable to use the thermal comfort zone 23.7°C - 29.6°C in assessment of indoor thermal environments and setpoint setting for HVAC systems in Vietnamese dwellings.

Table 4.4: Comparison of thermal comfort experiments in hot humid climates

Authors	Year	Location	No. of subjects	Neutral temperature (°C) & Comfort zone (°C)
de Dear et al.	1991	Singapore	32	Preferred temperature: 25.4
de Dear et al.	1991	Singapore	98[b]	Upper limit: 27.6 (70% RH) (80% acceptance)
Abdulmalik & Young	1993	Malaysia	N/A	25.5 – 29.5
H.M. Nguyen et al.	2003	Hanoi, Vietnam	40	24 – 29 (90% acceptance)
Maiti	2014	Bangalore, India	40	24.8 23.3 – 26.3 (90% acceptance)
Y. Yang et al.	2015	Chongqing, China	80	Upper limit: 26.8 SET (90% acceptance)
Karyono et al.	2015	Jakarta, Indonesia	54 [b] 36 [c]	24.1 (22.6 – 25.7) (90% acceptance) 24.9 (23.6 – 26.1) (90% acceptance)
Zhang et al.	2016	Guangzhou, China	30[a] 30[b]	27.1 (24.5 – 29) SET (90% acceptance) 26.4 (24.5 – 28.1) SET (90% acceptance)
Jin et al.	2017	Guangdong, China	30[a]	25.3 (60%RH) Upper limit: 29 (69%RH) (90% acceptance)
This study	**2018**	**Tuy Hoa, Vietnam**	**128**	**23.7 – 29.6 T_{op} (80% acceptance)** **24.8 – 28.8 T_{op} (90% acceptance)**

[a] Subjects have long-term exposure to naturally ventilated environment
[b] Subjects have long-term exposure to mechanically ventilated environment
[c] 50% of subjects have long-term exposure to mechanically ventilated environment
RH: relative humidity; SET: standard effective temperature; N/A: not available; T_{op}: operative temperature

4.2.2 Comparison with PMV and PPD model

In order to compare the experimental results with the prediction of the PMV-PPD model, the PMV and PPD index corresponding to the mean operative temperature (T_{op}) obtained from the experiments were calculated by using the Centre for the Built Environment (CBE) Thermal Comfort Tool (Tartarini, Schiavon, Cheung, & Hoyt, 2020). The input variables include: T_{op}; 0.1 m/s air speed; 1 metabolic rate; and 0.5 clothing level. The PMV-PPD predictions are shown in Table 4.5 alongside the results derived from the experiments.

Using the PMV-PPD model, the neutral temperature was found at 25.9°C whilst the comfort range is 23.2 – 28.5°C, corresponding to the PMV from -1 to +1. In addition, the 80% acceptable range is 23.6 – 28.1°C and the 90% acceptable range is 24.6 – 27.2°C. It is interesting to know that the neutral temperature predicted by the PMV model is equal to that of cool season. Moreover, at 80% and 90% satisfaction level, the lower-limit temperatures of acceptable ranges in both current study (23.7°C and 24.8°C) and the PMV-PPD prediction are almost identical. This could be explained by the formation of the PMV-PPD model which was derived from the experiments on subjects living in temperate climates. On the other hand, the upper-limit temperatures of the PMV-PPD prediction are around 1.5°C lower than those of current experiments (29.6°C and 28.8°C). This finding indicated that the PMV-PPD model overestimated the value of the thermal sensation votes of the occupants in hot humid environments. This conclusion was also found by Y. Yang (2015) and Maiti (2014). Therefore, the PMV-PPD predictions are not reliable in hot humid climates, including Vietnam.

Table 4.5: Comparison of actual mean votes, PMV and PPD

Experimental results				PMV-PPD prediction		
Season	Mean T_{op} (°C)	Actual mean votes	Percentage of actual dissatisfied votes	SET (°C)	PMV	PPD (%)
Cool	22.8	-1.48	54.2	21.8	-1.13	32
	23.9	-0.85	14.6	23.0	-0.73	16
	24.9	-0.52	10.4	24.1	-0.35	8
Hot	26.2	-0.98	22.9	25.6	0.13	5
	27	-0.63	12.5	26.6	0.44	9
	28.1	-0.08	6.3	27.9	0.86	20
	28.9	0.56	10.4	28.9	1.16	34
	30.2	1.08	33.3	30.5	1.67	60

T_{op}: operative temperature; SET: standard effective temperature
PMV: Predicted Mean Vote; PPD: Predicted Percentage of Dissatisfied

4.2.3 Comparison with the neutral temperature proposed by subjects

In order to assess the participants' awareness in terms of comfort temperature, at the beginning of every experiment, participants were asked to estimate their desired comfort temperature. A statistical analysis on the collected data indicated that the males proposed an average temperature of 26°C and that of the females is 26.5°C. Although the females selected a warmer temperature than the males did, the difference is not statistically significant (mean difference = 0.561; sig. = 0.221). In combination of both sexes, the mean proposed comfort temperature is 26.2°C (95% confidence interval, 25.8 to 26.7°C) with a standard deviation of ±1.5°C. Although the desired comfort temperatures were collected in both hot and cool seasons, the participants selected relatively similar mean values.

In comparison with the comfort temperatures derived from the actual thermal sensation votes, the initially proposed comfort temperature of 26.2°C is similar to the comfort temperature of 25.9°C for cool season, but around 2°C lower than the comfort temperature of 28.1°C for hot season and 1.7°C lower than that of the whole year. The result generally shows that people do not have a right awareness of comfort temperature, especially in hot season. This can result in the waste of energy for excess cooling.

4.3 Chapter conclusion

This chapter presents the design and results of a comfort experiment to investigate the thermal acceptability of Vietnamese people. 8 experiments on thermal sensation at temperatures from 23 to 30°C were carried out in a controlled room with the participation of 128 college-aged volunteers. The results derived from the analysis of 640 responses were summarised in Table 4.6. The comfort temperature for Vietnamese people is 27.9°C. The acceptable temperatures for 80% satisfaction level are 23.7°C and 29.6°C respectively for the lower and the upper limit.

Table 4.6: Summary of the experimental results

	Neutral Temperature (°C)	Comfort range (°C) (TSV: -1 to +1)	Thermal acceptability (°C)	
			(80% acceptance)	(90% acceptance)
Cool season (23-25°C)	25.9	23.7 – 28.1	**23.7**	24.8
Hot season (26-30°C)	28.1	26.2 – 30	**29.6**	28.8
Whole year (23-30°C)	27.9	24.5 – 31.2	-	-
PMV-PPD model	25.9	23.2 – 28.5	23.6 – 28.1	24.6 – 27.2

The PMV-PPD model overestimated thermal sensations of the subjects especially at high temperatures, therefore, the PMV-PPD predictions are not reliable in the hot humid climate of Vietnam. In addition, the acceptable temperature range found in this study (23.7 – 29.6°C) is significantly different from the temperature requirement of the Passive House Standard (20 – 25°C). Consequently, the application of the 20 – 25°C criterion to buildings in Vietnam would be not suitable for the indigenous people whilst wasting much energy for excess cooling. For these reasons, this study proposes the use of a comfort zone from 23.7 to 29.6°C for Passive House buildings in Vietnam, including dwellings. This would help to save much energy consumption for cooling demand in buildings compared to the use of the 20 – 25°C criterion.

The determination of the correct thermal acceptability of Vietnamese people plays an important role in this project. The new comfort zone will be used as a criterion to evaluate the effectiveness of housing design techniques in terms of thermal performance. In addition, the upper and lower limits of acceptable temperatures will be used as set points for HVAC systems in the next simulation steps.

Chapter 5 Household appliance use and energy consumption in existing housing

Alongside the economic development in the past decade, housing supply in Vietnam has improved remarkably. The rapid increase in both quantity and quality of dwellings along with the improvement of living standard has resulted in the increase in energy consumption in the residential sector. The energy demand for housing in Vietnam is projected to increase 3.1% per year over the period 2016-2035 (Danish Energy Agency, 2017). This leads to concerns about energy shortage, greenhouse gas emission and environmental pollution since fossil fuel accounted for the majority of total primary energy and electricity supply in Vietnam in 2015 (Figure 5.1). In this context, energy efficiency policies for the residential sector are needed as a priority.

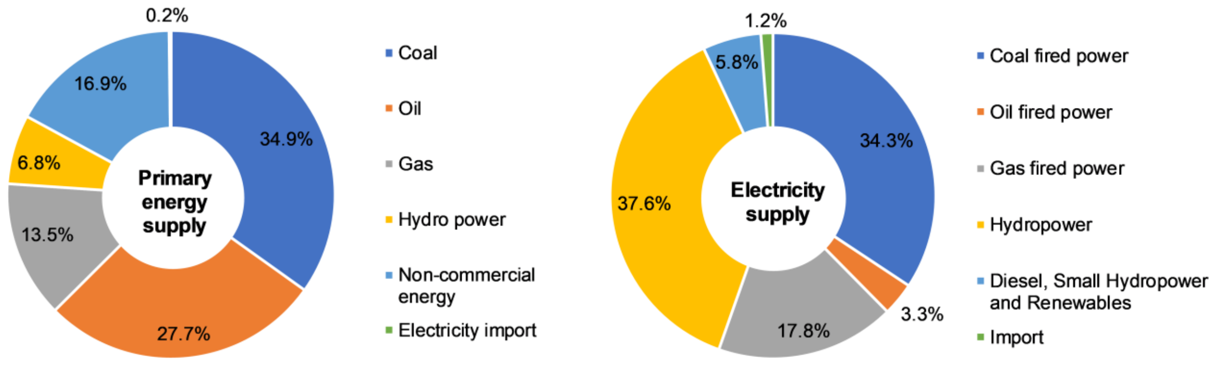


Figure 5.1: Share of Vietnamese primary energy supply and electricity supply in 2015.

Researching on low energy housing necessarily requires an understanding on the energy usage in existing housing including the amount of energy consumption, the ownership of electrical appliances and user behaviour. The identification of key factors contributing to energy consumption in households will be valuable in orienting appropriate energy efficiency solutions in terms of building design and energy policy making. However, research on the details of energy consumption in housing in Vietnam is relatively poor and there is a lack of data on actual energy use in households (V. T. Le & Pitts, 2019).

In order to partially fill the gap of knowledge, this study carried out a survey with the following objectives: (1) to understand the characteristics of Vietnamese households, appliance penetration and actual energy consumption; (2) to investigate usage behaviour and identify appliances that significantly affect household energy consumption. It focused on gathering detailed data from households in Tuy Hoa, a medium scale city in the central part of the country. Conducting surveys at national level would have been a more ideal scenario however this would require very substantial resources which are rarely available within the developing economies. Although the survey reported here was carried out in a specific urban area, Tuy Hoa city itself exhibits characteristics typical for other cities in Vietnam. The author therefore believe these features make it a good representative option for study and the outcomes have value for the country as a whole. However, the application of the result to large cities including Hanoi and Ho Chi Minh must be done with care and further studies on these special cities are necessary. The author further believe that in the absence of other contemporary and detailed information, the research has value for both researchers and users.

Regarding the contributions to the whole research, this survey helps to identify the typical household-appliance-use pattern including equipment and the frequency of use, which significantly influence on energy consumption of housing. This pattern will be applied to proposed housing models in modelling and simulation stages of the project. The results of actual electricity consumption will be used as a baseline in comparison with simulation results to assess the energy efficiency of proposed design techniques. In addition, the results of this study are a valuable reference for policy makers, energy planners, housing designers and Vietnamese households themselves to understand the existing energy consumption characteristics and identify potential ways to improve energy efficiency in dwellings.

It is noted that most of this chapter's content was represented from a journal paper (V. T. Le & Pitts, 2019) written by the author of this thesis and reviewed by the supervisor.

5.1 Materials and methods

5.1.1 Survey method

There are several statistical techniques that can be employed to collect data on household energy consumption, namely: energy business surveys; household surveys; use of data collected for administrative purposes; simulation/modelling studies; and in situ measurement. The Eurostat organisation has provided descriptive information on strengths and weaknesses of each of these methods in their manual produced in 2013. Among these methods, it was stated that in situ measurement can provide high-quality results with detailed information on energy consumption and the usage pattern of individual household appliances. In situ measurement was the technique used in some studies such as STAND-BY POWER (France, 1997-1999), the End-use Metering Programme (Sweden, 2005-2008), the Household Electricity Survey (UK, 2010-2011), and REMODECE (12 European countries, 2006-2008) (Eurostat, 2013). However, the disadvantages of this method are the cost, the need for time-consuming data gathering, use of restrictive monitoring equipment, and difficulties in finding participants due to household privacy concerns. The most common method of energy consumption survey in the domestic sector is the household survey. This traditional method is now associating with the rapid expansion of the internet and has many strengths to be used more widely in studies across the global.

Within the limitation of time and budget, in order to collect sufficient comprehensive information on appliance ownership and usage behaviour in households, this study employed a questionnaire-based survey in both face-to-face interviews and email-based methods. Care was taken in devising the interview structure and questionnaires to elicit information about appliance use and energy in a form that could be analysed and linked to other surveys. The face-to-face interviews of household energy usage were conducted in combination with the in-situ measurements of housing environmental performance, while the email-based questionnaire method was used to reach a larger number of participants due to its convenience. In addition to household surveys, the administrative-data-use method was employed to collect the actual electricity consumption of the surveyed households. These monthly actual electricity consumptions were obtained from the online database of the Vietnam Electricity company, with the consent of the household owners.

5.1.2 Subject selection and survey items

It can be observed that urban households consume more energy than rural households which is associated with higher incomes and modern lifestyles and appliances (Supasa, Hsiau, Lin, Wongsapai, & Wu, 2017). Additionally, the proportion of people living in urban areas of developing countries in Southeast Asia such as Vietnam, has increased rapidly in recent years and is predicted to reach 60% by 2040 (IEA, 2017). Urbanisation has become one of key factors affecting final energy consumption of residential sector, hence, research on urban household energy use is an essential requirement. In Vietnam, excluding the 5 largest cities, there are 58 significant cities, which are the capitals of the remaining provinces. Thus, in addition to studies in large cities such as Hanoi or Ho Chi Minh city, energy consumption in the smaller cities should also be paid adequate attention. Therefore, the main household energy use survey reported here was conducted in Tuy Hoa, a city in the South-Central Coast of Vietnam. A comparison of key data with other areas is shown in Table 5.1; though Tuy Hoa is located in a modestly poor province, Phu Yen, the city itself is more prosperous than its rural hinterland and exhibits typical characteristics for other cities in Vietnam. The authors believe these features make it a good representative option for study.

Table 5.1: Comparison data for area, population and GDP (Vietnam General Statistics Office, 2018)

Location	Area (km^2)	Population 2017 (million)	GDP/capita 2017 (USD)
Vietnam (5 major cities and 58 provinces)	330957	95.54	2343
Phu Yen province	5060	0.899	1565
Tuy Hoa city	107	0.202	n/a
Ho Chi Minh city	2061	8.445	5500
Hanoi city	3329	7.420	3900

The questionnaire, which is shown in Appendix A, was designed with the questions covering household and dwelling characteristics; home appliance ownership; power rating; user behaviour; and monthly energy bills. Table 5.2 indicates the types of information gathered. Seventy households in Tuy Hoa city were contacted to gain their participation in this survey in summer

2017. The households surveyed in this study were selected randomly regardless of circumstances in order to give a range of types and status and to provide the best basis for future comparisons and give validity for outcomes. As mentioned above, face-to-face interviews were carried out in 13 households; the remaining 57 households were asked to respond the questionnaire via email. Among them, 3 households did not respond, and 7 responses were insufficient. In total, there are 60 responses considered in the analysis.

Table 5.2: Questionnaire data categories

Questionnaire items	Details of types of information gathered
Household characteristics	Number of household members, age
Dwelling characteristics	Building type, site area, construction area, main structure type, number of floors, number of bedrooms and other rooms
Electricity consumption	Monthly electricity consumption, electricity account information
Other energy use	Liquefied petroleum gas, kerosene, coal, biomass
Home appliances	Air conditioners, fans and other home appliances (number, power rating, frequency of use)
Domestic hot water	Electric water heater details, Solar water heater details
Cooling usage pattern	Typical time of use for air conditioners and fans each day

5.1.3 Analysis of appliance energy consumption

In order to understand appliances energy consumption in households, it is essential to determine the energy consumption breakdown. However, except for liquefied petroleum gas (LPG), understanding the detailed electricity consumption of lighting and other appliances is challenging. On-site measurement could be the best solution, however that method is complex, expensive and requires much effort from both surveyors and participants (Eurostat, 2013). Currently, there are some developments occurring in modern measurement systems which claim to be able to monitor multiple appliances in a household (Sense, 2019; Smappee, 2019). Instead of using monitors for individual appliances, only one monitor is connected to the main electricity lines of the house and can recognise every appliance via its unique frequency when operating. However, the accuracy of such modern equipment needs to be carefully verified before wide use in scientific research. Therefore, this study is based on more traditional survey methods to determine the energy consumption breakdown. Electricity consumption of each type of appliance was theoretically calculated by the following formula:

$$\text{Electricity consumption} = \text{power rating} \times \text{working hours} \times \text{number of items} \quad (5.1)$$

This method has been widely used in many studies (Y. T. Chen, 2017; Kubota, Jeong, Toe, & Ossen, 2011; Ozawa, Kudoh, & Yoshida, 2018; Surahman, Maknun, & Krisnanto, 2016; Tso & Yau, 2003; Zheng et al., 2014). The number of appliances and the frequency of use were the average values from the survey. Power ratings of appliances were selected from common products in the market in accordance with the actual power ratings of appliances in surveyed households. It is noted that the annual electricity consumption of a fridge is often introduced instead of the power rating. In order to determine the operational hours, information was gathered from residents; this indicated variations according to the weather conditions with occupants using mechanical ventilation in the warm season and only using energy for hot water provision in the cool season. Therefore, the corresponding numbers of using days of use per year of air conditioners, fans and water heater were assumed based on the climate condition and the discussion with the occupants. For less frequently used appliances such as washing machines, hair dryers or food blenders, the frequency of use was converted into a daily hours of use value for energy calculations. Apart from these appliances, others were assumed used every day and the specific values of appliance working hours are shown in the result subsection 5.2.3.2.

5.2 Results and discussion

The results of this study firstly describe the household characteristics and existing housing conditions of Vietnamese households. Secondly, the ownership rates of common home appliances and the frequency of use were represented. Finally, actual household energy consumption was analysed in detail. The actual electricity consumption was compared among households classified by the ownership level of air conditioners. The energy consumption breakdown was determined using a theoretical calculation method. This breakdown highlighted the dominant factors in terms of energy consumption in Vietnamese household. In this results section, some data acquired from this study are compared with the available official statistics of Vietnam. A more comprehensive comparison will be mentioned in the discussion session.

5.2.1 Household characteristics

Analysis of data collected from the survey showed that households are scattered throughout the city, from existing urban areas to new residential areas. The majority of household owners work for the local authority, educational institutions or private companies. Some socio-economic groups were less well represented however, the collected data does represent well the middle-income group which is most significant in terms of changing energy consumption patterns in developing countries such as Vietnam.

Figure 5.2 shows the distributions of household size, number of storeys and floor area of the surveyed dwellings. The graph shows that there are average 4.3 people living in a household. This number is also the family size found in other studies (Murakoshi, Xuan, Takayama, Nakagami, & Takaguchi, 2017; Parkes & Burrage, 2013), but slightly higher than the average national census statistic which was 3.7 (Vietnam General Statistics Office, 2015b). Nuclear families with 2 adults and 2 children are the predominant type, accounting for 50% of total household, followed by extended families with 5 or 6 people consisting of householders, their children and their parents, at 30%. Households with one child account for 13.3% of the total. The proportion of households having less than 3 or more than 6 people is relatively low, at 6.7%.

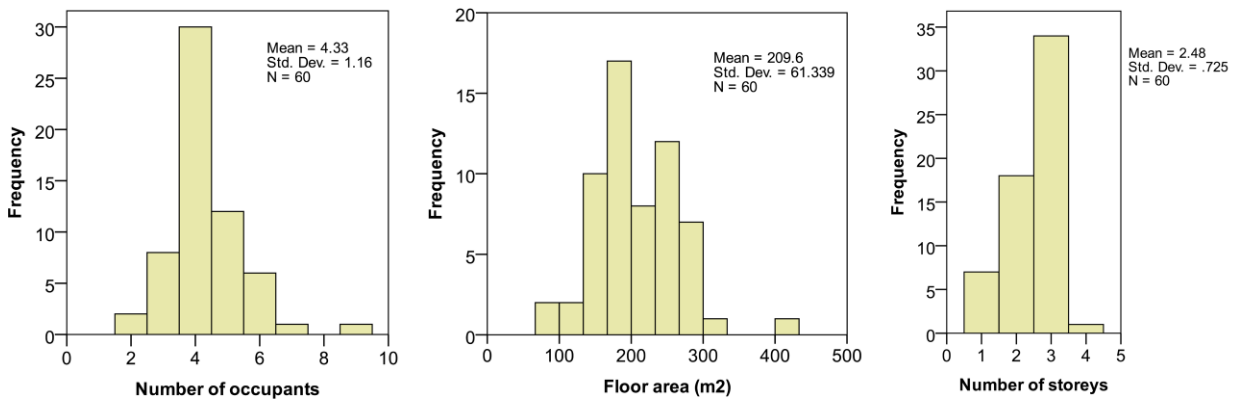


Figure 5.2: Distribution of household characteristics.

Regarding housing characteristics, 97% of the surveyed households live in terraced houses. These ‘tube-form’ dwellings are very popular in urban areas of Vietnam. This result is in line with the 2014 national population and housing census since individual houses (terraced houses and detached houses) were the choice of most households, of which villas were negligible at 0.1%, while apartments accounted for a small share of 1.4% (Vietnam General Statistics Office, 2015b). It is noted that the apartment housing type does not yet exist in many cities in Vietnam such as in Tuy Hoa. Terraced houses are characterised by a narrow width of 4 to 6 metres and a long depth of 15 to 25 metres, and the number of floors typically ranges from 2 to 5 storeys. The common materials of construction for existing terraced houses are concrete frames, brickwork infill for walls, and concrete flat or corrugated metal roofs (Figure 5.3).

In this survey, 3-storey houses are dominant, accounting for 57% of the total number of households, followed by 2-storey houses at 30%. The average floor area is 210 m^2 (standard deviation of 61) which is higher than the 167 m^2 value found in the Cimigo study. The average floor area per capita is 48 m^2 which is double that of 2014 national census statistic of 23 m^2 in major urban areas. This could be explained by the significant differences of housing sizes and types among cities. The floor area of an apartment, ranging from 50 to 120 m^2, is usually smaller than an individual house; and the average for an individual house in large cities tends to be smaller than that in small cities due to the higher density and higher cost.

Figure 5.3: Terraced houses in Vietnam

5.2.2 Appliance ownership and usage behaviour

The ownership rates of main household appliances that are used in Vietnamese homes are listed in Figure 5.5. It should be noted that the questionnaire on electric appliances did not involve lighting system due to its complications and potential confusions for respondents. Most urban houses in Vietnam are equipped with a large number of varying types of light sources, not only to meet visual lighting needs but also for decorative purposes (Figure 5.4). The frequencies of use normally vary between different types of lights. It was therefore deemed too complicated to obtain detailed electricity consumption patterns for lighting in a household by questionnaire. This difficulty is also mentioned by Eurostat (Eurostat, 2013).

Figure 5.4: Diversity of lighting systems in housing

As shown in Figure 5.5, a rice cooker, fridge, fan, television and iron are indispensable in Vietnamese urban households; most households also have a washing machine (95%). Some other appliances are also relatively common with the ownership level from 77% to 83%, such as air conditioners, water heaters and kettles. Less than 50% of households possess equipment such as microwaves, induction cookers, ovens or DVD player. According to the Vietnam household living standard survey conducted in 2014, ownership rates of major household appliances in urban areas were: 96% for a television, 81% for a fridge, 56% for a washing machine, 42% for a water heater and 32% for an air conditioner (Vietnam General Statistics Office, 2016). Appliance ownership levels found in this study varied from the previous national study with most being higher; however, the national study represents both urban and rural areas and cities might be expected to have higher ownership of such appliances. The appliance ownerships in Hanoi and HCMC (Murakoshi et al., 2017) are comparable to that of Tuy Hoa City and reflect typical appliance ownership of an urban household in Vietnam. For instance ownership of TVs is 100% in Tuy Hoa; 85% in Hanoi and 91% in HCMC, with fridge ownership at 100% in Tuy Hoa; in 99% Hanoi and 96% in HCMC.

Meanwhile, Cimigo's statistics from 2013 produced values somewhere between this study and the national survey results. For instance, ownership levels of washing machines, water heaters and air conditioners in Cimigo's survey were 72%, 51% and 48% respectively (Parkes &

Burrage, 2013). These variations could be explained by the differences between the survey timing and the subjects of the surveys.

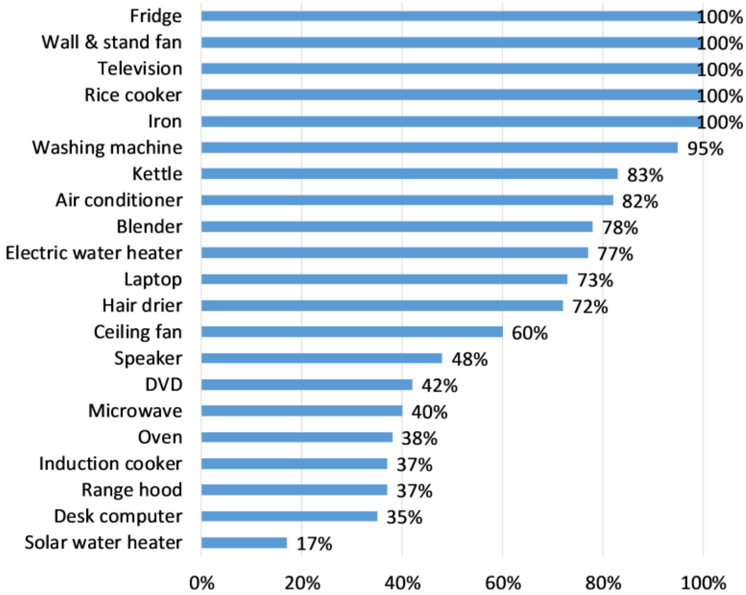


Figure 5.5: Appliance ownership of surveyed households

Among household appliances, the use of air conditioners should be considered because of their potential high energy demand and also because air conditioner ownership can be an indicator of living standards. In this study, there are 49 houses using air conditioners, account for 82% of participating houses. This number reflects the fact that using air conditioners for cooling if available is a common solution for urban dwellings in the hot humid climate of Vietnam. There are 37% of households using one air conditioner; these were mostly located in master bedrooms. The same proportion (37%) is found for households owning two air conditioners while 8% of households use more than two air conditioners. The rest (18% of households) do not use air conditioners; this is unlikely to be due to a preference for natural ventilation but rather due to the high costs. This situation is also observed in rural or suburban areas of Vietnam where the majority of housing is free running in terms of ventilation.

It is noted that the rate of solar water heater possession is only 17% whilst that of electricity water heater is 77%. This contrast reveals an inadequate attention to renewable energy in housing in Vietnam, a country with high solar radiation at most times of year. Despite the energy-saving benefits of a solar water heater, poor awareness of more sustainable lifestyles and high initial investment costs could be the main barriers to this system's application.

The ownership of appliances only partly shows the level of electricity use in a household. It is also important to understand the operating time/schedules of those appliances, however, data on household appliance usage time are absent from the statistics of both national surveys and other research in Vietnam. Participants of this study were therefore asked about the average daily usage time of appliances in their homes; the result is shown in Figure 5.6. Alongside the incessant operation of fridges, fans and air conditioners are the second and the third appliances most frequently used, at 8.75 and 7.23 hours respectively per day. In addition to high levels of ownership, high numbers of operating hours of fans and air conditioners once again confirm the significant effect of cooling demand on household energy consumption.

For entertainment, people usually watch television for an average 5.8 hours per day, whilst the use of DVD players and music system are negligible. People also use their laptops for 3.43 hours at home for recreation besides at work. Desktop computer working time is relatively high at 2.21 hours per day, but this appliance is absent in two-thirds of households. This is also the case for induction cookers. Some other appliances have low operating times at less than 2 hours per day, such as rice cookers, electric water heater, irons or kettles, but they are necessary for household functions and possibly consume significant electricity due to their high-power ratings. Microwave and other ovens are less used in Vietnamese households, possibly due to the cooking habits and culinary culture.

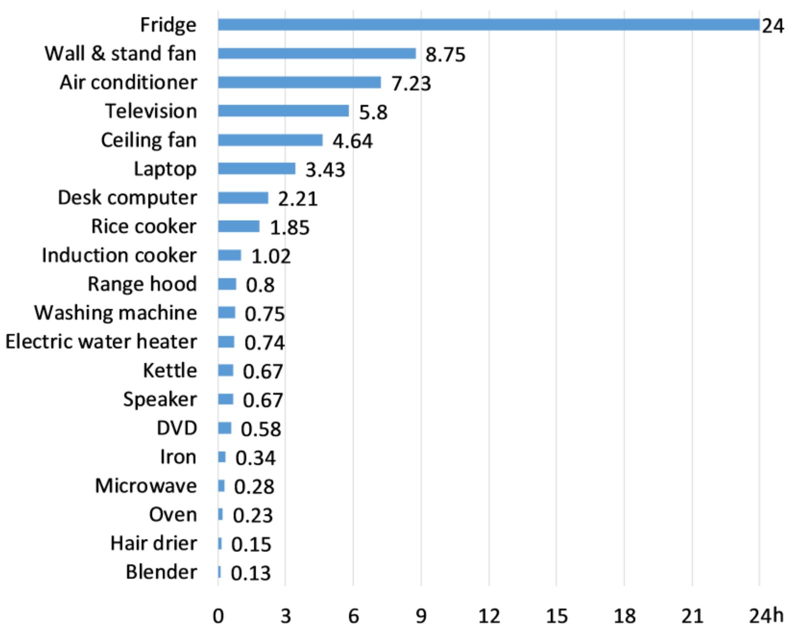


Figure 5.6: The duration of appliance use (hour per day)

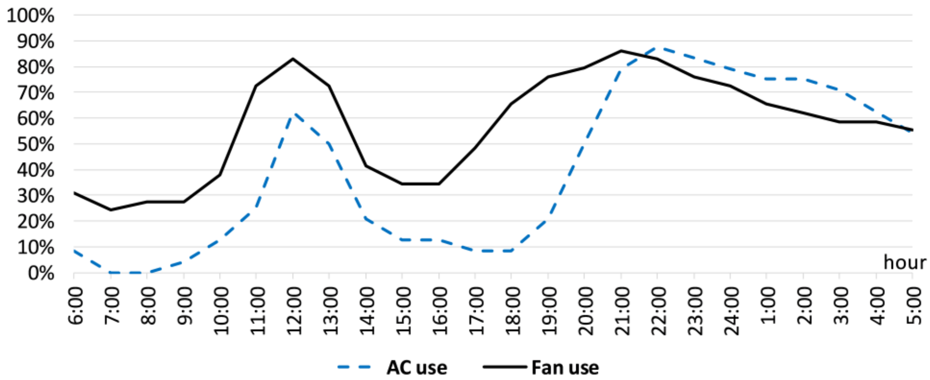


Figure 5.7: Daily using pattern of fans and air conditioners

Since cooling appliances including fans and air conditioners have high level of ownership and high frequency of use, it is necessary to investigate the usage patterns of these appliances. As shown in Figure 5.7, people usually use cooling appliances at noon and in the evening. This is in line with the occupied time of houses. It is interesting to note that in small cities like Tuy Hoa, with early start for working time, people have enough time to go home at noon to prepare/cook lunch and even taking a nap before the afternoon shift. This explains the high cooling demand at around noon, a feature which usually does not exist in the largest cities.

The operation of fans is more frequent than air conditioners: 60% of households turn on the fans when they are at home while air conditioners are used more reservedly. Most people only operate air conditioners when they sleep, especially at night time. Around 60% of households use air conditioners at noon time, from 12 to 1pm. This proportion reaches a peak of 87% at 10pm. Subsequently, there is evidence of some household turning off the air conditioners at 2am while 55% of households keep the air conditioners operating until 5am. It is noted that when air conditioners are used in certain rooms, fans could be simultaneously used in other occupied spaces.

5.2.3 Actual energy consumption

5.2.3.1 Electricity consumption

The monthly actual electricity consumptions of surveyed households in 2017 were obtained from the online database of Vietnam Electricity company; this was achieved with the consent of the house owners. Figure 5.8 shows the distribution of total electricity consumption of the surveyed households in 2017. The average electricity consumption was 3340 kWh (standard deviation = 1423), which cost 6.54 million Vietnam dong, approximately GB£ 221 or US$ 280. 67% of the households consumed between 2000 and 4000 kWh of electricity a year. Only 10% of households consumed less than 2000 kWh and households consuming more than 4000 kWh accounted for 23% of the total. Average annually electricity consumption per capita was 771 kWh.

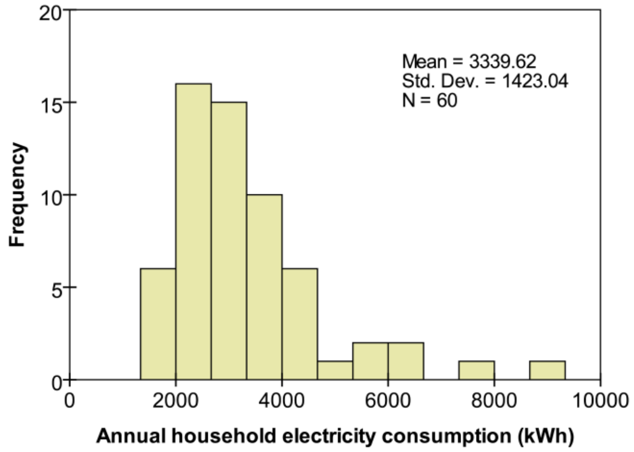


Figure 5.8: Distribution of 2017 electricity use

A glance at Figure 5.9 shows that monthly electricity consumptions during the hot period from May to September, were significantly higher than those in the cool period, from November to February. This is due to the increased cooling demand in summer. It is interesting to see that the trend line of electricity use in 2017 is in line with that of monthly temperatures in the year. The peak of consumption is in June, at 348 kWh, when the average temperature reaches the highest at 30°C. The lowest electricity consumption is found in February, at 206 kWh, when the average outdoor temperature falls to 24°C.

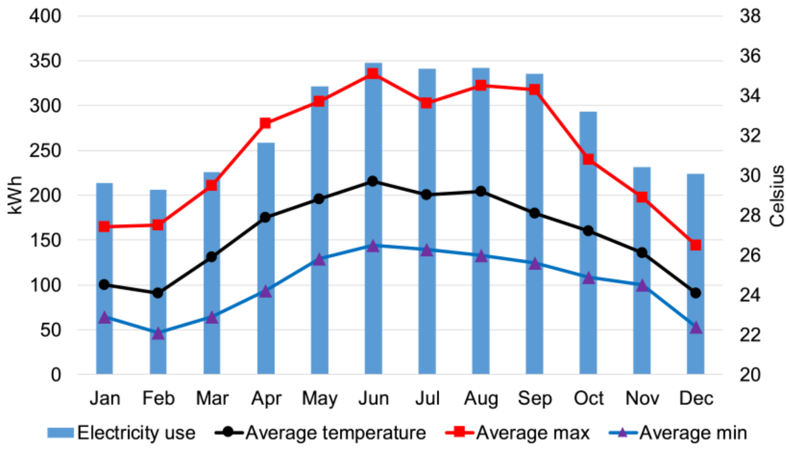


Figure 5.9: Monthly electricity use and average temperature

The average electricity consumption of natural-ventilated (NV) houses is 2276 kWh/year which is two-thirds of the air-conditioned (AC) houses' average (3578 kWh/year). As can be seen in Figure 5.10, the monthly electricity consumption of NV houses is relatively stable, while that of AC houses shows a contrary picture. In hot months from May to October, AC houses consumed roughly double the electricity NV houses used. Meanwhile, the difference in cool season is much less. Hence, it can be said that air conditioners have responsibility for a large amount of electricity consumption in households.

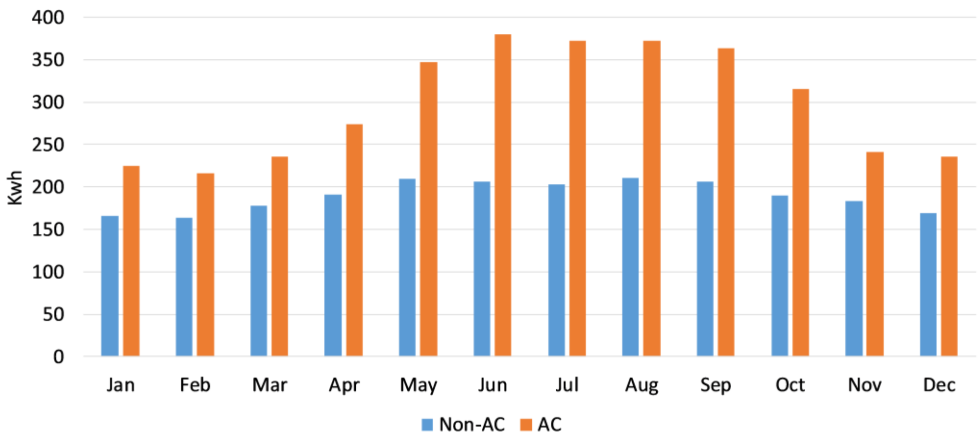


Figure 5.10: Monthly electricity consumption of households with air conditioners (AC) and non-AC

It is apparent from Figure 5.11 that on average, the more air conditioners the households have, the more electricity they consume. However, the electricity consumptions among households owning the same number of air conditioners are variable, though the difference among NV houses (standard deviation = 565 kWh/year) is much less than that of AC houses (standard deviation = 1499 kWh/year). This could be explained by the high electrical load capacity of air conditioners and the different usage among households in terms of the frequency of use and temperature settings.

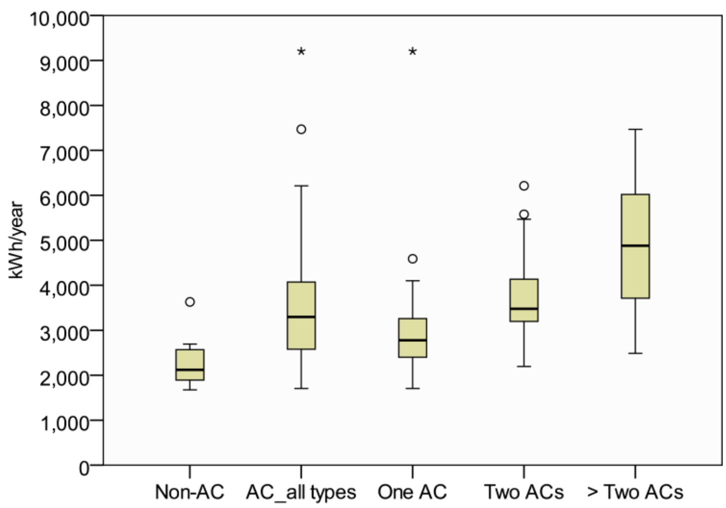


Figure 5.11: Distribution of electricity consumption by household types

5.2.3.2 Energy consumption breakdown

In urban areas of Vietnam, while electricity is the main source of energy for most appliances in households, liquefied petroleum gas (LPG) is the dominant energy for cooking. In rural areas, people still use biomass fuels, mainly as firewood and charcoal, however, this option is reducing because of impacts of urbanisation. There are some households in cities using charcoal or kerosene, but the amount is negligible. therefore, energy consumption in an urban household could be estimated from the sum of electricity and LPG consumption. In Vietnam, LPG is primarily supplied for households in the form of 12kg cylinders. In this survey on LPG consumption, on average, a household in Vietnam replaces the LPG cylinder every 1.7 months; this is equivalent to a consumption of 1152 kWh per year. Thus, including 3340 kWh of electricity use, a household typically consumed 4492 kWh of energy annually, equivalent to 16.2 GJ. Electricity and LPG consumption accounted for 74.4% and 25.6% of total energy use respectively. Annual energy consumption per capita was 1037 kWh while energy consumption on a floor area basis was 24.5 kWh/m^2.

In order to determine the energy consumption breakdown, the method and formula (5.1) mentioned in subsection 5.1.3 was employed. According to Tuy Hoa city's weather, warm season is from April to October when the local residents often use mechanical ventilations for achieving thermal comfort. This period of use was confirmed by one of the authors in discussion with the occupants. Therefore, it is assumed that housing occupants use fans for cooling for 210 days per year. The same period of use was also proposed in another study in Vietnam (T. T. B. Le & Nguyen, 2015). It is generally thought that people tend to use air conditioners more reservedly because of their high electricity consumption and cost. Air conditioners are usually used in hot summer, from May to September, when fan use cannot satisfy the thermal comfort. It is therefore reasonable to assume that people use air conditioners for the 150 days per year which satisfy this condition. Also, hot water is only needed for 90 days per year (in the cool season from December to February when the daily average of outdoor temperature falls below 25°C). The demand of hot water is absent in the rest of the year.

As mentioned above, lighting systems were not surveyed in this study due to their complexity of type, number and methods of control/switching. In order to estimate the electricity consumption for lighting, data were proposed based on the calculated normal lighting demand of an existing typical three-bedroom house in Vietnam and made use of information on use provided by householders. The calculations produce outcomes in line with other cities in the region: for instance, the lighting electrical energy fraction for Tuy Hoa is 10.9% compared well with Hong Kong at 10.4%; and lighting energy as a percentage of all energy use for Tuy Hoa of 8.2% compares with Johor Bahru, Malaysia at 8% and Jakarta, Indonesia at 9%. Calculated average electricity consumption for a range of appliances is shown in Table 5.3.

The surveyed actual average electricity consumption of households (3340 kWh) is 74.1% of the theoretically calculated electricity consumption (4508 kWh). This difference could be explained by the fact that in reality people usually do not operate appliances at full capacity. This result is also in line with two studies in India where the authors applied a scaling factor of 0.75 when they estimated electricity consumption of appliances (McNeil, Iyer, Meyers, Letschert, & McMahon, 2008; Singh, Mantha, & Phalle, 2018). Thus, in order to estimate the electricity consumption breakdown of the actual total use of 3340 kWh, this study assumed that occupants normally operate the appliances at 75% of full capacity. The formula (5.1) was adapted to:

$$\text{Electricity consumption} = \text{power rating} \times \text{working hours} \times \text{number of items} \times 0.75 \qquad (5.2)$$

The electricity consumption of every appliance was recalculated by formula (5.2) and shown in descending order of value per annum in Figure 5.12. Air conditioners consumed the largest amount of electricity at 1078 kWh, accounting for 32% of the total 3340 kWh, followed by rice cookers, fans and fridges respectively at 325, 303 and 301 kWh.

Taking into account cooking gas, Figure 5.13 shows the breakdown of total energy consumption in households. In general, electricity for cooling is responsible for 31.9% of overall energy consumption, followed by cooking gas with 25.4%. Kitchen appliances, including fridge, rice cooker and kettle, are the third contributor with 18.5%. Lighting accounts for 8.2% while the shares of water heater and television are less than 5%. The above numbers reveal that the most effective solutions for energy saving in households are associated with cooling and with cooking; therefore, the reduction of energy used to meet cooling demands, particularly in air conditioner usage, is of great significance.

Table 5.3: Theoretical calculation of average electricity consumption in a household

Type of end-use	Appliances	Power Rating (W)	Frequency of use (h/day)	Days of use	Electricity use/item/year (kWh)	Average number (surveyed)	Electricity use/year (kWh)	% of electricity use
Cooling	Air conditioner	960	7.23	150	1041.1	1.38	1436.7	42.8%
	Wall & stand fan	55	8.75	210	101.1	4	404.3	
	Ceiling fan	75	4.64	210	73.1	1.22	89.2	
Kitchen appliances	Rice cooker	600	1.85	365	405.2	1.07	433.5	24.8%
	Fridge	-	24	365	365.0	1.1	401.5	
	Kettle	700	0.67	365	171.2	0.9	154.1	
	Oven	1500	0.23	365	125.9	0.38	47.9	
	Microwave	1000	0.28	365	102.2	0.4	40.9	
	Range hood	240	0.8	365	70.1	0.37	25.9	
	Blender	400	0.13	365	19.0	0.82	15.6	
Laundry	Iron	1200	0.34	365	148.9	1.1	163.8	6.7%
	Washing machine	500	0.75	365	136.9	1	136.9	
Television	Television	50	5.8	365	105.9	1.8	190.5	4.2%
Water heater	Electric water heater	3500	0.74	90	233.1	1.1	256.4	5.7%
Other	Desk computer	200	2.21	365	161.3	0.38	61.3	4.8%
	Laptop	50	3.43	365	62.6	1.07	67.0	
	Hair drier	1500	0.15	365	82.1	0.8	65.7	
	Speaker	150	0.67	365	36.7	0.58	21.3	
	DVD	30	0.58	365	6.4	0.45	2.9	
Lighting	Fluorescent light	36	5	365	65.7	5	328.5	10.9%
	Compact light	5	5	365	9.1	10	91.3	
	Decorative light	100	1	365	36.5	2	73.0	
	Yearly electricity consumption						4508	100%

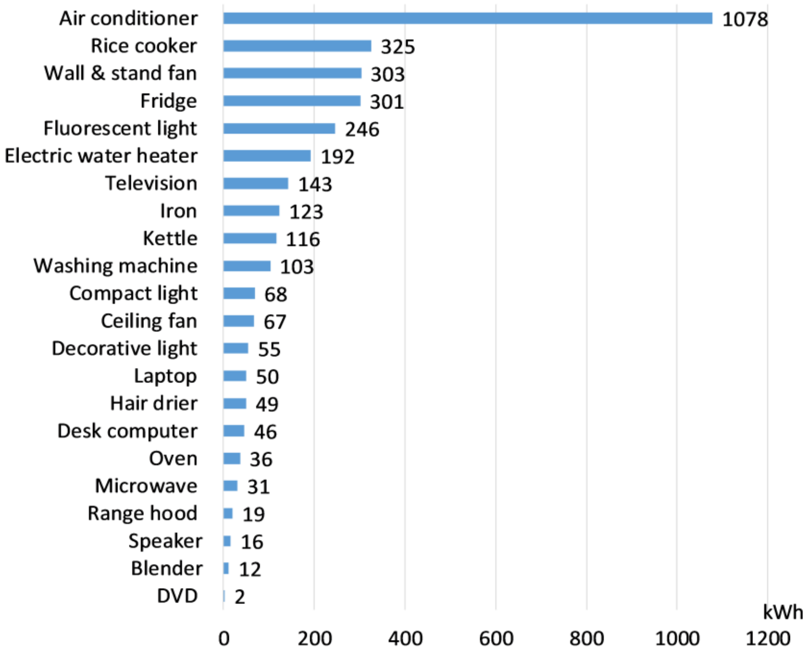


Figure 5.12: Yearly electricity consumption of appliances

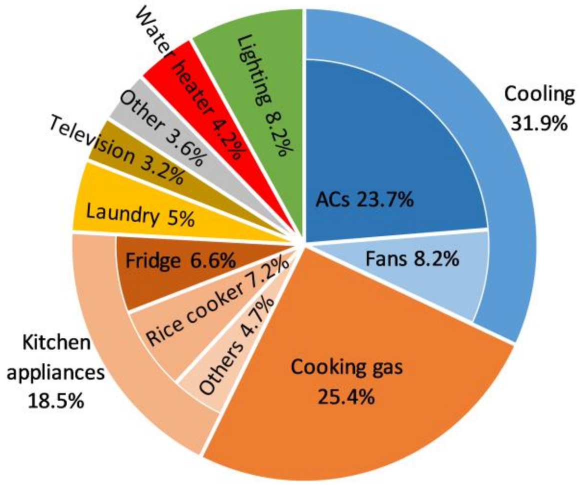


Figure 5.13: Energy consumption breakdown in households

5.2.4 Comparison with energy consumption from previous studies and other countries

Regarding electricity consumption, surveyed households in Tuy Hoa city consume on average 3340 kWh per year. This result is similar to the consumption (3356 kWh) of current urban households in India (Singh et al., 2018). In comparison with other studies in Vietnam, this result is slightly lower than that of the Cimigo survey (3722 kWh) and also lower than the published consumption levels of households in Ho Chi Minh city and the capital Hanoi, which are 4473 and 4694 kWh respectively (Murakoshi et al., 2017). These are the two largest cities of Vietnam with much economic development and high living standards, which could help explain the differences of household electricity consumptions between them and Tuy Hoa. In case income was a factor affecting energy use, the authors compared monthly income per capita for those different areas of Vietnam can derived from the National Statistics Office report of 2016. Phu Yen province had the average income of 2.358 million VND (US$ 129); Ho Chi Minh City 5.109 million VND (US$ 219); and Hanoi City 4.875 million VND (US$ 209). Although Phu Yen province in which Tuy Hoa is located has a lower value this represents an average taken across urban and rural areas. The climate is also significantly different in each location also affecting demand.

It is noted that some of the above data of electricity consumption were acquired from urban households which could be much higher than the values representing the whole country. Thus, in order to compare to other countries in the world, the average electricity use of a household in Vietnam was needed for use in further analysis. Because this information is not readily available, it has been estimated by dividing the total residential electricity consumption of 45703 GWh (obtained from International Energy Agency (IEA)) by the total of 24 million of households in Vietnam (2014).

Figure. 5.14 shows the average household electricity consumptions of countries and regions in the world; data were adapted from World Energy Council via website wec-indicators.enerdata.net (World Energy Council, 2014). It can be seen from the graph that the Vietnamese household electricity consumption approximately equals the Asia average and is half the EU figure. In comparison with other Asian countries, the Vietnamese average is double that of Philippines and almost equal to that of Indonesia but 400kWh less than that of Thailand. In Southeast Asia, Singapore households consume a considerable amount of electricity; this is due to the prosperous economy and high urbanisation of this small island. The Middle East and America are areas consuming high levels of electricity; however, the comparison of electricity use among countries with different climate zones could lead to less confidence in the results because there are many factors driving electricity consumption in households. These could be, for instance, the house size, the severity of the climate, and the types of energy used for cooking, heating or cooling.

Figure. 5.15 shows the comparison between several cities and countries in terms of household energy consumption by types of end use. The data were synthesised from various sources and studies (Eurostat, 2016; Kubota et al., 2011; Kubota, Surahman, & Hisagi, 2014; Singapore Energy Market Authority, 2017; U.S. Energy Information Administration, 2015). Data on lighting and water heater consumption of Ho Chi Minh city were not available, they were therefore combined into other end-use categories. It is easy to recognise from the chart the significant difference between Asian countries and Western countries both in total energy use and the usage patterns. Space heating is the dominant end use of households in temperate countries while space cooling accounts for a large proportion of the total energy use in warm countries' households. The share of energy for cooling demand is approximately 30% in Tuy Hoa, Johor Bahru and Singapore and is slightly lower in Jakarta (22%) and Ho Chi Minh city (20%). Cooking is the second energy-consuming category in Asian households accounting for 34% in Jakarta, 27% in Johor Bahru and 25.4% in Tuy Hoa. In general, total energy consumption in Tuy Hoa's household is less than that of bigger cities in Southeast Asia. However, there is a similarity between energy usage patterns of households in Tuy Hoa city and other cities in the same climate zone, especially with Johor Bahru in Malaysia.

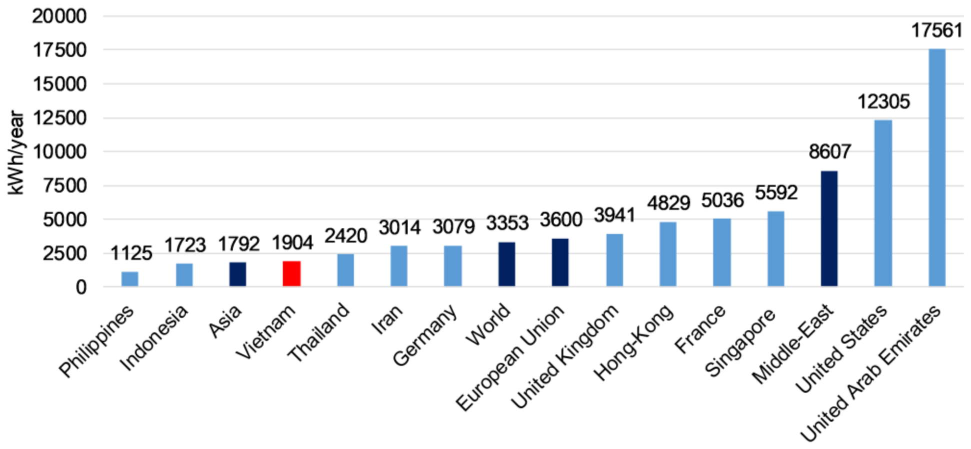


Figure. 5.14: Average household electricity consumption of countries in 2014

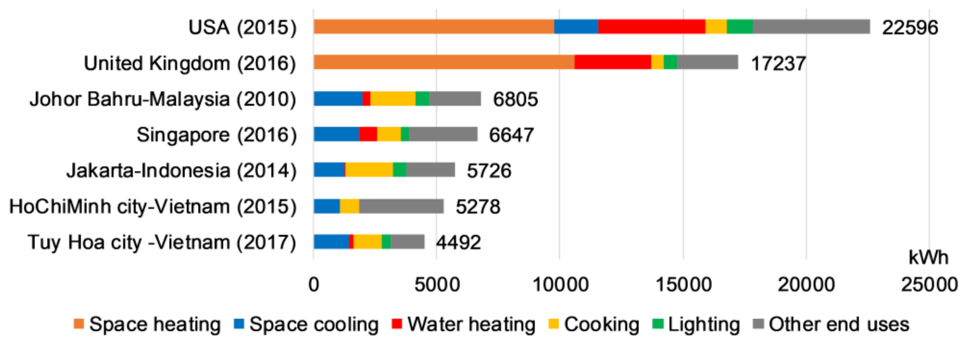


Figure. 5.15: Average household energy consumption by end-use types

5.2.5 Challenges for energy conservation in Vietnamese household

Economic development and rapid urbanisation in Vietnam have led to the improvement of living standards. Accordingly, the demand for electrical appliances has increased in terms of both quantity and range of types. Also, cooling demand for ensuring indoor thermal comfort has been much emphasised; according to an IEA report, the air conditioner market is rapidly expanded in Southeast Asia countries and in Vietnam, it has tripled between 2012 and 2017 (IEA, 2017). These trends lead to an increase of energy consumption in residential sector.

The Government of Vietnam has made efforts to conserve energy during the last decade. The Energy Efficiency and Conservation Law came into effect in January 2011, followed by many decrees and circulars being promulgated. Some energy saving programmes have been implemented to promote the production and import of energy saving equipment and energy saving technologies. The energy efficiency support fund was also set up to support these programmes.

The Energy efficiency appliance labelling programme, (a programme which is part of the Vietnam Energy Efficiency Programme (VNEEP) implemented from 2006), has so far achieved positive results. For instance, 90% of air conditioners and fridges have been labelled and the annual consumption of incandescent bulbs significantly decreased from 55 million bulbs in 2011 to 5 million bulbs in 2015 (Energy Efficiency and Conservation Office of Vietnam Ministry of Industry and Trade, 2017). However, it can be seen that energy efficiency policies have mainly focused on industrial and commercial sector whilst the residential sector has not been paid adequate attention.

The integration of renewable energy sources such as solar hot water or photovoltaic systems in households is still limited, with particularly low uptake of photovoltaic systems, although Vietnam has a high potential for use of solar systems. This could be explained by the high cost and partly by poor awareness about renewable energy of householders and even building designers.

Poor building thermal performance is another challenge to energy conservation effort (thermal performance of existing housing in Vietnam are presented in the next chapter). Thus, much energy is used for cooling demand which was shown in this study. There is no mandatory building efficiency code for dwellings so far.

In addition to the concern of the high cooling demand, energy use in cooking and kitchen appliances should be paid adequate attention since they accounted for total 43.9% of the energy use in current households. Because these end uses are essential, the reduction of energy use in kitchen is a difficult challenge. Improving energy efficiency of gas stoves and kitchen appliances could be an effective solution besides raising awareness of the energy use in kitchen.

5.3 Chapter conclusion

This chapter presents the methodology and results of a survey on household energy consumption in Vietnam in 2017. An analysis of the data collected provided comprehensive information on household characteristics, housing types, appliance ownership, usage behaviour and energy consumption. The main results are as follows:

The average household size is 4.3 people/household. 50% of households is nuclear family with 2 adult and 2 children. 97% households live in terraced houses. Average floor area is 209 m^2 per household (std. deviation = 61), which means 48 m^2 per capita. Average household appliance ownership and daily usage time were calculated. 82% of households own air conditioners and they averagely operate 7.23h per day mostly when they sleep at night and noon time.

Average energy consumption is 4492 kWh/household/year in which electricity and LPG account for 74.4% and 25.6% respectively. Energy consumption breakdown was figured out by using a theoretical calculation method. Cooling demand accounted for 31.9% with 23.7% belong to air conditioner use. Cooking gas accounted for 24.5% followed by kitchen appliances of 18.5%.

The result of this survey is a valuable reference, especially in the context of lacking seriously information on household energy consumption in Vietnam. For the whole research in particular, this survey determined the typical household-appliance-use pattern that will be applied to the proposed housing models in modelling and simulation stages. The results of actual electricity consumption will be used as a baseline in comparison with simulation results to assess the energy efficiency of proposed design techniques. These applications are described in the next two chapters.

Chapter 6 Thermal performance of existing housing in Vietnam and potential of energy saving

Chapter 5 indicated that energy consumption in residential buildings makes up a third of total energy consumption in Vietnam, in which energy for cooling accounts for 31.9%. In the context of ongoing global warming along with economic development, the incorporation of mechanical cooling systems to maintain indoor thermal comfort has been much encouraged in dwellings. The air conditioner market in Vietnam has tripled between 2012 and 2017 (IEA, 2017). This trend results in an increase of energy consumption in the residential sector. Therefore, in order to achieve the low energy housing target, it is necessary to understand the thermal performance of existing housing in Vietnam and the potentials of energy saving for this building type.

This chapter covers the above issues with a focus on four main themes. Firstly, a field study on building characteristics and environmental performance of Vietnamese existing housing in hot and cool seasons was reported. Secondly, this chapter presents a simulation on the whole-year thermal performance and energy consumption of the proposed housing models representing existing housing. Thirdly, the energy-saving potentials for Vietnamese housing was identified through an application of passive design techniques to improve the existing housing models. The thermal performance of existing housing and the effectiveness of passive design techniques will be evaluated using the thermal comfort zone found in Chapter 4. Finally, the high humidity problem and dehumidification demand of the improved housing models were determined, which bring up the necessity of an advanced and integrated approach to building design.

6.1 A field study on thermal performance of existing terraced housing

This field study aims to understand the prevailing construction materials and thermal performance of existing housing in Vietnam. The results of this study contributed to the whole project in following aspects:

- The understanding of housing characteristics and prevailing construction materials helped to explain the thermal performance of existing housing. Moreover, these data were used to create housing models representing existing housing in the next simulation step.
- On-site measurement on environmental variables revealed the actual thermal performance of existing housing. Thereby, the limitations of existing housing were identified, followed by the proposed solutions.

6.1.1 Survey method

Time scale: This study employed a cross-sectional survey. This time scale was selected rather than longitudinal one due to the constrains of time and measuring instruments of the field study conducted in Vietnam. Moreover, this study does not aim to improve the energy efficiency of any specific house, therefore, longitudinal surveys for comparison and model calibration are not vitally necessary. However, cross-sectional surveys were conducted in hot and cool seasons to properly understand the thermal performance of existing housing in the two extreme seasons.

Sample: Terraced housing was the subject of this survey due to the largest proportion of this building type in the residential sector. The houses were selected based on following criteria: Firstly, the façade width is 4m or above; from 2 to 5 storeys; and only being used for residential living. These criteria ensure a focus on the common type of existing terraced housing as well as the common type in new residential planning projects. Secondly, the houses are orientated to different orientations to take into account the effects of solar radiation and prevailing wind. Finally, the houses are scattered around the city to cover the effect of micro-climate in different city zones.

Table 6.1: Surveyed houses' properties and time of survey

Number	House's properties				Starting time of survey	
	Orientation	Number of storeys	Land dimension (m)	Land coverage (m)	Hot season (August 2017)	Cool season (February 2018)
1	Southwest	3	5 x 18	5 x 14	10:00	15:00
2	Northwest	3	5 x 25	5 x 20	14:00	17:40
3	Southwest	3	5 x 17	5 x 11	10:00	15:20
4	Southwest	3	5 x 25	5 x 19	14:00	14:00
5	Southwest	3	5 x 18.5	5 x 18.5	10:00	09:30
6	Southeast	3	5 x 25	5 x 23	10:00	16:00
7	Southeast	3	5 x 20	5 x 17	14:00	17:20
8	Southeast	3	6 x 25	6 x 21	14:00	17:15
9	Northeast	3	6 x 25	6 x 20	14:00	17:15
10	North	2	5 x 20	5 x 16	10:00	16:30
11	Northeast	2	5 x 22	5 x 19	14:00	10:00
12	East	3	5 x 20	5 x 20	10:00	16:20

Figure 6.1: Locations of surveyed houses in Tuy Hoa city
(Source: Google map 2017)

Figure 6.2: Typical façade and interior images of surveyed houses

There are 12 terraced houses in Tuy Hoa city participating in this survey. Table 6.1 shows a summary of the housing properties and the survey time in both hot and cool seasons. It is noted that due to the urban plan of the city (Figure 6.1), major orientations of the buildings are SW, SE, NW, and NE. Figure 6.1 shows locations of the surveyed houses whilst Figure 6.2 shows typical façades and interior spaces of the houses.

Data collection techniques: Observation technique was used to collect data on housing design and construction materials including the materials of main structure, façade, and roof. On-site spot measurement was used to collect data on indoor and outdoor environmental variables in surveyed houses.

Before measuring environmental variables, the surveyors (author and assistants) recorded the housing characteristics including orientation, land dimensions, building size, main structure and materials. The floor plans were measured, sketched and subsequently redrawn on computer. Photos were also captured and stored.

On-site spot measurements were carried out to collect data on environmental variables including air temperature, black globe temperature, relative humidity, natural light and air velocity. The measurements were taken room by room, both indoor and outdoor. During the measurement process, all cooling equipment including fans and air conditioners were turned off whilst windows and doors were opened to be able to collect environmental data in free-running mode. It is noted that in cool season when outdoor temperature drops below 25°C, occupants often close windows and doors to prevent low outdoor temperature and cold winds. Consequently, natural light and air velocity variables were not measured in the cool season. The measurement process in each house lasted about 2.5 to 3 hours depending on the size of the house. In hot season, the measurements were taken between 10:00 and 17:00 to ensure the house was surveyed in the hot period of a day, in which the starting time was strictly managed at 10:00 or 14:00. In cool season, the starting time was more flexible since temperature amplitude in daytime was small and the measuring time was shorter.

Five environmental variables were measured by handheld instruments. The corresponding measuring protocols were based on the 2009 ASHRAE Handbook – Fundamentals (ASHRAE, 2009) and the Vietnam building code TCXDVN 306:2004 (MOC, 2004). Air temperature, black globe temperature and relative humidity were measured at the centre point in each room at the height of 1.1m above the floor level. The values shown on digital thermometers were recorded when the devices completed the calibration. Air velocities were also measured at the height 1.1m and the data were recorded under the form of 2D mesh corresponding to the floor plans of the house. The mesh boundary is indented 0.5m compared to the interior wall edges. The recorded air velocity at each dot of the mesh was the average value of the automatic measurements over 30 seconds. Air velocities at windows and doors were also measured. Daylight data on the same grid were collected at 0.8m above the floor (the height of working plane). Figure 6.3 shows an example of the way the 5 environmental variables were recorded for a floor plan.

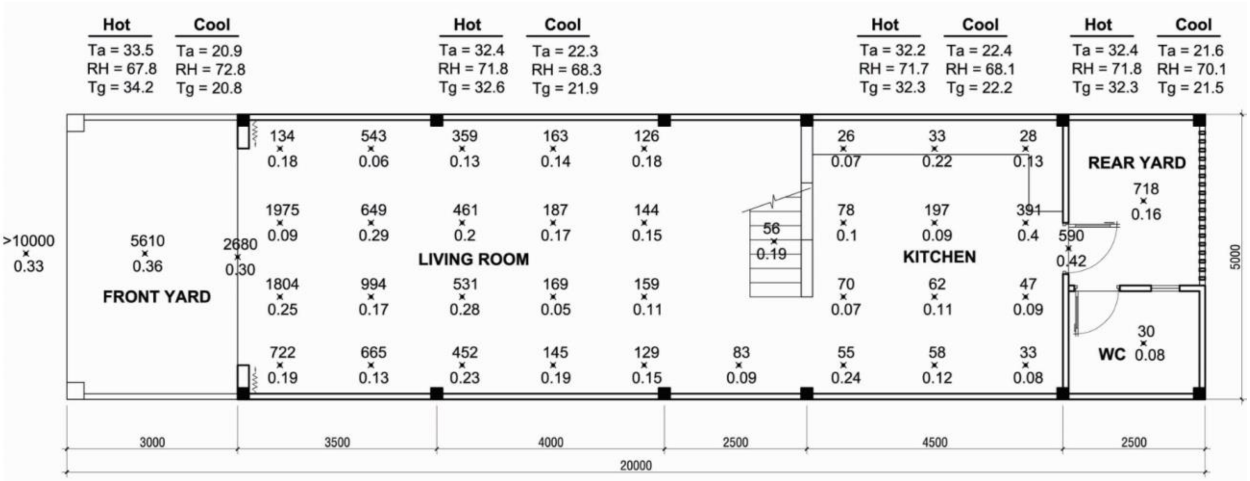


Figure 6.3: An example of recording method of environmental variables on a floor plan

Instrumentation: Information of the instruments used in this survey are shown in Table 6.2. According to technical information provided by the manufactures, these instruments have high resolution and accuracy. The equipment used in this survey were in good condition. Their accuracy was validated by comparison with other measuring devices before being used in on-site measurements.

Table 6.2: Instruments used for measurements of environmental variables

Equipment		Measuring functions used	Manufacturer and code	Resolution	Accuracy
Heat Index WBGT meter		Air temperature (°C) Black globe temperature (°C) Relative humidity (%)	PCE WB – 20 SD	0.6°C 0.1% RH	± 0.6°C ± 3% RH
Mini thermal anemometer		Air velocity (m/s)	Testo 425	0.01 m/s	± 0.03 m/s
4 in 1 environmental meter		Illuminance (lux)	CEM DDT 8820	0.1 lux	± 5%

Data analysis techniques: The collected data were summarised and analysed using a spreadsheet software Microsoft Excel (Office 365) and a more advanced data analysis software IBM SPSS Statistics (version 24). Descriptive statistics to understand the distributions of environmental variables and T-test analyses for comparison purpose are the main analysis techniques in this survey.

6.1.2 Prevailing construction materials

According to the field study on 12 surveyed houses and further observations on many houses in Tuy Hoa city and in other cities in Vietnam, it is observed that the prevailing materials of existing housing are reinforced concrete frame, brick wall covered by plaster, single-glazed windows with simple frame made of wood, steel, or aluminium, concrete flat or corrugated metal roofs, all without use of insulation material (Figure 6.4). The common construction materials of urban houses are listed in Table 6.3.

Table 6.3: Prevailing construction materials of housing in Vietnam

Building element	Common material	Other material
Column, beam and slab	Reinforced concrete	-
Wall	Clay brick, cement plaster and paint coating	-
Roof	Reinforced concrete flat roof	Pitched roof: Wooden structure with roof tiles; steel structure with corrugated metal sheets.
Window	Simple wooden, steel or aluminium frame with single glazing	PVC frame with single or double glazing
Ceiling	Gypsum board	Timber, PVC
Floor	Ceramic tile	Timber

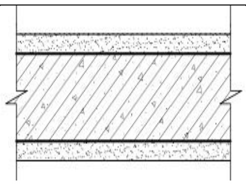
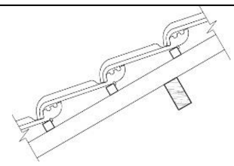
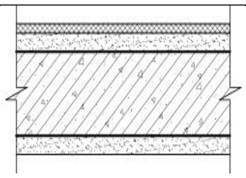
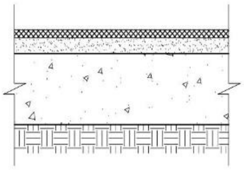
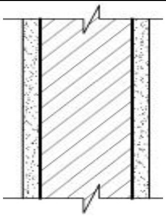
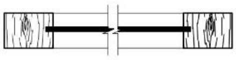
Figure 6.4: Common construction materials in Vietnamese housing

Table 6.4 shows properties of common construction materials including density and thermal conductivity values. Based on these data, thermal transmittance (U-values) of existing housing components were calculated and shown in Table 6.5. It can be seen that the common construction materials have high thermal conductivity which result in the high U-values of housing components. For example, the U-values (W/(m^{2}K)) are 3.18 for concrete flat roof, 2.97 for 110mm brick wall and 5.59 for window. These values are much higher than the National Technical Regulation on Energy Efficiency Buildings (QCVN 09:2013) which requires U-value of 1.8 W/(m^{2}K) for external walls and 1.0 W/(m^{2}K) for flat roofs. Consequently, a considerable amount of energy was used for cooling demand which was shown in chapter 5. It is noted that QCVN 09:2013 is only applied to buildings over 2,500 m^2 of floor area. There is no mandatory building efficiency code for dwellings so far.

Table 6.4: Density and thermal conductivity of common building materials
(source: TCVN 9258:2012 (VIAP, 2012a)*)*

Material	Density (kg/m^3)	Thermal conductivity (W/(mK))
Hollow clay brick	1350	0.58
Cement plaster	1700	0.87
Reinforced concrete	2400	1.55
Lining concrete	1800	1.28
Ceramic tile	2022	1.1
Clay roof tile	2100	1.5
Gypsum board for ceiling	530	0.16
Glass	2500	0.75
Wood	700	0.23

Table 6.5: Common structural properties and thermal transmittance of housing components

Housing component	Section	Layers	Thickness (mm)	U-value* (W/(m^{2}K))
Flat roof		Cement plaster Waterproof layer Reinforced concrete Cement plaster Paint coating	20 - 100 15 -	3.18
Pitched roof		Clay roof tile Wooden frame (batten, rafter, purlin)	20 -	-
Slab		Ceramic tiles Cement plaster Reinforced concrete Cement plaster Paint coating	8 20 100 15 -	3.11
Ground floor		Ceramic tiles Cement plaster Lining concrete Levelled sand Soil layer	8 20 100 100 -	2.60
Wall		Paint coating Cement plaster Clay brick Cement plaster Paint coating	- 15 80 (or 180) 15 -	2.97 (for 110mm wall) (or 1.93 for 220mm wall)
Window		Simple frame Single-layer glass	- 5	5.59
Gypsum ceiling		Gypsum boards	6	4.55

* Includes thermal transmittances of indoor surface at 7.7 W/(m^{2}K) and of outdoor surface at 25 W/(m^{2}K)

In summary, the building elements of Vietnamese existing housing have high thermal transmittance values. This poor insulation could result in poor thermal performance of existing housing. The question then arises to determine the thermal performance of current housing. To find the answer for this question, on-site measurements of environmental variables in the 12 houses were conducted and reported in the next subsection.

6.1.3 Thermal performance of existing housing

Environmental variables were carefully measured in all spaces of the surveyed houses. Table 6.6 shows the average data of each house and the mean values of 12 houses. As mentioned above, most houses in Tuy Hoa city often close all windows and doors in the cool season, therefore, indoor air velocities in cool season were not measured. Although data on daylight were collected, they were not analysed further in this particular investigation.

Table 6.6: Average environmental data of 12 surveyed houses

House number		01	02	03	04	05	06	07	08	09	10	11	12	Mean	SD
Orientation		SW	NW	SW	SW	SW	SE	SE	SE	NE	N	NE	E		
Outdoor (Hot season)	T_a (°C)	31.4	32.3	33.2	32.9	33.9	33.6	33.5	32.9	32.5	32.4	32.4	34.4	33.0	0.8
	T_g (°C)	31.8	32.9	33.3	33.3	35.7	34.5	34.2	33.6	33.4	33.7	34.3	35.7	33.9	1.1
	RH (%)	64.3	65.1	60	68.7	54.8	60.2	67.8	68.9	68.1	65.9	67.3	56.3	64.0	4.9
	V (m/s)	0.32	0.4	0.15	0.37	1.07	0.84	0.33	0.74	0.45	0.67	0.46	0.55	0.5	0.3
	T_{op} (˚C)	31.8	32.8	33.3	33.3	35.6	34.4	34.1	33.5	33.3	33.6	34.1	35.6	33.8	1.1
Indoor (Hot season)	T_a (°C)	31.0	31.8	31.8	32.6	32	32.4	32.7	31.7	32.1	30.7	31.1	31.3	31.8	0.6
	T_g (°C)	31.1	31.8	31.7	32.6	32	32.4	32.7	31.7	32.1	30.7	31.1	31.2	31.8	0.6
	RH (%)	66.3	65.6	64.5	69.7	65.8	63.4	70.7	68.2	72.2	70.4	72.3	66.5	68.0	3
	V (m/s)	0.12	0.18	0.11	0.17	0.2	0.17	0.16	0.13	0.12	0.11	0.15	0.09	0.1	0.03
	T_{op} (˚C)	31.1	31.8	31.7	32.6	32	32.4	32.7	31.7	32.1	30.7	31.1	31.2	31.8	0.6
Outdoor (Cool season)	T_a (°C)	24.7	22	23.9	24.8	25	22.4	20.9	24.2	20	21.8	24.5	23.5	23.1	1.7
	T_g (°C)	25.2	21.8	24.7	25.9	26.8	22.6	20.8	23.8	19.8	22	25	23.6	23.5	2.1
	RH (%)	63.7	67.5	68.9	64.1	60	70	72.8	78.6	70	72.2	61.2	68.6	68.1	5.3
Indoor (Cool season)	T_a (°C)	24.4	23.5	24.8	24.9	24.2	23.6	22.9	25.6	22.8	23.6	23.9	24.5	24.1	0.8
	T_g (°C)	24.3	23.2	24.5	24.8	23.9	23.3	22.7	25.3	22.4	23.4	23.7	24.2	23.8	0.9
	RH (%)	66.3	68.9	66	66	65.8	67.6	66.1	71.6	65.5	68.9	68.3	67.7	67.4	1.8

T_a: Air temperature; T_g: Globe temperature; T_{op}: Operative temperature; RH: Relative humidity; V: Air velocity; SD: Standard deviation
SW: Southwest; SE: Southeast; NW: Northwest; NE: Northeast; N: North; E: East

Table 6.7: Paired samples T-test results of outdoor and indoor environmental variables

	Pair	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
					Lower	Upper			
Pair 1	Outdoor - Indoor T_{op} (Hot season)	2.03	1.19	0.34	1.27	2.78	5.87	11	0.000
Pair 2	Outdoor - Indoor V (Hot season)	0.39	0.25	0.07	0.23	0.54	5.41	11	0.000
Pair 3	Outdoor - Indoor RH (Hot season)	-4.02	3.54	1.02	-6.27	-1.77	-3.93	11	0.002
Pair 4	Outdoor - Indoor T_a (Cool season)	-0.92	1.11	0.32	-1.62	-0.21	-2.86	11	0.016
Pair 5	Outdoor - Indoor RH (Cool season)	0.74	4.57	1.31	-2.16	3.65	0.56	11	0.585

T_a: Air temperature (°C); T_{op}: Operative temperature (°C); RH: Relative humidity (%); V: Air velocity (m/s)

Figure 6.5 shows the distribution of outdoor and indoor temperature in hot and cool seasons. This figure reveals that there was a significant difference of temperatures between hot and cool seasons which was approximate 10°C. A paired samples T-test was carried out to compare the outdoor and indoor environmental variables. According to the results shown on Table 6.7, there was a significant difference of 2.03°C between the outdoor and indoor operative temperature in hot season (p=0.00). In cool season, this difference of air temperatures reduced to 0.92°C which was still significant (p=0.016). It is interesting to see that in hot season, the mean outdoor temperature (33.8°C) was higher than the mean indoor temperature (31.8°C) whilst a comparison of those values in cool season show the contrary. The mean outdoor and indoor temperature in cool season were 23.1°C and 24.1°C respectively. This could be explained by the influence of high solar radiation in summer and the thermal capacity of materials of enclosed houses in winter.

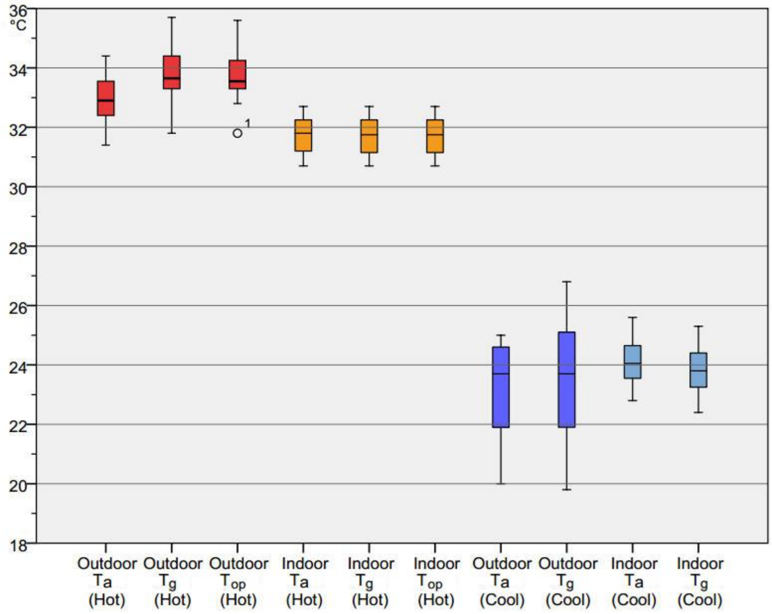


Figure 6.5: Distribution of outdoor and indoor temperature in hot and cool seasons

In comparison to the acceptable temperature range of 23.7 – 29.6°C in Chapter 4, it is affirmed that Vietnamese existing housing failed to satisfy thermal comfort in the extreme weather of the hot season since all of the measured indoor temperatures exceeded the upper limit of 29.6°C. In the cool season, the mean indoor temperature (24.1°C) was slightly higher than the lower limit. Although indoor temperature sometimes dropped below 23.7°C, it is noted that dwellings in Tuy Hoa city do not use any equipment for heating in the cool season. To cope with temperatures about 1°C below the comfort limit, the occupants simply adjust their clothes by adding a light jacket or jumper.

Regarding air velocity, Table 6.6 shows a significant difference of 0.39 m/s between outdoor and indoor air velocity in the hot season. While mean outdoor air velocity was 0.53 m/s, the indoor value was only 0.14 m/s and that has little impact on indoor thermal comfort. Moreover, according to the distribution of outdoor and indoor air velocities shown in Figure 6.6, while the outdoor air velocities fluctuated within a wide range from 0.15 to 1.1 m/s, the indoor values were always less than 0.25 m/s. This means the housing design was not effective in terms of catching outdoor winds. These results indicate a poor performance of natural ventilation in existing housing if it is to be used to increase air movement. It is worth mentioning that the average wind speed in August 2017 (when this survey was conducted) obtained from the local meteorological station was 1.35 m/s. This value is much higher than the average air velocity of 0.53 m/s measured outside the surveyed houses. It is due to a fact that wind speed data from meteorological stations are measured at the heigh of 10m and has no obstructions around, which is totally different from the context of low-rise housing in the neighbourhood. This raises further questions about the effectiveness of the natural ventilation design approach in urban areas.

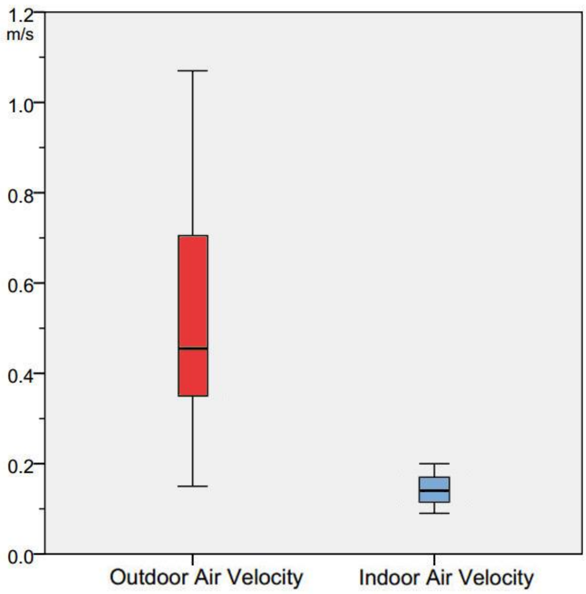


Figure 6.6: Distribution of outdoor and indoor air velocity in hot season

Figure 6.7 shows the distribution of outdoor and indoor relative humidity (RH) in hot and cool seasons. In the hot season, mean indoor RH was higher than mean outdoor RH whilst the contrary was observed in the cool season. Table 6.7 shows a difference of 4% and 0.74% between outdoor and indoor RH in hot and cool season respectively. Although the paired samples T-test showed a p-value of 0.002, the difference 4% between indoor and outdoor RH in hot season are not significant in practice. Generally, all measured indoor RH data exceed the upper threshold of 60% recommended by the ASHRAE 55 - 2017. Moreover, it is noted that the measurements were taken between 10:00 and 17:00 when the outdoor RH values are lower than the rest of the day (Figure 6.8). In addition, monthly average outdoor RHs in Tuy Hoa city are always higher than 74%, particularly in rain season from October to December when the values exceed 85%. Therefore, high humidity problem should be paid adequate attention in tropical dwellings to ensure thermal comfort and the quality of indoor air.

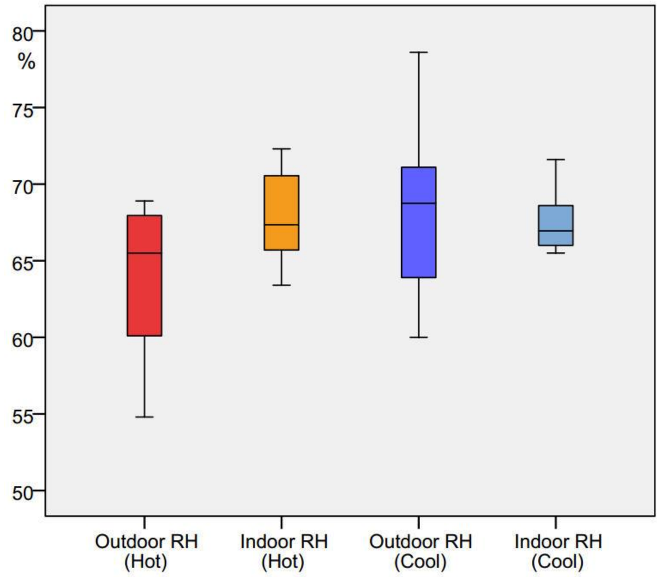
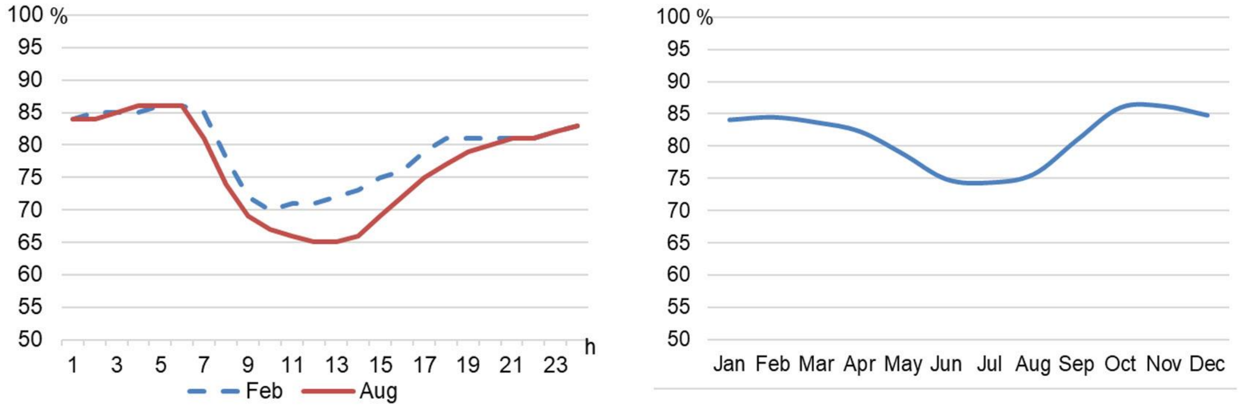


Figure 6.7: Distribution of outdoor and indoor relative humidity in hot and cool seasons



Diurnal variations of RH **Monthly average RH**

Figure 6.8: Diurnal variations and monthly average RH of Tuy Hoa city
(Source: Vietnam Building Code QCVN 02:2009/BXD ((MOC, 2009))

In summary, this field study provided an understanding of common construction materials and thermal performance of existing housing in Vietnam. In general, the housing components without use of insulation materials have high thermal transmittance (U-value). As a result, mean measured indoor temperature in hot season was relatively high, at 31.8°C which is 2.2°C higher than the upper limit of 29.6°C derived from the thermal comfort experiment. Moreover, the average indoor air velocity was only 0.14 m/s that indicated the inefficiency of natural ventilation in existing housing. Humidity is another problem since all measured RH data exceed the 60% threshold of acceptable RH. Consequently, Vietnamese existing housing showed a poor thermal performance and failed to satisfy thermal comfort in extreme weather.

This field study only collected the environmental data in the extreme months. Whole-year on-site measurement or data logging for 12 houses require considerable efforts as well as resources and are therefore out of the scope of this research. In order to obtain whole-year thermal performance of Vietnamese existing housing, computational simulation would be a suitable method. This approach also facilitated the prediction of energy consumption to maintain year-round thermal comfort for an existing house. The details are presented in the next section.

6.2 Simulation of whole-year thermal performance and energy consumption of the proposed existing housing models

This section firstly presents the proposal of housing models based on national regulations of housing design and common practices, and then describes the modelling of these models in the EnergyPlus software. Secondly, whole-year thermal performance in natural ventilation mode of these models using existing housing properties was simulated. Various natural ventilation schemes were tested to understand the thermal performance of existing housing in different conditions. Finally, further simulations were carried out to determine the energy demand for maintaining year-round thermal comfort in existing housing.

6.2.1 Modelling the proposed housing models

It is observed that the size and architectural designs of Vietnamese single-family houses are incredibly diverse. Therefore, defining typical housing models is a difficult task. Consequently, to simulate the whole-year thermal performance of existing housing while facilitating the investigation of energy-efficiency solutions for future housing, this study proposed housing models based on the combination of national housing design regulations and the observation of existing housing as well as housing in new residential projects.

Vietnam has two building regulations related to the size of housing, namely QCXDVN 01:2008/BXD (VIUP, 2008) and TCVN 9411:2012 (VIAP, 2012b). The size of land lot for housing is determined according to the need of users, in accordance with the urban planning and design of the area. However, the building code QCXDVN 01:2008/BXD specifies that the minimum area of a housing land lot is 45m^2 with the minimum width of 5 m for roads wider than 20m. For narrower roads, these requirements are 36m^2 and 4m respectively. Meanwhile, the standard TCVN 9411:2012 dedicated to terraced housing specifies that the minimum width of a terraced house is 4.5m with the minimum area of 45m^2. For terraced housing in new residential projects, these minimum numbers are 5m and 50m^2 respectively. The maximum number of storeys is limited at 6 and the minimum height of ground floor is 3.6m. The rear yard of a terraced house if available must be at least 2m long. It can be seen the minimum requirement of terraced housing length is only around 10 m that is rarely observed in new residential projects.

The urban planning of Ho Chi Minh city until 2025 defines more specific sizes of the prioritised terraced housing types in the future (HCMC People's Committee, 2013). The length of a terraced house is from 15 m to 20. The width is 4 or 5m, complied with the above national building codes. The number of floors is from 2 to 5. The front yard and rear yard if available are 3m and 2m respectively.

Regarding detached houses, so far there is no national standard dedicated to this housing type. Depending on the specific residential project, there will be separate rules for the size and architectural design of the detached houses in the neighbourhood. The national regulations only specify the land coverage ratio of single-family housing. For example, these ratio for 200m^2 and 300m^2 land lots are 70% and 60% respectively (VIUP, 2008).

Considering recent residential projects, it is observed that the terraced housing with 5 m width, 17 – 20m length, and 3 – 5 floors is preferred. It is due to this housing size can provide desired living spaces for the occupants in a normal-sized family with 4 or 5 members. For similar reason, the common land lot of detached housing is between 200 and 300m^2 with approximately 60% of the land coverage ratio. The number of floors of detached housing is often 3 or 4. Figure 6.9 and Figure 6.10 show some examples of terraced and detached housing in recent residential projects across the country.

Project in Tuy Hoa city
Land size: 5 x 18.5 m
House size: 5 x 18.5 m
(Source: author)

Project in Nha Trang city
Land size: 5 x 20 m
House size: 5 x 18 m
(Source: H.T.A. Nguyen)

Project in Ho Chi Minh city
Land size: 5 x 20 m
House size: 5 x 17 m
(Source: landgroup.vn)

Figure 6.9: Examples of terraced housing in recent residential projects

Project in Tuy Hoa city
Land area: 270 m^2
Land coverage: 60%
(Source: author)

Project in Ho Chi Minh city
Land area: 275 m^2
Land coverage: 60%
(Source: cuongthinhland.vn)

Project in Bien Hoa city
Land area: 300 m^2
Land coverage: 50%
(Source: dothi-aquacity.vn)

Figure 6.10: Examples of detached housing in recent residential projects

Based on the mentioned-above national building standards and the observation of existing housing and housing in recent residential projects, this study proposed two single-family housing models for terraced housing and detached housing as shown in Figure 6.11 and Figure 6.12.

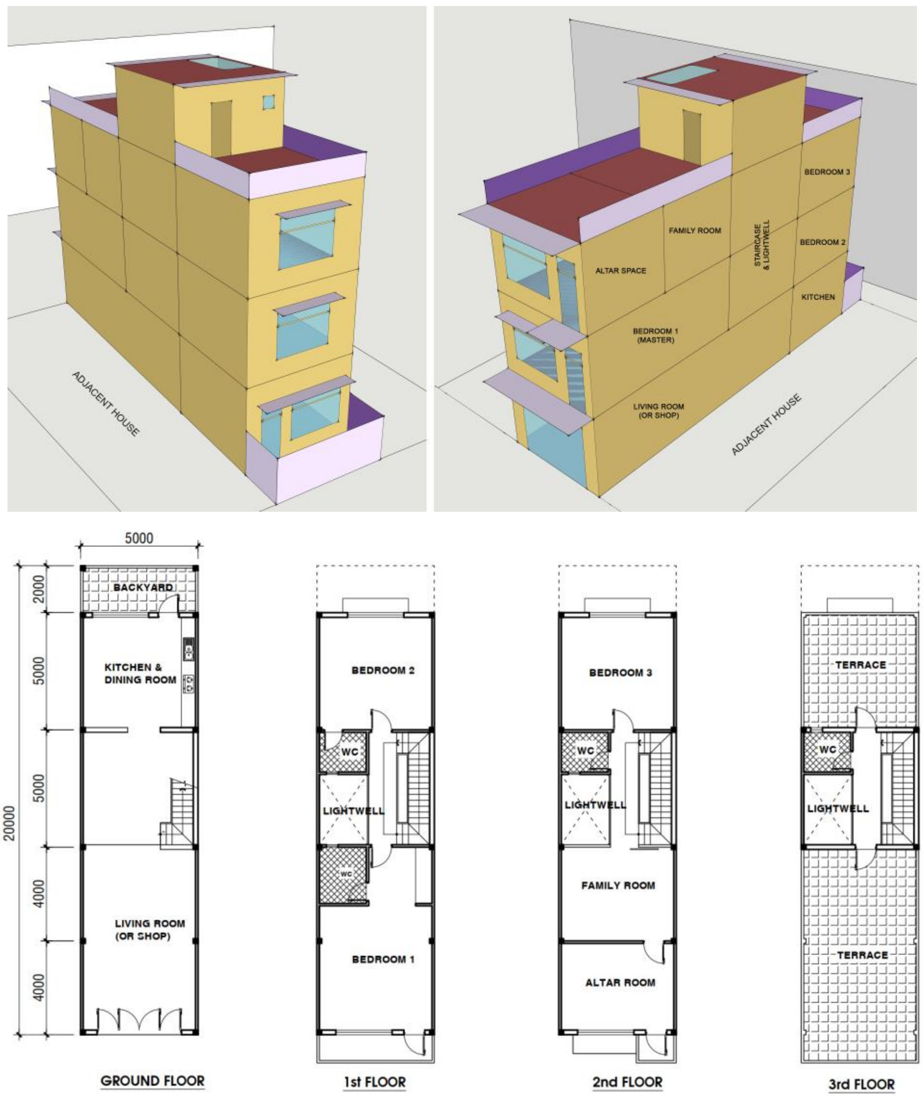


Figure 6.11: Terraced house model and floor plans

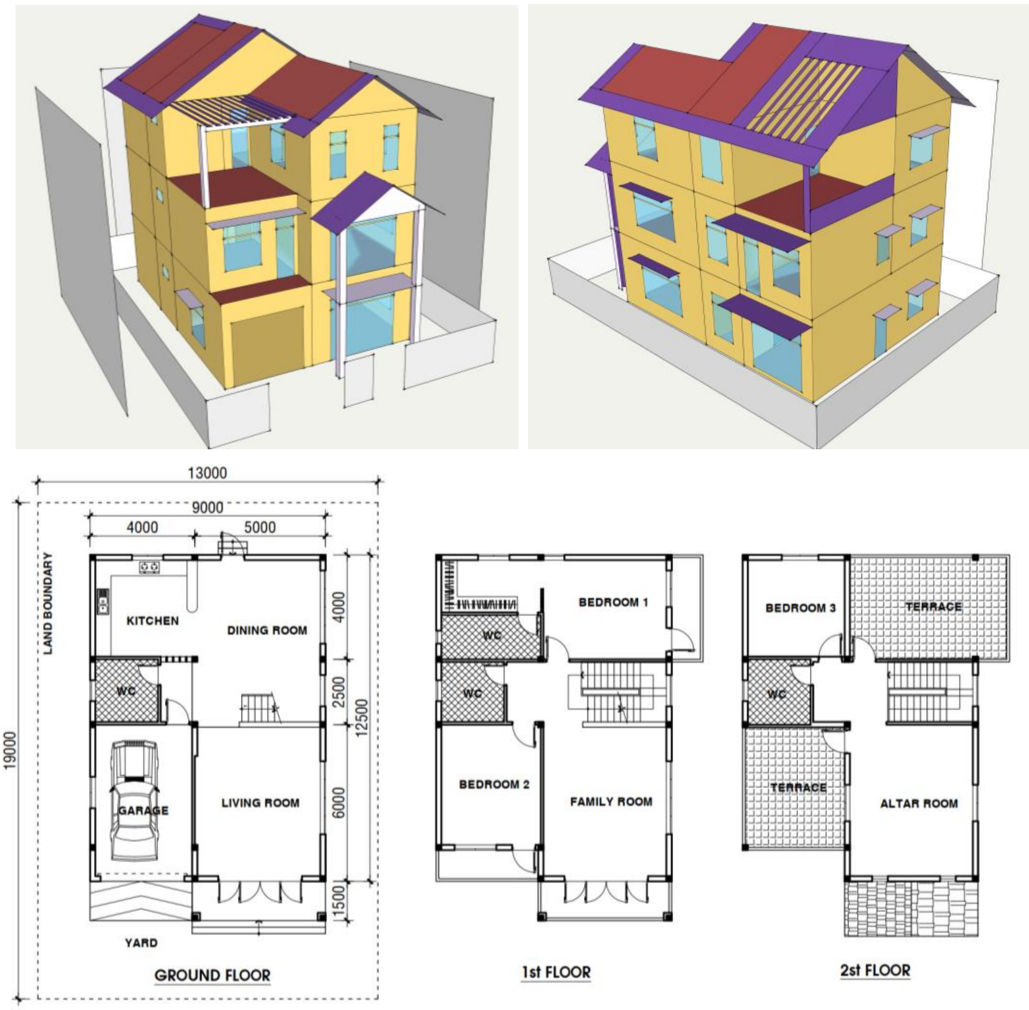


Figure 6.12: Detached house model and floor plans

The terraced house model is a mid-row house located on a land lot of 5 x 20m, in which the length of back yard is 2m. The house has 3 storeys and a flat roof. As mentioned above, this housing size can provide living spaces for major demands of the occupants. These spaces include a living room (or shop), a kitchen and dining room, 3 bedrooms for 4 members of a nuclear family, a family room for entertainment or working, and an altar room which is important in Vietnamese culture. Flat roof is preferred in terraced housing since it provides a space for garden and clothes drying. A lightwell of 2 x 3m is located in the centre of the terraced house for daylighting and ventilation. The window-to-wall ratios are 35% and 23% for front and rear façades respectively. The windows and doors are shaded by 1.2m-deep balconies or 0.6m-deep overhangs. Regarding site shading, there are an adjacent housing row at the rear and an opposite housing row across the 20m-wide street. These housing rows are represented by plains for shading calculation.

The detached house model is located on a 247m^2 land lot with the land coverage of 60%. Apart from the living spaces shown in the terraced house model, a parking garage was added. In contrast to terraced housing, pitched roof is commonly used in detached housing. The window-to-wall ratio of the whole house is 17%. The depth of roof canopy is 0.8m. Two terraces are shaded by pergolas. Site shading is provided by surrounding detached houses.

The 3D models shown in Figure 6.11 and Figure 6.12 were created by Euclid, a SketchUp extension, for use in EnergyPlus simulation programme. EnergyPlus is a free, open-source programme which is funded by the U.S. Department of Energy. It is simply a simulation engine and does not have a user interface. There are a number of software with graphical interface based on EnergyPlus such as OpenStudio and DesignBuilder. The EnergyPlus package includes free utilities to support the operation of the programme, namely IDF-Editor for creating and editing input files and EP-Launch for running the simulation (U.S. Department of Energy, n.d.). However, it is difficult to create an input file with all building information simply using the spreadsheet-like interface of the IDF-Editor. Therefore, this study used Euclid extension for SketchUp to create the 3D models of the proposed houses. All housing information was then exported to an input file that was read and edited by the IDF-Editor. The Euclid of the Big Ladder Software was based on the Legacy OpenStudio extension that was developed (but no longer supported) by the U.S. National Renewable Energy Laboratory (Big Ladder Software, n.d.).

To simulate the long-term thermal performance of Vietnamese existing housing in EnergyPlus, the housing models were assigned the existing housing properties derived from the field study including construction materials, number of occupants and occupancy schedule, household equipment and lighting system. The common construction structures and materials of existing housing applied to the models are shown in Table 6.8 and Table 6.9.

Table 6.8: Building elements properties of the existing terraced house model (V. T. Le & Pitts, 2020)

Element	Structural layers and thickness	U-value W/(m^2K)
Exterior walls	15mm cement plaster + 190 mm hollow clay brick + 15mm cement plaster	1.93
Walls to neighbour	15mm cement plaster + 80 mm hollow clay brick + 15mm cement plaster	2.97
Flat concrete roof	20mm cement screed + 100mm concrete slab + 15mm cement plaster	3.18
Ground floor	8mm ceramic tile + 20mm cement screed + 100mm lining concrete + 100mm levelled sand + natural soil layer	2.60
Window glazing	Single layer of 6mm ordinary glass	5.59
Window frame	100mm single frame	2.5

Table 6.9: Building elements properties of the existing detached house model (V. T. Le & Pitts, 2020)

Element	Structural layers and thickness	U-value W/(m^2K)
Exterior walls	15mm cement plaster + 190 mm hollow clay brick + 15mm cement plaster	1.93
Flat concrete roof	20mm cement screed + 100mm concrete slab + 15mm cement plaster	3.18
Pitched concrete roof	30mm cement roof tile + 30mm air layer with 10% batten wood + 100mm concrete slab + 15mm cement plaster	1.84
Ground floor	8mm ceramic tile + 20mm cement screed + 100mm lining concrete + 300mm levelled sand + natural soil layer	1.37
Window glazing	Single layer of 6mm ordinary glass	5.59
Window frame	100mm single frame	2.5

Each housing model has 4 occupants. The occupancy schedules were set for the main rooms based on the daily routine of local residents. Power capacities of electricity equipment and lighting system were assigned to every room so that the total energy consumption for electricity appliances and lighting system are equal to the energy consumption obtained from the field study presented in chapter 5. Similarly, the corresponding power capacity of gas equipment was assigned to the kitchen zone. These settings aim to ensure the similarity of the energy consumption (excluding cooling energy) and the internal heat gain between the proposed models and the existing housing.

The orientation of both housing models is South. All windows and glass doors were outfitted with curtains that have medium solar transmittance (0.4) and medium solar reflection (0.5). The opening schedules of windows and doors depend on the particular ventilation mode of the building. The next subsection presents the thermal performance of the housing models in naturally ventilated mode.

6.2.2 Thermal performance of naturally ventilated housing with Airflow Network model

The field study on household appliance use in existing housing presented in chapter 5 showed that the dominant ventilation mode in existing housing is free-running. Although thermal performance of existing housing in extreme weather conditions was examined through the on-site measurement, that performance in the rest of a year is still in question. Therefore, this study carried out a simulation to investigate the thermal performance of existing housing in free-running mode.

Two approaches to model the airflow between indoor zones and the outdoor environment are the use of design flow rates of ventilation and infiltration, and the use of Airflow Network model. The first approach is dedicated to simplistic ventilation simulations in which the design flow rate or air change rate is assigned to each thermal zone of the building. Such consistent air exchange during the simulation time ignores the influence of various wind speeds on the building. Therefore, the second approach using the Airflow Network model was developed for advanced simulation of natural ventilation in buildings. This model allows prediction of wind-driven multizone airflows through openings and cracks using hourly data on wind speed and direction (U.S. Department of Energy, 2012). Consequently, to obtain more precise thermal performance of free-running existing housing, the Airflow Network was applied to the housing models.

The thermal performance of the existing housing models was examined in different natural ventilation schemes, including no ventilation, whole-day ventilation, daytime ventilation, night ventilation, and automatic ventilation. The opening schedules of windows and doors for these ventilation schemes are shown in Table 6.10. It is noted that this study considered the ventilation schemes in existing housing that may occurred in practice, regardless of the high humidity problem related to night ventilation. This issue was later discussed in Section 6.4.

A weather file of the typical meteorological year (.epw format) of Tuy Hoa city was used in the EnergyPlus simulations. This weather file was created based on the actual weather data from two meteorological stations of the neighbouring cities, namely Quy Nhon and Nha Trang cities. The weather data were collected over 10 years from 2005 to 2014. The weather file was obtained from a US-based company specialising in supplying weather files for locations around the world.

Table 6.10: Window and door opening schedules in various ventilation schemes

Ventilation scheme	Opening schedule of windows and doors
No ventilation	Always closed. Air exchange is handled by infiltration.
Whole-day ventilation	Always open
Daytime ventilation	Open from 07:00 to 21:00
Night ventilation	Open from 18:00 to 07:00
Automatic ventilation	Open when indoor temperature is equal to or above 25°C and is higher than the outdoor temperature.

In this study, thermal performances of the housing models were evaluated by the percentage of total comfort hours (TCH) in a year. The thermal comfort range of 23.7 – 29.6°C for Vietnamese people derived from the comfort experiment was used to determine the TCH of main spaces and the mean TCH of the building. Due to the different occupancies of dwellings from day to day and from home to home, the TCH were determined throughout 8760 hours of a year, regardless the occupancy status of the building.

Table 6.11: Total comfort hours of the terraced house model in different ventilation schemes

Ventilation Scheme	Total comfort hours per year								
	Living room	Kitchen	Bedroom 1	Bedroom 2	Bedroom 3	Family room	Altar room	Average	%
No vent.	5501	5488	3758	4430	3688	3127	2933	4132	47.2%
Whole day	6645	6424	5693	5657	4778	4797	4767	5537	63.2%
Daytime	6351	6189	4873	5104	4296	3997	3926	4962	56.6%
Night	7277	7000	5885	5938	4845	4816	4494	5751	65.6%
Automatic	7406	7083	6123	6082	5043	5055	4895	5955	68.0%

Table 6.12: Total comfort hours of the detached house model in different ventilation schemes

Ventilation Scheme	Total comfort hours per year								
	Living room	Kitchen	Bedroom 1	Bedroom 2	Bedroom 3	Family room	Altar room	Average	%
No vent.	4480	4605	3704	4209	3721	3516	3172	3915	44.7%
Whole day	5974	5793	5528	5380	5166	4652	4776	5324	60.8%
Daytime	5364	5276	4692	4840	4481	4080	3996	4676	53.4%
Night	6167	6041	5522	5511	5132	4647	4560	5369	61.3%
Automatic	6357	6186	5822	5695	5374	4851	4914	5600	63.9%

Table 6.11 and Table 6.12 respectively show the TCH of main living spaces and the average TCH of the existing terrace house and detached house models under various natural ventilation schemes. The percentages of the TCH per year of both houses were graphically shown in Figure 6.13. In every ventilation scheme, the TCH of the terraced house was around 3 or 4% higher than that of the detached house. This could be explained by the larger external surface and glazing area of the detached house. Comparing the thermal performance among different ventilation schemes, both houses showed the same trend in which the ascending order of the thermal performance was no ventilation, daytime, whole-day, night, and automatic ventilation. Unsurprisingly, automatic ventilation was the most effective scheme since the adverse heat exchanges between indoors and outdoors were avoided by employing an automatic opening-closing system controlled by thermal sensors for windows and doors.

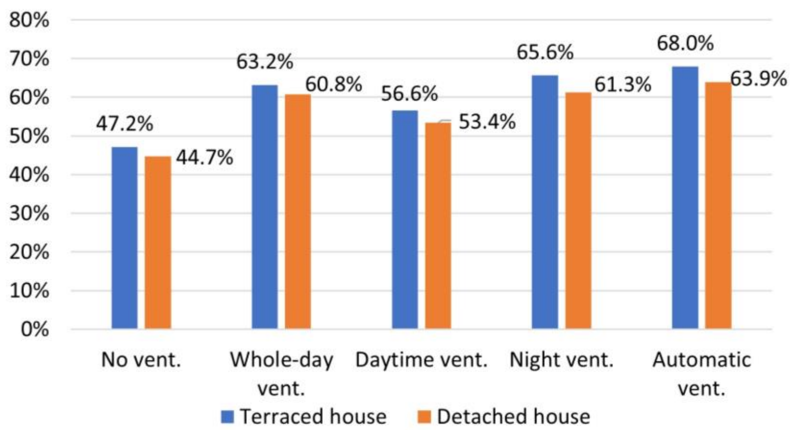


Figure 6.13: Percentages of the total comfort hours per year in different ventilation schemes

However, an automatic ventilation system would be complicated and costly to widely apply to residential buildings. Therefore, this study aimed to propose a venting schedule that can deliver a high thermal performance as with the automatic ventilation. Following a number of calibrations, the best proposed venting schedule was determined as shown in Table 6.13.

Table 6.13: The proposed ventilation schedule for existing housing

Season	Opening schedule of windows and doors
Hot season (from March 01st to November 20th)	Open from 17:00 to 9:00
Cool season (from November 21st to February 28th)	Open from 10:00 to 16:00

The thermal performances of the two existing housing models using the proposed ventilation schedule are shown in Figure 6.14, Figure 6.15, Figure 6.16, and Figure 6.17. The average TCH of the terraced and detached houses were 67% and 62.6% respectively, which were only slightly different from those values of 68% and 63.9% of the buildings with the automatic ventilation mode. The charts of hourly operative temperatures in a year of both houses show that in the majority of the summer time, the indoor temperatures exceeded the upper threshold of 29.6°C. This indicated the poor thermal performance of existing housing in summer, which was shown in the field study. On the other hand, there was only about 1% of the total hours of a year when indoor temperatures fell below the lower threshold of 23.7°C.

The difference in indoor temperature between the ground floor and the top floor in the terraced house was about 1.6°C, resulting in the difference of about 30% of the TCH between the two floors. These differences in the detached house were about 1°C and 20%. The use of a concrete flat roof in the terraced house and a pitched roof with gypsum ceiling in the detached house might cause that temperature discrepancy.

In conclusion, to maintain year-round thermal comfort, both the existing terraced and detached houses need to use mechanical cooling systems to cope with the annually total discomfort hours of 33% and 37.4%. The next subsection gives a prediction of the energy for cooling demand in both housing types.

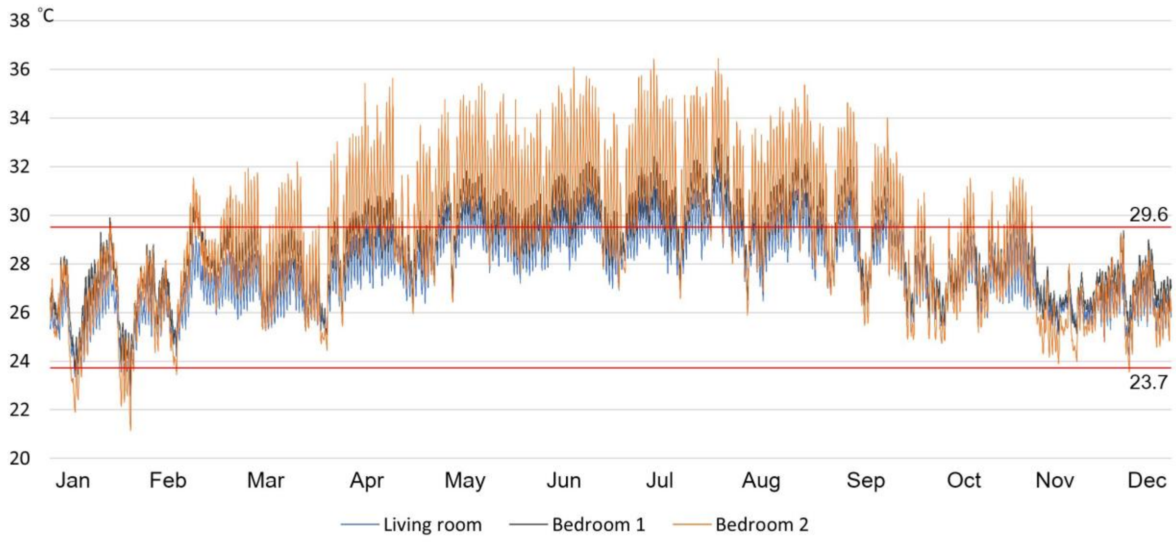


Figure 6.14: Hourly operative temperatures of 3 rooms on 3 floors of the terraced house

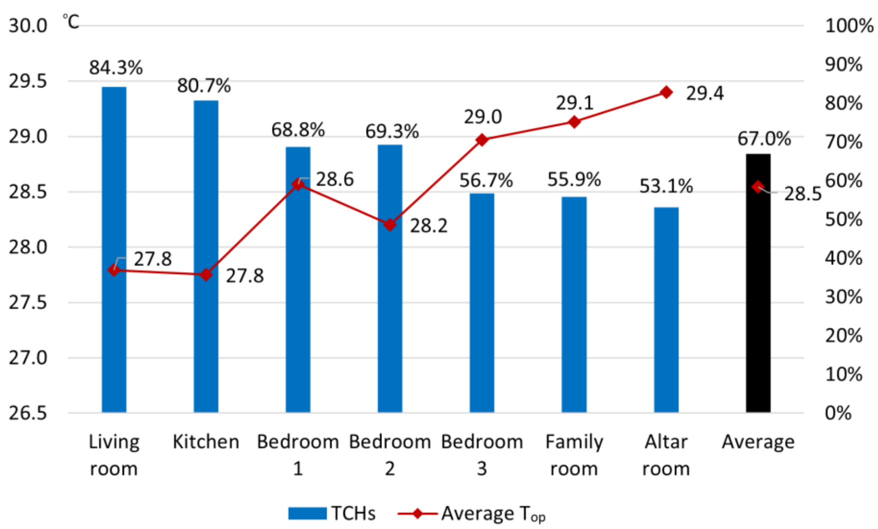


Figure 6.15: Thermal performance of the terraced house with the proposed ventilation scheme

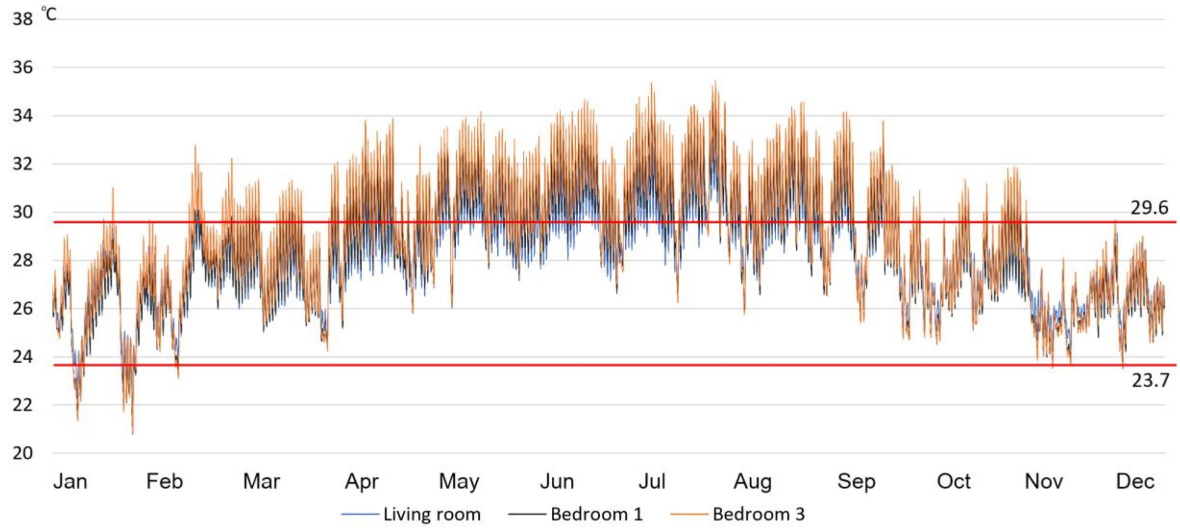


Figure 6.16: Hourly operative temperatures of 3 rooms on 3 floors of the detached house

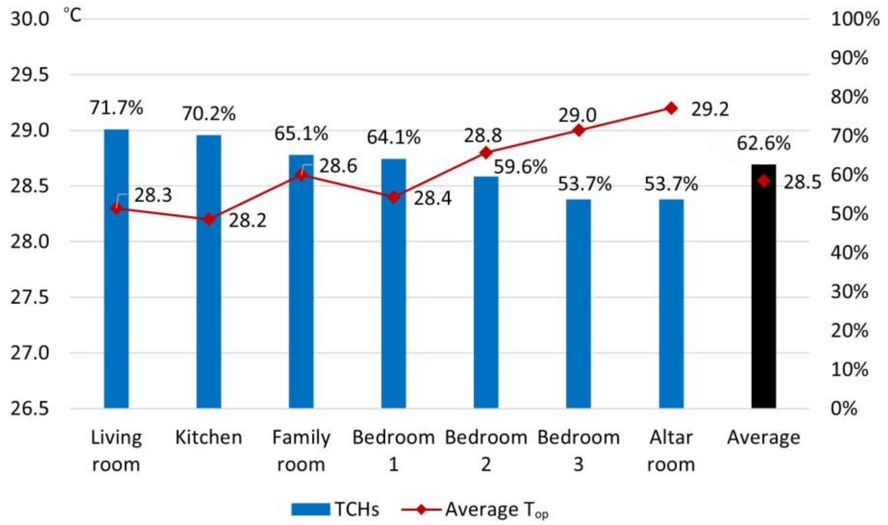


Figure 6.17: Thermal performance of the detached house with the proposed ventilation scheme

6.2.3 Energy consumption of the air-conditioned housing models

This subsection determines the energy consumption for cooling demand of the existing housing models in hybrid mode (a combination of air conditioning and natural ventilation). Split air conditioners, the most common cooling system in residential buildings were equipped in the main rooms. These cooling systems were simulated in the EnergyPlus software by using the Packed Terminal Air Conditioner (PTAC) objects. Each PTAC includes a cooling coil, a heating coil using electricity and a supply fan. The cooling coil coefficient of performance (COP) was 3. The supply fan total efficiency was 0.7. The design supply air temperatures of cooling and heating were 14°C and 50°C. Other settings related to heating and cooling coil capacities, cooling coil sensible heat ratio, supply air flow rates were set as auto size, which were calculated by the EnergyPlus software according to the thermal loads of the spaces. The outdoor air flow rate of the PTAC was set as 0 to reproduce indoor air circulation of conventional split air conditioners.

The fresh air is normally supplied through air infiltration when air conditioners are in operation. The heating and cooling coil operations were controlled by a thermostat dedicated to each main room. The heating and cooling setpoints were 23.7 and 29.6°C respectively, based on the thermal acceptability of Vietnamese people found from the previous comfort experiment.

Table 6.14 shows the annual cooling demand of main spaces in the existing housing model. Unsurprisingly, the lower the thermal comfort hours of the rooms, the higher the energy consumption for cooling. To maintain year-round temperatures within the thermal comfort zone 23.7 – 29.6°C, the cooling demand of the detached house is nearly twice that of the terraced house even though the detached house has a smaller treated floor area (185m^2 compared to 220m^2). The heating demands of both houses are negligible.

Table 6.14: Annual cooling demand of main spaces in the existing housing models (kWh)

	Living room	Kitchen	Bedroom 1	Bedroom 2	Bedroom 3	Family room	Altar room	Total
Terraced house	3345	1019	722	1092	753	2959	2187	12078
Detached house	1315	2347	2812	2731	4225	2189	7603	23221

Figure 6.18 shows the electric energy needed to satisfy the cooling demand of the existing houses (with cooling coil COP of 3). Compared to the actual cooling electricity consumption found from the field study, the electric energy for cooling demand of the terraced house and detached house models increased by 280% and 540% respectively. However, it is noted that the actual houses only used air conditioners in a certain time of the year (mostly in sleeping time) to cope with extremely hot weather, therefore, thermal comfort was not maintained year-round as assumed in the simulation.

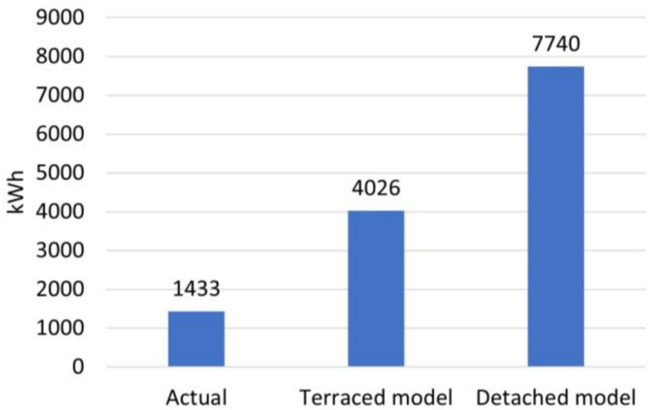


Figure 6.18: Annual electric energy for cooling demand of the existing houses

Total energy consumption of an existing house is the sum of electricity consumed by cooling system, lighting system, household appliances and liquefied petroleum gas consumed by gas stoves. Except for annual cooling energy determined by the simulations, other energy needs in existing houses were obtained from the field study presented in Chapter 5. Thereby, the total energy consumption of the existing terraced and detached house models were calculated to be 7085 and 10799 kWh per year respectively, which are considerably higher than the 4492 kWh average value of the actual buildings. To maintain year-round thermal comfort, the cooling energy accounted for 56.8% and 71.7% of the total energy consumption in the existing terraced and detached house models respectively.

In summary, the whole-year simulations on thermal performance of existing housing reaffirmed the on-site measurement results since thermal discomfort was the dominant indoor condition during summer period. The thermal discomfort hours in the two housing types accounted for 33% and 37.4% of the total hours in a year. This resulted in the corresponding cooling demands of 12078 and 23221 kWh per year to maintain year-round thermal comfort. The poor thermal performance and high cooling demand of existing housing strongly indicate that existing housing needs improvements in building design and construction to achieve better energy efficiency and provide comfort. One of the most common and effective solutions is the application of passive design techniques. Therefore, the energy-saving potential of passive designs for existing housing was examined and presented in the next section. The above simulation results of the existing housing models were used to compare and assess the efficiency of the proposed design techniques in terms of thermal comfort and cooling demand.

6.3 Potentials of energy saving in existing housing by applying passive design strategies

Since energy for cooling demand accounts for the largest proportion of the total energy consumption in Vietnamese existing housing, cooling demand reduction is indicated as the most needed potential solution for energy saving. The literature review on low energy design strategies (Section 2.2) showed that in hot humid climate, natural ventilation along with the controls of solar radiation and thermal transmittance are the key passive design strategies for reducing cooling demand. The detailed techniques are shown in Table 2.10. Moreover, a climate analysis using the Climate Consultant tool (version 6.0) resulted in a list of design guidelines for Vietnamese housing, in which the notable techniques were natural ventilation (cross and stack ventilation), solar shading with deep overhangs and verandas, window movable shading devices, and high mass internal surfaces. T.A. Nguyen (2013) carried out sensitivity analyses of 24 – 34 input parameters on housing thermal performance, including building material properties, building design and operation. The result showed that the most sensitive parameters were roof colour, roof thermal insulation, external wall colour, ventilation schemes, and window size and properties.

Base on the above findings, the potential passive design techniques selected to improve the energy efficiency of existing housing in this study include: adding thermal insulation layer to roof and external wall structures, improving thermal performance of windows and doors, using external shading devices for glazing areas, and reducing solar absorptivity of external surfaces. Note that an efficient ventilation scheme was already applied to the existing housing models. The parametric simulation method was employed to conduct this task. This method allows to evaluate the effect of each design parameter on the thermal performance and energy consumption of the building. Details of the selected parameters are described in the next subsections.

6.3.1 Improving thermal insulation of external walls

Thermal resistance of the external walls in both existing terraced and detached houses were improved by adding a layer of extruded polystyrene (XPS), which has a small thermal conductivity of 0.035 W/(mK). The structural layers of external walls now include: 15mm cement plaster, XPS insulation layer, 190 mm hollow clay brick, and 15mm cement plaster. 4 variants of external walls corresponding to 4 different thicknesses of the insulation layer were examined. The thermal transmittance values of the 4 options are showed in Table 6.15.

Table 6.15: Variants of the external walls

	Existing	Option 1	Option 2	Option 3	Option 4
Insulation thickness	0 mm	25 mm	50 mm	100 mm	150 mm
U-value (W/(m^2K))	1.93	0.81	0.51	0.30	0.21

The simulation results are shown in Table 6.16, including the percentage of total comfort hours, annual cooling demands, and the cooling demand reductions compared to the base cases (existing houses). The TCH and cooling demands are graphically shown in Figure 6.19. Generally, wall insulation did not significantly influence the cooling demand of the terraced house whilst the contrast was observed in the detached house. This is due to the large external surface area of the detached house that results in a substantial heat transfer through the external walls.

The most significant change in the TCH as well as the cooling demand occurred with the first application of insulation layer (25mm) in both houses. In the terraced house, this first change of cooling demand was 5.3% while the other changes were negligible. In the detached house, after the significant cooling demand reduction by 17.2% with a 25mm XPS layer, the increases of insulation layer still reduced the cooling demand, but the changes were much smaller.

Table 6.16: Thermal and energy performance of the housing models with different external walls

	Insulation thickness (mm)	Total comfort hours (%)	Annual cooling demand (kWh)	Cooling demand reduction (%)
Terraced house	0	67%	12078	(base case)
	25	67.7%	11442	5.3%
	50	67.8%	11455	5.2%
	100	67.9%	11415	5.5%
	150	68.0%	11386	5.7%
Detached house	0	62.6%	23221	(base case)
	25	64.5%	19233	17.2%
	50	65.0%	18395	20.8%
	100	65.4%	17755	23.5%
	150	65.6%	17496	24.7%

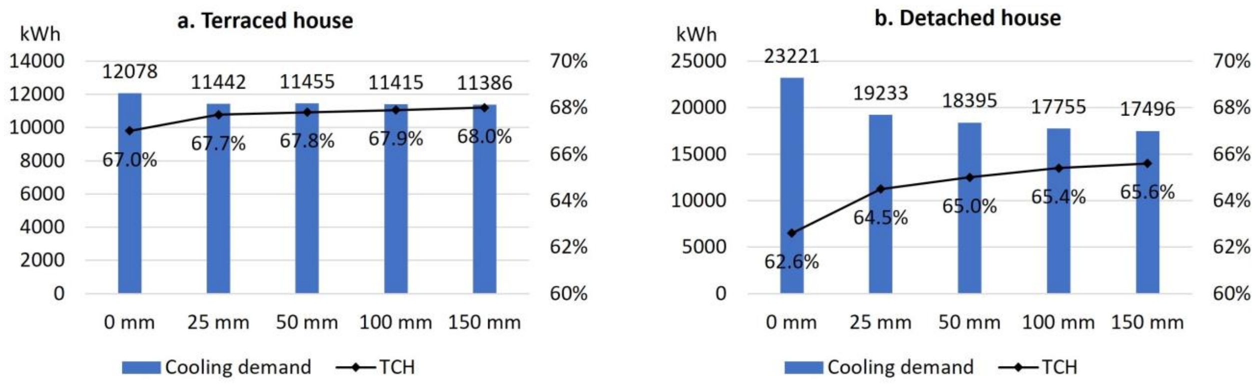


Figure 6.19: TCH and cooling demands of the housing models with different external walls

6.3.2 Improving thermal insulation of roofs

Similar to external wall insulation, 4 thickness levels of XPS insulation material from 25mm to 150mm were in turn added into the roof structural layers. The corresponding U-values of the 4 variants of flat and pitched roofs are shown in Table 6.17. The TCH, annual cooling demand and the energy saving potential of each case are shown in Table 6.18 and Figure 6.20. It is clear that roof insulation significantly reduced cooling demand in both houses. For example, only with 25mm insulation layer addition, cooling demand in the terraced and detached houses decreased by 54% and 28.7% respectively. In contrast to the case of the external wall, roof insulation showed higher efficiency in the terraced house than in the detached house. The pitched roof with gypsum ceiling and pergolas of the detached house is the main reason for that result.

Table 6.17: Variants of the roofs

	Existing	Option 1	Option 2	Option 3	Option 4
Insulation thickness	0 mm	25 mm	50 mm	100 mm	150 mm
U-value (W/(m^2K)) of flat roof	3.18	0.97	0.57	0.32	0.22
U-value (W/(m^2K)) of pitched roof	1.84	0.80	0.51	0.29	0.21

Table 6.18: Thermal and energy performance of the housing models with differently insulated roofs

	Insulation thickness (mm)	Total comfort hours (%)	Annual cooling demand (kWh)	Cooling demand reduction (%)
Terraced house	0	67%	12078	(base case)
	25	74.4%	5559	54.0%
	50	76.1%	4819	60.1%
	100	77.4%	4372	63.8%
	150	77.8%	4200	65.2%
Detached house	0	62.6%	23221	(base case)
	25	65.7%	16549	28.7%
	50	66.4%	15579	32.9%
	100	66.9%	14878	35.9%
	150	67.1%	14660	36.9%

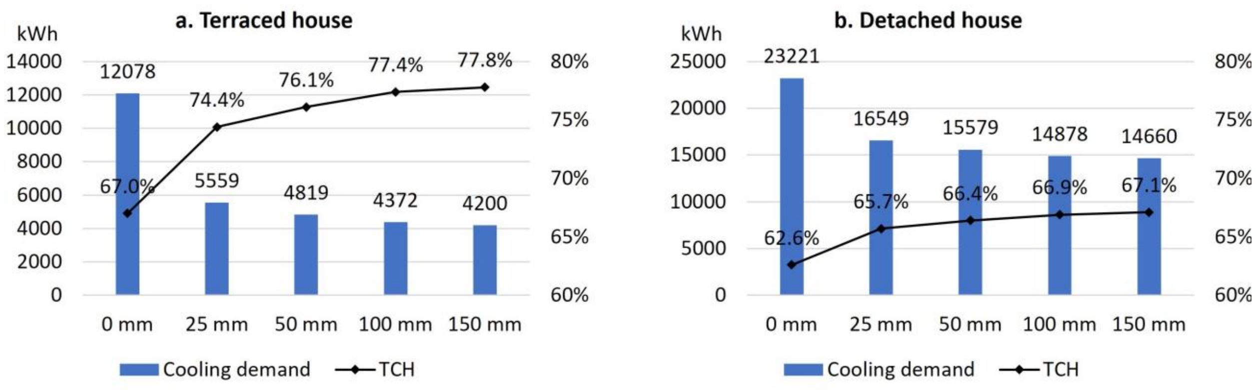


Figure 6.20: TCH and cooling demands of the housing models with differently insulated roofs

The above results reaffirmed that roof insulation is one of the most sensitive factor to thermal performance and energy consumption in single-family housing, especially in terraced houses with concrete flat roofs.

6.3.3 Improving thermal performance of windows and doors

High performance windows and doors can help to reduce solar transmittance and thermal transfer through glazing areas. Except for the single glazing currently used in the existing houses, two higher-quality window and door types were examined, including ordinary double-glazing type with 6mm air gap and low emission (low-E) double glazing type with 6mm argon filling. It is noted that triple glazing type is not necessary for buildings in hot humid climates (ASHRAE, 2008; Schnieders, Feist, & Rongen, 2015). The frames for these two window types were upgraded from simple frame (U-value = 2.5 W/(m^{2}K)) to standard frame (U-value = 1.6 W/(m^{2}K)). SHGC and U-values of the three glazing types are shown in Table 6.19 alongside the corresponding thermal performances, cooling demands and energy saving potentials of the housing models. These results are graphically shown in Figure 6.21.

Table 6.19: Thermal and energy performance of the housing models with different glazing types

	Glazing type	SHGC	U-value W/(m^{2}K)	Total comfort hours (%)	Annual cooling demand (kWh)	Cooling demand reduction (%)
Terraced house	Single (simple frame)	0.87	5.59	67%	12078	(base case)
	Ordinary double (standard frame)	0.78	2.8	67.5%	11347	6.1%
	Low-E double (standard frame)	0.51	1.1	68.4%	10756	10.9%
Detached house	Single (simple frame)	0.87	5.59	62.6%	23221	(base case)
	Ordinary double (standard frame)	0.78	2.8	62.2%	23542	-1.4%
	Low-E double (standard frame)	0.51	1.1	63.3%	21904	5.7%

SHGC: solar heat gain coefficient

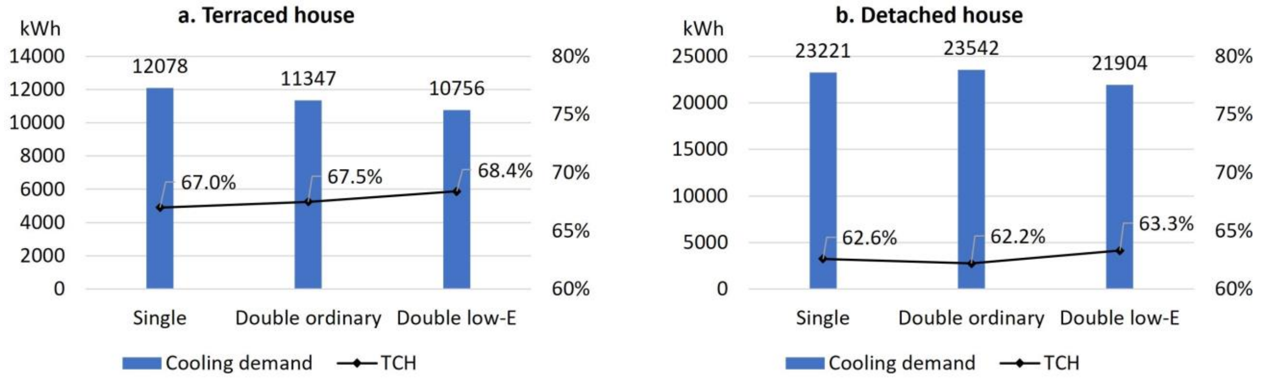


Figure 6.21: TCH and cooling demands of the housing models with different glazing types

A review of the results shows that the glazing factor was more sensitive to thermal performance in the terraced house than in the detached house. The terraced house with low-E double glazed windows and doors reduced the cooling demand by 10.9% whilst that reduction of the detached house was only 5.7%. This could be explained by the smaller window to wall ratio of the detached house (17%) compared to the 29% ratio of the terraced house. In the case of ordinary double glazing, while cooling demand of the terraced house decreased by 6.1%, cooling demand of the detached slightly increased by 1.4%. In the existing detached house with large uninsulated external wall and East-oriented glazing area, the solar gain is substantial and ordinary double glazing may prevent the dissipation of indoor heat to the outdoor environment through glazing areas. Therefore, solar shading, particularly for glazing areas is essential in hot humid climates.

6.3.4 The effect of internal and external shading

Solar shading for glazing areas includes two types: internal shading and external shading. It is the common knowledge that external shading is more effective than internal shading since solar radiation is blocked before entering the buildings. However, internal shading devices possess advantages of easy installation, operation, and maintenance (Toe, 2013). Therefore, internal shading is the dominant shading type in existing housing. In this study, windows and glass doors of the existing housing models were already outfitted by internal shading devices. Hence, the next simulation examined the effect of external shading on housing thermal and energy performance.

Blinds with high reflectivity slats, which are available in the EnergyPlus dataset, were equipped to the outer leaf of the glazing areas. A blind includes horizontal slats with 25mm width, 1mm thickness, 45-degree angle and 20mm separation. The slats' solar reflection is 0.8. The blind to glass distance is 50mm. To investigate the best performance of these shading devices, the shading operation was automatically controlled. The blinds will operate when indoor temperature of the zone exceeds 27°C.

Table 6.20 and Figure 6.22 show annual thermal performances and cooling demands of the terraced and detached houses with internal and external shadings. The simulation results confirmed common expectations since the cooling demands of the terraced and detached houses with external blinds reduced by 16.3% and 8.6% respectively compared to the use of internal shading. Again, the difference in window-to-wall ratios between the houses could explain the difference in the energy-saving potentials. These results showed that shading improvements were more effective in energy saving compared to the improvements in window properties.

Table 6.20: Thermal and energy performance of the housing models with different shading types

	Shading type	Total comfort hours (%)	Annual cooling demand (kWh)	Cooling demand reduction (%)
Terraced house	Internal	67%	12078	(base case)
	External	69%	10113	16.3%
Detached house	Internal	62.6%	23221	(base case)
	External	64.5%	21213	8.6%

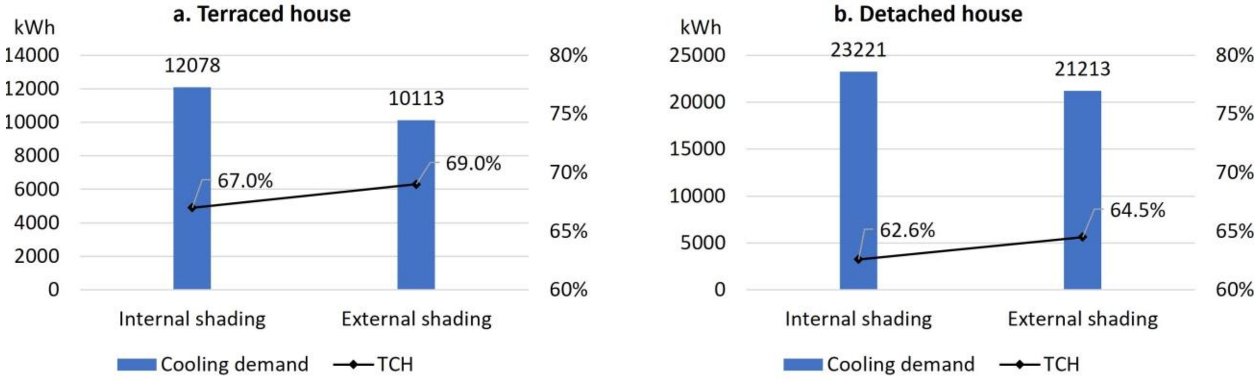


Figure 6.22: TCH and cooling demands of the housing models with different shading types

6.3.5 Reducing solar absorptivity of the envelope

The amount of heat absorbed by the envelope significantly affects the building's thermal performance. Hence, reducing solar absorptivity of the envelope is an effectively passive solution. Colour and roughness of an external surface are the two major elements that determine its solar absorptivity (Dornelles, Roriz, & Roriz, 2007), in which the selection of suitable colours is the easier mean in practice. Solar absorptivity often varies from 0.25 to 0.98 with the corresponding white to black colours (ASHRAE, 2009; Dornelles et al., 2007; Santamouris & Asimakopolou, 1996). Generally, the lighter the colour, the smaller the solar absorptivity of external surfaces.

In this study, the solar absorptivity of the existing house's envelope was assumed at 0.7. To investigate the energy saving potentials when reducing solar absorptivity, the two lower values of 0.5 and 0.3 were used to replace the 0.7 value. In Vietnam, paint coating on mason walls plastered with putty is the most common practice for external walls of residential buildings. According to ASHRAE (2009) and Dornelles et al. (2007), solar absorptance values of 0.7, 0.5, 0.3 correspond to the paint colours of white, yellow (sandstone) and blue respectively.

Table 6.21: Thermal and energy performance of the housing models with different solar absorptivity

	Envelope solar absorptivity	Total comfort hours (%)	Annual cooling demand (kWh)	Cooling demand reduction (%)
Terraced house	0.7	67%	12078	(base case)
	0.5	71.8%	7712	36.1%
	0.3	77.8%	4534	62.5%
Detached house	0.7	62.6%	23221	(base case)
	0.5	67.7%	15913	31.5%
	0.3	73.6%	8387	63.9%

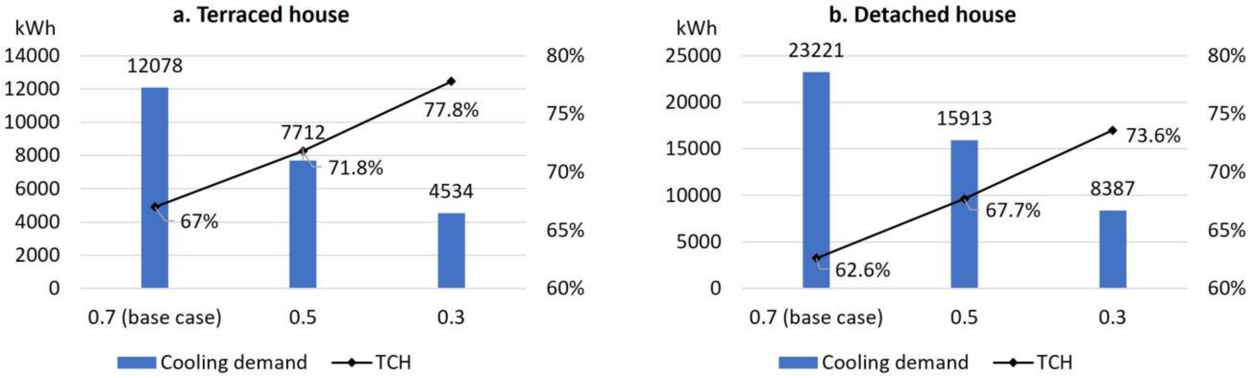


Figure 6.23: TCH and cooling demands of the models with different envelope solar absorptance values

Table 6.21 and Figure 6.23 show thermal and energy performances of the existing houses with various envelope solar absorptance values. The TCH and cooling demands in both housing types were considerably changed when reducing the solar absorptivity from 0.7 to 0.5 and to 0.3. External surfaces with white paint can reduce the annual cooling demand by about 60%. This result indicated that light colours should be used for opaque surfaces of buildings in the hot humid climate of Vietnam. This technique is both energy-efficient, economical and easy to apply. In practice, however, the application of white or other light colours to external surfaces is limited by the aesthetic issue and the regulation of exterior colours of the neighbourhood if any.

6.3.6 Energy efficiency of the strategies-combined model

The above simulations indicated the energy-saving potentials of individual passive design techniques. The combination of several of those design techniques in a building is expected to save much more energy. The best-performance case could be determined using a parametric simulation method or an advanced method called optimisation that take into account a large number of input parameters and variants. However, these methods require considerable effort and are time-consuming. Moreover, defining the best-performance improved case for existing housing was not essential in this study. Therefore, although the combination of the best-performance variants of building parameters may not result in the best result due to the complex non-linear interactions among those parameters (T.A. Nguyen, 2013), this method was considered in this section with the aim to propose good-performance buildings combining major passive design techniques.

Table 6.22: Properties of the improved existing houses

	Walls		Roof		Glazing		Window shading	Solar absorptivity
	Insulation layer	U-value W/(m²K)	Insulation layer	U-value W/(m²K)	Type	U-value W/(m²K)		
Terraced house	25 mm	0.81	100 mm	0.32	Low-E double	1.1	External blinds	0.3
Detached house	100 mm	0.3	100 mm	0.29	Low-E double	1.1	External blinds	0.3

Table 6.22 shows the properties of the improved existing houses which combined positive passive design solutions. It is noted that the wall insulation layer of the terraced house was only 25mm because the thicker layers did not significantly change the TCH and cooling demand of the house. The other insulation layers for walls and roofs were selected due to the same reason. Meanwhile, glazing type, window shading type and solar absorptivity were selected as the best-performance variants in the previous simulations.

Figure 6.24 shows the TCH and cooling demands of the existing houses and the improved houses. It is clear that the cooling demands were significantly reduced by 87.3% and 87.7% in the terraced and detached houses respectively. This indicated the great energy-saving potential of the improved houses using passive design techniques. It is worth mentioning that even though the TCH of both housing types only increased by about 22%, the cooling demands significantly dropped by about 87%. This was due to the significant decrease of indoor temperatures although the total number of hours when indoor temperatures were above the upper threshold of 29.6°C were still high. Figure 6.25 and Figure 6.26 show hourly operative temperatures of major spaces in the improved houses. Compared to those charts of the existing houses shown in Subsection 6.2.2, it was observed that the maximum daily indoor temperatures significantly decreased by 4°C, from around 36°C to 32°C. Most times of a year, the indoor temperatures were below 31°C. Therefore, the cooling demands were sharply dropped by about 87% despite the THC increase of only 22%.

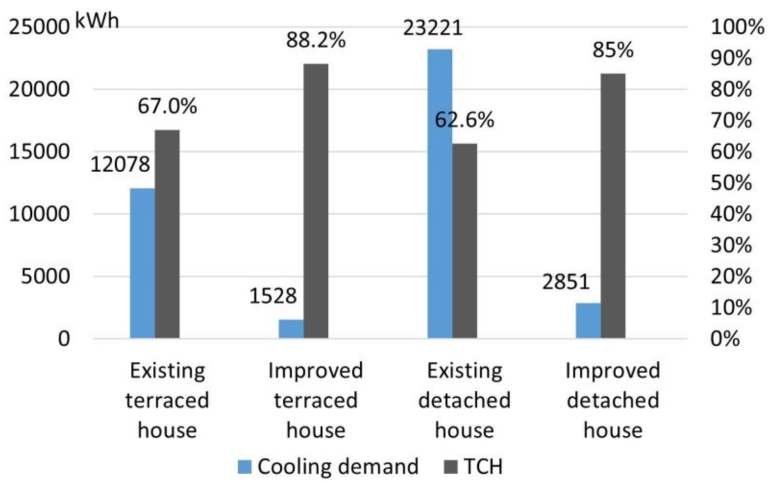


Figure 6.24: TCH and cooling demands of the existing and the improved houses

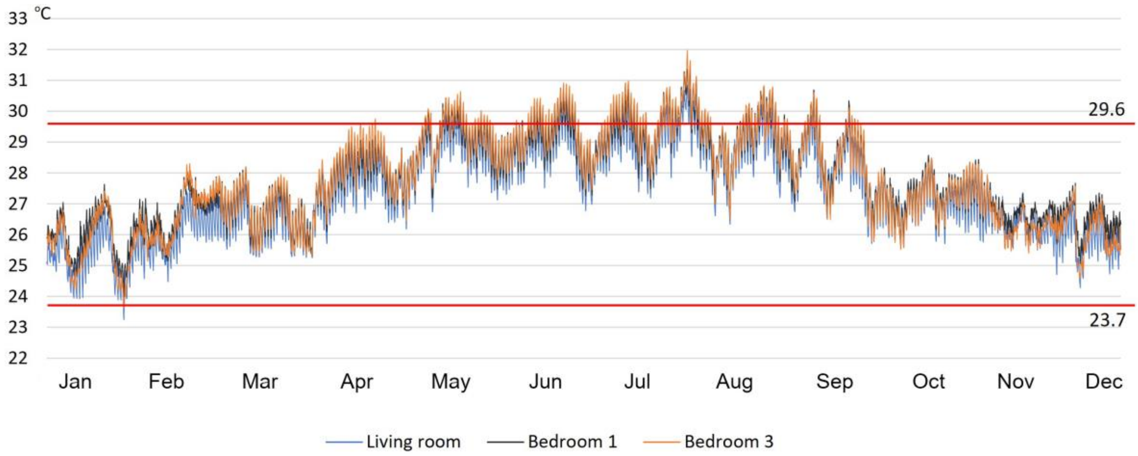


Figure 6.25: Hourly operative temperatures of 3 rooms on 3 floors of the improved terraced house

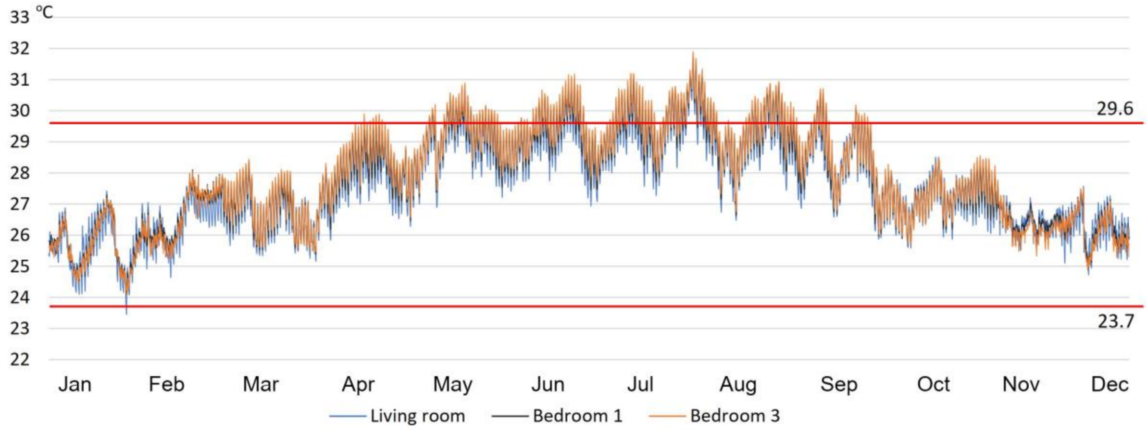


Figure 6.26: Hourly operative temperatures of 3 rooms on 3 floors of the improved detached house

In summary, the above simulation results showed the great potentials of energy saving when applying passive design techniques to the existing houses. Those passive techniques significantly reduced the indoor temperatures, and consequently reduced the majority of energy consumption for cooling demand. In addition to temperature concerns, buildings in hot humid climates such as Vietnam need to pay adequate attention to the indoor humidity conditions since it is an important factor for thermal comfort and indoor air quality in buildings. The next section presents the humidity performances of the improved houses and the corresponding dehumidification demands.

6.4 High humidity problem and the dehumidification demand

Although the impact of temperature changes on thermal comfort is more robust than the impact of changes in humidity (Fanger, 1970), humidity issue in buildings is of particular concern in hot humid climates. Humidity above the 70% RH threshold significantly influences on thermal sensation of occupants in hot conditions (de Dear et al., 1991; Jin et al., 2017). Moreover, humid environment is related to a number of health problems and building damages (CEN, 2019; WHO, 2009). If indoor humidity remains high for a long period of time (more than 12 hours), mould and microbial growth will occur (CEN, 2019; McIntyre, 1980). Therefore, it is necessary to maintain indoor humidity at a suitable level for occupants and buildings themselves.

Suitable humidity or dampness in buildings are vague concepts (Bornehag et al., 2001). Hence, individual researchers and organisations have specified limits of indoor humidity, however, these limits are significantly different as shown in Table 6.23.

Table 6.23: Recommended indoor humidity in existing standards and studies

Recommended RH	Studies and standards	Details of indoor humidity
≤ 60%	ASHRAE Standard 55–2017	Humidity ratio limit: 12 g/kg
	ASHRAE Standard 160	30 – 60% RH
	ASHRAE Standard 62.1–2019	Maximum dew point of 15°C (or RH < 65% during unoccupied periods)
	Arundel et al. (1986)	40 – 60% RH
≤ 70%	CEN Standard EN 16798-1:2019	(I) 30 – 50%; (II) 25 – 60%; and (III) 20 – 70% RH Humidity ratio limit: 12 g/kg
	CIBSE Guide A: Environmental design	40 – 70% RH
	Malaysian Standard MS1525:2014	50 – 70% RH
	Vietnam Standard TCVN 5687:2010	60 – 70% RH
	Tanabe & Kimura (1994)	70% RH limit
	Bauman et al. (1996)	
	Verdier et al. (2014)	
	Jin et al. (2017)	
> 70%	WHO (2009)	75% RH limit
	Viitanen & Ritschkoff (1991)	
	Rowan et al. (1999)	
	Vietnam Standard TCVN 9411:2012	75-80% RH limit for cool season and 80% RH limit for hot season
	Adan (1994)	80% RH limit
	Johansson et al. (2005)	75% to 90% RH limit, depending on materials

ASHRAE Standard 55–2017 suggested the upper limit of indoor absolute humidity is 12 g/kg, which is equal to 60%RH at 25°C. The lower limit was not specified in this standard (ASHRAE, 2017). ASHRAE Standard 160 recommended the indoor RH range for moisture-controlled buildings is 30 – 60% (ASHRAE, 2016). The upper limit of 60% RH was also proposed by Arundel et al. (1986) since they claimed that the optimum RH range for human health was 40 – 60%. ASHRAE Standard 62.1–2019 specified a slightly strict upper limit of indoor humidity based on the maximum dew point of 15°C, which is equal to 60%RH at 23°C or 10.5 g/kg humidity ratio. During unoccupied periods, RH should be less than 65%, regardless of the dew points (ASHRAE, 2019).

A number of researchers argued that the humidity limit of 60% RH is too strict, and proposed a higher limit of 70% RH (Bauman et al., 1996; Jin et al., 2017; Shin ichi Tanabe & Kimura, 1994; Verdier, Coutand, Bertron, & Roques, 2014). The 70% RH limit is also recognised in some international and national standards. CEN Standard EN 16798-1:2019 proposed 3 categories of RH range: (I) 30 – 50%; (II) 25 – 60%; and (III) 20 – 70%. In addition, the absolute humidity should be limited to 12 g/kg in all cases, similar to the recommended value in ASHRAE Standard 55–

2017 (CEN, 2019). CIBSE "Guide A: Environmental design" specified an optimum range of 40–70% RH for indoor air (CIBSE, 2015). Malaysian Standard MS1525:2014 recommended a similar range of 50-70% RH (Department of Standards Malaysia, 2014).

There is evidence for the use of humidity limits above 70% RH. Based on experiments on buildings and finishing materials, Viitanen & Ritschkoff (1991) and Rowan et al. (1999) found that maintaining indoor RH below 75% can prevent fungal growth whilst Adan (1994) recommended a higher limit of 80% RH. A literature review conducted by Johansson et al. (2005) indicated that microbial growth is favoured in humidity conditions higher than 75% RH, and the critical moisture is from 75% to 90%, depending on building materials. Based on these studies, the World Health Organisation (WHO) recommended a humidity limit of 75% RH (WHO, 2009).

In Vietnam, the humidity limits specified in national building standards are not identical. The standard TCVN 9411:2012 developed by VIAP (2012b) indicated the limits of 75-80% RH for cool season and 80% RH for hot season. Meanwhile, the standard TCVN 5687:2010 developed by NUCE (2010) recommended a RH limit of 70%.

In summary, the recommended limits of indoor humidity vary within a wide range of 60 - 80% RH. The specification of a certain limit can lead to controversies. Therefore, this study sequentially evaluated the indoor humidity in Vietnamese housing based on the four commonly recommended RH limits, including 60%, 70%, 75%, and 80%. By these means, this study hopes to provide a comprehensive understanding of indoor humidity conditions in Vietnamese housing, which could be of interest to policy makers.

Figure 6.27 and Figure 6.28 show hourly RH of two bedrooms of the improved terraced and detached houses. It is clearly that for most of a year, the indoor RH in both bedrooms exceeded 60%. The similar humidity conditions were observed in the other rooms in both houses. Table 6.24 shows the average percentages of total hours in a year when the outdoor RH and the indoor RH of two houses surpassed 60%, 70%, 75% or 80%. These results indicated the humid conditions in the two houses that need to be resolved for a better indoor environment. The necessity of humidity control for buildings in hot humid climates was also derived from the studies of Kubota et al. (2009), T.A. Nguyen (2013) and Sigalingging et al. (2017).

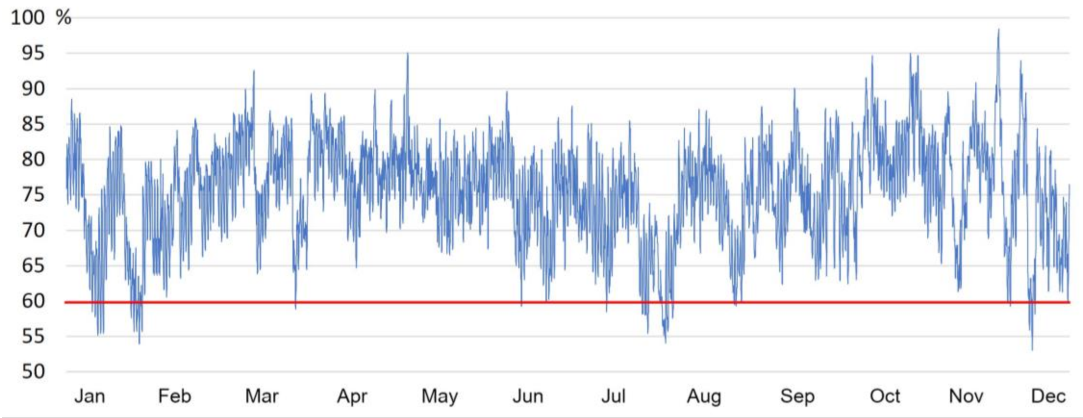


Figure 6.27: Hourly RH in the bedroom 1 of the improved terraced house

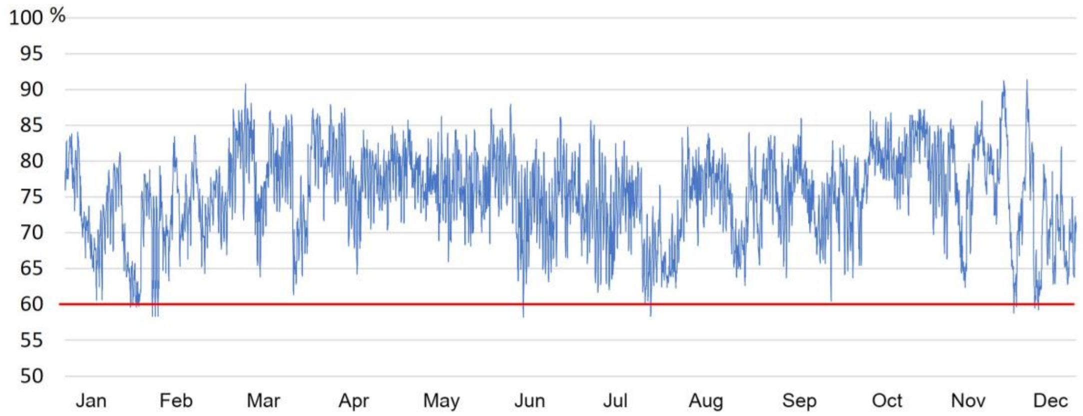


Figure 6.28: Hourly RH in the bedroom 1 of the improved detached house

Table 6.24: Percentages of total hours when the indoor RH exceeded the criteria

	Outdoor	Terraced house	Detached house
RH > 60%	97.4%	96.2%	99%
RH > 70%	80.4%	75.9%	78.5%
RH > 75%	63.0%	54.5%	54.0%
RH > 80%	41.8%	24.9%	23.4%

In hot and humid climates, the moisture content of the outdoor air may be higher than that of indoor air, therefore, natural ventilation is not an effective solution to remove indoor moisture (WHO, 2009). In such cases, dehumidification is commonly handled by using portable dehumidifiers. In the next step of this study, dehumidification demands of the improved terraced and detached houses were determined by computational simulation method using the EnergyPlus software. Due to high outdoor humidity, the natural ventilation scheme with the Air Flow Network model was turned off to be able to determine the dehumidification demands. This means all windows and doors were closed during the simulation to prevent the penetration of high humidity outdoor air. The hygiene ventilation demand was satisfied by air infiltration through the building envelope, which was set at a constant value of 0.7 air change per hour. A conventional direct expansion cooling-based room air dehumidifier (reject 100% condenser heat to the zone air) was equipped to each main room. Its rated energy factor was 3.4 L/kWh. The dehumidifying setpoint was sequentially set at 80%, 75%, 70%, and 60% RH.

Figure 6.29 shows the cooling and dehumidification demands of the terraced and detached houses. In the first simulation when the dehumidifiers were turned off, the cooling demands only were more than double those of the housing models with natural ventilation scheme. This result indicated the effectiveness of natural ventilation in terms of cooling. However, as discussed above, the high humidity problem needs to be addressed. Hence, in the next simulations, the dehumidifiers were turned on. The cooling and dehumidification demands in both houses gradually increased with 80%, 75% and 70% RH setpoints, but sharply increased with the RH setpoint of 60%.

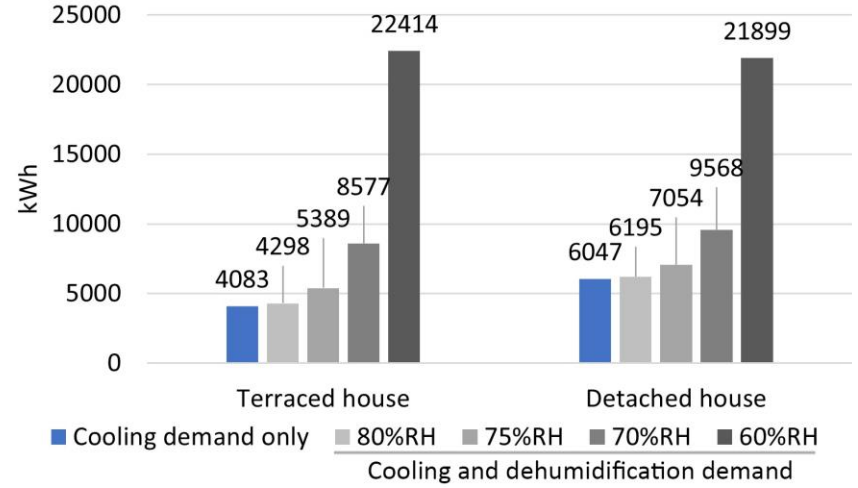


Figure 6.29: Cooling and dehumidification demands of the housing models

Although the limit setting of 75 or 80% RH can save substantial energy for dehumidification, these high humidity limits should be carefully considered. Laboratory experiments have indicated that the RH thresholds for the development of dust mites and some fungi is 45 – 50% and 62 – 65% respectively, and they grow rapidly at higher RH (WHO, 2009). In addition, soft furniture, textile surfaces, and carpets may locally increase indoor humidity, and create favourable conditions for mould growth. The RH in zone air may be 10% less than in carpets (WHO, 2009). On the other hand, the use of low humidity setpoints may provide better indoor air quality, but result in significant energy consumption for dehumidification purpose. Therefore, the selection of an indoor humidity limit for the hot humid climate of Vietnam should be done with care and needs more supportive evidence from further research.

6.5 Chapter conclusion

This chapter presents the thermal performance of existing housing in Vietnam and the energy-saving potentials from applying passive design solutions, which were investigated through a field study and computer simulation methods. The field study using observation and on-site measurement methods provided an understanding of common construction materials and thermal performance of existing housing in Vietnam. The remarkable results are as follows:

- The common housing materials are reinforced concrete structure, clay brick walls, single-glazed windows with simple frame, and concrete flat or corrugated metal roofs, all without use of insulation materials. These housing components have high thermal transmittance.
- The differences between the measured indoor and outdoor temperature were 2.03°C and 0.92°C in hot and cool season respectively. The mean indoor air temperature in hot season was relatively high, at 31.8°C while that of cool season was 24.1°C.
- The average indoor air velocity was only 0.14 m/s which revealed the inefficiency of natural ventilation in existing housing.
- All measured RH data exceeded the 60% threshold of acceptable RH.

In short, from the field study, Vietnamese existing housing showed a poor thermal performance and failed to satisfy thermal comfort in hot weather. The whole-year simulations on thermal performance of existing housing showed that the thermal discomfort hours in the terraced and detached houses accounted for respectively 33% and 37.4% of the total hours in a year. This resulted in the corresponding cooling demands of 12078 and 23221 kWh per year to maintain year-round thermal comfort. The poor thermal performance and high cooling demand of existing housing strongly indicate that existing housing needs to be improved for better energy efficiency.

The energy efficiency of major passive design techniques was examined, including: adding thermal insulation layer to roof and external wall structures, improving thermal performance of windows and doors, using external shading devices for glazing areas, and reducing solar absorptivity of external surfaces. The combination of the positive techniques helped to reduce significantly the cooling demands by 87.3% and 87.7% in the terraced and detached houses respectively. This indicated the great energy-saving potential of the improved houses using passive design techniques.

Although passive design techniques were particularly beneficial for reducing the majority of cooling demand, these conventional solutions failed to provide a healthy humidity environment for the occupants. For about 95%, 75%, and 54% of the total hours in a year, the indoor humidity in both houses exceeded the recommended limits of 60%, 70%, and 75% RH respectively. As a result, large cooling and dehumidification demands were determined in the houses. The penetration of hot and damp outdoor air through the leaky building envelope could be the main reason for this high demand. One of advanced building design solutions can prevent this adverse air penetration whilst satisfying hygiene ventilation requirement is the use of Passive House approach. An air-tight envelope alongside a mechanical ventilation system with energy recovery in a Passive House building could be premising solutions for the humidity problem in Vietnamese housing. Consequently, the next chapter presents the adoption of these solutions along with other design principles of the Passive House approach to achieve low energy housing in the context of hot humid Vietnam.

Chapter 7 Passive House approach for Vietnam

Chapter 6 shows the poor thermal and energy performance of the existing housing in Vietnam. It also identified the drawbacks of conventional housing design strategies and indicated the need for an investigation on the Passive House approach for Vietnamese housing. Consequently, this chapter presents an in-depth study on the application of this building-design methodology to the context of Vietnam. Firstly, the adaptation and energy efficiency of the Passive House approach for the hot humid Vietnam were determined. Secondly, to facilitate the proposal of Passive House design techniques for Vietnam, the influences of main building parameters on energy consumption were investigated. Subsequently, the most influencing parameters and the corresponding variants were selected for the next parametric simulation step to determine the potential design strategies for Vietnamese housing built to the adapted Passive House standard. Based on these results, a reference design guideline for Passive House housing in Vietnam was generated. Finally, this chapter describes the validity of the proposed design guideline in discussion with experts using a questionnaire method.

It is noted that part of Section 7.1 involves re-presentation from the Passive and Low Energy Architecture (PLEA) conference paper (V. T. Le & Pitts, 2020) written by the author of this thesis, with all data collected by him, and reviewed by the supervisor.

7.1 Potentials of the Passive House application to the hot humid climate of Vietnam

The benefits of Passive House buildings have been verified by theoretical research and practical application in many countries around the world. However, Passive House is a completely new concept in Vietnam since there has been no investigation on this building methodology in both theory and practice. Therefore, the applicability and potentials of the Passive House approach to the context of Vietnam need to be determined as an important first step.

This section firstly describes the adaptation of the original Passive House standard to the Vietnam climate, including revisions of the criteria for cooling and dehumidification demand, thermal comfort range, humidity ratio limit, and air tightness. Secondly, the modelling of existing terraced and detached houses in the Passive House Planning Package (PHPP) is presented as the base cases. Thirdly, these housing models were sequentially modified to meet the original and adapted Passive House standards, and then the energy savings of these Passive House houses compared to the existing models were determined. The last part of this section shows a comparation between the energy consumptions of Passive House dwellings in different hot humid regions of Vietnam.

7.1.1 The adaptation of the Passive House standard to Vietnam climate

Although the Passive House methodology was originally developed for buildings in temperate zones, it has gradually been applied in more extreme climates, including hot dry, hot humid and extremely cold. Consequently, the Passive House standard is designed to be applicable to all regions of the world (PHI, 2018b). Table 7.1 presents the criteria for the certification of residential Passive House buildings. It can be seen that the heating demand criteria are constant values whilst the criteria for cooling and dehumidification demand depend on the particular climate, which is characterised by the annual mean outdoor temperature and the dry degree hours (DDH). Based on provided weather data, the corresponding criteria are automatically calculated in the Passive House Planning Package (PHPP). Despite recognising the discrepancy in cooling and dehumidification demand in different climates, the criterion for total primary energy demand is constant. Also, the air tightness requirement remains at a high level of 0.6 ACH at 50 Pascal differential pressure across climate types.

Table 7.1: Certification criteria for residential Passive House buildings (PHI, 2013)

Heating	Specific space heating demand ≤ 15 kWh/(m²a) *or alternatively:* heating load ≤ 10 W/m²
Cooling and dehumidification	Total cooling demand ≤ 15 kWh/(m²a) + 0.3 W/(m²aK) * DDH *or alternatively:* cooling load ≤ 10 W/m² AND cooling demand ≤ 4 kWh/(m²aK) * ϑ_e + 2 * 0.3 W/(m²aK) * DDH - 75 kWh/(m²a) but not greater than: 45 kWh(m²a) + 0.3 W/(m²aK) * DDH
Total primary energy	≤ 120 kWh/(m²a)
Air tightness	Pressure test result, n_{50} ≤ 0.6 ACH

ϑ_e: Annual mean outdoor temperature (°C)

DDH: dry degree hours (the reference temperature of 13°C); ACH: air changes per hour

To determine the criteria for cooling and dehumidification demand of residential Passive House buildings in Vietnam, the weather data of Tuy Hoa city, an example of hot humid climates of Vietnam, were considered. These monthly weather datasets for use in the PHPP were created by the Meteonorm software. As a result, the energy requirement for cooling and dehumidification for dwellings in Tuy Hoa city is equal to or less than 40 kWh/(m^{2}a). Alternatively, cooling and dehumidification demand is equal to or less than 76 kWh/(m^{2}a) and cooling load does not exceed 10 W/m^2 (V. T. Le & Pitts, 2020).

In addition to the criteria listed in Table 7.1, the Passive House standard requires an indoor thermal environment within the range of 20 – 25°C (≤ 10% of the total hours per year the indoor temperature exceeds 25°C), regardless of climate types. This comfort range was derived from the heat balance model. The Passive House Institute claimed various reasons why the adaptive theory was not adopted in the Passive House methodology (Schnieders, 2019). However, it is observed from the literature that the PMV-PPD model overestimated thermal sensations of the subjects especially at high temperatures, and people in different climate types may suit to different thermal comfort zones (as mentioned in Section 2.1). Consequently, the use of the constant 20 – 25°C criterion for Passive House buildings throughout the world needs to be carefully considered. Based on the thermal comfort experiment described in Chapter 4, this study proposed a thermal comfort zone of 23.7 – 29.6°C for Passive House buildings in Vietnam, including dwellings. This would help to save substantial energy consumed for cooling demand in buildings compared to the use of the 20 – 25°C criterion.

Regarding indoor humidity, the Passive House standard requires a maximum humidity ratio of 12 g/kg, which is recommended in ASHRAE Standard 55 and CEN Standard EN 16798-1. This humidity ratio is equal to approximately 60% RH at 25°C or 82% RH at 20°C, the upper and lower limits of indoor temperature in a Passive House building. Thus, the Passive House standard accepts a maximum RH that varies from about 60% to 80% depending on the indoor temperature. In hot humid climates with higher acceptable temperatures, the application of the 12 g/kg humidity limit seems to be inappropriate. Considering the Vietnamese acceptable temperature range found in this study as an example, the 12 g/kg humidity ratio is equivalent to about 46% RH at 29.6°C or 65% RH at 23.7°C. It is clear that humidity control at such low level is not necessary and could waste energy for excessive dehumidification. Therefore, this study proposed a higher humidity limit of 14 g/kg for Passive House buildings in the hot humid climate of Vietnam. This humidity ratio is equivalent to about 54% RH at 29.6°C or 76% RH at 23.7°C, which complies with the required RH in Passive House buildings and the recommended RH limits from the literature (as shown in Section 6.4).

Due to the relaxations of the thermal comfort zone and the maximum humidity ratio for Passive House buildings in Vietnam, the requirement of very air-tight buildings could be eased whilst the buildings are still able to meet the criteria of primary energy demand and cooling and dehumidification demand of the Passive House standard. The relaxation of air tightness requirement would be beneficial since achieving an air tightness less than 0.6 ACH is one of the most difficult work in Passive House building construction. It requires advance materials (air tight windows and doors, membranes, taps) and substantial on-site efforts (Figure 7.1). This study proposed air tightness as a modifiable building parameter rather than a constant criterion.

In summary, some criteria of the Passive House standard when being applied to hot humid climates need to be adjusted to suit the local climates and residents. On that point of view, this study proposed some modifications for Passive House buildings in Vietnam as follows: replacing the 20 - 25°C temperature range by the 23.7 - 29.6°C; increasing the humidity limit from 12 g/kg to 14 g/kg. As a result, the building air tightness does not need to be at a very high level of 0.6 ACH, which is suitable to the quality of building components and construction techniques in developing Vietnam. These adjustments are expected to save substantial energy and construction costs compared to the application of the original Passive House standard, and thereby facilitate the development of the Passive House approach in hot humid regions.

Construction requirements for air tightness
(Source: greenbuildingstore.co.uk)

Taping for air tightness in Kirkburton Passive House
(Source: author)

Figure 7.1: Construction techniques for air-tight buildings

7.1.2 Modelling typical existing housing models with the PHPP

To investigate the energy saving potential of the Passive House approach for housing in Vietnam, the models of existing houses are necessary for computational simulations. Therefore, the proposed terraced and detached houses shown in Subsection 6.2.1 were modelled in the designPH software, a geometry-creating tool to support the PHPP. It is noted that the PHPP was the major simulation tool employed in this chapter. This is because the PHPP is dedicated for modelling Passive House buildings, and the use of this software is essential for Passive House certification. Moreover, the PHPP has shown accurate predictions compared to measured data in various large building projects (Figure 7.2).

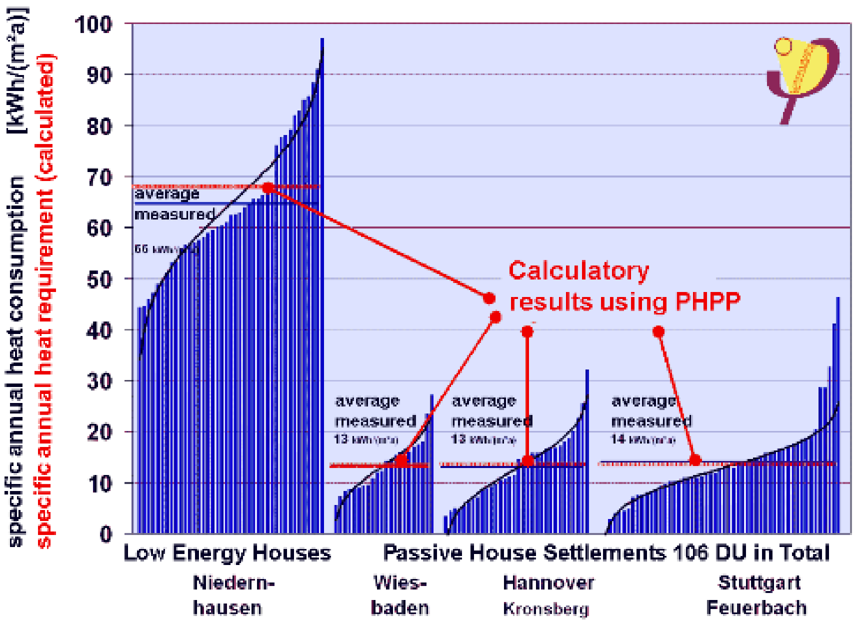


Figure 7.2: The accuracy of PHPP calculations compared to measured data (PHI, 2020)

The 3D models of the proposed terraced and detached houses shown in Figure 7.3 were created by designPH, an extension for the SketchUp software. All housing information was then exported to the PHPP for further adjustments and calculations. The building details of existing housing described in Subsection 6.2.1, including the construction structures and materials, air tightness, internal heat gain, and other building elements, were applied to the PHPP models. A summary of building properties is shown in Table 7.2.

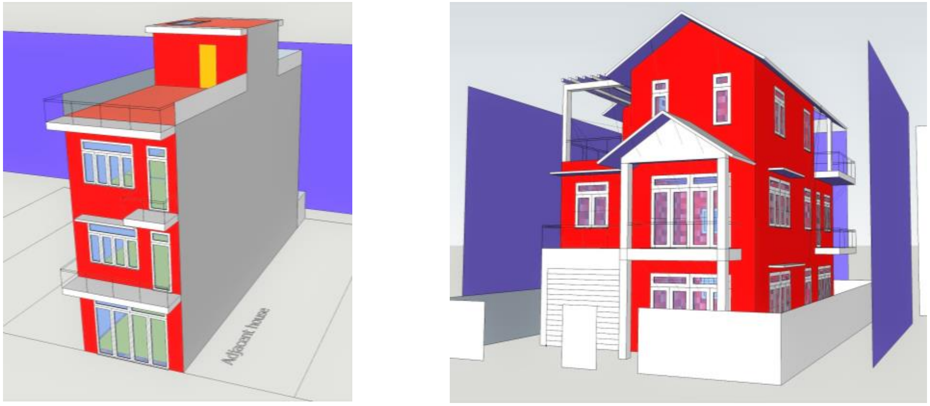


Figure 7.3: Terraced and detached house models in the designPH software

Table 7.2: Building properties of the existing houses modelled in the PHPP

Building properties	Terraced house	Detached house
200mm masonry wall: U-value	1.93 W/(m^{2}K)	1.93 W/(m^{2}K)
100mm wall to neighbour: U-value	2.97 W/(m^{2}K)	
Flat concrete roof: U-value	3.18 W/(m^{2}K)	3.18 W/(m^{2}K)
Pitched concrete roof: U-value		1.84 W/(m^{2}K)
Ground floor: U-value	2.6 W/(m^{2}K)	1.37 W/(m^{2}K)
Solar absorptivity of external walls, roofs	0.7	0.7
Simple window frame: U-value	2.5 W/(m^{2}K)	2.5 W/(m^{2}K)
Single glazing: U-value / SHGC	5.59 W/(m^{2}K) / 0.87	5.59 W/(m^{2}K) / 0.87
Window shading ratio*	60%	70%
Air exchange at 50 Pascal differential pressure (n_{50}) (= 0.7 ACH at normal pressure)	9.5 ACH	9.7 ACH
Internal heat gain	2.3 W/m^2	2.3 W/m^2
Mechanical ventilation with energy recovery	no	
Cooling type	Recirculation cooling (SEER = 3.5)	
Dehumidification	Waste heat to room (SEER = 2)	

* Window shading ratio is the total value provided by building shading devices (overhangs, balconies, curtains) and site shading objects (terrain, surrounding buildings, trees)

SHGC: solar heat gain coefficient; SEER: seasonal energy efficiency ratio

Note that although the existing houses were already simulated using EnergyPlus software in Chapter 6, it is necessary to remodel these houses with the PHPP due to differences between the two simulation methods. The previous EnergyPlus simulations reflected conventional housing where cooling equipment is installed only for main spaces. Meanwhile, all indoor spaces of a Passive House building are taken into account in cooling calculation. Therefore, this results in the differences in the treated floor area and the total energy consumption between these simulation methods. Consequently, for comparison with the improved houses built to the Passive House standard, modelling of the existing houses using the PHPP is necessary.

Table 7.3 shows cooling and dehumidification demand, maximum cooling load and total primary energy consumption of the existing terraced and detached houses to maintain different thermal comfort zones of 20 – 25°C and 23.7 – 29.6°C. These values are graphically described in Figure 7.4. It is observed that cooling and dehumidification demands significantly reduced in both houses when using the higher temperature setpoints. This indicated the benefit in terms of energy saving of choosing a correct thermal comfort zone for Vietnamese housing. The energy demands of the existing houses were used as base values to determine energy-saving potential of the improved houses built to the Passive House standard.

Table 7.3: Energy demand of the existing houses with different temperature setpoints

	Existing terraced house			Existing detached house		
	20–25°C	23.7–29.6°C	Reduction rate (%)	20–25°C	23.7–29.6°C	Reduction rate (%)
Cooling and dehumidification demand (kWh/(m^{2}a))	260	123.4	52.5%	372.2	155.2	58.3%
Cooling load (W/m^2)	70.6	23.9	66.1%	71	35.8	49.6%
Primary energy demand (kWh/(m^{2}a))	279	190	31.9%	347	213	38.6%

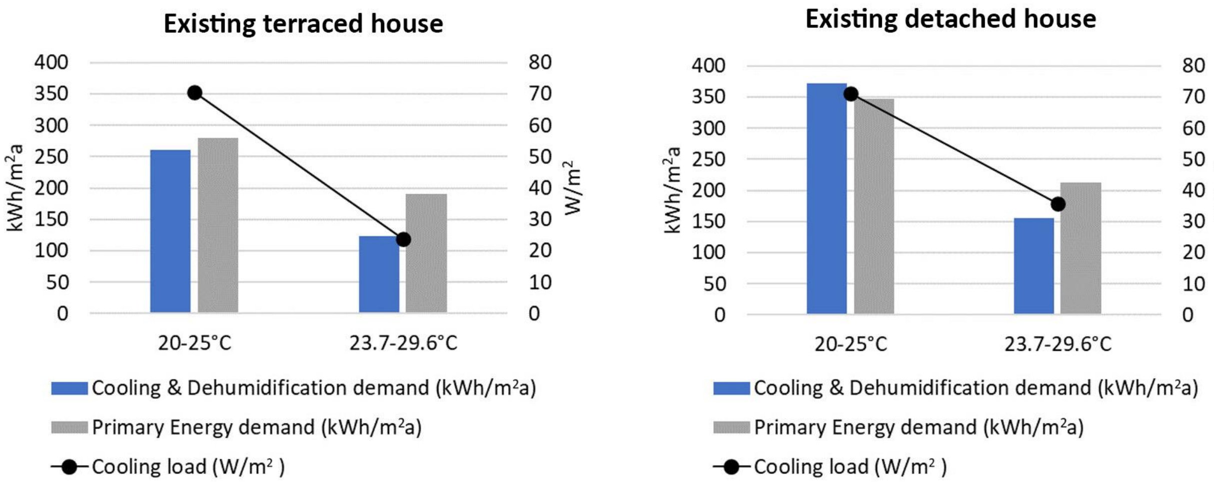


Figure 7.4: Energy demand of the existing houses with different temperature setpoints

7.1.3 Energy saving by adapting the Passive House approach to Vietnamese housing

In order to investigate the potential of the Passive House approach applied to housing in the hot humid climate of Vietnam, the existing terraced and detached houses were improved to meet the Passive House standard. Each house was equipped with a mechanical ventilation system with energy recovery (75% cooling recovery and 77% humidity recovery) for fresh air supply. Cooling was mainly handled by supply-air-cooling equipment. Conventional air conditioners were installed to support the main cooling system when necessary. Also, portable dehumidifiers, which waste heat to room, were used to ensure the required indoor humidity. Air tightness was improved to avoid penetration of the outdoor air which usually brings in heat and humidity. To reduce heat gain through building envelope, the existing walls, roofs, and ground floor were added a layer of extruded polystyrene (XPS, thermal conductivity of 0.035 W/mK), and exterior absorptivity of walls, roofs was reduced. In addition, shading ratio of windows and glass doors was increased. This shading ratio is the average value provided by building shading devices (overhangs, balconies, curtains) and site shading objects (terrain, surrounding buildings, trees), which was automatically calculated in the PHPP worksheet. Windows and glass doors were improved from single glazing with simple frame to double glazing or double low-E glazing with standard frame. Thermal bridges were assumed to be generally avoided. (V. T. Le & Pitts, 2020)

The above building properties of the terraced and detached houses were amended to sequentially meet the original Passive House standard (with 20 – 25°C comfort range) and the revised one (with 23.7 – 29.6°C comfort range) as shown in Table 7.4 and Table 7.5. Note that apart from using higher temperature setpoints, the revised Passive House standard for Vietnam has also eased the indoor humidity and air tightness requirements as discussed in Subsection 7.1.1.

Table 7.4: Building properties of the Passive House terraced house with different temperature setpoints

Building properties	20 – 25°C	23.7 – 29.6°C
Exterior wall: U-value; insulation thickness	0.3 W/(m^{2}K); 10 cm	0.81 W/(m^{2}K); 2.5 cm
Wall to neighbour: U-value; insulation thickness	0.31 W/(m^{2}K); 10 cm	0.95 W/(m^{2}K); 2.5 cm
Flat concrete roof: U-value; insulation thickness	0.32 W/(m^{2}K); 10 cm	0.576 W/(m^{2}K); 5 cm
Ground floor: U-value; insulation thickness	0.55 W/(m^{2}K); 5 cm	2.6 W/(m^{2}K); 0 cm
Solar absorptivity of external walls, roofs	0.3	0.5
Window frame: U-value	1.6 W/(m^{2}K)	1.6 W/(m^{2}K)
Glazing: U-value; SHGC	1.1 W/(m^{2}K); 0.23 (low-E double, Argon filling, solar protection)	2.8 W/(m^{2}K); 0.78 (ordinary double, air filling)
Window shading ratio	75%	75%
Air exchange at 50 Pascal differential pressure (n_{50})	0.6 ACH	4.0 ACH
Internal heat gain	2.3 W/m^2	2.3 W/m^2
Indoor humidity limit	12 g/kg	14 g/kg
Mechanical ventilation with energy recovery	Cooling recovery efficiency: 0.75 Humidity recovery efficiency: 0.77	
Supply air cooling	On/off mode (SEER = 3.5)	
Additional cooling	Recirculation cooling (SEER = 3.5)	
Dehumidification	Waste heat to room (SEER = 2)	
Overnight ventilation via windows	No	

SHGC: solar heat gain coefficient; SEER: seasonal energy efficiency ratio

Table 7.5: Building properties of the Passive House detached house with different temperature setpoints

Building properties	20 – 25°C	23.7 – 29.6°C
Exterior wall: U-value; insulation thickness	0.160 W/(m^{2}K); 20 cm	0.208 W/(m^{2}K); 15 cm
Flat concrete roof: U-value; insulation thickness	0.217 W/(m^{2}K); 15 cm	0.315 W/(m^{2}K); 10 cm
Pitched concrete roof: U-value; insulation thickness	0.207 W/(m^{2}K); 15 cm	0.293 W/(m^{2}K); 10 cm
Ground floor: U-value; insulation thickness	0.279 W/(m^{2}K); 10 cm	1.370 W/(m^{2}K); 0 cm
Solar absorptivity of external walls, roofs	0.3	0.5
Window frame: U-value	1.6 W/(m^{2}K)	1.6 W/(m^{2}K)
Glazing: U-value; SHGC	1.1 W/(m^{2}K); 0.23 (low-E double, Argon filling, solar protection)	2.8 W/(m^{2}K); 0.78 (ordinary double, air filling)
Window shading ratio	80%	80%
Air exchange at 50 Pascal differential pressure (n_{50})	0.6 ACH	3.0 ACH
Internal heat gain	2.3 W/m^2	2.3 W/m^2
Indoor humidity limit	12 g/kg	14 g/kg
Mechanical ventilation with energy recovery	Cooling recovery efficiency: 0.75 Humidity recovery efficiency: 0.77	
Supply air cooling	On/off mode (SEER = 3.5)	
Additional cooling	Recirculation cooling (SEER = 3.5)	
Dehumidification	Waste heat to room (SEER = 2)	
Overnight ventilation via windows	No	

SHGC: solar heat gain coefficient; SEER: seasonal energy efficiency ratio

Table 7.6: Energy demand of the existing and Passive House buildings with 20 - 25°C setpoints

	Terraced house			Detached house		
	Existing	Passive House	Reduction rate (%)	Existing	Passive House	Reduction rate (%)
Cooling and dehumidification (kWh/(m^{2}a))	260	69.8	73.2%	372.2	74.9	79.9%
Maximum cooling load (W/m^2)	70.6	10.4[a]	85.3%	71	10.3	85.5%
Primary energy demand (kWh/(m^{2}a))	279	95	65.9%	347	98	71.8%

[a] In PHPP verification sheet, decimals of cooling load value are rounded off to the nearest integer number.

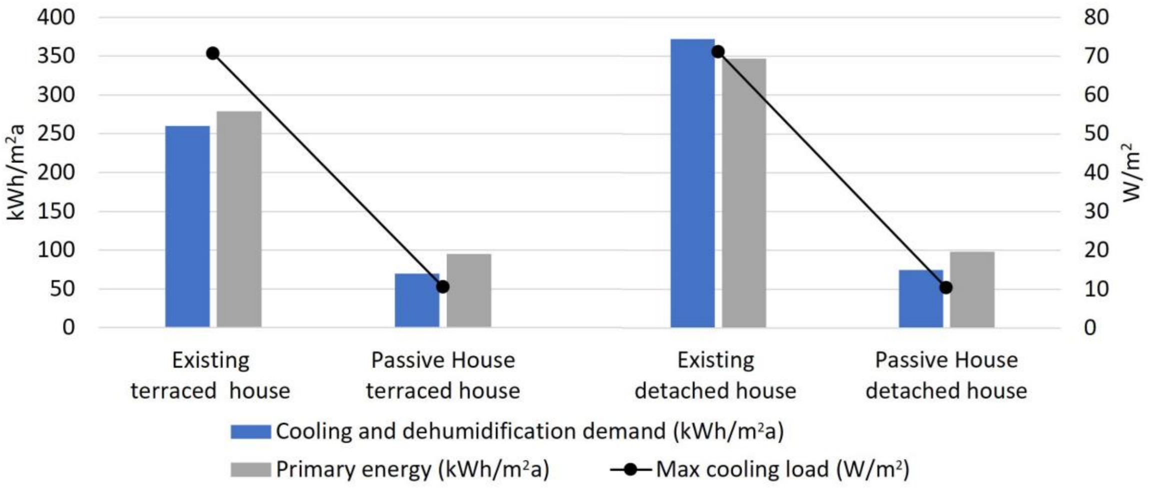


Figure 7.5: Energy demand of the existing and Passive House buildings with 20 - 25°C setpoints

Table 7.7: Energy demand of the existing and Passive House buildings with 23.7 – 29.6°C setpoints

	Terraced house			Detached house		
	Existing	Passive House	Reduction rate (%)	Existing	Passive House	Reduction rate (%)
Cooling and dehumidification (kWh/(m²a))	123.4	66.5	46.1%	155.2	62	60.1%
Maximum cooling load (W/m²)	23.9	10.4	56.5%	35.8	10	72.1%
Primary energy demand (kWh/(m²a))	190	111	41.6%	213	103	51.6%

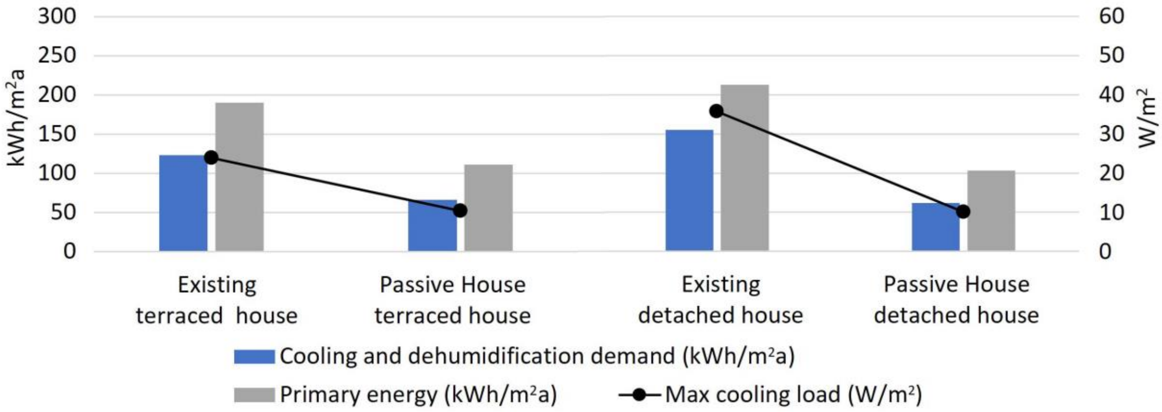


Figure 7.6: Energy demand of the existing and Passive House buildings with 23.7 – 29.6°C setpoints

Table 7.6 and Table 7.7, show energy demands of the existing houses and the improved houses built to the Passive House standard. These data are graphically shown in Figure 7.5 and Figure 7.6. Note that cooling and dehumidification demand is the product of the corresponding electrical-energy consumption and the coefficient of performance of the equipment. Table 7.6 and Figure 7.5 show that the Passive House buildings sharply reduced by about 73% and 80% of the cooling and dehumidification demands of the existing terraced and detached houses respectively to maintain indoor temperature within 20 – 25°C. Similarly, the maximum cooling loads were reduced by about 85% in both houses. These substantial energy savings were due to the significant improvement of housing properties to meet the original Passive House standard.

On the other hand, Table 7.7 and Figure 7.6 show that the existing houses required less energy to maintain the higher thermal comfort zone of 23.7 – 29.6°C. As a result, the Passive House terraced and detached houses achieved lower energy-saving levels of about 46% and 60% for cooling and dehumidification demand. However, building properties of the existing houses did not need significant improvements to meet the revised Passive House standard for Vietnam as shown in Table 7.4 and Table 7.5. By using the 23.7 – 29.6°C setpoint, the Passive House energy requirements (cooling and dehumidification demand ≤ 76 kWh/m²a; cooling load ≤ 10 W/m²; and primary energy demand ≤ 120 kWh/m²a) can be met with higher thermal-transmittance materials and a lower level of airtightness compared to the use of the 20 – 25°C setpoint. For example, in the terraced house, the insulation layer thicknesses of external walls and roof were cut down three quarters (from 100 mm to 25 mm) and a half (from 100 mm to 50 mm), respectively. The solar absorptivity of exterior opaque elements rose from 0.3 to 0.5, which means exterior surfaces did not need to be painted very bright colours such as white. Window quality only required double layers of ordinary clear glass instead of low-E window with argon filling and solar protection. Air infiltration of the envelope was 4 ACH (n_{50}) rather than a strict value of 0.6 ACH (V. T. Le & Pitts, 2020).

The use of simpler windows and thinner insulation layers for external walls, roofs and ground floor can save much in construction costs. In addition, the lower requirement of airtightness would also be financially beneficial and appropriate to the construction techniques of many countries especially of developing ones. In short, the benefits of energy saving and affordable construction cost can be achieved by adapting the Passive House approach with higher temperature setpoints for hot humid regions (V. T. Le & Pitts, 2020).

7.1.4 A comparison of Passive House buildings in different hot humid areas of Vietnam

According to the Vietnam building code QCVN 02:2009/BXD about climatic data for construction, the southern part of Vietnam has a tropical monsoon climate which is divided into three sub-regions including the South Central Coast, Western Highland, and Southern Delta. Among them, the South Central Coast and Southern Delta feature hot and humid climate. Therefore, these sub-regions were selected to investigate the discrepancies of Passive House residential buildings located in these areas. Tuy Hoa city in the South Central Coast and Ho Chi Minh city (HCMC) in the Southern Delta were selected as case studies.

Figure 7.7 shows monthly outdoor temperature and relative humidity in the two cities. It is observed that the monthly temperature of HCMC does not fluctuate as much as that of Tuy Hoa city. The annually average temperature of HCMC (27.4°C) is about 1°C higher than that of Tuy Hoa city (26.5°C), however, the weather in Tuy Hoa city is more extreme in hot season. Although the fluctuations of relative humidity in the two cities have different trends, the yearly average values are identical at about 80% RH. Due to a higher annually average temperature, the criterion for cooling and dehumidification demand of Passive House buildings in HCMC is 78 kWh/m^{2}a, slightly higher than that for Tuy Hoa city.

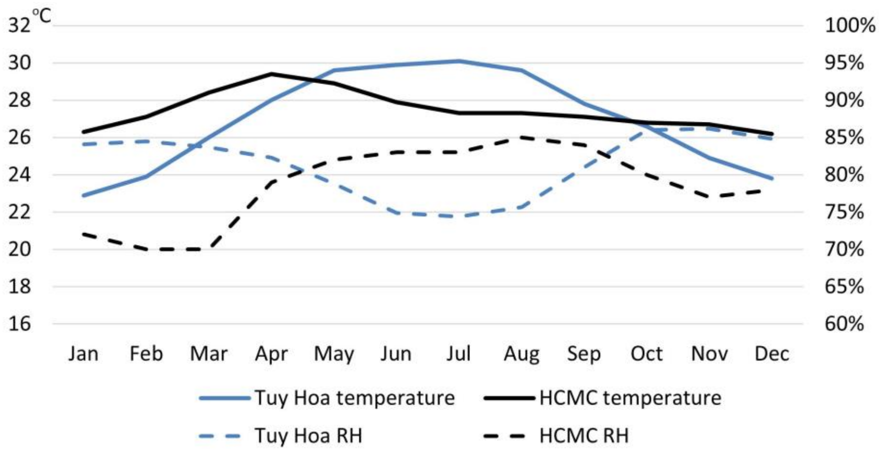
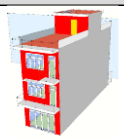


Figure 7.7: Monthly outdoor temperature and RH in Tuy Hoa and Ho Chi Minh cities

To compare energy performance between Passive House dwellings in Tuy Hoa and HCM cities, the climate data of the two cities were sequentially used for the terraced and detached models. Table 7.8 shows cooling and dehumidification demand and maximum cooling load of these Passive House models with two different temperature setpoints in Tuy Hoa and HCM cities. With the 20 – 25°C setpoint, the housing models in HCMC required more energy for cooling and dehumidification demand. The opposite results were observed when applying the 23.7 – 29.6°C setpoint. Meanwhile, the maximum cooling loads of the houses in HCMC were smaller than in Tuy Hoa city for all cases. These results accurately reflected the climates of the two cities since HCMC has a higher average temperature whilst Tuy Hoa city has a more extreme hot season.

Table 7.8: Energy demand of the Passive House buildings in Tuy Hoa and HCM cities

Building type	Thermal comfort zone	20 – 25°C		23.7 – 29.6°C	
	Location	Tuy Hoa	HCMC	Tuy Hoa	HCMC
	Cooling and dehumidification (kWh/(m^{2}a))	69.8	73.3	66.5	63.6
	Maximum cooling load (W/m^2)	10.4	10.1	10.4	9.3
	Cooling and dehumidification (kWh/(m^{2}a))	74.9	79	62	58.6
	Maximum cooling load (W/m^2)	10.3	10.1	10	9.6

In general, the differences between Passive House dwellings in Tuy Hoa and HCM cities were not significant, and the Passive House dwellings in Tuy Hoa city can also meet the Passive House standard for HCMC. Therefore, this study focuses on housing in Tuy Hoa city for an in-depth investigation on the Passive House approach for the hot humid climate of Vietnam. It is worth mentioning that in-depth study on Passive House buildings for each specific location is ideal, but it takes time and is not the aim of this research. This could be done by further work.

In conclusion, the Passive House dwellings showed substantial energy savings compared to the existing ones. In addition, more energy saving and affordable construction cost were achieved by adapting the Passive House standard with higher temperature and humidity setpoints for hot humid regions. These results indicated the great potential of the Passive House approach for housing in the context of Vietnam. It is noted that the building components of the Passive House models in this section are only examples to examine the opportunities of the Passive House application to Vietnamese housing. They are not the only or the optimum building components for Passive Houses in Vietnam. In order to determine possible building assemblies that meet the Passive House standard, parametric study is an effective method. Therefore, this study firstly conducted parametric simulations to consider the influences of individual building parameters on the energy consumption. Secondly, the assemblies of positive variants of building components were examined to determine the potential cases of Vietnamese housing that meet the Passive House standard. These contents are described in the following sections.

7.2 *Sensitivity analysis of Passive House parameters for Vietnam*

In this section, nine key parameters that strongly affect energy consumption in a Passive House building were individually examined, including orientation, thermal insulation of walls, roofs, exterior solar absorptivity, window area, glazing type, solar shading, air tightness, cool recovery, and humidity recovery. Parameter variants covering a wide range were sequentially applied to a Passive House base case to calculate the energy performance of the building and then determine the positive variants for each parameter. The Passive House terraced and detached houses in the previous section (as described in Table 7.4 and Table 7.5) were selected as the base cases for further considerations. Note that from now on, only the revised Passive House standard for Vietnamese buildings associated with the comfort zone of 23.7 – 29.6°C was applied.

It is worth mentioning that although a number of parametric simulations on housing components were carried out in Chapter 6, those investigations were for the hybrid houses with the common use of natural ventilation. By contrast, this section examined the effects of various component variants on sealed Passive House buildings. In addition, more building parameters were considered compared to the work in Chapter 6, some of which are dedicated to Passive House buildings such as air tightness and mechanical ventilation system with energy recovery. It is a simplistic analysis to get some understanding of the features and that it would obviously be worthy of more intense analysis but nevertheless gives some indication of key relationships.

7.2.1 Orientations

Building orientation is an important factor that should be considered when designing any building. To investigate the effect of this parameter on energy performance of the Passive Houses, 8 principal orientations were sequentially applied to the terraced and detached models. The results are shown in Figure 7.8 and Figure 7.9. The different influences of orientations on annual cooling demand and maximum cooling load of the terraced house are clear and comprehensible. This is because this housing type has only two front and rear façades. A more complicated trend was observed in the detached house due to the large glazing areas on different façades of the house.

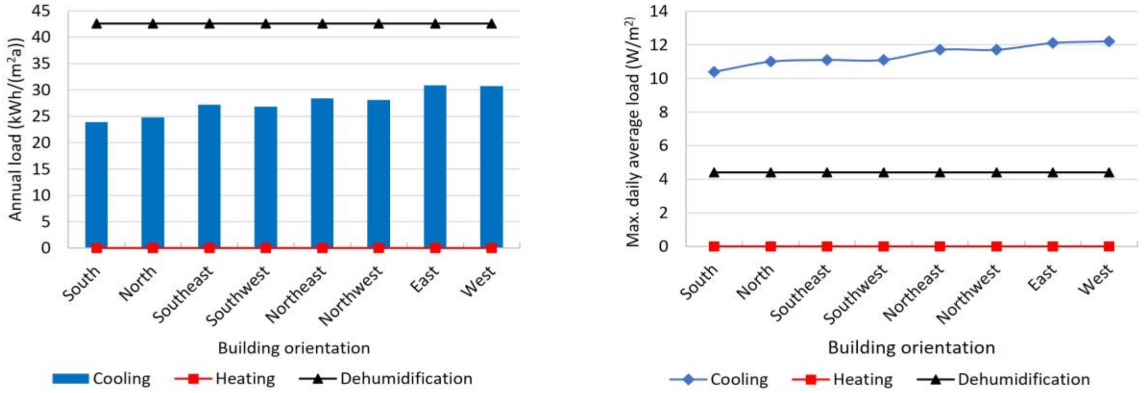


Figure 7.8: Energy load of the terraced house with various building orientations

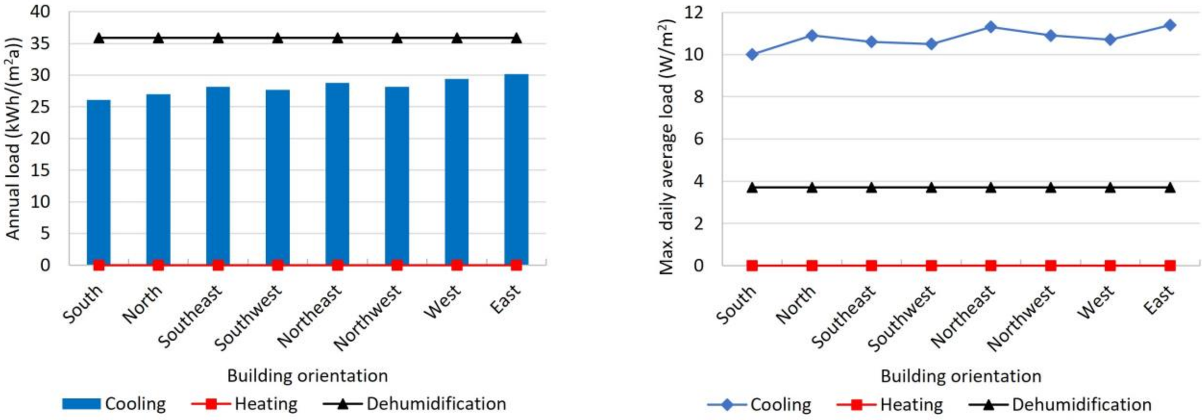


Figure 7.9: Energy load of the detached house with various building orientations

In both houses, the differences of annual cooling demand among the orientations were less than 6 kWh/(m^2a), which maintained the annual cooling and dehumidification demand below the criterion of 76 kWh/(m^2a). However, the maximum cooling load increased and exceeded the limit of 10 W/m^2 in all orientations except for the base case of South. In general, the South is the best orientation for Passive House dwellings in Vietnam while East and West orientations should be avoided. This is in line with the general knowledge on building orientation in hot humid Vietnam.

It is clear from the figures that the humidity loads were stable. This was due to the assumption of a constant humidity gain from interior sources, air infiltration, and mechanical ventilation. Meanwhile, in a hot humid climate, the heating loads were absent or negligible. This condition was observed on the simulation results of most building parameters.

7.2.2 Thermal insulation of walls, roofs and ground floor

One of the Passive House principles is the high thermal insulation level of the building envelope. To determine the appropriate level for Passive House dwellings in Vietnam, this study sequentially applied various thicknesses of XPS insulation layer to external walls, roofs, and ground floor of the housing models. Table 7.9 shows a wide range of XPS thicknesses from 0 to 300 mm and the corresponding U-values of the building components.

Table 7.9: U-values of various walls, roofs, and ground floors (W/(m^2K))

Insulation layer thickness (mm)	0	10	25	50	75	100	150	200	300
External wall	1.93	1.24	0.81	0.51	0.38	0.30	0.21	0.16	0.11
Wall to neighbour	2.97	1.61	0.95	0.57	0.40	0.31	0.22	0.65	0.11
Flat roof	3.18	1.67	0.97	0.57	0.41	0.32	0.22	0.17	0.13
Pitched roof	1.84	1.20	0.80	0.51	0.37	0.29	0.21	0.16	0.11
Ground floor (terraced house)	2.60	1.49	0.91	0.55	0.40	0.31	0.21	0.16	0.11
Ground floor (detached house)	1.37	0.99	0.69	0.46	0.35	0.28	0.20	0.15	0.11

Figure 7.10 and Figure 7.11 show the energy loads of the terraced and detached houses with various insulation thicknesses of the external walls. The influences of this parameter on the two houses were significantly different. When increasing the insulation thickness, the decreases of annual cooling demand of the terraced house were negligible whilst the maximum daily cooling load saw the largest reduction of only 19%. In the detached house, thermal insulation of exterior walls strongly affected energy performance of the house since the annual cooling demand and the daily cooling load were significantly decreased by 37% and 54% respectively. It is observed that the greatest energy load reduction rate occurred when the first 25mm insulation layer was applied. This reduction rate gradually reduced with the insulation layers of 50, 100, and 150mm, then negligibly reduced with the application of the 2 thicker layers. This result indicated that insulation thickness more than 150mm is not necessary in Vietnamese housing.

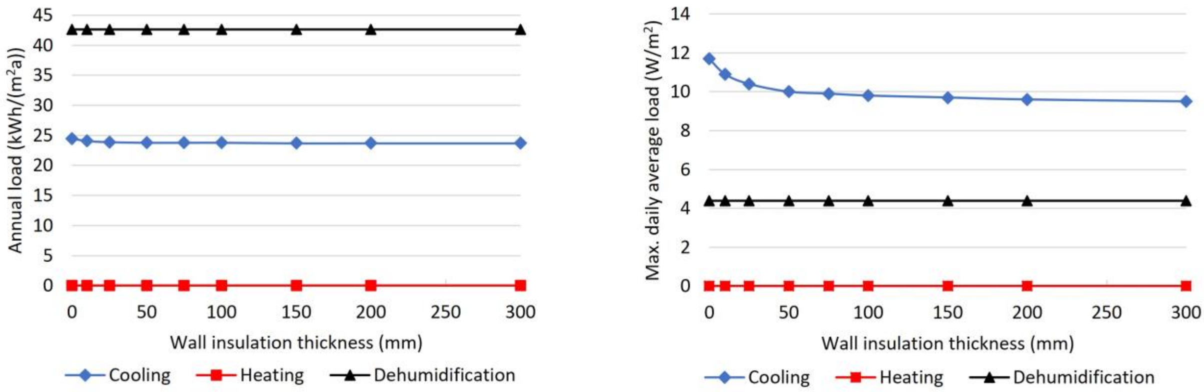


Figure 7.10: Energy load of the terraced house with various external walls

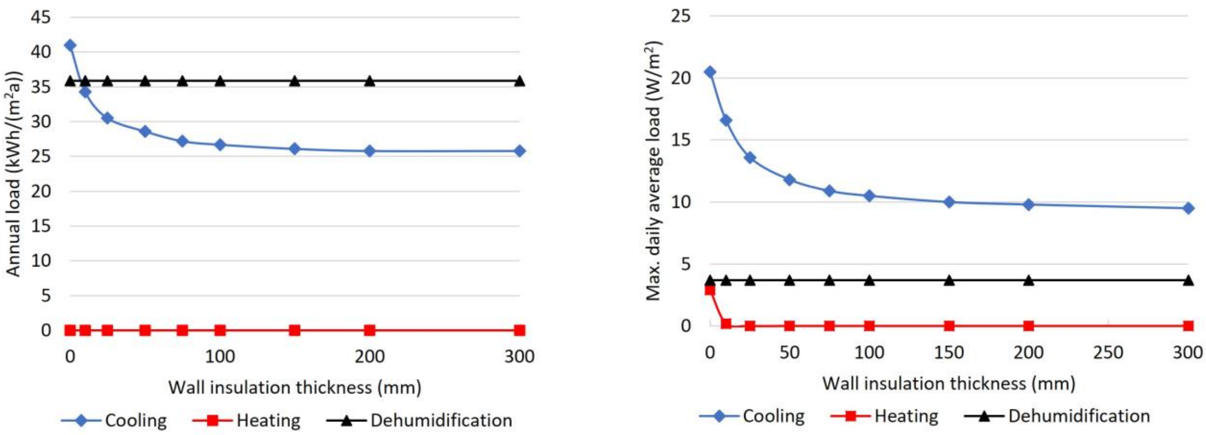


Figure 7.11: Energy load of the detached house with various external walls

Figure 7.12 shows the energy loads of the terraced house with various insulation levels for the walls toward neighbour. The maximum daily cooling load significantly reduced only with the first 10 and 25mm insulation layer. Thicker layers were ineffective. Note that the PHPP does not take into account walls toward adjacent buildings in the calculation of annual energy loads. This approach is also applied in other simulation software such as EnergyPlus and DesignBuilder.

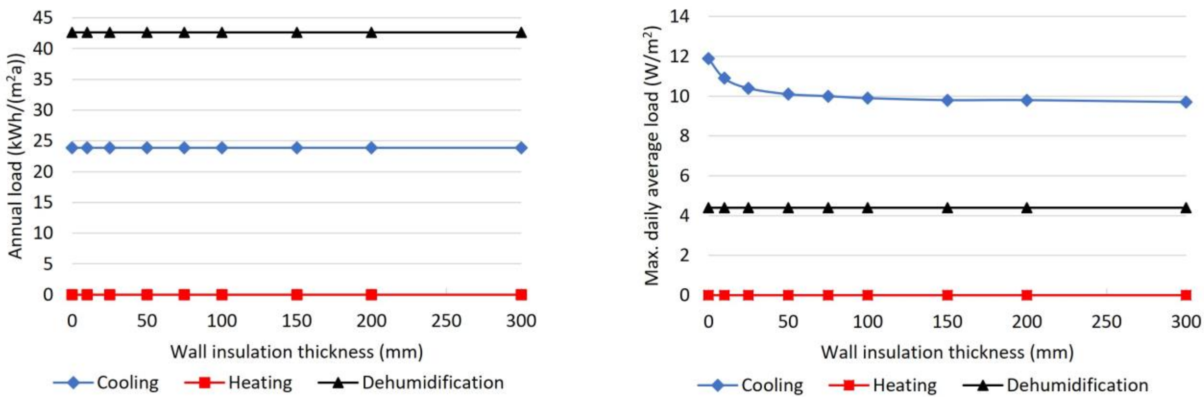


Figure 7.12: Energy load of the terraced house with various walls toward neighbour

Figure 7.13 and Figure 7.14 show the strong influence of roof insulation parameter on energy performance of the housing models. Sharp decreases were observed in both annual cooling demand and maximum daily average cooling load. Again, the first 25mm insulation layer created the significant reduction whilst insulation thickness more than 100mm is ineffective.

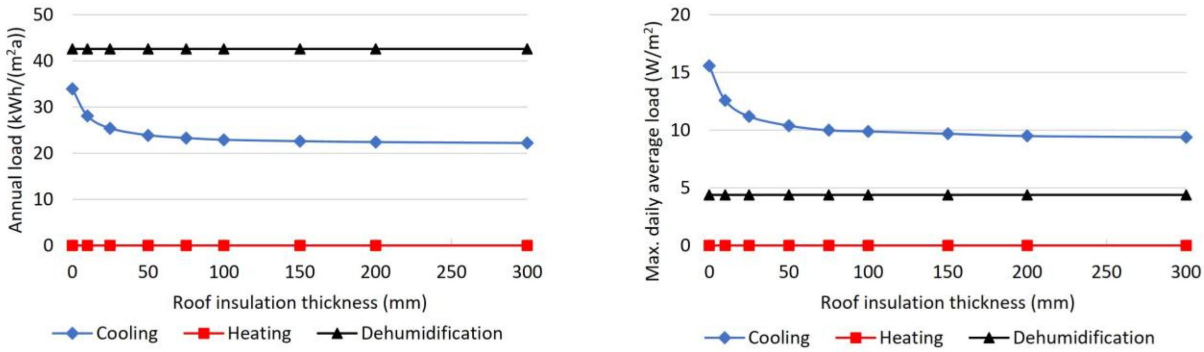


Figure 7.13: Energy load of the terraced house with various roofs

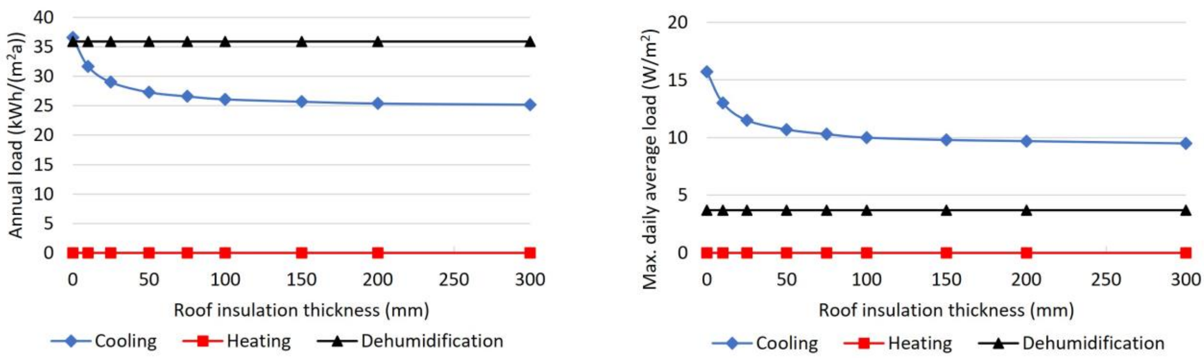


Figure 7.14: Energy load of the detached house with various roofs

Figure 7.15 and Figure 7.16 show the energy loads of the terraced and detached houses with various insulation thicknesses of the ground floor. It is clear from the figures that increasing ground floor insulation caused adverse effects on the annual cooling load. This is because the insulation layer prevented heat exchanges between the buildings and the cool ground. Therefore, despite a slight decrease of the maximum daily average cooling load, ground floor insulation should be avoided under the climate of Vietnam.

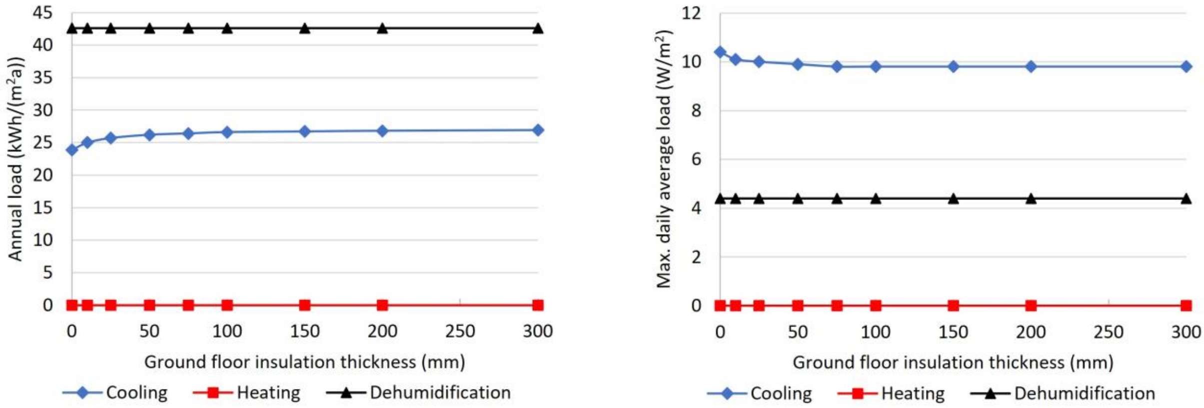


Figure 7.15: Energy load of the terraced house with various ground floors

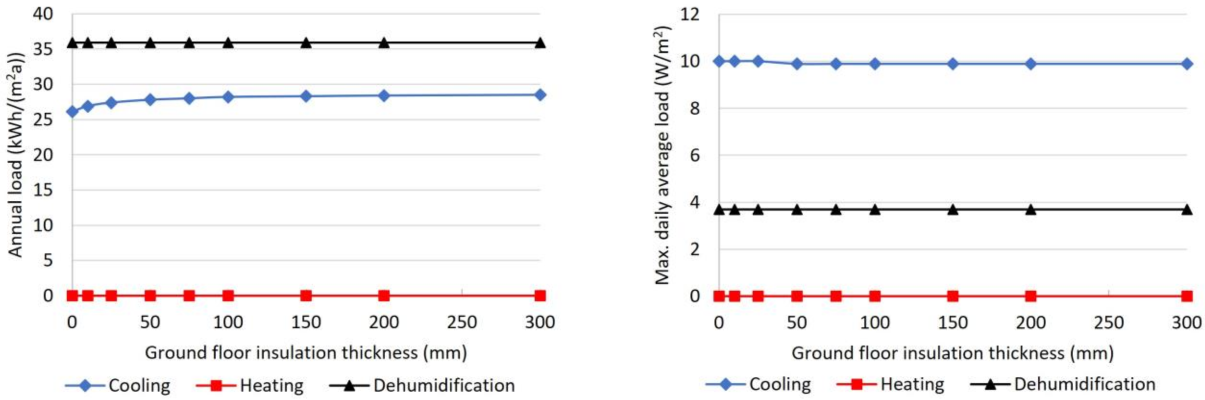


Figure 7.16: Energy load of the detached house with various ground floors

7.2.3 Exterior solar absorptivity

As indicated in Subsection 6.3.5 of the previous chapter, low solar absorptivity envelope can improve thermal performance of hybrid buildings. To investigate the influence of this parameter on energy performance of Passive House dwellings in Vietnam, a wide range of solar absorptivity from 0.1 to 0.9 were simulated. The results are shown in Figure 7.17 and Figure 7.18.

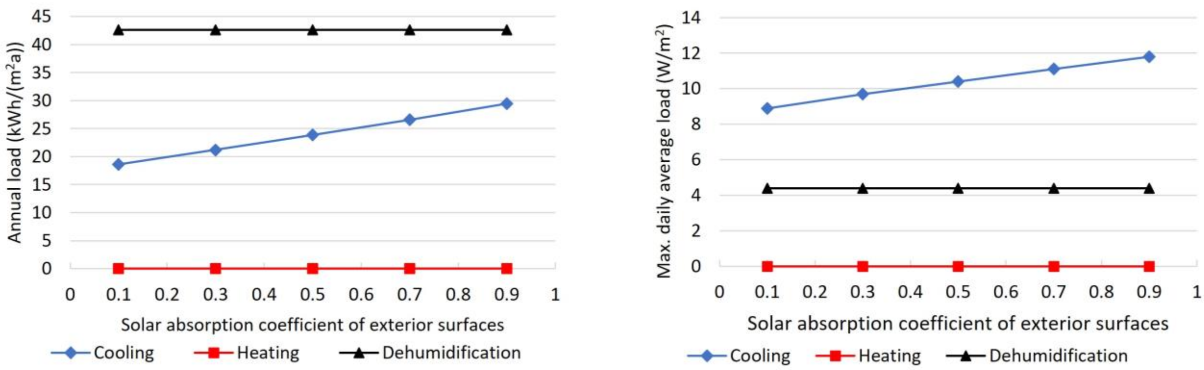


Figure 7.17: Energy load of the terraced house with various exterior solar absorptance coefficients

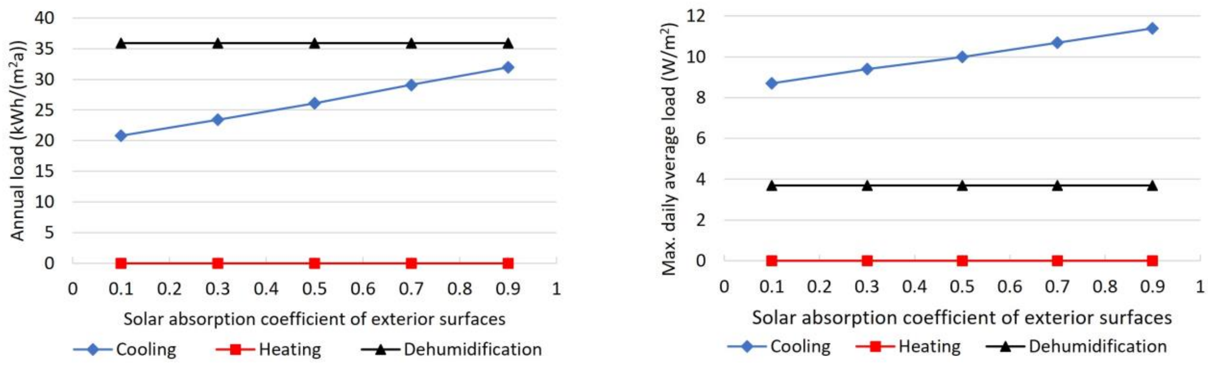


Figure 7.18: Energy load of the detached house with various exterior solar absorptance coefficients

The figures show a linear relationship between solar absorptance coefficient of exterior surfaces and the cooling loads of the houses. The higher solar absorptivity, the higher annual cooing demand and daily average cooling load. It is worth mentioning that the effect of solar absorptivity on the Passive Houses was not as strong as that on the existing house, which is shown in Figure 6.23 of Subsection 6.3.5. This is due to the existence of an insulation layer in the Passive House walls and roofs. Further simulations indicated that when a low solar absorptivity was applied, the efficiency of insulation layer was reduced. Therefore, in the context of Vietnam, the use of low solar absorptivity should be prioritised in order to reduce the thickness of insulation layer.

7.2.4 Window area

Selecting window area (or glazing area) is one of the most important tasks of building design since it relates to daylighting, natural ventilation (if necessary), and thermal performance of indoor spaces. This study focussed on the influence of window area parameter on thermal performance of Passive House dwellings in Vietnam, which is mainly expressed by the cooling load. The window-to-wall ratios (WWR) of 15%, 20%, 30% (base case), 40%, and 45% were sequentially applied to the terraced house model. Note that two walls toward neighbour were not taken into account in the WWR calculations. The WWR of 15%, 17% (base case), 25%, and 35% were sequentially applied to the detached house. The simulation results are shown in Figure 7.19 and Figure 7.20.

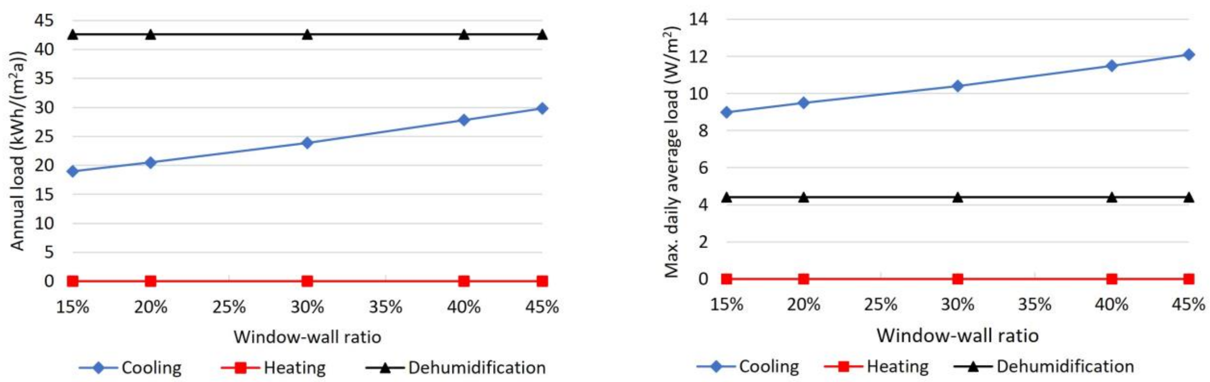


Figure 7.19: Energy load of the terraced house with various window-to-wall ratios

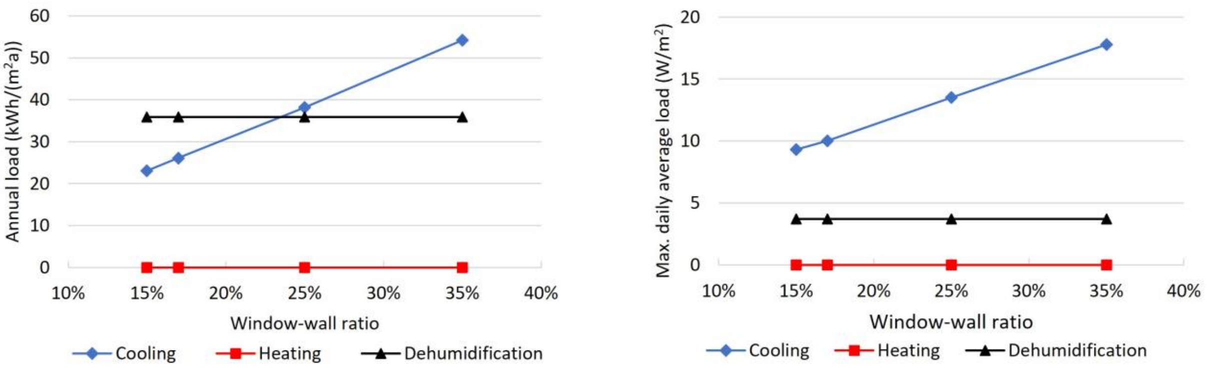


Figure 7.20: Energy load of the detached house with various window-to-wall ratios

In general, the annual cooling demand and the maximum daily average cooling load were linearly dependent on the WWR. The increase of WWR caused the increase of cooling demand. It is clear from the figures that the impact of window area parameter on energy performance was stronger in the detached house than in the terraced house. For example, a WWR increase from 15% to 35% resulted in a cooling demand increase by 135% in the detached house whilst this value was only 37% in the terraced house. This could be explained by the large window areas on all façades of the detached house. In conclusion, window area should be minimised as much as possible to reduce the solar heat gain in buildings, especially in detached houses.

7.2.5 Glazing types

Glazing type determines solar transmittance and thermal transfer through glazing areas, which cause internal heat gain. Therefore, alongside well-insulated walls and roofs, high performance windows are essential components of Passive House envelopes. Table 7.10 shows the thermal transmittance (U-value) and solar heat gain coefficients (SHGC) of various glazing types that be used in this parameter study.

Table 7.10: Properties of various glazing types

Glazing type	U-value W/(m^{2}K)	SHGC
Single	5.59	0.87
Ordinary double + air filling	2.8	0.78
Low-E double + Argon filling	1.1	0.51
Low-E double + Argon filling + solar protection	1.1	0.23
Low-E triple + Argon filling + solar protection	0.6	0.23

Figure 7.21 and Figure 7.22 show energy loads of the terraced and detached houses with different types of glazing. It can be seen that the influences of the glazing types on both houses were almost identical although a slightly higher cooling load reduction was observed in the detached house. The figures indicated that SHGC of glazing was more efficient than the U-value in terms of reducing cooling demand. This means controlling transmittance of solar radiation through glazing areas is more important than controlling thermal transfer. The use of a high upper

temperature setpoint of 29.6°C reduces the importance of controlling heat exchange between indoors and outdoors, which is a serious concern in temperate and cold climates. As a result, the use of triple glazing was ineffective in the hot humid climate of Vietnam.

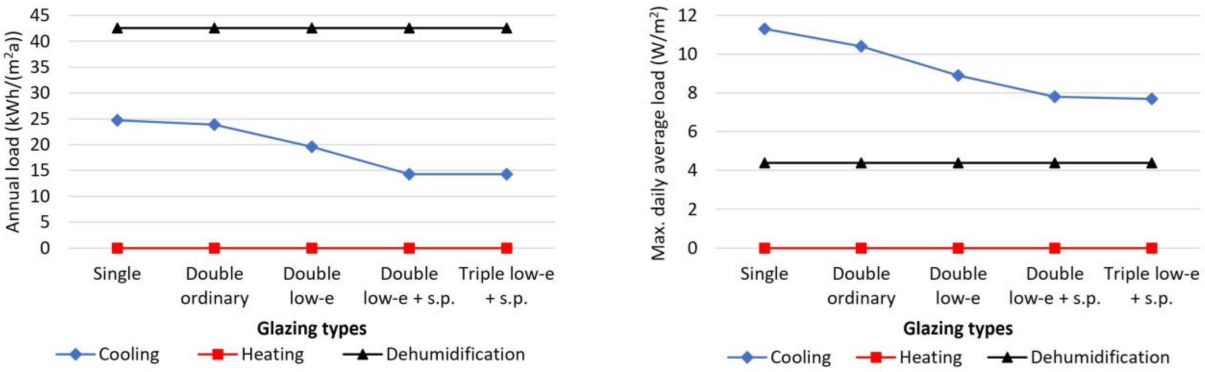


Figure 7.21: Energy load of the terraced house with various glazing types

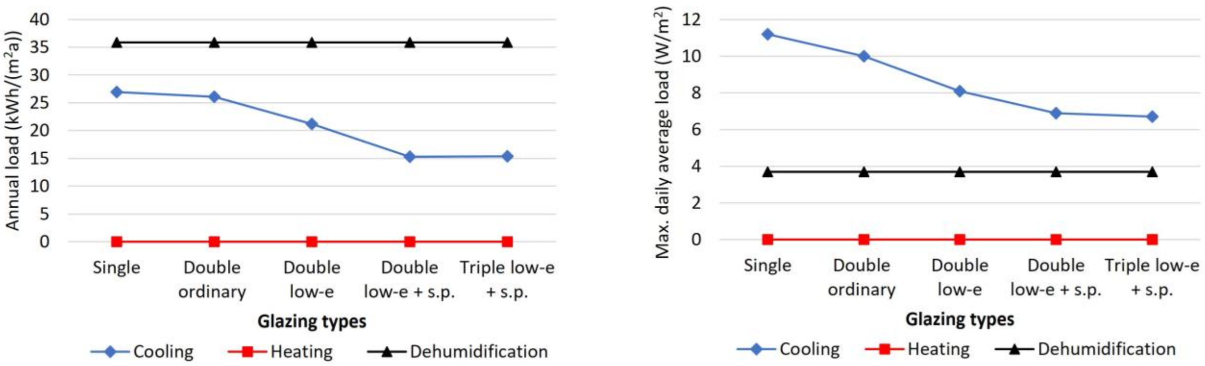


Figure 7.22: Energy load of the detached house with various glazing types

7.2.6 Solar shading

Along with window area and glazing type, solar shading for glazing areas is another parameter that affects the solar heat gain of indoor air. In general knowledge, solar shading is essential for buildings in hot humid climates. This study investigated the effect of solar shading on energy performance of Passive House dwellings in Vietnam by sequentially applying five solar shading ratios from 40% to 80% to the terraced and detached houses (no shading = 0%). As mentioned in the previous section, shading ratio represents the aggregate shading efficiency provided by building shading devices (overhangs, balconies, curtains) and site shading objects (terrain, surrounding buildings, trees), which was automatically calculated in the PHPP worksheet.

Figure 7.23 and Figure 7.24 show a linear relationship between shading ratio and cooling loads in both terraced and detached houses. As expected, annual and maximum daily average cooling loads increased when shading ratio decreased. The more significant increases of cooling loads were observed in the detached house due to its large glazing area. When shading ratio was reduced from 80% to 40%, the annual and maximum daily cooling loads of the detached house sharply increased by 157% and 85% respectively. Consequently, in the hot humid climate of

Vietnam, solar shading should be maximised in accordance with daylighting and visibility demands.

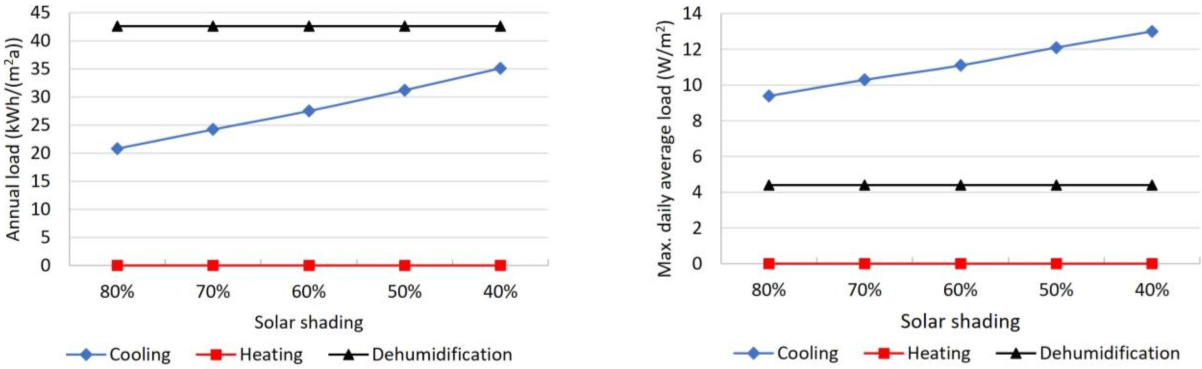


Figure 7.23: Energy load of the terraced house with various solar shading ratios

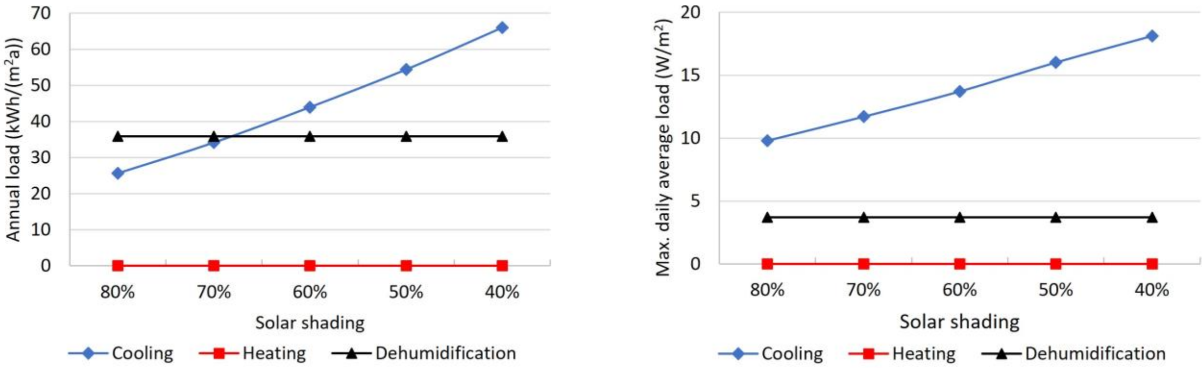


Figure 7.24: Energy load of the detached house with various solar shading ratios

7.2.7 Air tightness

A very airtight envelope is an essential requirement of a Passive House building in temperate and cold climates to prevent heat loss. By contrast, in hot and humid climates, the air tightness helps Passive House buildings by reducing both heat gain and humidity gain, which are caused by the infiltration of hot humid outdoor air. To investigate the effect of air tightness on Passive House dwellings in Vietnam, this study sequentially applied a number of air tightness variants covering a wide range from 0.4 to 7 ACH (n50) to the terraced and detached housing models. The results are shown in Figure 7.25 and Figure 7.26.

In contrast to the previous building parameter, air tightness strongly affected the dehumidification loads of the Passive Houses. The line charts indicated a linear relationship between these parameters. The annual dehumidification demands of both houses sharply increased by about 160% when the air tightness decreased from 0.6 ACH (the recommended value in the Passive House standard) to 6 ACH. Meanwhile, the annual cooling demand decreased negligibly, and the maximum daily average cooling load increased slightly. Again, the use of a high temperature setpoint of 29.6°C can explain the decrease of annual cooling demand.

Consequently, the main concern of a leaky Passive House building in hot humid Vietnam is the moisture gain. Therefore, an airtight building envelope is necessary. However, the strict limit of 0.6 ACH should be eased since the sum of cooling and dehumidification demands in some higher air tightness levels did not exceed the criterion of the Passive House standard.

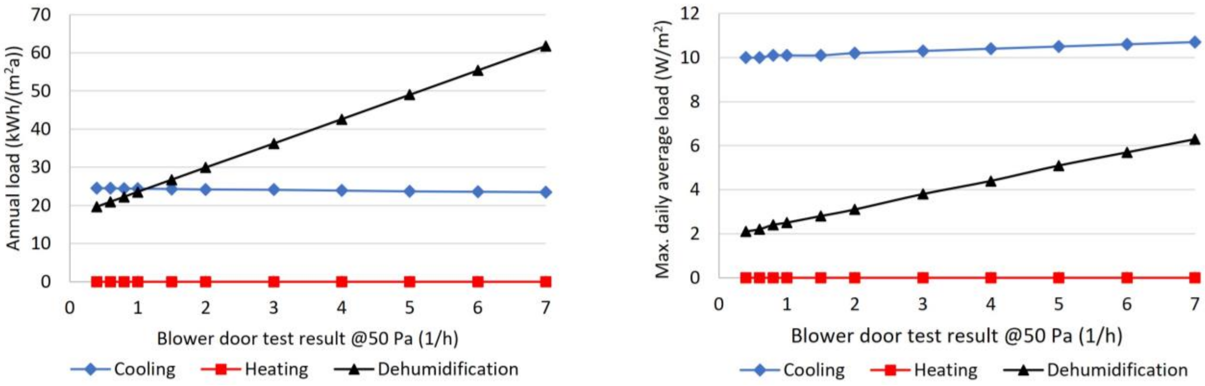


Figure 7.25: Energy load of the terraced house with various air tightness levels

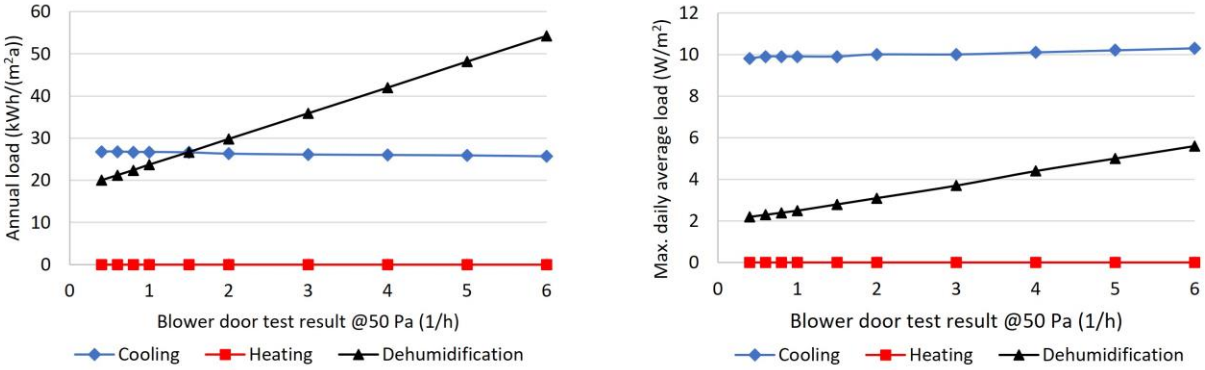


Figure 7.26: Energy load of the detached house with various air tightness levels

7.2.8 Cooling energy recovery

Mechanical ventilation system with heat (or energy) recovery is an indispensable component in a Passive House building to provide fresh outdoor air and retain indoor heat (or cool). The effectiveness of heat recovery has been proved in temperate climates. Subsequently, cooling recovery function is expected to work efficiently in warm climates to maintain indoor temperature within 20 – 25°C. In Vietnam, with a higher thermal comfort zone of 23.7 – 29.6°C, the effect of cooling recovery on energy demand of Passive House dwellings needs to be examined. Five heat recovery coefficients from 0.1 to 0.9 were sequentially simulated. Note that the cooling recovery coefficients are 0.1 less than the corresponding heat recovery coefficients (PHI, 2018b).

Figure 7.27 and Figure 7.28 show the insignificant influence of cooling recovery on the annual cooling demands of both houses. The maximum daily average cooling loads slightly decreased but the changes were negligible. Therefore, with the use of 23.7 – 29.6°C comfort range, cooling recovery is not essential in Passive House dwellings in Vietnam.

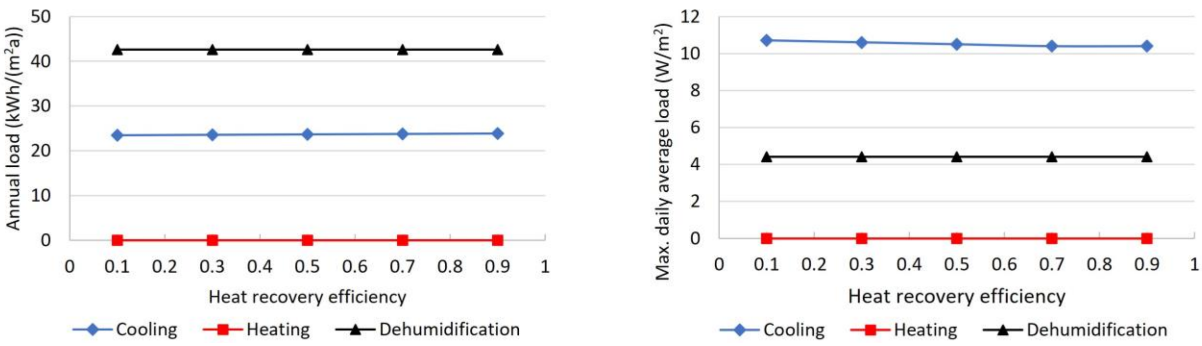


Figure 7.27: Energy load of the terraced house with various heating recovery coefficients

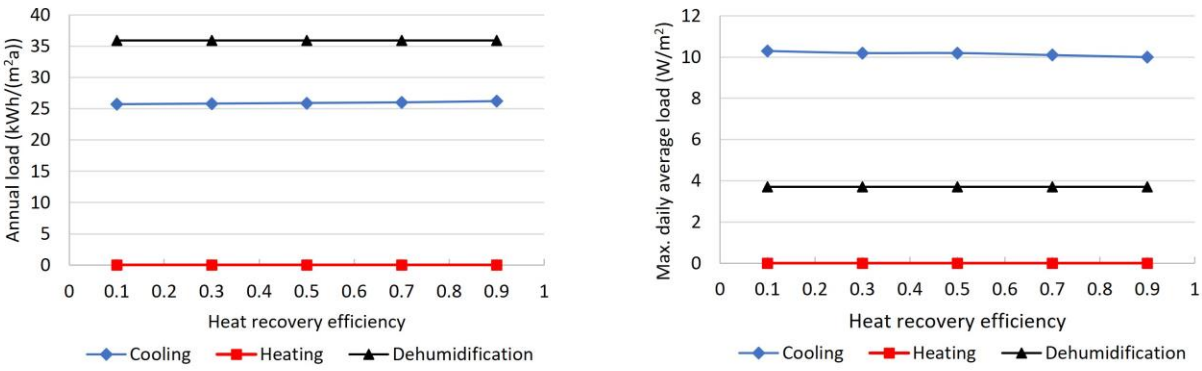


Figure 7.28: Energy load of the detached house with various heating recovery coefficients

7.2.9 Humidity recovery

Humidity recovery is another function of a mechanical ventilation system with energy recovery dedicated to Passive House buildings in humid areas, where the outdoor moisture is significantly higher than the indoor moisture requirement for most of a year. For example, annual average humidity ratio of Tuy Hoa city in Vietnam is 17.5 g/kg whilst the original and revised Passive House criteria are 12 and 14 g/kg respectively. In addition, moisture gain or loss due to ventilation is the most influencing factor in moisture balance in Passive House buildings (PHI, 2019a). To investigate the effect of humidity recovery on energy performance of Passive Houses in Vietnam, this study carried out a number of simulations covering a wide range of humidity recovery coefficients from 0.1 to 0.9. The results are shown in Figure 7.29 and Figure 7.30.

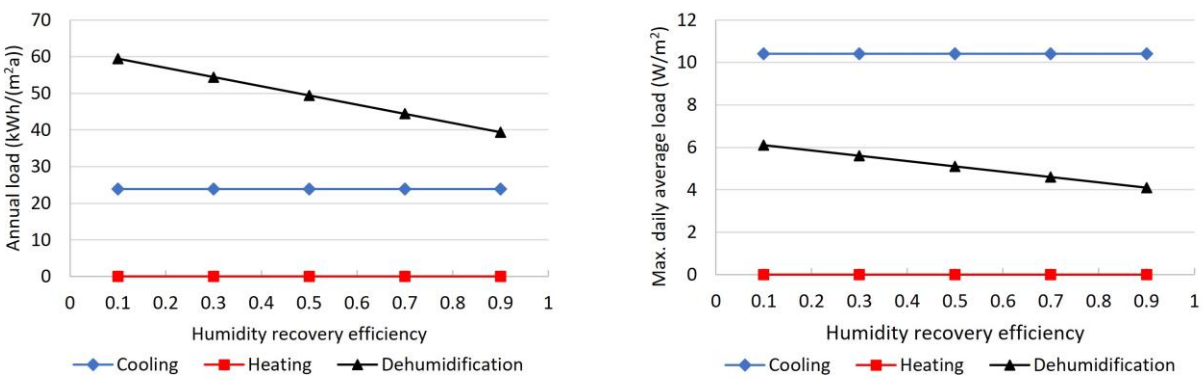


Figure 7.29: Energy load of the terraced house with various humidity recovery coefficients

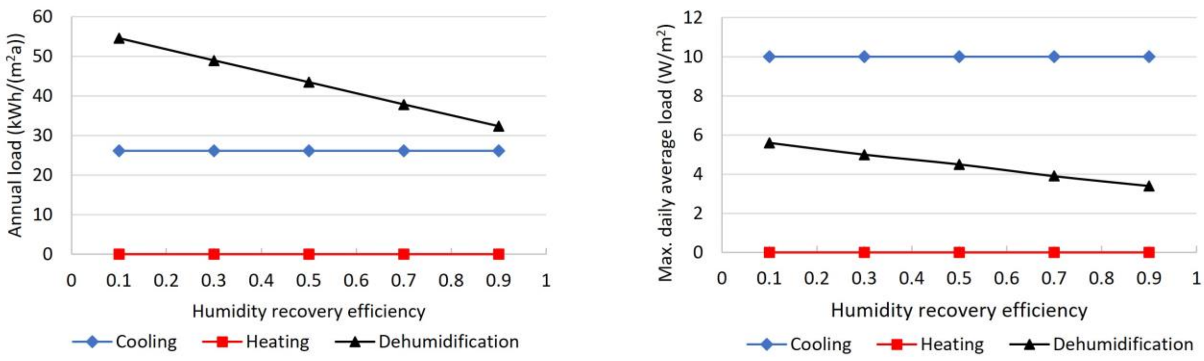


Figure 7.30: Energy load of the detached house with various humidity recovery coefficients

A linear relationship between humidity recovery coefficient and the dehumidification demand of the terraced and detached houses was illustrated in the line charts. As expected, the higher humidity recovery efficiency, the lower dehumidification loads. The use of 0.9 humidity recovery coefficient significantly reduced the annual dehumidification demands of the terraced and detached houses by 36% and 44% respectively compared to those of the houses without humidity recovery function. Consequently, a highly effective humidity recovery is recommended to Passive House residential buildings in Vietnam.

In summary, this section analysed the effects of nine key building parameters with various respective variants on energy performance of the Passive House dwellings in Vietnam. The results of this analysis were the basis for selecting appropriate building parameters and their variants for the next parametric simulation step to propose Passive House design strategies for the hot humid climate of Vietnam.

7.3 Proposed Passive House design strategies for Vietnamese housing

The first section of this chapter indicates that the Passive House approach is beneficial and applicable to Vietnamese housing. To quantify in more detail the housing components linked to various energy performances of buildings and thus to determine good practices of Passive House building design for use by stakeholders, a detailed energy analysis in the form of a parametric study was carried out.

This quantitative analysis included a large number of analyses based on the combinations of variations of key Passive House parameters. In the first step, the suitable parameters and their variants were specified. Secondly, the parametric simulations for each case were conducted, followed by the result analysis. Finally, based on these results, a reference design guidance for Passive House dwellings in Vietnam is proposed.

The PHPP (version 9.6) was the chosen tool to perform the parametric study. This tool was selected due to its necessity for the planning of Passive House buildings. In addition, the PHPP's spreadsheet format can speed up simulations so that numerous cases were analysed.

7.3.1 Selection of the Passive House parameters and their variants

The first step of the parametric study is the determination of key influencing building parameters and their variations that need to be considered in designing Passive House dwellings in the hot humid of Vietnam. Based on the sensitivity analysis of Passive House features in Section 7.2, seven main parameters and the most influencing variants were specified for use in the parametric study as shown in Table 7.11.

Table 7.11: Parameter variations for parametric simulation

Parameter		Variant	
		Terraced house	Detached house
1	Orientation	North, South, West	North, South, East, West
2	Window-to-wall ratio	15%; 30%; 45%	15%; 25%; 35%
3	Air tightness (n_{50})	3; 4; 5 ACH	2; 3; 4 ACH
4	Glazing type	Single; Ordinary double; Low-E double; Low-E double + solar protection	
5	Solar shading	40%; 60%; 80%	
6	Insulation layer for walls, roofs	25; 50; 100; 150 mm	
7	Exterior solar absorptivity	0.3; 0.5; 0.9	

Based on the building orientation analysis shown in Subsection 7.2.1, the orientations of North, South, and West were selected for the terraced house and the four principal orientations of North, South, East, West were chosen for the detached houses. It is a fact that in reality, housing orientation may not be a choice open to those designing and buildings as it depends on the urban plan of the location, especially for terraced housing. Therefore, while not providing analyses of all eight principal orientations, the selected orientations did cover the extremes. Further orientations might be investigated in future research.

The selected variations of window to wall area ratio were likely to support diverse building façade designs in terms of glazing area. Note that the WWR of the terrace house only considered the wall area of the two external façades. The average WWRs of the base-case terraced and detached houses are about 30% and 17% respectively.

Based on the air tightness analysis shown in Subsection 7.2.7, the variations of building air tightness, which are higher than the strict limit of 0.6 ACH of the Passive House standard, were selected. Those selected values are in line with the recommended air tightness of the LEED homes (≤ 3 or ≤ 4.25 ACH) (USGBC, 2016b).

Regarding glazing types and insulation thicknesses for walls, roofs, based on the study on individual parameters, triple-glazed window and insulation layer more than 150mm are not necessary in Vietnam.

Despite the limited impact of high exterior solar absorptivity, the variations of this parameter covered a wide range from 0.3 to 0.9. This can satisfy the use of various exterior colours for different aesthetic demands and design purposes. The similar reasoning explains the selection of solar shading variations of 40%, 60%, and 80%.

It was assumed that the cooling and humidity recovery coefficients of the mechanical ventilation system were not changed during the parametric study. These coefficients were 75% (85% heat recovery) and 77% respectively, which were relatively good values in the MVHR market. According to the Passive House certified components listed in the PHPP, the existing heat recovery efficiency is 75 – 94% whilst the humidity recovery efficiency is 60 – 80%.

In conclusion, the seven building parameters with variations covering wide ranges were expected to provide the energy performance of numerous cases of housing that could be chosen in practice.

7.3.2 Results of parametric simulations

The simulations were carried out for a total of 3888 and 5184 cases of terraced and detached houses respectively. The energy performance of all simulation cases, including annual cooling and dehumidification demand, maximum daily average cooling load, and total primary energy demand, are presented in Appendix B. The energy performance was evaluated based on the Passive House standard and the Low energy standard for Vietnam. The Low energy standard is offered by the Passive House Institute (PHI) for buildings that cannot meet the Passive House standard. The criteria of these two standards are shown in Table 7.12.

In addition, for the convenience of observation and comparison, the energy performances of all simulation cases were classified in six categories and indicated in different colours as shown in Table 7.13. By this mean, the energy efficiency of each building feature combination was easily evaluated. The potential combinations that met the Passive House standard were determined, and the energy-inefficient solutions were highlighted.

Table 7.12: Criteria of the Passive House and Low energy standards for Vietnam

Standard	Criteria	
Passive House standard	Annual cooling and dehumidification demand	≤ 76 kWh/(m^{2}a)
	Maximum daily average cooling load	≤ 10 W/m^2
	Primary energy demand	≤ 120 kWh/(m^{2}a)
PHI Low energy standard	Annual cooling and dehumidification demand	≤ 91 kWh/(m^{2}a)
	Primary energy demand	≤ 120 kWh/(m^{2}a)

Table 7.13: Building categories for Vietnamese housing

Colour	Building category	Annual cooling + dehumidification demand (kWh/m^{2}a)
	Passive House standard for Vietnam (very good)	≤ 55
	Passive House standard for Vietnam (good)	56 - 76
	Low energy standard (high level)	≤ 55
	Low energy standard (medium level)	56 - 76
	Low energy standard (low level)	77 - 91
	Not energy efficiency	> 91 (or primary energy > 120)

A summary of the simulation results of the two housing types are presented in Table 7.14 and Table 7.15. In these tables, all simulation cases of each parameter variant were classified into three categories: Passive House, PHI Low energy house, and energy-inefficient house for the analysis and comparison purpose. According to these summarised values, the effectiveness of each variation was evaluated in comparison with the others.

Totally, the percentages of these categories of the terraced house were 50.3%, 21.2%, and 28.5% whilst these values of the detached house were 12%, 41.4%, and 46.6% respectively. Consequently, it was much easier for terraced houses to meet the Passive House standard than detached houses. This was due to the larger areas of external surfaces and glazing of the detached houses.

Table 7.14: A summary of the simulation results of the terraced house

Parameter	Variant	Number of cases and the respective percentage within each option below		
		Passive House standard	PHI Low energy standard	Not energy efficiency
Orientation	North	698 (53.9%)	265 (20.4%)	333 (25.7%)
	South	711 (54.9%)	241 (18.6%)	344 (26.5%)
	West	545 (42.0%)	320 (24.7%)	431 (33.3%)
Thermal insulation layer	25 mm	288 (29.7%)	355 (36.5%)	329 (33.8%)
	50 mm	474 (48.8%)	220 (22.6%)	278 (28.6%)
	100 mm	582 (59.9%)	125 (12.9%)	265 (27.2%)
	150 mm	610 (62.8%)	126 (13.0%)	236 (24.2%)
Solar absorptivity	0.3	779 (60.2%)	217 (16.7%)	300 (23.1%)
	0.5	682 (52.6%)	250 (19.3%)	364 (28.1%)
	0.9	493 (38.1%)	359 (27.7%)	444 (34.3%)
Window area (WWR)	15%	963 (74.3%)	139 (10.7%)	194 (15.0%)
	30%	607 (46.8%)	344 (26.5%)	345 (26.7%)
	45%	384 (29.6%)	343 (26.5%)	569 (43.9%)
Glazing type	Single	243 (25.1%)	328 (33.7%)	401 (41.3%)
	Ordinary double	341 (35.1%)	236 (24.3%)	395 (40.6%)
	Low-E double	548 (56.3%)	194 (20.0%)	230 (23.7%)
	Low-E double + solar protection	822 (84.6%)	68 (7.0%)	82 (8.4%)
Solar shading	40%	429 (33.1%)	336 (25.9%)	531 (41.0%)
	60%	616 (47.6%)	323 (24.9%)	357 (27.5%)
	80%	909 (70.1%)	167 (12.9%)	220 (17.0%)
Air tightness (n_{50})	3 ACH	774 (59.7%)	440 (34.0%)	82 (6.3%)
	4 ACH	758 (58.5%)	385 (29.7%)	153 (11.8%)
	5 ACH	422 (32.6%)	1 (0.1%)	873 (67.3%)

The comparisons of the simulation results between parameter variations gave the following conclusions:

The effect of building orientation on energy performance of terraced housing was strong. Dwellings toward South and North have a higher chance to meet the Passive House standard compared to dwellings toward West or East. With detached housing type, the differences in the total Passive House cases of the four principal orientations were not significant, although the houses with the main façade toward South achieved a slightly higher percentage of Passive House cases.

Thermal insulation layer was one of the most important features of both housing types, especially for detached housing. When the insulation layer increased from 25mm to 150mm, the ratio of Passive House cases to the total 972 cases of terraced housing increased from 29.7% to 62.8% whilst that ratio of detached housing increased from only 0.9% to 22.8%. It is worth mentioning that 12 Passive House cases out of 1296 cases of detached housing with 25mm insulation layer were achieved by using very high-performance window along with high level of solar shading. Consequently, insulation layer from 25mm is acceptable for Passive House terraced housing while the minimum of 50mm is recommended for detached housing.

Table 7.15: A summary of the simulation results of the detached house

Parameter	Variant	Number of cases and the respective percentage within each option below		
		Passive House standard	PHI Low energy standard	Not energy efficiency
Orientation (and the orientation has largest glazing area)	North (and West)	154 (11.9%)	553 (42.7%)	589 (45.4%)
	South (and East)	158 (12.2%)	541 (41.7%)	597 (46.1%)
	East (and North)	138 (10.6%)	527 (40.7%)	631 (48.7%)
	West (and South)	174 (13.4%)	524 (40.4%)	598 (46.2%)
Thermal insulation layer	25 mm	12 (0.9%)	573 (44.2%)	711 (54.9%)
	50 mm	86 (6.6%)	609 (47.0%)	601 (46.4%)
	100 mm	230 (17.7%)	504 (38.9%)	562 (43.4%)
	150 mm	296 (22.8%)	459 (35.4%)	541 (41.8%)
Solar absorptivity	0.3	305 (17.7%)	758 (43.8%)	665 (38.5%)
	0.5	211 (12.2%)	764 (44.2 %)	753 (43.6%)
	0.9	108 (6.3%)	623 (36.0%)	997 (57.7%)
Window area (WWR)	15%	420 (24.3%)	933 (54.0%)	375 (21.7%)
	25%	143 (8.3%)	684 (39.6%)	901 (52.1%)
	35%	61 (3.5%)	528 (30.6%)	1139 (65.9%)
Glazing type	Single	5 (0.4%)	403 (31.1%)	888 (68.5%)
	Ordinary double	39 (3.0%)	439 (33.9%)	818 (63.1%)
	Low-E double	124 (9.6%)	585 (45.1%)	587 (45.3%)
	Low-E double + solar protection	456 (35.2%)	718 (55.4%)	122 (9.4%)
Solar shading	40%	71 (4.1%)	444 (25.7%)	1213 (70.2%)
	60%	164 (9.5%)	653 (37.8%)	911 (52.7%)
	80%	389 (22.5%)	1048 (60.7%)	291 (16.8%)
Air tightness (n_{50})	2 ACH	215 (12.4%)	885 (51.3%)	628 (36.3%)
	3 ACH	208 (12.0%)	788 (45.6%)	732 (42.4%)
	4 ACH	201 (11.6%)	472 (27.3%)	1055 (61.1%)

In both housing types, the use of solar absorptivity of 0.3 and 0.5 helped to obtained higher number of Passive House cases compared to the value of 0.9. Therefore, bright colours should be used for exterior surfaces rather dark colours.

A low glazing area was more beneficial for Passive House dwellings in Vietnam, especially for detached housing where the use of 15% WWR increased the number of Passive House cases by about 3 times and 8 times compared to the use of 25% and 35% WWR respectively.

Dwellings using high performance windows were highly likely to meet the Passive House standard. However, it is observed that 25% of 972 cases of terraced houses using single glazed windows were Passive Houses whist that value was only 0.4% (5 out of 1296 cases) for detached houses with the same glazing type. Consequently, single glazed windows could be used in terraced housing whilst more energy-efficient windows are required for detached housing.

High level of solar shading was significantly important for detached housing, where the number of Passive House cases increased 5 times when changing solar shading ratio from 40% to 80%. Solar shading was less important for terraced housing compared to detached housing, however, it was also a key parameter that strongly influenced the building energy performance.

The numbers of Passive House cases between the air-tight levels of 2, 3, and 4 ACH were not significantly different in both housing types. However, the use of 5 ACH air tightness in terraced houses sharply reduced the total cases of both Passive House and Low energy houses since the dehumidification demand significantly increased and made the primary energy demand exceeded the limit of 120 kWh/(m^{2}a). Consequently, an air tightness below 4 ACH is considered acceptable for Passive House dwellings in Vietnam.

In summary, the simulation outcomes indicated substantial potential of Passive House dwellings in Vietnam with about 50.3% and 12% of the total cases for terraced and detached housing respectively. It is worth mentioning that within the scope of this research, building costs were not analysed since the Passive House concept is relatively new in Vietnam and the market for Passive House components is not yet available. This therefore requires more detailed further research, but these findings indicate the general issues and potential. Therefore, no attempt was made to determine the optimal cases of Passive House dwellings for Vietnam as the determination of optimal cases is not the aim of this study. However, due to the diverse nature of architecture, it is reasonable to propose numerous possible solutions for Passive House design that could satisfy diverse demands of stakeholders. Therefore, the author believes that it would be valuable to propose a reference design guide be pursued for Passive House dwellings in Vietnam based on these simulation outcomes.

7.3.3 Proposing reference design guidance for Passive House dwellings in Vietnam

The proposal of design guidance has been driven by the need for more information to support stakeholders in designing and constructing low energy dwellings in Vietnam using the Passive

House approach. The purposes of this design guidance are to select reference design solutions for Passive House dwellings, and to predict the energy efficiency of housing proposals built to the Passive House approach. The use of tabular results of the previous simulations is suitable for these purposes since they cover numerous cases of Passive House and low energy housing design that could be chosen in practice.

The structure of the design guidance is divided into 2 sections. The first section provides information about the guidance, including the aim, the explanations of building parameters, design criteria, and the guide to use. The second section is the design tables which includes 9 tables for 3 orientations of terraced housing, and 12 tables for 4 orientations of detached housing. For the simplicity and ease for stakeholders to use, the specific terms were simplified in the guidance tables, for example solar absorptivity was changed to respective paint colours. In addition, the specific numeric data of energy demands are no longer necessary and energy performance of each case is expressed by respective colours as shown in Table 7.13. A sample version of this design guidance is presented in Appendix D.

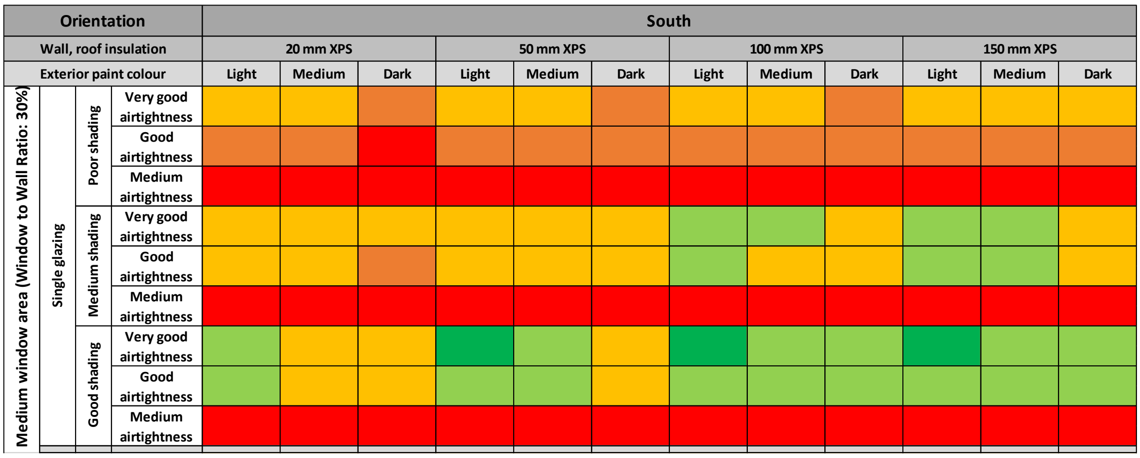


Figure 7.31: An example of design tables in the guidance

It is recognised by the author that many more variants of building parameters could be selected in reality. In such cases, a prediction based on the nearest values would be effective to estimate energy performance of the design proposals.

According to the analysis in Section 7.1.4, the differences between Passive House dwellings in Tuy Hoa and HCM cities were not significant, and the Passive House dwellings in Tuy Hoa city can also meet the Passive House standard for HCMC. Therefore, this design guidance could be applied to HCMC and in a wider context of the hot humid regions in the South Vietnam, if applied sensitively by professional designers.

In short, this proposed design guidance is an easy-to-use and valuable reference for supporting the planning of Passive House and low energy dwellings in Vietnam. The use of this design guidance and the development of the Passive House approach in general would have significant impacts on energy consumption of dwellings in Vietnam.

7.4 *Validity of the design guidance in discussion with professionals*

To investigate the possibility and applicability of the proposed design guidance for Passive House dwellings in practice, this study carried out a questionnaire survey with the participation of professionals in building design and construction. This section presents the contents of the survey including the questionnaire design and the major results as follows.

7.4.1 Questionnaire design

Aims: The aims of the survey were to obtain experts' viewpoints about a Passive House approach in Vietnam and about the proposed design guidance for Passive House dwellings. The collected data were analysed for validating and improving the guidance for use as a valuable reference in the future.

Participants: The target respondents of this survey were experts and practitioners who are working in the field of architecture and civil engineering including architects, civil engineers, building contractors, and researchers.

Question types: This questionnaire mainly used closed questions in form of the Likert scale. In addition, some closed questions were in form of multiple-choice answers. The remaining two questions were open questions to gather further viewpoints of audiences about the Passive House approach in Vietnam and the design guidance.

Structure: This questionnaire was divided into three parts, apart from the general information of the survey at the beginning of the questionnaire:

- Part 1 includes 7 closed questions about energy-efficient housing design in Vietnam.
- Part 2 includes 8 questions related to the Passive House approach and its applicability in Vietnam. This part is accompanied with a brief introduction about the Passive House concept. Since this building methodology is relatively new in Vietnam, it would be helpful to provide respondents with basic information about it.
- Part 3 consists of 4 questions about the validity of the proposed design guidance for Passive House dwellings in Vietnam. This part comes with the pilot design guidance.

Ethical issues: Sensitive personal information (e.g., name, address) was not collected via this questionnaire. All collected information is kept confidential and only accessed by the author.

Pilot study: Before carrying out the official survey, a representative sample of 10 professionals were sent the pilot questionnaire to gather their feedback. A number of issues related to readability and understanding were identified and amended, in which some professionals required further information about the Passive House methodology and the technical terms.

A sample of the questionnaire is presented in Appendix C. Note that in the official survey carried out in 2019, this questionnaire was converted to an online version using the Google Forms tool. This online questionnaire facilitated the data collection and analysis.

7.4.2 Survey results

A total of 71 professionals in the field of architecture and construction responded to the questionnaire survey. Most of the respondents are architects, of which 38% of them are working as professional architects in architectural firms, 21% of them are lecturers in universities, and 30% of them are working as project managers or working for the government. The remaining 11% of the respondents are civil engineers and building contractors. Regarding career experience, the respondents having more than 10 years, 5 – 10 years, and less than 5 years of experience were 55%, 24%, and 21% respectively. The high proportion of experienced professionals helped to ensure the reliability of the data collected.

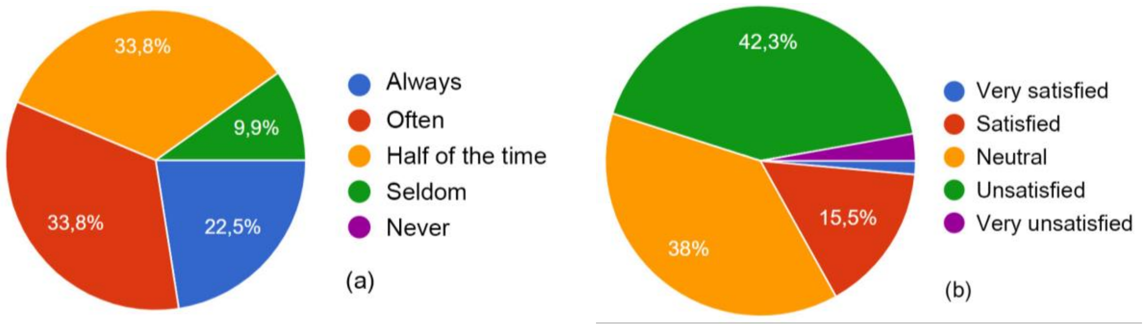


Figure 7.32: Frequency of using energy-efficiency design techniques (a) and the satisfaction with existing energy-efficiency standards for buildings (b)

All the surveyed professionals agreed that energy efficiency is an important requirement of building design. However, only about 56% of them frequently apply design solutions to save energy for buildings (Figure 7.32). 60% of the respondents have found that it is difficult to look for energy efficieny design guidance in Vietnam, especially for dwellings, and 45% of the respondents have been dissatisfied with the existing energy efficiency standards of Vietnam. The fact is that there is currently no mandatory energy efficiency building code for dwellings. These could be the reasons for the inadequate attention to energy-efficient building design in Vietnam. Consequently, 100% of the surveyed people agreed that energy efficiency design guidance for Vietnamese housing is necessary.

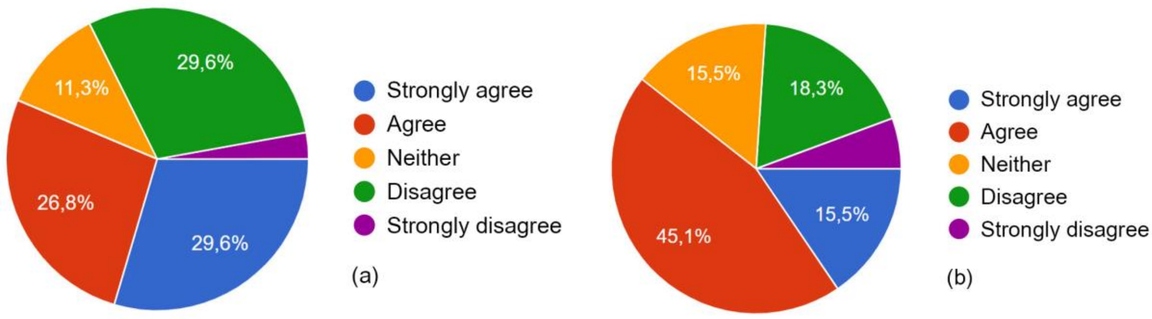


Figure 7.33: Responses on the effectiveness of natural ventilation (a) and the possibility of sealed building approach (b)

More than 50% of the respondents agreed with the statement that naturally ventilated buildings can satisfy thermal comfort and indoor air quality, despite the context of global warming effect and air pollution in high-density areas. While natural ventilation is a traditionally preferred choice for housing design, approximately 60% of the professionals agreed that sealed buildings with energy-efficient mechanical ventilation could be an effectively alternative solution to naturally ventilated buildings (Figure 7.33).

In response to questions about the Passive House approach, most professionals expressed their satisfaction about the benefits of Passive House buildings, especially in terms of energy saving and indoor air quality. However, half of respondents felt that it would be difficult for Vietnamese people, who are familiar with conventional naturally ventilated buildings, to accept and adapt to Passive House buildings whilst the others gave the contrary opinion. Although 38% of the respondents considered that the Passive House methodology is too complicated to apply (Figure 7.34), the majority of respondents agreed that Passive House approach needs to be researched and developed in Vietnam (Figure 7.35).

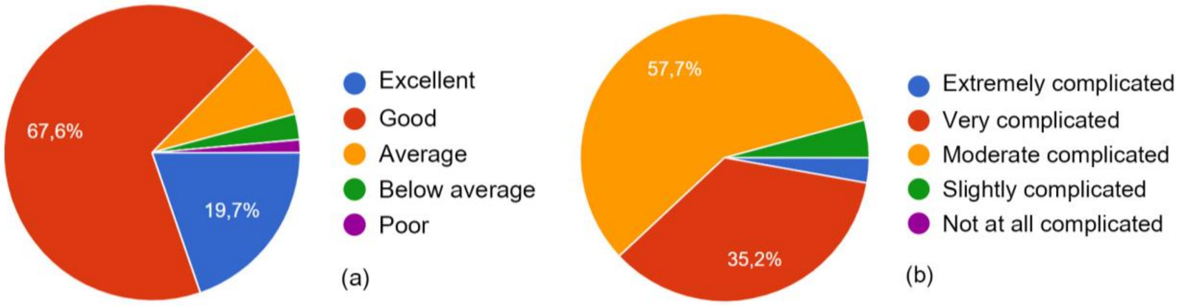


Figure 7.34: Responses on the benefits (a) and the complexity of Passive House buildings (b)

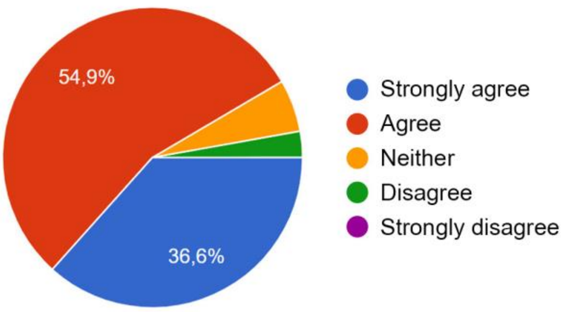


Figure 7.35: Responses on the need for research on Passive House in Vietnam

When being asked about other concerns about the adoption of Passive House approach in Vietnam, the surveyed professionals gave a substantial number of comments. The majority mentioned the construction cost of Passive House buildings. Some respondents showed concerns about the unfamiliar construction techniques and the supply of materials, high performance windows, and MVHR systems. The durability of Passive House components in the hot humid climate of Vietnam was another concern. Moreover, the lack of information, guidance and experts on Passive House buildings could be the main obstacle for the development of this building methodology in Vietnam.

While the above concerns were recognised by the author, they require substantial efforts from stakeholders to resolve, and cannot be fully covered by this study. However, in an attempt to fill the gap in Passive House information in Vietnam, design guidance for Passive House dwellings, which was the first version of what is shown in Appendix D, was proposed and delivered to professionals to gather feedback.

More than 70% of the surveyed professionals agreed that the design guidance is clear and easy to understand and apply. Although there were some negative comments about the presentation of the guidance, most of the respondents agreed that the guidance is a useful reference for designing Passive House dwellings in Vietnam (Figure 7.36 and Figure 7.37).

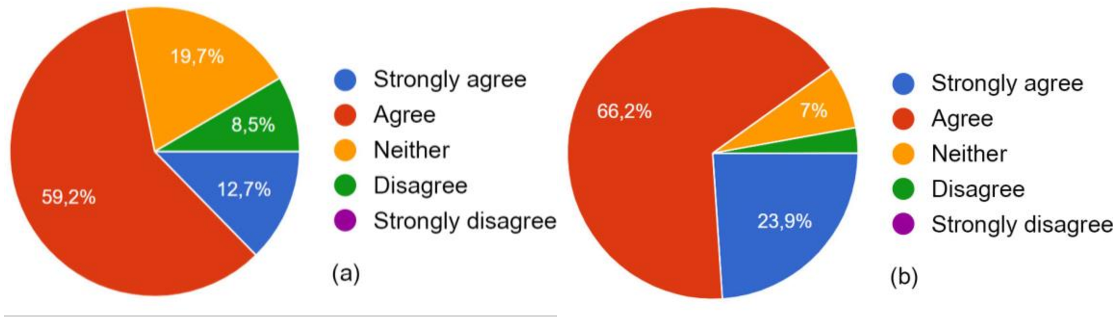


Figure 7.36: Responses on the clear presentation (a) and the practicality (b) of the design guidance

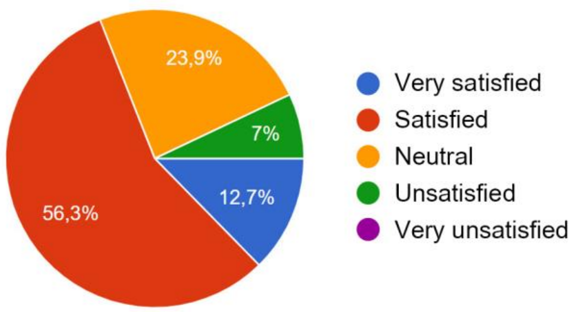


Figure 7.37: Responses on the satisfaction with the design guidance

When being asked about other concerns about the design guidance, a professional required more parameter variations to involve more building design solutions that could be chosen in reality. Some professionals indicated that the guidance needs more supporting information including detailed explanation of Passive House building features for direct use in design and construction. Some respondents suggested a regional limit for guidance application since they supposed that Passive House buildings is most beneficial in locations with extreme weather and air pollution.

While there are some recommendations regarding the design guidance expansion that could be fulfilled through further studies for better versions in future, the other recommendations were carefully considered in the revised version shown in Appendix D. Given the lack of information about energy efficient building design in Vietnam, particularly for Passive House buildings, the design guidance is a valuable reference to support decision making on low energy housing built to the Passive House approach.

7.5 Chapter conclusion

This chapter presents an in-depth study on the possible adoption of Passive House methodology for the design of dwellings in the hot humid climate of Vietnam. Notable conclusions were derived as follows.

The simulations of terraced and detached house examples built to the Passive House standard showed substantial energy savings compared to the existing houses. In addition, more energy saving and affordable construction cost were achieved by adapting the Passive House standard with higher temperature and humidity setpoints for hot humid regions. These results indicated the great potential of the Passive House approach for housing in the context of Vietnam.

An analysis on nine key building parameters showed different impacts on energy performance of Passive House dwellings in Vietnam. A parametric study on seven selected building features was then carried out to determine potential design solutions of Vietnamese housing that meet the Passive House standard. The simulation outcomes indicated substantial potential of Passive House dwellings in Vietnam since about 50.3% and 12% of the total 3888 and 5184 simulation cases of terraced and detached houses respectively, satisfied the Passive House standard. Based on the simulation results, reference design guidance for Passive House dwellings in Vietnam was generated.

The questionnaire survey with the participation of 71 professionals in the field of architecture and civil engineering indicated that the Passive House approach needs to be researched and developed in Vietnam, and that the proposed design guidance is useful to aid decision making at early stage of Passive House and low energy housing design in Vietnam.

Chapter 8 Conclusions and further work

The last chapter provides summary conclusions of the work carried out in this study, and then highlights the major contributions of the study to knowledge alongside the practical significance of the findings. Subsequently, the chapter discusses the limitations that exist in the research and outlines the potential work that could be performed in the future.

8.1 Conclusions

In the context of ongoing climate change and energy crisis, this study aimed to identify a new approach, which is based on the Passive House methodology, as an alternative solution to conventional natural ventilation design to support the development of more robust dwellings in Vietnam. Based on specific examinations on key features, which were the Passive House concept in its broadest sense, thermal comfort for the Vietnamese, and the design, construction and operation of housing in Vietnam, the most important conclusion of this study is that Passive House has great potential for use in low energy housing in the hot humid climate of Vietnam. In addition, the Passive House design techniques for use in Vietnam, that are required to improve energy efficiency in housing were identified. These final outcomes were derived from research carried out to fulfil the research objectives, and the main conclusions are summarised below.

(i) In Vietnam, single-family housing is the dominant type, accounted for 94.2% of the housing stock whilst the proportion of apartments is only 5.8% (2019 data). Residential buildings were responsible for 35% of the total electricity consumption and 27% of the total energy use in the country. Therefore, in the context of ongoing energy crisis, there is an urgent need to use energy efficiently in Vietnamese housing, especially single-family dwellings.

(ii) A review of thermal comfort studies in hot humid climates showed the differences in results between different locations, between air-conditioned and free-running buildings, between field studies and experimental research. In Vietnam, the existing thermal comfort standards and individual comfort studies also showed a variation between the results and a shortage of data on thermal comfort. Therefore, further studies are necessary to supplement the modest thermal comfort database of Vietnam.
In response to this need, this study carried out a thermal comfort experiment with the participation of 128 college-aged volunteers and found that thermal comfort zone of the participants was 23.7 – 29.6°C for 80% satisfaction level.

(iii) There are only few theoretical studies and practical applications of Passive House buildings in warm regions, and no such study has been carried out in Vietnam. Therefore, further studies are essential to capitalise on the Passive House techniques and develop appropriate solutions for Passive House dwellings in the hot humid climate of Vietnam. An example test building would be very useful for future research.

(iv) The survey on household appliances and energy consumption in Vietnam provided comprehensive information on household characteristics, appliance ownership, usage behaviour and the actual energy consumption. This information was the basis for the housing modellings and comparisons.

(v) The field study on building thermal performance indicated that Vietnamese existing housing showed a poor thermal performance and failed to satisfy thermal comfort in extreme weather. The measurement results showed high indoor temperatures in hot season and low indoor air velocities whilst high humidity was another concern.

The whole-year simulations on thermal performance of existing housing reaffirmed the on-site measurement results. The high percentage of annual discomfort hours required a high corresponding cooling demand to maintain year-round thermal comfort. While passive design techniques were able to significantly reduce cooling demand of the houses, high indoor humidity was a disadvantage of conventional naturally ventilated dwellings alongside other indoor air quality concerns.

(vi) Some criteria of the Passive House standard, including thermal comfort zone, humidity limit, and air tightness, when being applied to the hot humid climate of Vietnam required adjustment to suit the local climates and residents.

Simulation results indicated that the reference Passive House models saved substantial energy for cooling demand compared to the existing houses. Subsequently, a parametric simulation based on 7 key influencing building parameters indicated opportunities for Passive House dwellings in Vietnam. In this parametric study a significant number of the combinations, which accounted for 50.3% and 12% of the total cases for terraced and detached housing respectively, met the revised standard demonstrating real potential for application. Based on the simulation outcomes, design guidance for Passive House dwellings in Vietnam was proposed.

(vii) The design guidance was evaluated by 71 professionals through a questionnaire survey. The results indicated that the proposed design guidance is a useful reference to support stakeholders in the planning of low energy housing built to the Passive House approach.

8.2 Contributions to knowledge

The general contribution of the research is the better understanding of low energy housing design using Passive House as an alternative technique. This is a relatively new approach for hot humid climates which would seem to be contrary to expected design approaches of maximising cooling airflows from natural ventilation. While there are a few theoretical studies and practical constructions of Passive House buildings in warm climates around the world, this is the first comprehensive investigation on this field in Vietnam, with an ambition of laying the foundation for the development of Passive House approach in the nation. With a number of valuable studies, this research supplements existing knowledge with specific contributions as follows.

(i) **Thermal performance of existing housing in Vietnam**: The field study with on-site measurement method provided numerous data on environmental variables of existing housing in Vietnam, including air temperature, black globe temperature, relative humidity, air velocity, and daylight. The analysis of the collected data provided better understanding of the thermal performance of existing housing design and construction in Vietnam. The simulation of whole-year period provided deeper insight into thermal performance of the existing house. Moreover, the predicted high energy demand indicated the need for more energy efficient dwellings in Vietnam and formed the basis for the proposals of better design solutions to resolve existing disadvantages.

(ii) **Household appliance use and energy consumption in existing housing**: The results of this survey is a valuable reference, especially in the context of lacking seriously information on household energy consumption in Vietnam. This survey reported new empirical data for the use of household equipment and energy consumption in Vietnamese dwellings thus helping to fill a gap in knowledge. In addition, a breakdown of energy use according to appliances was estimated that helps to understand the details of energy use and the dominant energy-using factors in households. This survey places valuable information in the public domain that could be used for analyses of advanced energy-efficient building design and for associated future regulations (V. T. Le & Pitts, 2019).

(iii) **Thermal comfort zone for the Vietnamese**: A new set of thermal comfort zone for the Vietnamese (23.7 – 29.6°C) was proposed through experiments. Moreover, the experiment results indicated that the PMV-PPD model overestimated thermal sensations of the subjects especially at high temperatures, therefore, the PMV-PPD predictions are not reliable in the hot humid climate of Vietnam. This finding reaffirmed the nonconformity of the PMV-PPD model in hot humid climates, which was mentioned in previous studies. A significant amount of data on human thermal sensation from this experiment helps to partially address the shortage of thermal comfort data in Vietnam. The findings might contribute to the revisions of existing thermal comfort standards of Vietnam in the future. This experiment is a valuable reference for future studies on thermal comfort in hot humid climates around the world.

(iv) **A new application of Passive House methodology to warm climates**: This study proposed an adaptation of the Passive House approach to warm climates. In the hot humid climate of Vietnam, by replacing the 20 - 25°C comfort range by the 23.7 - 29.6°C, increasing the humidity limit from 12 g/kg to 14 g/kg, and easing the strict 0.6 ACH limit of air tightness, the Passive House standard would be more suitable to the local residents and climate whilst ensuring the requirements for thermal comfort and energy consumption. The study indicated that these revised criteria led to substantial energy and building cost saving in dwellings. While the revised Passive House standard needs to be validated by further in-depth research and practical implementations, this new application of Passive House methodology is a potential approach for low energy buildings in warm climates.

(v) **Design guidance for Passive House dwellings in Vietnam**: The intensive parametric study provided a substantial amount of new data which suggest design solutions for dwellings built to the Passive House approach. The results were refined for the release of design guidance to be used by stakeholders. Given the absence of Passive House studies and practices in Vietnam, the author believes the design guidance makes a significant contribution to knowledge of this building methodology in Vietnam. Moreover, along with the precious recommendations from 71 professionals, the design guidance and the whole study in general provide an important basis to develop more formalised guidance for Passive House dwellings in the future.

Apart from the above contributions to knowledge, this study gives great practical implications to Vietnam as follows.

Firstly, the indication of the poor thermal and energy performance of existing housing alongside the potential of energy saving and environmental benefits from better building designs help to raise the awareness of house owners as well as designers, and then gradually make the selection of energy efficiency design techniques inevitable, especially in the context of ongoing climate change and energy crisis.

Secondly, the determination of suitable temperature limits for the Vietnamese people helps to save substantial energy from excessive cooling in buildings.

Thirdly, the proposed Passive House dwellings design guidance provides designers with an alternative solution to conventional natural ventilation. The variety of housing design methods provides designers the most suitable selection for each particular context that results in good thermal performance and high energy efficiency in dwellings. Consequently, energy demand of the residential sector would be reduced, and this helps to address the national energy security. In conclusion, the guidance facilitates the development of Passive House dwellings in Vietnam and contributes to the sustainable development of Vietnamese architecture in general.

8.3 Limitations

Although a very substantial amount of work was done throughout the research, it is recognised by the author that there exist some limitations. In this section, the author attempts to identify clearly the specific limitation in each process.

Regarding the thermal comfort study, although the experiments were not carried out in a formal climate chamber, the experiments in a controlled room were designed with care and the influencing environmental variables were measured carefully to give credibility to the outcome. While a climate chamber is certainly the optimal facility for thermal comfort experiments, the procedure used in this study is a possible alternative method when an expensive climate chamber is not available.

In the field study on thermal performance of existing housing, while longitudinal measurement with data loggers was not carried out, the spot measurement allowed to collect environmental data of all main spaces in more houses, which enhanced the representativeness of the collected data for entire dwellings in the city.

In the survey on household appliance use and energy consumption in existing housing, due to the constraint of time, this survey was carried out with a relatively small number of samples in a single city. Although Tuy Hoa city does not represent the situation of the large cities such as Hanoi or Ho Chi Minh, it is a good example of common medium-scale cities in Vietnam. Nevertheless, applying the result to all Vietnamese homes must be done with care. Despite the sample size limitation, this study provides valuable knowledge of the survey framework, analysis methods, and outcomes that should be of interest for further comparison (V. T. Le & Pitts, 2019).

Regarding the parametric study and the design guidance, the author recognises that many more parameter variations could be selected in practical application, nevertheless the suggestion of ranges of data input suffice to cover the common and extreme cases of housing design. An ideal in research of this type would be to verify the simulated performance by comparison with a built example. However, since no built examples or research facilities currently exist, this research provides an important first step. Further much of the input data has been verified through tests carried out and the simulation programme is one of the most widely used and respected. Information derived using the industry standard Passive House Planning Package also adds support. It is hoped in due course a real building can be constructed and monitored to further develop and verify the research.

The lack of variety in housing types is another limitation since end-of-terrace and semi-detached houses have not been investigated due to the limited time of the research process. While the design guidance needs to expand in the future, the current version could be used more generally with sensitive applications by professional designers.

8.4 Further work

While this first study on the Passive House approach in Vietnam provides significant contributions to knowledge, there are much work that need to be done to facilitate the development of Passive House buildings in Vietnam. The possible studies to be undertaken in the future are outlined below.

(i) As identified above, one of the next stages of research would be to investigate performance of real dwellings construction to the standards described here.

(ii) Another necessary step is the expansion of the proposed design guidance to provide more useful outcomes to inform stakeholders. This might include the investigations on end-of-terrace houses, semi-detached houses, and apartments with more variations of building features. Further work with professionals and official bodies is necessary to develop and publish a formal design guidance for Passive House dwellings in Vietnam.

(iii) Research on Passive House office buildings in Vietnam is particularly important and beneficial since most office buildings use mechanical cooling and ventilation during working hours. Therefore, the application of the Passive House approach to office buildings could be more advantageous than to dwellings.

(iv) One of the most concerns about Passive House buildings is the construction and maintenance cost. Therefore, further studies on the capital and life circle cost of a Passive House building is essential to examine the economic benefit and the feasibility of this building type in Vietnam. Moreover, a supply chain of Passive House components and services, which is closely related to the cost issue, needs to be investigated and developed.

(v) The application of renewable energy such as solar or wind power to Passive House buildings, which is out of the scope of this study, is a promising approach that needs to be studied in the future since Vietnam has significant potential of these renewable resources.

(vi) Another concern about Passive House dwellings is the closed-space architecture issue, which is totally different from conventional housing in Vietnam, and thus might be less welcomed by local residents. Therefore, it would be an interesting study to combine the Passive House approach with the vernacular architecture of Vietnam. The integration of indigenous experiences with modern design and construction technology is the ideal solution to achieve sustainable architecture. The inheritance of vernacular architecture will be the key to preserving the identity for each nation (T. Q. Nguyen & Ho, 2017). A potential study is the application of the Passive House principles to certain parts rather than the whole building, where naturally ventilated areas provide a familiar ambiance to the locals. In addition, research on applying local construction techniques and materials to Passive House buildings is absolutely necessary.

(vii) Apart from researching on Passive House buildings themselves, there is also a need to establish a network of professionals and organisations to educate, propagate, encourage and support theoretical research and practical application of Passive House buildings in the architecture-construction community in Vietnam.

Bibliography

Abdulmalik, A., & Young, A. (1993). Thermal comfort study as an aid to determine energy savings in building in Malaysia. In *Energex 93*. Seoul.

Adan, O. (1994). *On the fungal defacement of interior finishes*. Eindhoven University of Technology.

Arens, E., Humphreys, M. A., de Dear, R., & Zhang, H. (2010). Are “class A” temperature requirements realistic or desirable? *Building and Environment*, *45*(1), 4–10. https://doi.org/10.1016/j.buildenv.2009.03.014

Arundel, A. V., Sterling, E. M., Biggin, J. H., & Sterling, T. D. (1986). Indirect health effects of relative humidity in indoor environments. *Environmental Health Perspectives*, *VOL. 65*, 351–361. https://doi.org/10.1289/ehp.8665351

ASHRAE. (2009). *ASHRAE Handbook - Fundamentals*. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

ASHRAE. (2016). *ANSI/ASHRAE Standard 160-2016: Criteria for Moisture-control Design Analysis in Buildings*. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

ASHRAE. (2017). *ANSI/ASHRAE Standard 55-2017: Thermal Enviornment Conditions for Human Occupancy*. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

ASHRAE. (2019). *ANSI/ASHRAE Standard 62.1-2019: Ventilation for Acceptable Indoor Air Quality*. Atlanta: American Society of Heating Refrigerating and Air Conditioning Engineers.

Attia, S. (2012). *A Tool for Design Decision Making: Zero Energy Residential Buildings in Hot Humid Climates*. Universite Catholique de Louvain.

Bae, C., & Chun, C. (2009). Research on seasonal indoor thermal environment and residents’ control behavior of cooling and heating systems in Korea. *Building and Environment*, *44*(11), 2300–2307. https://doi.org/10.1016/j.buildenv.2009.04.003

Baker, N., & Steemers, K. (2005). *Energy and Environment in Architecture: A Technical Design Guide*. London: E & FN Spon.

Bauman, F., Arens, E. A., Huizenga, C., Xu, T., Zang, H., Akimoto, T., & Miura, K. (1996). *The impact of humidity standards on energy efficient cooling in California*. California: Center of Environment Design Research, University of California.

Bere, J. (2013). *An Introduction to Passive House*. *An Introduction to Passive House*. https://doi.org/10.4324/9780429347696

Bhattacharya, S. (2003). The 2003 European heatwave caused 35,000 deaths. Retrieved July 18, 2020, from https://www.newscientist.com/article/dn4259-the-2003-european-heatwave-caused-35000-deaths/#:~:text=At least 35%2C000 people died,says an environmental think tank.

Big Ladder Software. (n.d.). Euclid. Retrieved November 1, 2020, from https://bigladdersoftware.com/projects/euclid/

Bornehag, C.-G., Blomquist, G., Gyntelberg, F., Järvholm, B., Malmberg, P., Nordvall, L., … Sundell, J. (2001). Dampness in Buildings and Health: Nordic Interdisciplinary Review of the Scientific Evidence on Associations between Exposure to “‘Dampness’” in Buildings and Health Effects (NORDDAMP). *Indoor Air*, (11), 72–86.

Brager, G., & De Dear, R. (1998). Thermal adaptation in the built environment: A literature review. *Energy and Buildings*. https://doi.org/10.1016/s0378-7788(97)00053-4

BREEAM. (2020). What is BREEAM? Retrieved October 1, 2020, from https://www.breeam.com/

Busch, J. F. (1990). Thermal Responses to the Thai Office Environment. *ASHRAE Transactions*, *96*(1), 859–872.

Campbell, D. (2018). Excess winter deaths in England and Wales highest since 1976. Retrieved July 18, 2020, from https://www.theguardian.com/society/2018/nov/30/excess-winter-deaths-in-england-and-wales-highest-since-1976

Cândido, C., de Dear, R. J., Lamberts, R., & Bittencourt, L. (2010). Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone. *Building and Environment*, *45*(1), 222–229. https://doi.org/10.1016/j.buildenv.2009.06.005

Carlucci, S., Bai, L., de Dear, R., & Yang, L. (2018). Review of adaptive thermal comfort models in built environmental regulatory documents. *Building and Environment*, *137*(February), 73–89. https://doi.org/10.1016/j.buildenv.2018.03.053

CEN. (2019). *EN 16798-1:2019 Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acous*. Brussels, Belgium.

Chen, D., & Chen, H. W. (2013). Using the Köppen classification to quantify climate variation and change: An example for 1901-2010. *Environmental Development*. https://doi.org/10.1016/j.envdev.2013.03.007

Chen, Y. T. (2017). The factors affecting electricity consumption and the consumption characteristics in the residential sector: a case example of Taiwan. *Sustainability (Switzerland)*, *9*(8). https://doi.org/10.3390/su9081484

CIBSE. (2015). *Guide A: Environmental design*. London: CIBSE.

CPHCSC. (2010). *The 2009 Vietnam population and housing census: Major findings*. Hanoi: Centre Population and Housing Census Steering Commettee.

CPHCSC. (2019). *Results of the Population and Housing Census on 01/4/2019*. (Central Population and Housing Census Steering Committee, Ed.). Hanoi: Statistical Publishing House.

Creswell, J. W., & Creswell, J. D. (2018). *Research design: Qualitative, quantitative & mixed methods approaches* (5th ed.). Los Angeles: SAGE.

Damiati, S. A., Zaki, S. A., Rijal, H. B., & Wonorahardjo, S. (2016). Field study on adaptive thermal comfort in office buildings in Malaysia, Indonesia, Singapore, and Japan during hot and humid season. *Building and Environment*, *109*, 208–223. https://doi.org/10.1016/j.buildenv.2016.09.024

Dang, H. T., & Pitts, A. (2018). Thermal environments and comfort perception in shophouse dwellings of Ho Chi Minh City. *Proceedings of 10th Windsor Conference: Rethinking Comfort*, 518–532.

Danish Energy Agency. (2017). Vietnam energy outlook report. Retrieved September 10, 2018, from https://ens.dk/sites/ens.dk/files/Globalcooperation/Official_docs/Vietnam/vietnam-energy-outlook-report-2017-eng.pdf

de Dear, R. (2004). Thermal comfort in practice. *Indoor Air, Supplement*, *14*(SUPPL. 7), 32–39. https://doi.org/10.1111/j.1600-0668.2004.00270.x

de Dear, R., & Brager, G. (1998). Developing an adaptive model of thermal comfort and preference. *ASHRAE Transactions*, *104*(Pt 1A), 145–167.

De Dear, R., & Brager, G. (2002). Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55. *Energy and Buildings*, *34*(6), 549–561. https://doi.org/10.1016/S0378-7788(02)00005-1

de Dear, R., Leow, K. G., & Ameen, A. (1991a). Thermal comfort in the humid tropics. Part I. Climate chamber experiments on temperature preferences in Singapore. *ASHRAE Transactions*, (pt 1). https://doi.org/10.1519/JSC.0b013e3181bac36a

de Dear, R., Leow, K. G., & Ameen, A. (1991b). Thermal Comfort in the Humid Tropics -Part II: Climate Chamber Experiments on Thermal Acceptability in Singapore. *ASHRAE Transactions*, *97*(1), 874–879.

de Dear, R., Leow, K. G., & Foo, S. C. (1991). Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore. *International Journal of Biometeorology*, *34*(4), 259–265. https://doi.org/10.1007/BF01041840

Department of Standards Malaysia. (2014). *MS 1525:2014 Energy efficiency and use of renewable energy for non-residential buildings- Code of practice*. Ministry of Science, Technology and Innovation.

Djamila, H., Chu, C. M., & Kumaresan, S. (2013). Field study of thermal comfort in residential buildings in the equatorial hot-humid climate of Malaysia. *Building and Environment*, *62*, 133–142. https://doi.org/10.1016/j.buildenv.2013.01.017

Dornelles, K., Roriz, V., & Roriz, M. (2007). Determination of the solar absorptance of opaque surfaces. *Sun, Wind and Architecture - The Proceedings of the 24th International Conference on Passive and Low Energy Architecture, PLEA 2007*, *3*(July 2015), 452–459. https://doi.org/10.13140/RG.2.1.2368.1764

Du, C., Li, B., Cheng, Y., Li, C., Liu, H., & Yao, R. (2018). Influence of human thermal adaptation and its development on human thermal responses to warm environments. *Building and Environment*, *139*(May), 134–145. https://doi.org/10.1016/j.buildenv.2018.05.025

Energy Efficiency and Conservation Office of Vietnam Ministry of Industry and Trade. (2017). Status and some results of the energy efficiency and conservation programme in Vietnam. Retrieved November 19, 2018, from https://www.german-energy-solutions.de/GES/Redaktion/DE/Publikationen/Praesentationen/2017/171222-iv-vietnam-dang-hai-dung.pdf?__blob=publicationFile&v=2

Eurostat. (2013). *Manual for statistics on energy consumption in households*. *Manuals and guidelines - Environment and energy*. https://doi.org/10.2785/45686

Eurostat. (2016). Energy consumption in households. Retrieved November 19, 2018, from https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households

Fanger, O. (1970). Thermal comfort. Analysis and applications in environmental engineering. *Copenhagen: Danish Technical Press*.

Fanger, O., & Toftum, J. (2002). Extension of the PMV model to non-air-conditioned buildings in warm climates. *Energy and Buildings*, *34*(6), 533–536. https://doi.org/10.1016/S0378-7788(02)00003-8

Feriadi, H., Wong, N. H., Chandra, S., & Cheong, K. W. (2003). Adaptive behaviour and thermal comfort in Singapore's naturally ventilated housing. *Building Research and Information*, *31*(1), 13–23. https://doi.org/10.1080/0961321021000013830

Földváry Ličina, V., Cheung, T., Zhang, H., de Dear, R., Parkinson, T., Arens, E., … Zhou, X. (2018). Development of the ASHRAE Global Thermal Comfort Database II. *Building and Environment*, *142*(June), 502–512. https://doi.org/10.1016/j.buildenv.2018.06.022

Griffiths, I. (1990). The comfort studies in buildings with passive solar features: Field studies. *Report to the Commission of the European Communities, ENS35 090 UK*.

Halawa, E., & Hoof, J. (2012). The adaptive approach to thermal comfort: A critical overview. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2012.04.011

HCMC People's Committee. (2013). *Master plan of economic and social development of Ho Chi Minh city until 2020 and the vision to 2025*. Ho Chi Minh city.

Hoang, T. M. (2005). Architecture and hot humid tropical climates. In *Vietnamese tropical architecture: Orientations and solutions*. Hanoi, Vietnam.

Humphreys, M. (1976). FIELD STUDIES OF THERMAL COMFORT COMPARED AND APPLIED. *Build Serv Eng*, *44*(1).

Humphreys, M. (1978). OUTDOOR TEMPERATURES AND COMFORT INDOORS. *Batim Int Build Res Pract*, *6*(2). https://doi.org/10.1080/09613217808550656

Humphreys, M., & Nicol, F. (1998). Understanding the adaptive approach to thermal comfort. In *ASHRAE Transactions* (Vol. 104, pp. 991–1004).

Humphreys, M., Rijal, B., & Nicol, F. (2010). Examining and developing the adaptive relation between climate and thermal comfort indoors. In *Proceedings of Conference: Adapting to Change: New Thinking on Comfort, WINDSOR 2010*.

Hussein, I., Rahman, M. H. A., & Maria, T. (2009). Field studies on thermal comfort of air-conditioned and non air-conditioned buildings in Malaysia. In *ICEE 2009 - Proceeding 2009 3rd International Conference on Energy and Environment: Advancement Towards Global Sustainability*. https://doi.org/10.1109/ICEENVIRON.2009.5398622

Hyde, R. (2000). *Climate responsive design: a study of buildings in moderate and hot humid climates*. London: E. & F. N. Spon.

IEA. (2017). *Southeast Asia energy outlook report*. https://doi.org/10.1787/weo-2013-en

Indraganti, M. (2010). Thermal comfort in naturally ventilated apartments in summer: Findings from a field study in Hyderabad, India. *Applied Energy*, *87*(3), 866–883. https://doi.org/10.1016/j.apenergy.2009.08.042

iPHA. (n.d.-a). iPHA affiliate Organisations. Retrieved October 6, 2020, from https://passivehouse-international.org/index.php?page_id=249

iPHA. (n.d.-b). Passive House certification criteria. Retrieved March 30, 2020, from https://www.passivehouse-international.org/index.php?page_id=150&level1_id=78

iPHA. (2020). Passive House database. Retrieved October 7, 2020, from https://passivehouse-database.org/index.php?lang=en#d_6340

ISO. (2005). ISO 7730: Ergonomics of the thermal environment Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. *Management*, *3*, 605–615. https://doi.org/10.1016/j.soildyn.2004.11.005

Jin, L., Zhang, Y., & Zhang, Z. (2017). Human responses to high humidity in elevated temperatures for people in hot-humid climates. *Building and Environment*, *114*, 257–266. https://doi.org/10.1016/j.buildenv.2016.12.028

Johansson, P., Samuelson, I., Ekstrand-Tobin, A., Mjörnell, K., Sandberg, P. I., & Sikander, E. (2005). *Microbiological growth on building materials – critical moisture levels. State of the art*. Borås.

Jowkar, M., de Dear, R., & Brusey, J. (2020). Influence of long-term thermal history on thermal comfort and preference. *Energy and Buildings*, *210*. https://doi.org/10.1016/j.enbuild.2019.109685

Kagioglou, M. (1998). *Generic design and construction process protocol: Final report*. University of Salford, Department of Radiology.

Karyono, T. H. (2000). Report on thermal comfort and building energy studies in Jakarta - Indonesia. *Building and Environment*, *35*(1), 77–90. https://doi.org/10.1016/S0360-1323(98)00066-3

Karyono, T. H., Heryanto, S., & Faridah, I. (2015). Air conditioning and the neutral temperature of the Indonesian university students. *Architectural Science Review*, *58*(2). https://doi.org/10.1080/00038628.2014.1002828

Keraminiyage, K. (2013). Research Methodology: what the nested model and the research onion have to say. In *Postgraduate workshop*.

Khalfan, M., & Sharples, S. (2016). The present and future energy performance of the first passivhaus project in the Gulf region. *Sustainability (Switzerland)*. https://doi.org/10.3390/su8020139

Khuat, H. T. (2007). *The relationship between culture and architecture in Northern Delta vernacular houses*. Hanoi Architecture University.

Kimura, K., & Tanabe, S. (1993). Recommended air velocity against combinations of temperature and humidity of sedentary occupants in summer clothing. *Indoor Air*, 61–66.

Konya, A. (2013). *Design Primer for Hot Climates*. London: Architectural Press.

Koob, G., Moal, M., & Thompson, R. (2010). *Encyclopedia of Behavioral Neuroscience* (1st ed.). Elsevier Science. https://doi.org/10.5860/choice.48-5432

Kubota, T., Chyee, D. T. H., & Ahmad, S. (2009). The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. *Energy and Buildings*, *41*(8), 829–839. https://doi.org/10.1016/j.enbuild.2009.03.008

Kubota, T., Jeong, S., Toe, D. H. C., & Ossen, D. R. (2011). Energy consumption and air-conditioning usage in residential buildings of Malaysia. *Journal of International Development and Cooperation*, *17*(3), 61–69.

Kubota, T., Surahman, U., & Hisagi, U. (2014). A comparative analysis of household energy consumption in Jakarta and Bandung. In *30th International PLEA Conference* (pp. 1–8). Ahmedabad, India.

Kwok, A., & Grondzik, W. (2007). *The Green Studio Handbook: Environmental Strategies for Schematic Design*. Elsevier.

Le, T. T. B., & Nguyen, T. N. (2015). *Green Building Guidebook: Design guidelines for single-family houses toward Green architecture standard in Hanoi*. Hanoi: Construction Publishing House.

Le, V. T., & Pitts, A. (2019). A survey on electrical appliance use and energy consumption in Vietnamese households: Case study of Tuy Hoa city. *Energy and Buildings*, *197*, 229–241.

https://doi.org/10.1016/j.enbuild.2019.05.051

Le, V. T., & Pitts, A. (2020). Energy saving by adapting Passive House buildings in warm climates: A case study of Vietnamese housing. In *PLEA 2020- 35th International Conference on Passive and Low Energy Architecture*. A Coruna.

Li, B., Du, C., Yao, R., Yu, W., & Costanzo, V. (2018). Indoor thermal environments in Chinese residential buildings responding to the diversity of climates. *Applied Thermal Engineering*, *129*, 693–708. https://doi.org/10.1016/j.applthermaleng.2017.10.072

Li, G. (2013). Achieving Zero Carbon for Buildings in a Densely Populated City and a Subtropical Climate. In *Sustainable Building 2013 Hong Kong Regional Conference* (pp. 1–13). Hong Kong.

Liu, H., Wu, Y., Li, B., Cheng, Y., & Yao, R. (2017). Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China. *Energy and Buildings*, *140*, 9–18. https://doi.org/10.1016/j.enbuild.2017.01.066

Maiti, R. (2014). PMV model is insufficient to capture subjective thermal response from Indians. *International Journal of Industrial Ergonomics*, *44*(3), 349–361. https://doi.org/10.1016/j.ergon.2014.01.005

McCartney, K. J., & Nicol, F. (2002). Developing an adaptive control algorithm for Europe. *Energy and Buildings*, *34*(6), 623–635. https://doi.org/10.1016/S0378-7788(02)00013-0

McGillick, P., & Kawana, M. (2013). *Sustainable Asian House : Thailand, Malaysia, Singapore, Indonesia, Philippines*. Singapore: Tuttle Publishing.

McIntyre, D. A. (1980). *Indoor Climate*. London: Applied Science Publishers Ltd.

McNeil, M. A., Iyer, M., Meyers, S., Letschert, V. E., & McMahon, J. E. (2008). Potential benefits from improved energy efficiency of key electrical products: The case of India. *Energy Policy*, *36*(9), 3467–3476. https://doi.org/10.1016/j.enpol.2008.05.020

Mihai, M., Tanasiev, V., Dinca, C., Badea, A., & Vidu, R. (2017). Passive house analysis in terms of energy performance. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2017.03.025

Mishra, A. K., & Ramgopal, M. (2014). Thermal comfort in undergraduate laboratories - A field study in Kharagpur, India. *Building and Environment*, *71*, 223–232. https://doi.org/10.1016/j.buildenv.2013.10.006

MOC. (2004). *Vietnam Building Code TCXDVN 306:2004: Dwelling and Public Buildings - Parameters for Micro-climates in The Room*. Hanoi: Ministry of Contrucstion of Vietnam.

MOC. (2009). *Vietnam Building Code QCVN02:2009/BXD: Natural Physical & Climatic Data for Construction*. Hanoi: Ministry of Contrucstion of Vietnam.

MOET. (2018). *Atlat - Geography of Vietnam*. Hanoi: Vietnam Education Publishing House.

Mollona, E. (2015). *Computational Analysis of Firms' Organization and Strategic Behaviour*. New York: Routledge.

MOST. (2004). *TCVN 7438:2004: Ergonomics - Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for the comfort*. Hanoi, Vietnam.

Murakoshi, C., Xuan, J., Takayama, A., Nakagami, H., & Takaguchi, H. (2017). State of residential energy consumption in Southeast Asia : need to promote smart appliances because urban household consumption is higher than some developed countries. In *ECEEE Summer Study* (pp. 1489–1499). France.

Nevins, R., Rohles, F., Springer, W., & Feyerherm, A. (1966). Temperature-Humidity Chart for Thermal Comfort of Seated Persons. *ASHRAE Transactions*, *72*, 283–291.

Nguyen, C. V. (2013). Eco architecture- Sustainable architecture. Retrieved October 2, 2020, from https://www.tapchikientruc.com.vn/chuyen-muc/phat-trien-ben-vung/kien-truc-sinh-thai-kien-truc-phat-trien-ben-vung.html

Nguyen, H. M., Doan, V. H., Pham, T. M. D., Nguyen, V. K., Nguyen, B. N., Oishi, T., & Tokura, H. (2003). Thermal comfort zones in the Vietnamese. *Journal of Human Ergology*, *32*(2), 107–110. https://doi.org/10.11183/jhe1972.32.107

Nguyen, T. A. (2013). *Sustainable housing in Vietnam: climate responsive design strategies to optimize thermal comfort*. University of Liege.

Nguyen, T. A., Singh, M. K., & Reiter, S. (2012). An adaptive thermal comfort model for hot humid South-East Asia. *Building and Environment*, *56*. https://doi.org/10.1016/j.buildenv.2012.03.021

Nguyen, T. A., Tran, B. Q., Tran, Q. D., & Reiter, S. (2011). An investigation on climate responsive design strategies of vernacular housing in Vietnam. *Energy and Buildings*, *46*, 2088–2106.

Nguyen, T. Q., & Ho, T. P. (2017). Green architecture and sustainable development from Asian experience: Developing new technology or returning to indigenous wisdom. *Architecture*, *5*.

Nicol, F. (2004). Adaptive thermal comfort standards in the hot-humid tropics. *Energy and Buildings*, *36*(7), 628–637. https://doi.org/10.1016/j.enbuild.2004.01.016

Nicol, F. (2011). Adaptive comfort. *Building Research & Information*, *39*(2), 105–107.

Nicol, F., & Humphreys, M. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, *34*(6), 563–572. https://doi.org/10.1016/S0378-7788(02)00006-3

Nicol, F., & Humphreys, M. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment*, *45*(1), 11–17. https://doi.org/10.1016/j.buildenv.2008.12.013

Nicol, F., Humphreys, M., & Roaf, S. (2012). *Adaptive thermal comfort: Principles and practice*. *Adaptive Thermal Comfort: Principles and Practice*. https://doi.org/10.4324/9780203123010

Ning, H., Wang, Z., & Ji, Y. (2016). Thermal history and adaptation: Does a long-term indoor thermal exposure impact human thermal adaptability? *Applied Energy*, *183*, 22–30. https://doi.org/10.1016/j.apenergy.2016.08.157

NUCE. (2010). *TCVN 5687:2010: Ventilation-air conditioning Design standards*. Hanoi, Vietnam.

Oettl, F. (2014). *Austrian Embassy Jakarta*.

Olgyay, V. (2015). *Design with Climate: Bioclimatic Approach to Architectural Regionalism - New and expanded Edition*. Oxford: Princeton University Press.

Ozawa, A., Kudoh, Y., & Yoshida, Y. (2018). A new method for household energy use modeling: A questionnaire-based approach. *Energy and Buildings*, *162*, 32–41. https://doi.org/10.1016/j.enbuild.2017.12.032

Parkes, M., & Burrage, R. (2013). Vietnam residential energy use. Retrieved November 23, 2018, from http://www.cimigo.com/vi/research-report/cimigo-residential-energy-use-vietnam-2013

Pham, D. N., & Pham, H. H. (2002). *Heat and climate in architecture* (2nd ed.). Hanoi, Vietnam: Construction Publishing House.

Pham, D. N., & Pham, H. H. (2015). Green building development is an inevitable trend and a smart choice of Vietnamese architecture. Retrieved April 15, 2020, from http://moitruongxaydung.vn/News/NewsDetail/2050

Pham, N. D. (2002). *Bioclimatic architecture: Bioclimatic design in the built environment of Vietnam*. Hanoi: Publising House of Construction.

Pham, N. D. (2016). Green Architecture design methods for Vietnam. *Architecture*, (7).

Pham, N. D. (2017a). Controlled natural air ventilation - New proposal for open-space designs. *Architecture*, *1*.

Pham, N. D. (2017b). *Developing sustainable architecture, Green architecture in Vietnam* (3nd ed.). Hanoi: Knowledge Publishing House.

Pham, N. D., Nguyen, H. T., & Tran, B. Q. (1998). *Climate responsive design strategies in Vietnam*. Hanoi: Science and Technology Publishing House.

PHI. (n.d.). About Passive House - What is a Passive House? Retrieved March 30, 2020, from http://www.passivehouse.com/02_informations/01_whatisapassivehouse/01_whatisapassivehouse.htm

PHI. (2013). Certified Passive House - Certification Criteria for Residential Passive House Buildings. *Passive House Institute*, 1–6. Retrieved from www.passivehouse.com

PHI. (2018a). Examples of certified Passive House buildings. Retrieved October 6, 2020, from https://passipedia.org/examples#certified_passive_house_buildings

PHI. (2018b). Passive House buildings in different climates. Retrieved March 30, 2020, from https://passipedia.org/basics/passive_houses_in_different_climates

PHI. (2019a). PHPP: Active cooling algorithms. Retrieved November 10, 2020, from https://passipedia.org/planning/calculating_energy_efficiency/phpp_-_the_passive_house_planning_package/calculations_in_hot_and_humid_climates/phpp_active_cooling_algorithms

PHI. (2019b). The Passive House - historical review.

PHI. (2020). PHPP - validated and proven in practice. Retrieved November 5, 2020, from https://passipedia.org/planning/calculating_energy_efficiency/phpp_-_the_passive_house_planning_package/phpp_-_validated_and_proven_in_practice

Polo, J., Martínez, S., Fernandez-Peruchena, C. M., Navarro, A. A., Vindel, J. M., Gastón, M., … Olano, M. (2015). *Maps of Solar Resource and Potential in Vietnam*. Retrieved from http://renewables.gov.vn/Uploads/documents/tailieu/Maps of Solar Resource and Potential in Vietnam REPORT FOR PUBLISHING .pdf

Rangsiraksa, P. (2006). Thermal comfort in Bangkok residential buildings, Thailand. *PLEA 2006 - 23rd International Conference on Passive and Low Energy Architecture, Conference Proceedings*, (September), 6–8.

Riley, M., Cotgrave, A., & Farragher, M. (2018). *Building Design, Construction and Performance in Tropical Climates*. London: Routledge.

Rowan, N., Johnstone, C., Craig McLean, R., Anderson, J., & Clarke, J. (1999). Prediction of toxigenic fungal growth in buildings by using a novel modelling system. *Applied and Environmental Microbiology*, *65*, 4814–4821.

Santamouris, M., & Asimakopolou, D. (1996). *Passive Cooling of Buildings*. London: James and James (Science Publishers) Ltd.

Santy, Matsumoto, H., Tsuzuki, K., & Susanti, L. (2017). Bioclimatic analysis in pre-design stage of passive house in Indonesia. *Buildings*. https://doi.org/10.3390/buildings7010024

Saunders, M., Thornhill, A., & Lewis, P. (2019). *Research Methods for Business Students* (8th ed.). Pearson Education Limited.

Schnieders, J. (2019). Adaptive versus Heat Balance Comfort Models. Retrieved November 1, 2020, from https://passipedia.org/basics/building_physics_-_basics/thermal_comfort/heat_balance_vs_comfort_models

Schnieders, J., Feist, W., & Rongen, L. (2015). Passive Houses for different climate zones. *Energy and Buildings*, *105*, 71–87. https://doi.org/10.1016/j.enbuild.2015.07.032

Sense. (2019). Sense products. Retrieved October 9, 2020, from https://sense.com/product

Sexton, M. (2003). Positivism vs Realism. In *Research Institute of Built and Human Environment Postgraduate Workshop, University of Salford*.

Sigalingging, R. C., Chow, D., & Sharples, S. (2017). Assessing cooling energy load and dehumidification in housing built to Passivhaus standard in Jakarta, Indonesia. In *PLEA 2017- 33rd International Conference on Passive and Low Energy Architecture*. Edinburgh.

Sigalingging, R. C., Chow, D., & Sharples, S. (2020). Applying the Passivhaus standard to a terraced house in a hot and humid tropical climate – Evaluation of comfort and energy performance. *Building Services Engineering Research and Technology*, *41*(3), 247–260. https://doi.org/10.1177/0143624420912511

Singapore Energy Market Authority. (2017). Singapore energy statistics. Retrieved October 9, 2018, from https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/SES17/Publication_Singapore_Energy_Statistics_2017.pdf

Singh, J., Mantha, S. S., & Phalle, V. M. (2018). Characterizing domestic electricity consumption in the Indian urban household sector. *Energy and Buildings*, *170*, 74–82. https://doi.org/10.1016/j.enbuild.2018.04.002

Smappee. (2019). Smappee infinity. Retrieved October 9, 2020, from https://www.smappee.com/infinity/

Stetiu, C. (1999). Energy and peak power savings potential of radiant cooling systems in US commercial buildings. *Energy and Buildings*, *30*(2), 127–138. https://doi.org/10.1016/S0378-7788(98)00080-2

Supasa, T., Hsiau, S. S., Lin, S. M., Wongsapai, W., & Wu, J. C. (2017). Household energy consumption behaviour for different demographic regions in Thailand from 2000 to 2010. *Sustainability (Switzerland)*, *9*(12). https://doi.org/10.3390/su9122328

Surahman, U., Maknun, J., & Krisnanto, E. (2016). Survey on household energy consumption of public apartments in Bandung City , Indonesia. In *8th International Conference on Architecture Research and Design* (pp. 181–187). Surabaya, Indonesia.

Szokolay, S. (2008). *Introduction of architectural science: The basis of sustainable design* (2nd ed.). Oxford: Elsevier.

Tanabe, S., Kimura, K., & Hara, T. (1987). THERMAL COMFORT REQUIREMENTS DURING THE SUMMER SEASON IN JAPAN. In *ASHRAE Transactions*.

Tanabe, Shin ichi, & Kimura, K. (1994). Effects of air temperature, humidity, and air movement on thermal comfort under hot and humid conditions. *ASHRAE Transactions*, *100*(2), 953–969.

Tartarini, F., Schiavon, S., Cheung, T., & Hoyt, T. (2020). CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations. *SoftwareX*, *12*, 100563. https://doi.org/10.1016/j.softx.2020.100563

The Energy Commission. (n.d.). The Energy Commission Diamond Building. Retrieved October 21, 2020, from https://www.st.gov.my/en/details/aboutus/9

The Prime Minister of Vietnam. (2011). *Decision 2127/QĐ-TTg: Approving the strategies for national housing development until 2020, the vision until 2030*. Hanoi.

Toe, D. H. C. (2013). *Application of Passive Cooling Techniques to Improve Indoor Thermal Comfort of Modern Urban Houses in Hot-Humid Climate of Malaysia*. Hiroshima University.

Tso, G. K. F., & Yau, K. K. W. (2003). A study of domestic energy usage patterns in Hong Kong. *Energy*, *28*(15), 1671–1682. https://doi.org/10.1016/S0360-5442(03)00153-1

U.S. Department of Energy. (n.d.). EnergyPlus. Retrieved November 1, 2020, from https://energyplus.net/

U.S. Department of Energy. (2012). *Input Output Reference: The Encyclopedic Reference to EnergyPlus Input and Output*. *The Encyclopedic Reference to EnergyPlus Input and Output*.

U.S. Department of Energy. (2016). Biomass For Electricity Generation. Retrieved October 22, 2020, from https://www.wbdg.org/resources/biomass-electricity-generation#:~:text=Biomass can be converted into electric power through several methods.&text=Typically%2C woody biomass such as,gas using an anaerobic digester.

U.S. Energy Information Administration. (2015). Residential Energy Consumption Survey (RECS). Retrieved November 2, 2018, from https://www.eia.gov/consumption/residential/

UIA. (1993). Declaration of Interdependence for a Sustainable Future. Retrieved April 14, 2020, from http://www.comarchitect.org/wp-content/architectsguide/declaration_of_interdependence_for_a_sustainable_future.htm

USGBC. (2016a). LEED by the numbers: 16 years of steady growth. Retrieved October 1, 2020, from https://www.usgbc.org/articles/leed-numbers-16-years-steady-growth

USGBC. (2016b). *LEED v4 for home design and construction*.

VACEE. (2013). *QCVN 09:2013/BXD: National technical regulation on energy efficiency buildings*. Hanoi, Vietnam.

Van Craenendonck, S., Lauriks, L., Vuye, C., & Kampen, J. (2018). A review of human thermal comfort experiments in controlled and semi-controlled environments. *Renewable and Sustainable Energy Reviews*, *82*(June 2017), 3365–3378. https://doi.org/10.1016/j.rser.2017.10.053

Verdier, T., Coutand, M., Bertron, A., & Roques, C. (2014). A review of indoor microbial growth across building materials and sampling and analysis methods. *Building and Environment*, *80*, 136–149. https://doi.org/10.1016/j.buildenv.2014.05.030

VGBC. (n.d.). LOTUS certification system. Retrieved October 5, 2020, from https://vgbc.vn/en/lotus-en/rating-systems/

VGBC. (2017). *LOTUS Homes V1 - Technical manual*. Hanoi, Vietnam.

VIAP. (2012a). *TCVN 9258:2012: Heat protection for residential buildings – Design guide*. Hanoi, Vietnam.

VIAP. (2012b). *TCVN 9411:2012: Row houses - Design standards*. Hanoi, Vietnam.

Vietnam General Statistics Office. (2015a). *Mid-term population and housing census 01/04/2014 - Major results*. Hanoi: Statistical Publishing House.

Vietnam General Statistics Office. (2015b). Vietnam mid-term population and housing census: Major findings.

Vietnam General Statistics Office. (2016). *Result of the Vietnam household living standard survey 2014*. Hanoi: Statistical Publishing House.

Vietnam General Statistics Office. (2018). *Result of the 2017 economic census*. Hanoi: Statistical Publishing House.

Viitanen, H., & Ritschkoff, A. C. (1991). *Mould growth in pine and spruce sapwood in relation to air humidity and temperature (Report No. 221)*. Uppsala.

VIUP. (2008). *QCXDVN 01:2008/BXD: Regional and Urban Planning and Rural Residental Planning*. Hanoi.

Wang, Z., de Dear, R., Luo, M., Lin, B., He, Y., Ghahramani, A., & Zhu, Y. (2018). Individual difference in thermal comfort: A literature review. *Building and Environment*, *138*(April), 181–193. https://doi.org/10.1016/j.buildenv.2018.04.040

WCED. (1987). *Our Common Future*.

WHO. (2009). *WHO guidelines for indoor air quality: Dampness and mould*. Copenhagen: World Health Organization.

Williamson, T., Radford, A., & Bennetts, H. (2003). *Understanding sustainable architecture*. *Understanding Sustainable Architecture*. https://doi.org/10.4324/9780203217290

World Energy Council. (2014). Average electricity consumption per electrified household. Retrieved May 25, 2018, from https://wec-indicators.enerdata.net/secteur.php#/household-electricity-use.html

Yamtraipat, N., Khedari, J., & Hirunlabh, J. (2005). Thermal comfort standards for air conditioned buildings in hot and humid Thailand considering additional factors of acclimatization and education level. *Solar Energy*, *78*(4 SPEC. ISS.), 504–517. https://doi.org/10.1016/j.solener.2004.07.006

Yang, L., Yan, H., & Lam, J. C. (2014). Thermal comfort and building energy consumption implications - A review. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2013.10.062

Yang, Y., Li, B., Liu, H., Tan, M., & Yao, R. (2015). A study of adaptive thermal comfort in a well-controlled climate chamber. *Applied Thermal Engineering*, *76*, 283–291. https://doi.org/10.1016/j.applthermaleng.2014.11.004

Yau, Y. H., & Chew, B. T. (2014). Adaptive thermal comfort model for air-conditioned hospitals in Malaysia. *Building Services Engineering Research and Technology*, *35*(2), 117–138. https://doi.org/10.1177/0143624412474829

Yeang, K. (2008). *Ecodesign : a Manual for Ecological Design*. Chichester: John Wiley & Sons, Ltd.

Zhang, Y., Chen, H., Wang, J., & Meng, Q. (2016). Thermal comfort of people in the hot and humid area of China—impacts of season, climate, and thermal history. *Indoor Air*, *26*(5), 820–830. https://doi.org/10.1111/ina.12256

Zheng, X., Wei, C., Qin, P., Guo, J., Yu, Y., Song, F., & Chen, Z. (2014). Characteristics of residential energy consumption in China: Findings from a household survey. *Energy Policy*, *75*, 126–135. https://doi.org/10.1016/j.enpol.2014.07.016

Appendices

Appendix A

QUESTIONNAIRE
Household appliances and energy consumption in dwellings

Household electricity account number: ……………………………………………………..................

1. Building characteristics

Housing type:	Orientation:
Site area:	Construction area:
Number of floors:	Main structure:
Number of bedrooms:	Number of occupants:

2. Number, location of cooling equipment and typical type of use

	Living room	Kitchen	Family room	Bedroom	Other rooms
Air conditioners (AC)					
Ceiling fans (F)					
Standing and wall fans (F)					

Typical time of use in 24 hours of a day:

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
AC																									
F																									

3. Number of household appliances and the frequency of use
(Units of frequency of use: hour/day; hour/week; or hour/month)

Appliance	***Number***	***Power rating***	***Frequency of use***	***Note***
Air conditioner				
Ceiling fans				
Ceiling fans				
Standing and wall fans				
Electric water heater				
Solar water heater				
Fridge				
Television				
Washing machine				
Induction cooker				
Range hood				
Rice cooker				
Microwave				
Oven				
Blender				
Kettle				
Iron				
Hair drier				
Desk computer				
Laptop				
Speaker				
DVD				

4. Other energy use: ………………………………………………………………………………………

QUESTIONNAIRE

Date:

Thermal comfort experiment

Please do not discuss your answers with anyone throughout the experiment.

1. Survey number:
2. Sex: ☐ Male ☐ Female
3. Age:
4. Height:
5. Weight:
6. Survey time (from the beginning):
   ☐ 00:00 ☐ 00:30 ☐ 01:00 ☐ 01:30 ☐ 02:00
7. How do you feel about the thermal environment in the room at the moment?

Cold (-3)	Cool (-2)	Slightly cool (-1)	Neutral (0)	Slightly warm (+1)	Warm (+2)	Hot (+3)

8. Is the present thermal environment acceptable to you?
   ☐ Yes ☐ No
9. What do you think is your most preferred temperature?

Appendix B

SIMULATION RESULTS

The tabular results presented in this appendix show the energy demand and building classification of terraced and detached houses, which are assembled from different variations of building parameters. Building classifications are based on the Passive House standards for Vietnam. The colour of building category is based on the annual cooling and dehumidification demand as shown in the following table.

Table B1: Building categories for Vietnamese housing

Colour	Building category	Annual cooling + dehumidification demand (kWh/m^{2}a)
	Passive House standard for Vietnam (very good)	≤ 55
	Passive House standard for Vietnam (good)	56 - 76
	Low energy standard (high level)	≤ 55
	Low energy standard (medium level)	56 - 76
	Low energy standard (low level)	77 - 91
	Not energy efficiency	> 91 (or primary energy > 120)

Four types of energy demands of a simulation case are presented in a coloured rectangle as follows. The colour indicates the housing category.

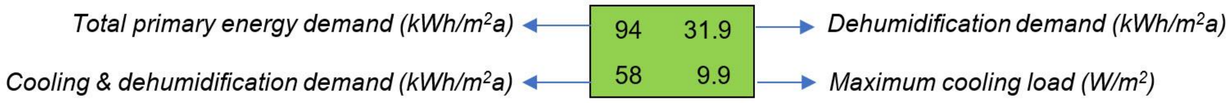


Figure B1: Energy demand presentation of a simulation case

Below are 9 result tables for 3 orientations of terraced housing and 12 result tables for 4 orientations of detached housing.

Table B2: Terraced house: North orientation and low glazing area (WWR 15%)

Orientation				North																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Low glazing area (WWR 15%)	Single glazing	40% shading	3 ACH	99	36.2	102	36.2	105	36.2	100	36.2	100	36.2	102	36.2	99	36.2	100	36.2	101	36.2	99	36.2	99	36.2	100	36.2
				58	10.8	63	11.9	71	14	59	9.7	61	10.4	66	11.7	59	9	60	9.3	63	10.1	59	8.7	60	8.9	62	9.4
			4 ACH	110	42.6	113	42.6	116	42.6	111	42.6	111	42.6	113	42.6	110	42.6	111	42.6	112	42.6	110	42.6	111	42.6	111	42.6
				65	10.9	69	12	77	15	65	9.8	67	10.5	72	11.8	65	9.1	66	9.4	69	10.2	65	8.8	66	9	68	9.5
			5 ACH	122	49	123	49	127	49	121	49	123	49	124	49	122	49	122	49	123	49	122	49	122	49	122	49
				71	11	75	12.1	83	15.1	71	9.9	73	10.6	79	11.9	71	9.2	72	9.5	75	10.3	71	8.9	72	9.1	74	9.6
		60% shading	3 ACH	99	36.2	100	36.2	103	36.2	99	36.2	99	36.2	101	36.2	97	36.2	98	36.2	99	36.2	97	36.2	97	36.2	99	36.2
				55	9.8	59	10.8	68	13	55	8.7	58	9.3	63	10.6	55	7.9	57	8.3	60	9	55	7.6	56	7.9	58	8.4
			4 ACH	110	42.6	111	42.6	114	42.6	110	42.6	110	42.6	112	42.6	108	42.6	110	42.6	111	42.6	108	42.6	108	42.6	110	42.6
				62	9.9	66	10.9	74	13.1	62	8.8	64	9.4	69	10.7	62	8	63	8.4	66	9.1	62	7.7	63	8	65	8.5
			5 ACH	121	49	122	49	125	49	120	49	121	49	123	49	119	49	121	49	122	49	119	49	119	49	121	49
				68	10	72	11	80	13.2	68	8.9	70	9.5	75	10.8	68	8.1	69	8.5	72	9.2	68	7.8	69	8.1	71	8.6
		80% shading	3 ACH	98	36.2	99	36.2	102	36.2	96	36.2	98	36.2	99	36.2	96	36.2	96	36.2	97	36.2	96	36.2	96	36.2	97	36.2
				53	8.8	56	9.9	64	12	52	7.7	55	8.4	59	9.7	52	7	54	7.3	56	8.1	52	6.7	53	6.9	55	7.4
			4 ACH	109	42.6	110	42.6	113	42.6	107	42.6	109	42.6	111	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	108	42.6
				59	8.9	63	10	71	12.1	59	7.8	61	8.5	66	9.8	58	7.1	60	7.4	63	8.2	58	6.8	59	7	61	7.5
			5 ACH	120	49	121	49	124	49	118	49	120	49	122	49	117	49	118	49	120	49	117	49	117	49	119	49
				65	9	69	10.1	77	12.2	65	7.9	67	8.6	72	9.9	65	7.2	66	7.5	69	8.3	65	6.9	66	7.1	68	7.6
	Ordinary double glazing	40% shading	3 ACH	99	36.2	101	36.2	104	36.2	99	36.2	100	36.2	101	36.2	98	36.2	99	36.2	100	36.2	98	36.2	99	36.2	99	36.2
				57	10.1	61	11.2	70	13.4	57	9	60	9.7	65	11	58	8.3	59	8.6	62	9.4	58	8	59	8.2	61	8.8
			4 ACH	110	42.6	112	42.6	115	42.6	110	42.6	111	42.6	113	42.6	110	42.6	110	42.6	111	42.6	108	42.6	110	42.6	110	42.6
				63	10.2	68	11.3	76	13.5	64	9.1	66	9.8	71	12	64	8.4	65	8.7	68	9.5	64	8.1	65	8.3	67	8.9
			5 ACH	121	49	123	49	126	49	121	49	122	49	124	49	121	49	121	49	122	49	120	49	121	49	122	49
				70	10.3	74	11.4	82	13.6	70	9.2	72	9.9	77	12.1	70	8.5	71	8.8	74	9.6	70	8.2	71	8.4	73	9
		60% shading	3 ACH	98	36.2	99	36.2	103	36.2	97	36.2	99	36.2	100	36.2	96	36.2	97	36.2	99	36.2	96	36.2	96	36.2	97	36.2
				54	9.2	59	10.3	67	12.4	55	8.1	57	8.7	62	10	55	7.3	56	7.7	59	8.4	55	7.1	56	7.3	58	7.8
			4 ACH	109	42.6	111	42.6	114	42.6	108	42.6	110	42.6	111	42.6	108	42.6	108	42.6	110	42.6	107	42.6	108	42.6	108	42.6
				61	9.3	65	10.4	73	12.5	61	8.2	63	8.8	68	10.1	61	7.4	62	7.8	65	8.5	61	7.2	62	7.4	64	7.9
			5 ACH	120	49	122	49	125	49	119	49	121	49	122	49	118	49	119	49	121	49	118	49	119	49	119	49
				67	9.4	71	10.5	79	12.6	67	8.3	69	8.9	74	10.2	67	7.5	68	7.9	71	8.6	67	7.3	68	7.5	70	8
		80% shading	3 ACH	96	36.2	99	36.2	99	36.2	96	36.2	97	36.2	99	36.2	96	36.2	96	36.2	97	36.2	97	36.2	96	36.2	96	36.2
				52	8.3	56	9.4	56	9.4	52	7.2	54	7.9	59	9.2	52	6.5	53	6.9	56	7.6	52	6.2	53	6.5	55	7
			4 ACH	107	42.6	110	42.6	110	42.6	107	42.6	108	42.6	110	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	107	42.6
				58	8.4	62	9.5	62	9.5	58	7.3	60	8	65	9.3	58	6.6	59	7	62	7.7	58	6.3	59	6.6	61	7.1
			5 ACH	120	49	121	49	121	49	117	49	118	49	121	49	118	49	117	49	119	49	118	49	118	49	118	49
				65	8.5	68	9.6	68	9.6	64	7.4	67	8.1	72	9.4	64	6.7	66	7.1	68	7.8	64	6.4	65	6.7	67	7.2
	Double low-e glazing	40% shading	3 ACH	98	36.2	99	36.2	102	36.2	97	36.2	97	36.2	100	36.2	96	36.2	96	36.2	97	36.2	96	36.2	96	36.2	97	36.2
				53	8.8	57	9.8	65	12	53	7.7	56	8.3	61	9.6	53	6.9	55	7.3	58	8	53	6.6	54	6.9	56	7.4
			4 ACH	108	42.6	110	42.6	113	42.6	107	42.6	109	42.6	111	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	108	42.6
				59	8.9	63	9.9	72	12.1	59	7.8	62	8.4	67	9.7	60	7	61	7.4	64	8.1	60	6.7	61	7	63	7.5
			5 ACH	119	49	121	49	124	49	118	49	120	49	122	49	118	49	118	49	119	49	118	49	118	49	119	49
				65	9	69	10	78	12.2	65	7.9	68	8.5	73	9.8	66	7.1	67	7.5	70	8.2	66	6.8	67	7.1	69	7.6
		60% shading	3 ACH	96	36.2	99	36.2	101	36.2	96	36.2	97	36.2	99	36.2	97	36.2	96	36.2	97	36.2	96	36.2	97	36.2	96	36.2
				51	8.1	55	9.2	63	11.4	51	7	54	7.7	59	9	51	6.3	53	6.7	56	7.4	51	6	52	6.3	54	6.8
			4 ACH	107	42.6	109	42.6	112	42.6	107	42.6	107	42.6	110	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	107	42.6
				57	8.2	61	9.3	70	11.5	58	7.1	60	7.8	65	9.1	58	6.4	59	6.8	62	7.5	58	6.1	59	6.4	61	6.9
			5 ACH	118	49	120	49	123	49	117	49	118	49	121	49	118	49	118	49	119	49	118	49	118	49	118	49
				64	8.3	68	9.4	76	11.6	64	7.2	66	7.9	71	9.2	64	6.5	65	6.9	68	7.6	64	6.2	65	6.5	67	7
		80% shading	3 ACH	96	36.2	98	36.2	100	36.2	97	36.2	96	36.2	98	36.2	95	36.2	97	36.2	96	36.2	95	36.2	96	36.2	97	36.2
				50	7.6	54	8.7	62	10.8	50	6.5	52	7.1	57	8.4	50	5.7	51	6.1	54	6.8	50	8.4	51	5.7	53	6.2
			4 ACH	107	42.6	109	42.6	111	42.6	107	42.6	107	42.6	110	42.6	106	42.6	107	42.6	107	42.6	106	42.6	107	42.6	107	42.6
				56	7.7	60	8.8	68	10.9	56	6.6	58	7.2	63	8.5	56	5.8	57	6.2	60	6.9	56	8.5	57	5.8	59	6.3
			5 ACH	118	49	120	49	123	49	118	49	117	49	121	49	117	49	118	49	117	49	116	49	117	49	118	49
				62	7.8	66	8.9	74	11	62	6.7	64	7.3	69	8.6	62	5.9	63	6.3	66	7	62	8.6	63	5.9	65	6.4
	Double low-e + solar protection glazing	40% shading	3 ACH	96	36.2	96	36.2	100	36.2	97	36.2	96	36.2	97	36.2	95	36.2	96	36.2	96	36.2	95	36.2	95	36.2	97	36.2
				49	7.5	52	8.6	61	10.7	48	6.4	50	7	56	8.4	48	5.6	50	6	53	6.7	48	5.4	49	5.6	52	6.1
			4 ACH	107	42.6	108	42.6	111	42.6	107	42.6	106	42.6	109	42.6	105	42.6	106	42.6	107	42.6	106	42.6	105	42.6	107	42.6
				55	7.6	58	8.7	67	10.8	55	6.5	57	7.1	62	8.5	54	5.7	56	6.1	59	6.8	55	5.5	56	5.7	58	6.2
			5 ACH	117	49	119	49	122	49	118	49	117	49	121	49	115	49	118	49	118	49	115	49	116	49	118	49
				62	7.7	65	8.8	73	10.9	61	6.6	63	7.2	68	8.6	61	5.8	62	6.2	65	6.9	61	5.6	61	5.8	64	6.3
		60% shading	3 ACH	96	36.2	96	36.2	100	36.2	95	36.2	96	36.2	97	36.2	95	36.2	95	36.2	97	36.2	95	36.2	95	36.2	96	36.2
				48	7.2	51	8.3	60	10.4	48	6.1	50	6.8	55	8.1	47	5.4	49	5.7	52	6.5	48	5.1	49	5.3	51	5.9
			4 ACH	107	42.6	107	42.6	111	42.6	106	42.6	107	42.6	108	42.6	105	42.6	105	42.6	107	42.6	106	42.6	106	42.6	106	42.6
				54	7.3	58	8.4	66	10.5	54	6.2	56	6.9	61	8.2	54	5.5	55	5.8	58	6.6	54	5.2	55	5.4	57	6
			5 ACH	118	49	118	49	122	49	118	49	117	49	119	49	116	49	117	49	118	49	116	49	115	49	117	49
				61	7.4	64	8.5	72	10.6	60	6.3	62	7	67	8.3	60	5.6	61	5.9	64	6.7	60	5.3	61	5.5	63	6.1
		80% shading	3 ACH	97	36.2	96	36.2	99	36.2	95	36.2	96	36.2	97	36.2	95	36.2	95	36.2	97	36.2	96	36.2	95	36.2	95	36.2
				47	7	51	8	59	10.2	47	5.9	49	6.5	54	7.8	47	5.1	48	5.5	51	6.2	47	4.8	48	5.1	50	5.6
			4 ACH	107	42.6	107	42.6	110	42.6	105	42.6	107	42.6	107	42.6	105	42.6	105	42.6	107	42.6	106	42.6	106	42.6	107	42.6
				54	7.1	55	8.1	65	10.3	53	6	55	6.6	60	7.9	53	5.2	54	5.6	57	6.3	53	4.9	54	5.2	56	5.7
			5 ACH	118	49	118	49	122	49	115	49	118	49	118	49	116	49	115	49	118	49	116	49	116	49	117	49
				60	7.2	63	8.2	71	10.4	60	6.1	62	6.7	67	8	59	5.3	60	5.7	63	6.4	59	5	60	5.3	62	5.8

Table B3: Terraced house: North orientation and medium glazing area (WWR 30%)

Orientation			North																							
Wall, roof insulation			25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity			0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Medium glazing area (WWR 30%) – Single glazing	40% shading	3 ACH	106	36.2	108	36.2	113	36.2	106	36.2	107	36.2	109	36.2	106	36.2	106	36.2	107	36.2	105	36.2	106	36.2	107	36.2
			72	14.9	76	15.9	84	18	72	13.9	74	14.5	79	15.7	72	13.2	73	13.5	76	14.2	72	12.9	73	13.1	75	13.6
		4 ACH	117	42.6	119	42.6	124	42.6	117	42.6	118	42.6	120	42.6	117	42.6	117	42.6	118	42.6	117	42.6	117	42.6	118	42.6
			78	15	82	16	90	18.1	78	14	80	14.6	85	15.8	78	13.3	79	13.6	82	14.3	78	13	79	13.2	81	13.7
		5 ACH	128	49	130	49	135	49	128	49	129	49	131	49	128	49	128	49	130	49	128	49	128	49	129	49
			84	15.1	88	16.1	96	18.2	84	14.1	86	14.7	91	15.9	84	13.4	85	13.7	88	14.4	84	13.1	85	13.3	87	13.8
	60% shading	3 ACH	103	36.2	105	36.2	108	36.2	103	36.2	103	36.2	106	36.2	102	36.2	103	36.2	104	36.2	102	36.2	102	36.2	103	36.2
			65	12.8	68	13.9	77	15.9	64	11.8	67	12.4	72	13.6	64	11.1	66	11.4	69	12.1	64	10.8	65	11.1	67	11.5
		4 ACH	114	42.6	116	42.6	119	42.6	114	42.6	115	42.6	117	42.6	113	42.6	114	42.6	115	42.6	113	42.6	113	42.6	114	42.6
			71	12.9	75	14	83	16	71	11.9	73	12.5	78	13.7	71	11.2	72	11.5	75	12.2	71	10.9	72	11.2	74	11.6
		5 ACH	125	49	127	49	130	49	125	49	126	49	128	49	124	49	125	49	126	49	124	49	125	49	125	49
			77	13	81	14.1	89	16.1	77	12	79	12.6	84	13.8	77	11.3	78	11.6	81	12.3	77	11	78	11.3	80	11.7
	80% shading	3 ACH	99	36.2	101	36.2	104	36.2	99	36.2	100	36.2	102	36.2	99	36.2	99	36.2	100	36.2	99	36.2	99	36.2	100	36.2
			56	10.3	60	11.4	67	13.4	56	9.3	58	9.9	63	11.1	56	8.6	57	8.9	60	9.6	56	8.3	57	8.6	58	9
		4 ACH	110	42.6	112	42.6	115	42.6	110	42.6	111	42.6	113	42.6	110	42.6	110	42.6	111	42.6	110	42.6	110	42.6	111	42.6
			63	10.4	66	11.5	74	13.5	62	9.4	64	10	69	11.2	62	8.7	63	9	66	9.7	62	8.4	63	8.7	65	9.1
		5 ACH	121	49	123	49	126	49	121	49	122	49	124	49	121	49	121	49	122	49	121	49	121	49	122	49
			69	10.5	73	11.6	80	13.6	69	9.5	71	10.1	75	11.3	68	8.8	70	9.1	72	9.8	68	8.5	69	8.8	71	9.2
Ordinary double glazing	40% shading	3 ACH	105	36.2	107	36.2	110	36.2	104	36.2	105	36.2	108	36.2	104	36.2	105	36.2	106	36.2	104	36.2	105	36.2	106	36.2
			69	13.6	74	14.6	83	16.6	70	12.5	72	13.1	79	14.4	70	11.8	72	12.2	76	12.9	71	11.5	72	11.8	74	12.3
		4 ACH	116	42.6	118	42.6	121	42.6	115	42.6	116	42.6	119	42.6	115	42.6	116	42.6	117	42.6	115	42.6	116	42.6	117	42.6
			76	13.7	80	14.7	89	16.7	76	12.6	78	13.2	84	14.5	76	11.9	77	12.3	81	13	76	11.6	78	11.9	80	12.4
		5 ACH	127	49	129	49	132	49	126	49	128	49	130	49	126	49	127	49	128	49	126	49	126	49	128	49
			82	13.8	86	14.8	95	16.8	82	12.7	84	13.3	90	14.6	82	12	84	12.4	87	13.1	82	11.7	83	12	86	12.5
	60% shading	3 ACH	102	36.2	103	36.2	106	36.2	101	36.2	102	36.2	105	36.2	101	36.2	102	36.2	103	36.2	101	36.2	101	36.2	102	36.2
			63	11.7	67	12.7	76	14.8	63	10.7	66	11.3	71	12.5	63	10	65	10.3	68	11.5	64	9.7	65	9.9	67	10.4
		4 ACH	113	42.6	114	42.6	117	42.6	112	42.6	113	42.6	115	42.6	112	42.6	112	42.6	114	42.6	112	42.6	112	42.6	113	42.6
			69	11.8	73	12.8	82	14.9	69	10.8	72	11.4	77	12.6	69	10.1	71	10.4	74	11.6	69	9.8	71	10	73	10.5
		5 ACH	124	49	125	49	128	49	123	49	124	49	127	49	123	49	124	49	125	49	123	49	123	49	124	49
			76	11.9	79	12.9	88	15	76	10.9	78	11.5	83	12.7	76	10.2	77	10.5	80	11.7	76	9.9	77	10.1	79	10.6
	80% shading	3 ACH	99	36.2	100	36.2	103	36.2	99	36.2	99	36.2	101	36.2	97	36.2	99	36.2	100	36.2	97	36.2	97	36.2	99	36.2
			56	9.5	59	10.5	67	12.5	55	8.4	58	9	62	10.3	55	7.7	57	8.1	59	8.8	55	7.4	56	7.7	58	8.2
		4 ACH	110	42.6	111	42.6	114	42.6	110	42.6	110	42.6	112	42.6	109	42.6	110	42.6	111	42.6	108	42.6	109	42.6	110	42.6
			62	9.6	65	10.6	73	12.6	62	8.5	64	9.1	69	10.4	61	7.8	63	8.2	66	8.9	61	7.5	62	7.8	64	8.3
		5 ACH	121	49	122	49	125	49	121	49	121	49	123	49	120	49	121	49	122	49	119	49	120	49	121	49
			68	9.7	72	10.7	80	12.7	68	8.6	70	9.2	75	10.5	68	7.9	69	8.3	72	9	68	7.6	69	7.9	71	8.4
Double low-e glazing	40% shading	3 ACH	101	36.2	102	36.2	105	36.2	100	36.2	101	36.2	103	36.2	100	36.2	100	36.2	102	36.2	99	36.2	100	36.2	101	36.2
			61	10.9	65	11.9	73	14	61	9.9	63	10.5	68	11.7	61	9.2	63	9.5	66	10.2	61	8.9	62	9.1	65	9.6
		4 ACH	112	42.6	113	42.6	116	42.6	111	42.6	112	42.6	114	42.6	111	42.6	111	42.6	112	42.6	111	42.6	111	42.6	112	42.6
			67	11	71	12	79	14.1	67	10	70	10.6	75	11.8	67	9.3	69	9.6	72	10.3	67	9	68	9.2	70	9.7
		5 ACH	123	49	124	49	127	49	122	49	123	49	125	49	122	49	122	49	123	49	122	49	122	49	123	49
			73	11.1	77	12.1	85	14.2	73	10.1	76	10.7	81	11.9	74	9.4	75	9.7	78	10.4	74	9.1	75	9.3	76	9.8
	60% shading	3 ACH	99	36.2	100	36.2	104	36.2	99	36.2	99	36.2	101	36.2	98	36.2	99	36.2	100	36.2	98	36.2	99	36.2	99	36.2
			57	9.7	61	10.7	69	12.7	57	8.6	59	9.3	64	10.5	57	7.9	58	8.3	61	9	57	7.7	58	7.9	60	8.4
		4 ACH	110	42.6	111	42.6	115	42.6	110	42.6	111	42.6	112	42.6	110	42.6	110	42.6	111	42.6	109	42.6	110	42.6	110	42.6
			63	9.8	67	10.8	75	12.8	63	8.7	66	9.4	70	10.6	63	8	65	8.4	67	9.1	63	7.8	64	8	66	8.5
		5 ACH	121	49	122	49	126	49	121	49	122	3	123	49	121	49	121	49	122	49	120	49	121	49	122	49
			70	9.9	73	10.9	81	12.9	69	8.8	72	9.4	77	10.7	69	8.1	71	8.5	73	9.2	70	7.9	70	8.1	72	8.6
	80% shading	3 ACH	97	36.2	99	36.2	101	36.2	96	36.2	97	36.2	99	36.2	96	36.2	96	36.2	97	36.2	97	36.2	96	36.2	96	36.2
			52	8.2	56	9.2	63	11.3	52	7.2	54	7.8	59	9	52	6.5	53	6.8	56	7.5	52	6.2	53	6.4	55	6.9
		4 ACH	108	42.6	110	42.6	112	42.6	107	42.6	108	42.6	110	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	107	42.6
			58	8.3	62	9.3	70	11.4	58	7.3	60	7.9	65	9.1	58	6.6	59	6.9	62	7.6	58	6.3	59	6.4	61	7
		5 ACH	120	49	121	49	123	49	118	49	118	49	121	49	118	49	117	49	119	49	118	49	118	49	118	49
			65	8.4	68	9.4	76	11.5	64	7.4	67	8	71	9.2	64	6.7	66	7	68	7.7	64	6.4	65	6.5	67	7.1
Double low-e + solar protection glazing	40% shading	3 ACH	98	36.2	99	36.2	101	36.2	95	36.2	97	36.2	99	36.2	96	36.2	96	36.2	97	36.2	96	36.2	96	36.2	96	36.2
			52	8.5	55	9.5	64	11.5	51	7.4	54	8.1	59	9.3	51	6.7	53	7.1	56	7.8	51	6.5	53	6.7	55	7.2
		4 ACH	109	42.6	110	42.6	112	42.6	107	42.6	108	42.6	110	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	108	42.6
			58	8.6	62	9.6	70	11.6	57	7.5	60	8.2	65	9.4	58	6.8	59	7.2	62	7.9	58	6.6	59	6.8	61	7.3
		5 ACH	120	49	121	49	124	49	118	49	119	49	122	49	117	49	117	49	119	49	117	49	118	49	118	49
			64	8.7	68	9.7	76	11.7	64	7.6	66	8.3	71	9.5	64	6.9	66	7.3	68	8	64	6.7	65	6.9	67	7.4
	60% shading	3 ACH	96	36.2	98	36.2	101	36.2	96	36.2	97	36.2	99	36.2	96	36.2	96	36.2	96	36.2	96	36.2	97	36.2	96	36.2
			50	7.9	54	9	62	11	50	6.9	52	7.5	57	8.7	50	6.2	51	6.5	54	7.2	50	5.9	51	6.2	53	6.6
		4 ACH	107	42.6	109	42.6	112	42.6	107	42.6	107	42.6	110	42.6	107	42.6	107	42.6	107	42.6	106	42.6	107	42.6	107	42.6
			57	8	60	9.1	68	11.2	56	7	59	7.6	63	8.8	56	6.3	58	6.6	60	7.3	56	6	57	6.3	59	6.7
		5 ACH	118	49	120	49	123	49	117	49	118	49	121	49	117	49	118	49	118	49	118	49	118	49	118	49
			63	8.1	66	9.2	74	11.3	62	7.1	65	7.7	70	8.9	62	6.4	64	6.7	66	7.4	62	6.1	63	6.4	65	6.8
	80% shading	3 ACH	96	36.2	96	36.2	99	36.2	97	36.2	96	36.2	97	36.2	95	36.2	96	36.2	96	36.2	95	36.2	95	36.2	96	36.2
			48	7.3	52	8.3	59	10.3	48	6.2	50	6.9	55	8.1	48	5.5	49	5.9	52	6.6	48	5.3	49	5.5	51	6
		4 ACH	107	42.6	107	42.6	111	42.6	107	42.6	107	42.6	108	42.6	105	42.6	106	42.6	107	42.6	105	42.6	105	42.6	107	42.6
			55	7.4	58	8.4	66	10.4	54	6.3	57	7	61	8.2	54	5.6	55	6	58	6.7	54	5.4	55	5.6	57	6.1
		5 ACH	118	49	119	49	122	49	118	49	118	49	119	49	115	49	118	49	118	49	116	49	116	49	118	49
			61	7.5	64	8.5	72	10.5	61	6.4	63	7.1	67	8.3	60	5.7	62	6.1	64	6.8	60	5.5	61	5.7	63	6.2

Table B4: Terraced house: North orientation and high glazing area (WWR 45%)

Orientation			North																							
Wall, roof insulation			25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity			0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
High glazing area (WWR 45%) – Single glazing	40% shading	3 ACH	115	36.2	118	36.2	122	36.2	115	36.2	116	36.2	119	36.2	114	36.2	115	36.2	117	36.2	115	36.2	115	36.2	117	36.2
			88	19.6	92	20.5	101	22.4	88	18.6	91	19.1	96	20.3	89	17.9	90	18.2	94	18.9	89	17.6	90	17.9	93	18.3
		4 ACH	126	42.6	129	42.6	133	42.6	126	42.6	127	42.6	130	42.6	126	42.6	126	42.6	128	42.6	125	42.6	126	42.6	127	42.6
			94	19.7	98	20.6	107	22.5	94	18.7	97	19.2	103	20.4	95	18	96	18.3	99	19	95	17.7	96	18	99	18.4
		5 ACH	137	49	140	49	144	49	137	49	138	49	141	49	137	49	137	49	139	49	137	49	137	49	138	49
			100	19.8	104	20.7	113	22.6	100	18.8	103	19.3	109	20.5	101	18.1	102	18.4	105	19.1	101	17.8	102	18.1	104	18.5
	60% shading	3 ACH	108	36.2	110	36.2	114	36.2	107	36.2	108	36.2	111	36.2	107	36.2	108	36.2	109	36.2	107	36.2	108	36.2	108	36.2
			73	15.8	77	16.7	85	18.6	73	14.8	76	15.4	81	16.5	73	14.1	75	14.4	78	15.1	74	13.9	74	14.1	76	14.5
		4 ACH	119	42.6	120	42.6	125	42.6	118	42.6	120	42.6	122	42.6	118	42.6	119	42.6	120	42.6	118	42.6	119	42.6	120	42.6
			80	15.9	83	16.8	92	18.7	79	14.9	82	15.5	87	16.6	80	14.2	81	14.5	84	15.2	80	14	80	14.2	83	14.6
		5 ACH	130	49	131	49	136	49	129	49	131	49	133	49	129	49	130	49	131	49	129	49	130	49	130	49
			86	16	90	16.9	98	18.8	86	15	88	15.6	93	16.7	86	14.3	87	14.6	90	15.3	86	14.1	87	14.3	89	14.7
	80% shading	3 ACH	102	36.2	103	36.2	105	36.2	101	36.2	102	36.2	104	36.2	101	36.2	101	36.2	103	36.2	101	36.2	101	36.2	102	36.2
			61	12.1	64	13.1	78	15	60	11.2	63	11.7	67	12.9	60	10.5	61	10.8	64	11.5	60	10.2	61	10.5	63	10.9
		4 ACH	113	42.6	114	42.6	117	42.6	112	42.6	113	42.6	115	42.6	112	42.6	113	42.6	114	42.6	112	42.6	112	42.6	113	42.6
			67	12.2	71	13.2	78	15.1	67	11.3	69	11.8	73	13	66	10.6	68	10.9	70	11.6	66	10.3	67	10.6	69	11
		5 ACH	124	49	125	49	128	49	123	49	124	49	126	49	123	49	124	49	125	49	123	49	123	49	124	49
			74	12.3	77	13.3	84	15.2	73	11.4	75	11.9	79	13.1	73	10.7	74	11	76	11.7	73	10.4	74	10.7	75	11.1
Ordinary double glazing	40% shading	3 ACH	112	36.2	115	36.2	121	36.2	112	36.2	114	36.2	118	36.2	113	36.2	114	36.2	116	36.2	113	36.2	113	36.2	115	36.2
			85	17.4	90	18.4	100	20.3	87	16.4	90	17	96	18.2	88	15.8	90	16.1	93	16.8	89	15.5	90	15.8	92	16.2
		4 ACH	123	42.6	126	42.6	132	42.6	123	42.6	125	42.6	128	42.6	123	42.6	124	42.6	126	42.6	123	42.6	124	42.6	126	42.6
			92	17.5	96	18.5	106	20.4	93	16.5	96	17.1	101	18.3	93	15.9	95	16.2	99	16.9	94	15.6	95	15.9	98	16.3
		5 ACH	135	49	137	49	142	49	134	49	136	49	139	49	134	49	135	49	137	49	134	49	135	49	136	49
			98	17.6	102	18.6	112	20.5	99	16.6	101	17.2	107	18.4	99	16	101	16.3	104	17	100	15.7	101	16	103	16.4
	60% shading	3 ACH	106	36.2	108	36.2	112	36.2	106	36.2	107	36.2	109	36.2	106	36.2	106	36.2	107	36.2	106	36.2	106	36.2	107	36.2
			72	14	76	15	84	16.9	72	13.1	75	13.6	80	14.8	72	12.4	74	12.7	77	13.4	73	12.1	74	12.4	76	12.8
		4 ACH	117	42.6	119	42.6	123	42.6	117	42.6	118	42.6	120	42.6	117	42.6	117	42.6	119	42.6	117	42.6	117	42.6	118	42.6
			78	14.1	82	15.1	91	17	78	13.2	81	13.7	86	14.9	78	12.5	80	12.8	83	13.5	79	12.2	80	12.5	82	12.9
		5 ACH	128	49	130	49	134	49	128	49	129	49	131	49	128	49	128	49	130	49	128	49	128	49	129	49
			84	14.2	88	15.2	97	17.1	84	13.3	87	13.8	87	15	84	12.6	86	12.9	89	13.6	85	12.3	86	12.6	88	113
	80% shading	3 ACH	100	36.2	102	36.2	105	36.2	100	36.2	101	36.2	103	36.2	100	36.2	100	36.2	101	36.2	100	36.2	100	36.2	101	36.2
			60	10.8	63	11.8	71	13.7	60	9.8	62	10.4	66	11.5	60	9.1	61	9.5	63	10.1	60	8.9	60	9.1	62	9.6
		4 ACH	111	42.6	113	42.6	116	42.6	111	42.6	112	42.6	114	42.6	111	42.6	111	42.6	112	42.6	111	42.6	111	42.6	112	42.6
			66	10.9	70	11.9	77	13.8	66	9.9	68	10.5	73	11.6	66	9.2	67	9.6	70	10.2	66	9	67	9.2	68	9.7
		5 ACH	122	49	124	49	127	49	122	49	123	49	125	49	122	49	122	49	124	49	122	49	122	49	123	49
			72	11	76	12	83	13.9	72	10	74	10.6	79	11.7	72	9.3	73	9.7	76	10.3	72	9.1	73	9.3	75	9.8
Double low-e glazing	40% shading	3 ACH	105	36.2	107	36.2	110	36.2	105	36.2	106	36.2	108	36.2	105	36.2	105	36.2	106	36.2	105	36.2	105	36.2	106	36.2
			71	13.3	75	14.3	85	16.2	72	12.3	75	12.9	80	14.1	73	11.7	74	12	77	12.6	73	11.4	74	11.6	76	12.1
		4 ACH	116	42.6	118	42.6	121	42.6	115	42.6	117	42.6	119	42.6	116	42.6	116	42.6	117	42.6	116	42.6	116	42.6	117	42.6
			77	13.4	81	14.4	90	16.3	77	12.4	80	13	86	14.2	78	11.8	80	12.1	83	12.7	79	11.5	80	11.7	82	12.2
		5 ACH	127	49	129	49	132	49	126	49	128	49	130	49	127	49	127	49	129	49	127	49	127	49	128	49
			83	13.5	87	14.5	96	16.4	83	12.5	86	13.1	92	14.3	84	11.9	86	12.2	89	12.8	85	11.6	86	11.8	88	12.3
	60% shading	3 ACH	101	36.2	103	36.2	107	36.2	101	36.2	102	36.2	104	36.2	101	36.2	101	36.2	102	36.2	100	36.2	101	36.2	102	36.2
			62	11.1	66	12	75	14	63	10.1	65	10.7	70	11.8	63	9.4	64	9.8	67	10.4	63	9.2	64	9.4	66	9.9
		4 ACH	112	42.6	114	42.6	118	42.6	112	42.6	113	42.6	115	42.6	112	42.6	112	42.6	113	42.6	112	42.6	112	42.6	113	42.6
			69	11.2	72	12.1	81	14.1	69	10.2	71	10.8	76	11.9	69	9.5	70	9.9	73	10.5	69	9.3	70	9.5	72	10
		5 ACH	123	49	125	49	129	49	123	49	124	49	126	49	123	49	123	49	125	49	123	49	123	49	124	49
			75	11.3	79	12.2	87	14.2	75	10.3	77	10.9	82	12	75	9.6	77	10	79	10.5	75	9.4	76	9.6	78	10.1
	80% shading	3 ACH	99	36.2	99	36.2	102	36.2	98	36.2	99	36.2	100	36.2	98	36.2	99	36.2	99	36.2	98	36.2	99	36.2	99	36.2
			55	8.9	59	9.9	68	11.8	55	7.9	57	8.5	62	9.7	55	7.2	56	7.6	59	8.2	55	7.1	56	7.4	59	8
		4 ACH	110	42.6	111	42.6	114	42.6	109	42.6	110	42.6	111	42.6	109	42.6	110	42.6	110	42.6	109	42.6	110	42.6	110	42.6
			61	9	65	10	73	11.9	61	8	63	8.6	68	9.8	61	7.3	62	7.7	65	8.3	61	7.2	62	7.5	65	8.1
		5 ACH	121	49	122	49	125	49	120	49	121	49	123	49	120	49	121	49	121	49	120	49	121	49	121	49
			68	9.1	71	10.1	79	12	67	8.1	70	8.7	74	9.9	67	7.4	69	7.8	71	8.4	67	7.3	69	7.6	71	8.2
Double low-e + solar protection glazing	40% shading	3 ACH	99	36.2	100	36.2	103	36.2	99	36.2	99	36.2	101	36.2	99	36.2	99	36.2	99	36.2	99	36.2	99	36.2	99	36.2
			56	9.6	60	10.6	67	12.5	56	8.6	58	9.2	63	10.4	56	8	57	8.3	60	8.9	56	7.7	57	7.9	59	8.4
		4 ACH	110	42.6	111	42.6	114	42.6	110	42.6	110	42.6	112	42.6	110	42.6	110	42.6	111	42.6	110	42.6	110	42.6	110	42.6
			62	9.7	66	10.7	73	12.6	62	8.7	64	9.3	69	10.5	62	8.1	63	8.4	66	9	62	7.8	63	8	65	8.5
		5 ACH	121	49	122	49	125	49	120	49	121	49	123	49	120	49	121	49	122	49	120	49	121	49	121	49
			68	9.8	72	10.8	73	12.7	68	8.8	70	9.4	75	10.6	68	8.2	69	8.5	72	9.1	68	7.9	69	8.1	71	8.6
	60% shading	3 ACH	98	36.2	99	36.2	101	36.2	97	36.2	98	36.2	99	36.2	96	36.2	97	36.2	99	36.2	96	36.2	96	36.2	97	36.2
			52	8.6	56	9.6	63	11.5	52	7.9	55	8.5	59	9.7	52	7.4	54	7.8	56	8.4	52	7.3	53	7.5	55	7.9
		4 ACH	109	42.6	110	42.6	112	42.6	107	42.6	109	42.6	110	42.6	107	42.6	107	42.6	110	42.6	107	42.6	107	42.6	108	42.6
			59	8.7	62	9.7	70	11.6	59	8	61	8.6	65	9.8	59	7.5	60	7.9	62	8.3	59	7.4	59	7.6	61	8
		5 ACH	120	49	121	49	124	49	118	49	120	49	122	49	117	49	118	49	121	49	117	49	118	49	119	49
			65	8.8	68	9.8	76	11.7	65	8.1	67	8.7	71	9.9	65	7.6	66	8	68	8.2	65	7.5	66	7.7	67	8.1
	80% shading	3 ACH	97	36.2	98	36.2	100	36.2	97	36.2	97	36.2	99	36.2	97	36.2	97	36.2	96	36.2	97	36.2	97	36.2	97	36.2
			50	7.6	53	8.5	60	10.4	49	6.6	51	7.2	56	8.3	49	5.9	50	6.3	53	6.9	49	5.7	50	5.9	52	6.4
		4 ACH	108	42.6	109	42.6	111	42.6	107	42.6	108	42.6	110	42.6	107	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6
			56	7.7	59	8.6	66	10.5	56	6.7	58	7.3	62	8.4	55	6	57	6.4	59	7	55	5.8	56	6	58	6.5
		5 ACH	118	49	120	49	122	49	118	49	118	49	121	49	118	49	118	49	118	49	118	49	118	49	118	49
			62	7.8	66	8.7	72	10.6	62	6.8	64	7.4	68	8.5	62	6.1	63	6.5	65	7.1	62	5.9	62	6.1	64	6.6

Table B5: Terraced house: South orientation and low glazing area (WWR 15%)

Orientation				South											
Wall, roof insulation				25 mm			50 mm			100 mm			150 mm		
Exterior absorptivity				0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9
Low glazing area (WWR 15%)	Single glazing	40% shading	3 ACH	100 36.2	102 36.2	105 36.2	100 36.2	101 36.2	103 36.2	99 36.2	100 36.2	102 36.2	99 36.2	100 36.2	101 36.2
				61 10.8	65 11.9	74 14	61 9.7	63 10.3	69 11.7	61 8.9	62 9.3	66 10	61 8.6	63 8.9	65 9.4
			4 ACH	111 42.6	113 42.6	116 42.6	111 42.6	112 42.6	114 42.6	111 42.6	111 42.6	113 42.6	110 42.6	111 42.6	112 42.6
				67 10.9	71 12	80 14.1	67 9.8	69 10.4	75 11.8	67 9	69 9.4	72 10.1	67 8.7	68 9	71 9.5
			5 ACH	122 49	124 49	127 49	122 49	123 49	125 49	122 49	122 49	124 49	122 49	122 49	123 49
				73 11	77 12.1	86 14.2	73 9.9	76 10.5	81 11.9	73 9.1	75 9.5	78 10.2	73 8.8	74 9.1	77 9.6
		60% shading	3 ACH	99 36.2	100 36.2	104 36.2	99 36.2	99 36.2	101 36.2	99 36.2	99 36.2	99 36.2	99 36.2	99 36.2	99 36.2
				57 9.6	61 10.7	69 12.8	56 8.5	59 9.1	64 10.5	57 7.7	58 8.1	61 8.8	57 7.4	58 7.7	60 8.2
			4 ACH	110 42.6	111 42.6	115 42.6	110 42.6	110 42.6	112 42.6	110 42.6	110 42.6	111 42.6	110 42.6	110 42.6	110 42.6
				63 9.7	67 10.8	75 12.9	63 8.6	65 9.2	70 10.6	63 7.8	64 8.2	67 8.9	63 7.5	64 7.8	66 8.3
			5 ACH	121 49	122 49	126 49	121 49	122 49	123 49	121 49	121 49	122 49	121 49	121 49	121 49
				69 9.8	73 10.9	81 13	69 8.7	71 9.3	76 10.7	69 7.9	70 8.3	73 9	69 7.6	70 7.9	72 8.4
		80% shading	3 ACH	98 36.2	99 36.2	102 36.2	96 36.2	98 36.2	99 36.2	96 36.2	97 36.2	99 36.2	96 36.2	96 36.2	97 36.2
				52 8.4	56 9.5	64 11.7	52 7.3	55 8	60 9.3	52 6.6	54 6.9	56 7.7	52 6.3	53 6.5	55 7.1
			4 ACH	109 42.6	110 42.6	113 42.6	107 42.6	109 42.6	111 42.6	107 42.6	107 42.6	110 42.6	107 42.6	107 42.6	108 42.6
				59 8.5	63 9.6	71 11.8	59 7.4	60 8.1	66 9.4	58 6.7	60 7	63 7.8	58 6.4	59 6.6	61 7.2
			5 ACH	120 49	121 49	124 49	118 49	120 49	122 49	118 49	118 49	121 49	118 49	118 49	119 49
				65 8.6	69 9.7	77 11.9	65 7.5	67 8.2	72 9.5	65 6.8	66 7.1	69 7.9	65 6.5	66 6.7	68 7.3
	Ordinary double glazing	40% shading	3 ACH	100 36.2	101 36.2	105 36.2	99 36.2	100 36.2	103 36.2	99 36.2	100 36.2	101 36.2	99 36.2	99 36.2	100 36.2
				59 10.1	64 11.2	73 13.4	59 9	62 9.7	68 11	60 8.3	62 8.6	65 9.4	60 8	62 8.2	64 8.7
			4 ACH	111 42.6	112 42.6	116 42.6	110 42.6	111 42.6	114 42.6	110 42.6	110 42.6	112 42.6	110 42.6	111 42.6	111 42.6
				66 10.2	70 11.3	79 13.5	66 9.1	68 9.8	74 11.1	66 8.4	67 8.7	71 9.5	66 8.1	68 8.2	70 8.8
			5 ACH	122 49	123 49	127 49	122 49	122 49	125 49	121 49	121 49	123 49	121 49	121 49	122 49
				72 10.3	76 11.4	85 13.6	72 9.2	74 9.9	80 11.2	72 8.5	73 8.8	77 9.6	72 8.2	73 8.3	76 8.9
		60% shading	3 ACH	99 36.2	100 36.2	103 36.2	99 36.2	99 36.2	100 36.2	98 36.2	99 36.2	99 36.2	97 36.2	99 36.2	99 36.2
				56 9	60 10.1	68 12.3	56 7.9	58 8.6	63 9.9	56 7.2	57 7.6	60 8.3	56 6.9	57 7.2	59 7.7
			4 ACH	110 42.6	111 42.6	114 42.6	110 42.6	110 42.6	111 42.6	109 42.6	110 42.6	110 42.6	108 42.6	110 42.6	110 42.6
				62 9.1	66 10.2	74 12.4	62 8	64 8.7	69 10	62 7.3	63 7.7	66 8.4	62 7	63 7.3	65 7.8
			5 ACH	121 49	122 49	125 49	121 49	121 49	123 49	121 49	121 49	121 49	119 49	121 49	121 49
				68 9.2	72 10.3	80 12.5	68 8.1	70 8.8	76 10.1	68 7.4	70 7.8	72 8.5	68 7.1	69 7.4	71 7.9
		80% shading	3 ACH	98 36.2	99 36.2	101 36.2	97 36.2	97 36.2	99 36.2	97 36.2	96 36.2	97 36.2	97 36.2	96 36.2	97 36.2
				52 8	56 9.1	64 11.3	52 6.9	58 7.6	59 8.9	52 6.1	53 6.5	56 7.3	52 5.9	53 6.1	55 6.6
			4 ACH	109 42.6	110 42.6	112 42.6	108 42.6	108 42.6	110 42.6	107 42.6	107 42.6	108 42.6	107 42.6	107 42.6	108 42.6
				58 8.1	62 9.2	70 11.4	58 7	60 7.7	65 9	58 6.2	59 6.6	62 7.4	58 6	59 6.2	61 6.7
			5 ACH	120 49	121 49	124 49	118 49	119 49	121 49	118 49	117 49	119 49	118 49	118 49	118 49
				65 8.2	68 9.3	76 11.5	64 7.1	67 7.8	72 9.1	64 6.3	66 6.7	68 7.5	64 6.1	65 6.3	67 6.8
	Double low-e glazing	40% shading	3 ACH	98 36.2	99 36.2	102 36.2	98 36.2	99 36.2	100 36.2	97 36.2	98 36.2	99 36.2	97 36.2	97 36.2	99 36.2
				54 8.8	58 9.8	67 12	54 7.6	57 8.3	62 9.6	55 6.9	56 7.3	59 8	55 6.6	56 6.9	58 7.4
			4 ACH	109 42.6	110 42.6	113 42.6	109 42.6	110 42.6	11 42.6	108 42.6	109 42.6	110 42.6	108 42.6	108 42.6	110 42.6
				61 8.9	65 9.9	73 12.1	61 7.7	63 8.4	68 9.7	61 7	62 7.4	65 8.1	61 6.7	62 7	64 7.5
			5 ACH	120 49	121 49	125 49	120 49	121 49	122 49	118 49	121 49	121 49	118 49	119 49	121 49
				67 9	71 10	79 12.2	67 7.8	69 8.5	74 9.8	67 7.1	68 7.5	71 8.2	67 6.8	68 7.1	70 7.6
		60% shading	3 ACH	98 36.2	99 36.2	101 36.2	97 36.2	97 36.2	99 36.2	97 36.2	96 36.2	97 36.2	97 36.2	97 36.2	97 36.2
				52 8	56 9.1	64 11.3	52 6.9	54 7.6	59 8.9	52 6.2	54 6.6	56 7.3	53 5.9	53 6.2	55 6.7
			4 ACH	109 42.6	110 42.6	112 42.6	108 42.6	108 42.6	110 42.6	107 42.6	107 42.6	108 42.6	108 42.6	107 42.6	108 42.6
				58 8.1	62 9.2	70 11.4	58 7	61 7.7	66 9	58 6.3	60 6.7	63 7.4	58 6	59 6.3	61 6.8
			5 ACH	120 49	121 49	123 49	118 49	119 49	121 49	118 49	118 49	119 49	118 49	118 49	118 49
				65 8.2	69 9.3	77 11.5	64 7.1	67 7.8	72 9.1	64 6.4	66 6.8	69 7.5	65 6.1	66 6.4	68 6.9
		80% shading	3 ACH	97 36.2	98 36.2	100 36.2	97 36.2	96 36.2	99 36.2	96 36.2	97 36.2	96 36.2	96 36.2	96 36.2	97 36.2
				50 7.4	54 8.5	62 10.6	50 6.3	52 6.9	57 8.2	50 5.5	51 5.9	54 6.6	50 5.2	51 5.5	53 6
			4 ACH	108 42.6	109 42.6	111 42.6	107 42.6	107 42.6	110 42.6	107 42.6	108 42.6	107 42.6	107 42.6	107 42.6	107 42.6
				56 7.5	60 8.6	68 10.7	56 6.4	58 7	63 8.3	56 5.6	57 6	60 6.7	56 5.3	57 5.6	59 6.1
			5 ACH	118 49	120 49	123 49	118 49	118 49	121 49	118 49	118 49	118 49	117 49	118 49	118 49
				62 7.6	66 8.7	74 10.8	62 6.5	64 7.1	69 8.4	62 5.7	63 6.1	66 6.8	62 5.4	63 5.7	65 6.2
	Double low-e + solar protection glazing	40% shading	3 ACH	97 36.2	98 36.2	100 36.2	96 36.2	96 36.2	99 36.2	96 36.2	97 36.2	96 36.2	96 36.2	96 36.2	97 36.2
				49 7.5	53 8.6	61 10.8	49 6.4	52 7.1	57 8.4	49 5.6	51 6	53 6.8	49 5.4	50 5.6	52 6.1
			4 ACH	108 42.6	109 42.6	111 42.6	107 42.6	107 42.6	110 42.6	107 42.6	108 42.6	107 42.6	107 42.6	106 42.6	107 42.6
				56 7.5	59 8.7	67 10.9	55 6.5	58 7.2	63 8.5	55 5.7	57 6.1	60 6.9	55 5.5	56 5.7	58 6.2
			5 ACH	118 49	120 49	122 49	118 49	120 49	121 49	117 49	118 49	118 49	117 49	117 49	118 49
				62 7.6	66 8.8	74 11	61 6.6	64 7.3	69 8.6	61 5.8	63 6.2	66 7	61 5.6	62 5.8	65 6.3
		60% shading	3 ACH	96 36.2	96 36.2	100 36.2	97 36.2	97 36.2	97 36.2	95 36.2	96 36.2	97 36.2	95 36.2	95 36.2	96 6
				48 7.2	52 8.3	60 10.4	48 6.1	50 6.7	55 8.1	48 5.3	49 5.7	52 6.4	48 5	49 5.3	51 5.8
			4 ACH	107 42.6	108 42.6	111 42.6	107 42.6	107 42.6	108 42.6	106 42.6	106 42.6	107 42.6	106 42.6	106 42.6	108 42.6
				55 7.2	58 8.4	66 10.5	54 6.2	56 6.8	62 8.2	54 5.4	55 5.8	58 6.5	54 5.1	55 5.4	57 5.9
			5 ACH	118 49	120 49	122 49	118 49	117 49	120 49	116 49	117 49	118 49	116 49	116 49	118 49
				61 7.3	65 8.5	73 10.6	61 6.3	62 6.9	68 8.3	60 5.5	62 5.9	62 6.6	60 5.2	61 5.5	63 6
		80% shading	3 ACH	97 36.2	96 36.2	99 36.2	95 36.2	96 36.2	97 36.2	95 36.2	95 36.2	97 36.2	96 36.2	95 36.2	96 36.2
				47 6.9	51 8	59 10.1	47 5.8	49 6.4	54 7.7	47 5	48 5.4	51 6.1	47 4.7	48 5	50 5.5
			4 ACH	107 42.6	107 42.6	110 42.6	105 42.6	107 42.6	108 42.6	105 42.6	105 42.6	107 42.6	106 42.6	106 42.6	107 42.6
				54 7	57 8.1	65 10.2	53 5.9	55 6.5	60 7.8	53 5.1	54 5.5	57 6.2	53 4.8	54 5.1	56 5.6
			5 ACH	118 49	118 49	122 49	115 49	118 49	118 49	116 49	115 49	118 49	116 49	116 49	117 49
				60 7.1	63 8.2	71 10.3	60 6	62 6.6	67 7.9	59 5.2	60 5.6	64 6.3	59 4.9	60 5.2	62 5.7

Table B6: Terraced house: South orientation and medium glazing area (WWR 30%)

Orientation				South																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Medium glazing area (WWR 30%)	Single glazing	40% shading	3 ACH	105	36.2	107	36.2	112	36.2	105	36.2	106	36.2	108	36.2	105	36.2	105	36.2	107	36.2	104	36.2	105	36.2	106	36.2
				71	14	75	15	84	17.1	71	12.9	73	13.5	79	14.8	71	12.2	72	12.5	76	13.2	71	11.9	72	12.2	75	12.6
			4 ACH	116	42.6	118	42.6	123	42.6	116	42.6	117	42.6	119	42.6	116	42.6	116	42.6	118	42.6	115	42.6	116	42.6	117	42.6
				77	14.1	81	15.1	90	17.2	77	13	79	13.6	85	14.9	77	12.3	79	12.6	82	13.3	77	12	78	12.3	81	12.7
			5 ACH	127	49	129	49	134	49	127	49	128	49	130	49	127	49	127	49	129	49	127	49	127	49	128	49
				83	14.2	87	15.2	96	17.3	83	13.1	86	13.7	91	15	83	12.4	85	12.7	88	13.4	83	12.1	84	12.4	86	12.8
		60% shading	3 ACH	102	36.2	103	36.2	107	36.2	101	36.2	102	36.2	105	36.2	101	36.2	101	36.2	103	36.2	101	36.2	101	36.2	102	36.2
				63	11.8	67	12.8	75	14.9	63	10.8	65	11.4	70	12.6	63	10	64	10.4	67	11.1	63	9.8	64	10	66	10.5
			4 ACH	113	42.6	114	42.6	118	42.6	112	42.6	113	42.6	116	42.6	112	42.6	112	42.6	114	42.6	112	42.6	112	42.6	113	42.6
				69	11.9	73	12.9	81	15	69	10.9	71	11.5	76	12.7	69	10.1	70	10.5	73	11.2	69	9.9	70	10.1	72	10.6
			5 ACH	124	49	126	49	129	49	123	49	124	49	127	49	123	49	124	49	125	49	123	49	123	49	124	49
				75	12	79	13	87	15.1	75	11	77	11.6	82	12.8	75	10.2	76	10.6	79	11.3	75	10	76	10.2	78	10.7
		80% shading	3 ACH	99	36.2	100	36.2	103	36.2	99	36.2	99	36.2	101	36.2	99	36.2	99	36.2	100	36.2	99	36.2	99	36.2	99	36.2
				56	9.9	59	11	67	13	55	8.9	58	9.5	62	10.7	55	8.1	56	8.5	59	9.2	55	7.9	56	8.1	58	8.6
			4 ACH	110	42.6	111	42.6	114	42.6	110	42.6	110	42.6	112	42.6	110	42.6	110	42.6	111	42.6	110	42.6	110	42.6	110	42.6
				62	10	66	11.1	73	13.1	62	9	64	9.6	68	10.8	61	8.2	63	8.6	65	9.3	61	8	62	8.2	64	8.7
			5 ACH	121	49	122	49	125	49	121	49	122	49	123	49	121	49	121	49	122	49	121	49	121	49	121	49
				68	10.1	72	11.2	79	13.2	68	9.1	70	9.7	75	10.9	68	8.3	69	8.7	72	9.4	68	8.1	69	8.3	70	8.8
	Ordinary double glazing	40% shading	3 ACH	104	36.2	106	36.2	110	36.2	103	36.2	105	36.2	107	36.2	104	36.2	104	36.2	105	36.2	103	36.2	104	36.2	105	36.2
				69	12.7	73	13.7	83	15.8	69	11.7	72	12.3	79	13.5	71	11	72	11.3	76	12	71	10.8	72	11	75	11.5
			4 ACH	115	42.6	117	42.6	121	42.6	114	42.6	116	42.6	118	42.6	114	42.6	115	42.6	116	42.6	115	42.6	115	42.6	116	42.6
				75	12.8	79	13.8	89	15.9	75	11.8	78	12.4	85	13.6	76	11.1	78	11.4	82	12.1	77	10.8	78	11.1	80	11.5
			5 ACH	126	49	128	49	132	49	125	49	127	49	129	49	125	49	126	49	128	49	125	49	126	49	127	49
				81	12.9	85	13.9	95	16	81	11.9	84	12.5	90	13.7	81	11.2	83	11.5	87	12.2	82	10.9	84	11.2	86	11.6
		60% shading	3 ACH	101	36.2	102	36.2	106	36.2	100	36.2	101	36.2	104	36.2	100	36.2	100	36.2	102	36.2	100	36.2	100	36.2	101	36.2
				61	10.8	65	11.8	74	13.9	61	9.7	64	10.4	70	11.6	62	9	64	9.4	67	10.1	62	8.7	63	9	65	9.5
			4 ACH	112	42.6	113	42.6	117	42.6	111	42.6	112	42.6	115	42.6	111	42.6	112	42.6	113	42.6	111	42.6	111	42.6	112	42.6
				68	10.9	72	11.9	80	14	68	9.8	70	10.5	76	11.7	68	9.1	70	9.5	73	10.2	68	8.8	69	9.1	71	9.6
			5 ACH	123	49	124	49	128	49	122	49	123	49	126	49	122	49	122	49	124	49	122	49	122	49	123	49
				74	11	78	12	86	14.1	74	9.9	76	10.6	82	11.8	74	9.2	75	9.6	79	10.3	74	8.9	75	9.2	78	9.7
		80% shading	3 ACH	99	36.2	100	36.2	103	36.2	98	36.2	99	36.2	100	36.2	98	36.2	99	36.2	99	36.2	98	36.2	99	36.2	99	36.2
				55	9.1	59	10.1	67	12.2	55	8	57	8.7	62	9.9	55	7.3	56	7.7	59	8.4	55	7	56	7.3	58	7.8
			4 ACH	110	42.6	111	42.6	114	42.6	109	42.6	110	42.6	112	42.6	109	42.6	110	42.6	110	42.6	109	42.6	110	42.6	110	42.6
				61	9.2	65	10.2	73	12.3	61	8.1	63	8.8	68	10	61	7.4	62	7.8	65	8.5	61	7.1	62	7.4	64	7.9
			5 ACH	121	49	122	49	125	49	120	49	121	49	123	49	120	49	121	49	122	49	120	49	121	49	121	49
				68	9.3	71	10.3	79	12.4	67	8.2	70	8.9	74	10.1	67	7.5	68	7.9	71	8.6	67	7.2	68	7.5	70	8
	Double low-e glazing	40% shading	3 ACH	100	36.2	101	36.2	105	36.2	99	36.2	100	36.2	103	36.2	99	36.2	99	36.2	101	36.2	99	36.2	99	36.2	101	36.2
				60	10.3	64	11.4	73	13.4	60	9.3	63	9.9	69	11.2	61	8.6	62	8.9	66	9.6	61	8.3	62	8.5	65	9
			4 ACH	111	42.6	112	42.6	116	42.6	111	42.6	111	42.6	114	42.6	110	42.6	110	42.6	112	42.6	110	42.6	110	42.6	111	42.6
				67	10.4	71	11.5	79	13.5	67	9.4	69	10	74	11.3	67	8.7	68	9	72	9.7	67	8.4	68	8.6	71	9.1
			5 ACH	122	49	124	49	127	49	122	49	122	49	125	49	121	49	122	49	123	49	121	49	121	49	122	49
				73	10.5	77	11.6	85	13.6	73	9.5	75	10.1	80	11.4	73	8.8	74	9.1	77	9.8	73	8.5	74	8.7	76	9.2
		60% shading	3 ACH	99	36.2	100	36.2	103	36.2	99	36.2	99	36.2	100	36.2	98	36.2	99	36.2	99	36.2	99	36.2	99	36.2	99	36.2
				56	9.1	60	10.1	68	12.2	56	8	58	8.7	63	9.9	56	7.3	57	7.7	61	8.4	56	7	57	7.3	59	7.8
			4 ACH	110	42.6	111	42.6	114	42.6	110	42.6	110	42.6	111	42.6	110	42.6	110	42.6	110	42.6	109	42.6	110	42.6	110	42.6
				62	9.2	66	10.2	74	12.3	62	8.1	64	8.8	69	10	62	7.4	64	7.8	66	8.5	62	7.1	63	7.4	65	7.9
			5 ACH	121	49	122	49	125	49	121	49	121	49	123	49	121	49	121	49	121	49	121	49	121	49	121	49
				68	9.3	72	10.3	80	12.4	68	8.2	71	8.9	76	10.1	68	7.5	70	7.9	72	8.6	68	7.2	69	7.5	71	8
		80% shading	3 ACH	96	36.2	99	36.2	101	36.2	96	36.2	97	36.2	99	36.2	96	36.2	96	36.2	97	36.2	95	36.2	96	36.2	96	36.2
				52	8.1	55	9.1	63	11.2	51	7	54	7.7	58	8.9	51	6.3	53	6.7	55	7.4	51	6	52	6.3	54	6.8
			4 ACH	107	42.6	110	42.6	112	42.6	107	42.6	107	42.6	110	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	107	42.6
				58	8.2	61	9.2	69	11.3	58	7.1	60	7.8	64	9	58	6.4	59	6.8	61	7.5	56	6.1	58	6.4	60	6.9
			5 ACH	119	49	121	49	123	49	117	49	118	49	121	49	118	49	117	49	119	49	118	49	118	49	117	49
				64	8.3	68	9.3	75	11.4	64	7.2	66	7.9	71	9.1	64	6.5	65	6.9	68	7.6	64	6.2	65	6.5	66	7
	Double low-e + solar protection glazing	40% shading	3 ACH	98	36.2	98	36.2	101	36.2	96	36.2	98	36.2	99	36.2	96	36.2	97	36.2	98	36.2	96	36.2	97	36.2	97	36.2
				51	8.3	55	9.3	63	11.4	51	7.2	54	7.8	59	9.1	51	6.5	53	6.8	56	7.5	51	6.2	53	6.5	54	7
			4 ACH	109	42.6	109	42.6	112	42.6	107	42.6	109	42.6	110	42.6	107	42.6	108	42.6	109	42.6	107	42.6	107	42.6	108	42.6
				58	8.4	61	9.4	70	11.5	57	7.3	60	7.9	65	9.2	57	6.6	59	6.9	62	7.6	57	6.3	59	6.6	61	7.1
			5 ACH	120	49	121	49	123	49	118	49	120	49	121	49	118	49	118	49	121	49	118	49	118	49	118	49
				64	8.5	68	9.5	76	11.6	63	7.4	66	8	71	9.3	64	6.7	65	7	68	7.7	64	6.4	65	6.7	67	7.2
		60% shading	3 ACH	97	36.2	98	36.2	100	36.2	96	36.2	97	36.2	99	36.2	97	36.2	97	36.2	97	36.2	96	36.2	97	36.2	97	36.2
				50	7.7	53	8.7	61	10.8	49	6.6	52	7.3	57	8.5	49	5.9	51	6.3	54	7	49	5.6	51	5.9	52	6.4
			4 ACH	107	42.6	109	42.6	111	42.6	107	42.6	108	42.6	110	42.6	107	42.6	107	42.6	107	42.6	108	42.6	108	42.6	107	42.6
				56	7.8	60	8.8	67	10.9	56	6.7	58	7.4	63	8.6	56	6	57	6.4	60	7.1	56	5.7	57	6	59	6.5
			5 ACH	118	49	120	49	122	49	118	49	118	49	121	49	118	49	118	49	118	49	118	49	118	49	118	49
				62	7.9	66	8.9	74	11	62	6.8	64	7.5	69	8.7	62	6.1	63	6.5	66	7.2	62	5.8	63	6.1	65	6.6
		80% shading	3 ACH	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2
				48	7.3	51	8.3	59	10.4	48	6.2	50	6.9	54	8.1	48	5.5	49	5.9	51	6.6	48	5.3	48	5.5	50	6
			4 ACH	107	42.6	96	42.6	96	42.6	96	42.6	96	42.6	96	42.6	96	42.6	96	42.6	96	42.6	96	42.6	96	42.6	96	42.6
				55	7.4	58	8.4	65	10.5	54	6.3	56	7	61	8.2	54	5.6	55	6	58	6.7	54	5.4	55	5.6	56	6.1
			5 ACH	118	49	96	49	96	49	96	49	96	49	96	49	96	49	96	49	96	49	96	49	96	49	96	49
				61	7.5	64	8.5	71	10.6	60	6.4	62	7.1	67	8.3	60	5.7	61	6.1	64	6.8	60	5.5	61	5.7	63	6.2

Table B7: Terraced house: South orientation and high glazing area (WWR 45%)

Orientation				South											
Wall, roof insulation				25 mm			50 mm			100 mm			150 mm		
Exterior absorptivity				0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9
High glazing area (WWR 45%)	Single glazing	40% shading	3 ACH	116 36.2	119 36.2	124 36.2	116 36.2	118 36.2	121 36.2	116 36.2	117 36.2	119 36.2	116 36.2	117 36.2	118 36.2
				91 19.3	96 20.2	105 22.2	92 18.3	94 18.8	101 20	92 17.6	94 17.9	98 18.6	93 17.3	94 17.6	96 18
			4 ACH	127 42.6	129 42.6	135 42.6	127 42.6	128 42.6	132 42.6	127 42.6	128 42.6	130 42.6	127 42.6	128 42.6	129 42.6
				97 19.4	102 20.2	111 22.3	98 18.4	100 18.9	106 20.1	98 17.7	100 18	103 18.7	98 17.4	100 17.7	102 18.1
			5 ACH	138 49	140 49	146 49	138 49	139 49	143 49	138 49	139 49	141 49	138 49	138 49	140 49
				103 19.5	107 20.3	117 22.4	104 18.5	106 19	112 20.2	104 17.8	106 18.1	109 18.8	104 17.5	105 17.8	108 18.2
		60% shading	3 ACH	108 36.2	110 36.2	114 36.2	107 36.2	108 36.2	111 36.2	107 36.2	108 36.2	109 36.2	107 36.2	107 36.2	108 36.2
				74 15.4	78 16.3	86 18.3	74 14.4	77 14.9	82 16.1	75 13.7	75 14	79 14.7	74 13.4	75 13.7	77 14.1
			4 ACH	119 42.6	120 42.6	125 42.6	118 42.6	120 42.6	122 42.6	118 42.6	119 42.6	120 42.6	118 42.6	119 42.6	119 42.6
				80 15.5	84 16.4	93 18.4	80 14.5	83 15	88 16.2	80 13.8	82 14.1	84 14.8	80 13.5	81 13.8	83 14.2
			5 ACH	130 49	132 49	136 49	129 49	131 49	133 49	129 49	130 49	131 49	129 49	130 49	130 49
				86 15.6	90 16.5	99 18.5	86 14.6	89 15.1	94 16.3	86 13.9	88 14.2	91 14.9	86 13.6	87 13.9	89 14.3
		80% shading	3 ACH	101 36.2	103 36.2	106 36.2	101 36.2	102 36.2	104 36.2	100 36.2	101 36.2	102 36.2	100 36.2	101 36.2	102 36.2
				60 11.5	64 12.5	71 14.5	60 10.5	62 11.1	66 12.3	60 9.9	61 10.2	63 10.9	60 9.6	60 9.8	62 10.3
			4 ACH	112 42.6	114 42.6	117 42.6	112 42.6	113 42.6	115 42.6	111 42.6	112 42.6	113 42.6	111 42.6	112 42.6	113 42.6
				67 11.6	70 12.6	77 14.6	66 10.6	68 11.2	73 12.4	66 10	67 10.3	70 11	66 9.7	67 9.9	68 10.4
			5 ACH	123 49	125 49	128 49	123 49	124 49	126 49	122 49	123 49	124 49	122 49	123 49	124 49
				73 11.7	76 12.7	84 14.7	73 10.7	75 11.3	79 12.5	72 10.1	73 10.4	76 11.1	72 9.8	73 10	75 10.5
	Ordinary double glazing	40% shading	3 ACH	113 36.2	116 36.2	122 36.2	114 36.2	115 36.2	118 36.2	114 36.2	115 36.2	117 36.2	114 36.2	115 36.2	116 36.2
				89 17.2	94 18.1	104 20.1	90 16.2	93 16.8	100 17.9	92 15.5	94 15.8	98 16.5	93 15.2	94 15.5	97 15.9
			4 ACH	124 42.6	127 42.6	132 42.6	125 42.6	126 42.6	129 42.6	125 42.6	126 42.6	127 42.6	125 42.6	126 42.6	127 42.6
				95 17.3	100 18.2	109 20.2	96 16.3	99 16.9	105 18	97 15.6	99 15.9	103 16.6	98 15.3	99 15.6	102 16
			5 ACH	135 49	138 49	144 49	136 49	137 49	140 49	136 49	137 49	138 49	136 49	136 49	138 49
				101 17.4	105 18.3	115 20.3	102 16.4	105 17	111 18.1	103 15.7	105 16	108 16.7	103 15.4	105 15.7	107 16.1
		60% shading	3 ACH	106 36.2	108 36.2	112 36.2	106 36.2	107 36.2	109 36.2	106 36.2	106 36.2	107 36.2	105 36.2	106 36.2	106 36.2
				72 13.7	77 14.6	86 16.6	73 12.7	76 13.3	81 14.4	73 12	75 12.3	78 13	74 11.7	75 11.9	76 12.3
			4 ACH	117 42.6	119 42.6	123 42.6	117 42.6	118 42.6	120 42.6	117 42.6	117 42.6	118 42.6	117 42.6	117 42.6	117 42.6
				79 13.8	83 14.7	92 16.7	79 12.8	82 13.4	87 14.5	79 12.1	87 12.4	84 13.1	79 11.8	80 12	82 12.4
			5 ACH	128 49	130 49	134 49	128 49	129 49	131 49	128 49	128 49	129 49	128 49	128 49	129 49
				85 139	89 14.8	98 16.8	85 12.9	88 13.5	93 14.6	85 12.2	87 12.5	90 13.2	85 11.9	86 12.1	88 12.5
		80% shading	3 ACH	100 36.2	102 36.2	105 36.2	100 36.2	101 36.2	102 36.2	100 36.2	100 36.2	101 36.2	100 36.2	100 36.2	100 36.2
				59 10.3	63 11.2	71 13.2	59 9.3	61 9.8	66 11	59 8.6	60 8.9	63 9.6	59 8.3	60 8.6	62 9
			4 ACH	111 42.6	113 42.6	116 42.6	111 42.6	112 42.6	114 42.6	111 42.6	111 42.6	112 42.6	111 42.6	111 42.6	111 42.6
				66 10.4	69 11.3	77 13.3	65 9.4	68 9.9	72 11.1	65 8.7	67 9	69 9.7	65 8.4	66 8.7	68 9.1
			5 ACH	122 49	124 49	127 49	122 49	123 49	125 49	122 49	122 49	123 49	122 49	122 49	123 49
				72 10.5	75 11.4	83 13.4	72 9.5	74 10	78 11.2	71 8.8	73 9.1	75 9.8	71 8.5	72 8.8	74 9.2
	Double low-e glazing	40% shading	3 ACH	105 36.2	107 36.2	112 36.2	105 36.2	106 36.2	109 36.2	105 36.2	105 36.2	107 36.2	105 36.2	105 36.2	106 36.2
				73 13.1	77 14.1	87 16.1	74 12.1	76 12.7	83 13.9	75 11.5	77 11.8	80 12.5	75 11.2	77 11.4	79 11.9
			4 ACH	116 42.6	118 42.6	123 42.6	116 42.6	117 42.6	120 42.6	116 42.6	117 42.6	118 42.6	116 42.6	116 42.6	117 42.6
				78 13.2	83 14.2	92 16.2	79 12.2	82 12.8	88 14	80 11.6	82 11.9	86 12.6	81 11.3	82 11.5	85 12
			5 ACH	127 49	129 49	133 49	127 49	128 49	130 49	127 49	128 49	129 49	127 49	128 49	128 49
				84 13.3	89 14.3	98 16.3	85 12.3	88 12.9	94 14.1	86 11.7	88 12	91 12.7	86 11.4	88 11.6	90 12.1
		60% shading	3 ACH	101 36.2	102 36.2	105 36.2	100 36.2	101 36.2	103 36.2	100 36.2	101 36.2	102 36.2	100 36.2	101 36.2	102 36.2
				62 10.7	65 11.5	72 13.1	63 9.8	65 10.2	69 11.2	63 9.1	65 9.4	67 9.9	64 8.9	65 9.1	66 9.5
			4 ACH	112 42.6	113 42.6	116 42.6	111 42.6	112 42.6	114 42.6	111 42.6	112 42.6	113 42.6	111 42.6	112 42.6	113 42.6
				69 10.8	72 11.6	78 13.2	69 9.9	71 10.3	75 11.3	69 9.2	71 9.5	73 10	70 9	71 9.2	72 9.6
			5 ACH	123 49	124 49	127 49	123 49	123 49	125 49	123 49	122 49	124 49	122 49	123 49	124 49
				75 10.9	78 11.7	84 13.3	75 10	77 10.4	81 11.4	76 9.3	77 9.6	79 10.1	76 9.1	77 9.3	78 9.7
		80% shading	3 ACH	98 36.2	99 36.2	102 36.2	98 36.2	99 36.2	100 36.2	98 36.2	99 36.2	99 36.2	97 36.2	98 36.2	99 36.2
				55 8.6	58 9.6	66 11.5	54 7.6	57 8.2	61 9.4	55 6.9	56 7.3	58 7.9	55 6.7	55 6.9	57 7.4
			4 ACH	109 42.6	110 42.6	113 42.6	109 42.6	110 42.6	111 42.6	109 42.6	110 42.6	110 42.6	108 42.6	109 42.6	110 42.6
				61 8.7	64 9.7	72 11.6	61 7.7	63 8.3	67 9.5	61 7	62 7.4	64 8	61 6.8	62 7	63 7.5
			5 ACH	121 49	122 49	124 49	120 49	121 49	122 49	120 49	121 49	121 49	119 49	121 49	121 49
				67 8.8	71 9.8	78 11.7	67 7.8	69 8.4	74 9.6	67 7.1	68 7.5	71 8.1	67 6.9	68 7.1	70 7.6
	Double low-e + solar protection glazing	40% shading	3 ACH	99 36.2	100 36.2	103 36.2	99 36.2	99 36.2	100 36.2	99 36.2	99 36.2	99 36.2	99 36.2	99 36.2	99 36.2
				56 9.5	60 10.5	68 12.5	56 8.5	58 9.1	63 10.3	56 7.9	58 8.2	60 8.9	56 7.6	57 7.8	59 8.3
			4 ACH	110 42.6	111 42.6	114 42.6	110 42.6	110 42.6	112 42.6	110 42.6	110 42.6	110 42.6	110 42.6	110 42.6	110 42.6
				63 9.6	66 10.6	74 12.6	62 8.6	65 9.2	69 10.4	62 8	64 8.3	66 9	62 7.7	63 7.9	65 8.4
			5 ACH	121 49	122 49	125 49	121 49	121 49	123 49	121 49	121 49	122 49	121 49	121 49	121 49
				68 9.7	72 10.7	80 12.7	69 8.7	71 9.3	75 10.5	69 8.1	70 8.4	72 9.1	69 7.8	70 8	71 8.5
		60% shading	3 ACH	98 36.2	99 36.2	100 36.2	97 36.2	98 36.2	99 36.2	97 36.2	97 36.2	98 36.2	96 36.2	97 36.2	97 36.2
				52 8.4	55 9.1	61 10.7	52 7.4	54 7.9	58 8.9	52 6.8	53 7.1	55 7.6	52 6.6	53 6.7	55 7.1
			4 ACH	109 42.6	109 42.6	111 42.6	107 42.6	109 42.6	110 42.6	108 42.6	107 42.6	110 42.6	107 42.6	107 42.6	108 42.6
				59 8.5	61 9.2	67 10.8	59 7.5	60 8	64 9	59 6.9	60 7.2	62 7.7	59 6.7	59 6.8	61 7.2
			5 ACH	120 49	120 49	122 49	119 49	120 49	121 49	118 49	118 49	121 49	118 49	118 49	118 49
				65 8.6	67 9.3	73 10.9	65 7.6	67 8.1	70 9.1	65 7	66 7.3	68 7.8	65 6.8	66 6.9	67 7.3
		80% shading	3 ACH	97 36.2	98 36.2	100 36.2	96 36.2	96 36.2	99 36.2	97 36.2	97 36.2	96 36.2	96 36.2	97 36.2	97 36.2
				49 7.5	53 8.5	60 10.4	49 6.5	51 7.1	55 8.3	49 5.8	50 6.2	53 6.8	49 5.6	50 5.8	51 6.3
			4 ACH	107 42.6	109 42.6	111 42.6	107 42.6	107 42.6	110 42.6	107 42.6	107 42.6	107 42.6	106 42.6	107 42.6	107 42.6
				56 7.6	59 8.6	66 10.5	55 6.6	57 7.2	62 8.4	55 5.9	56 6.3	59 6.9	55 5.7	56 5.9	58 6.4
			5 ACH	118 49	120 49	122 49	118 49	118 49	121 49	118 49	118 49	118 49	118 49	118 49	118 49
				62 7.7	65 8.7	72 10.6	62 6.7	64 7.3	68 8.5	61 6	63 6.4	65 7	61 5.8	62 6	64 6.5

Table B8: Terraced house: West orientation and low glazing area (WWR 15%)

Orientation				West																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Low glazing area (WWR 15%)	Single glazing	40% shading	3 ACH	103	36.2	105	36.2	112	36.2	103	36.2	104	36.2	108	36.2	102	36.2	103	36.2	105	36.2	102	36.2	103	36.2	104	36.2
				67	12.7	72	13.9	83	16.4	67	11.5	71	12.3	77	13.8	68	10.7	69	11.1	73	12	68	10.4	69	10.7	72	11.3
			4 ACH	114	42.6	116	42.6	123	42.6	114	42.6	115	42.6	119	42.6	114	42.6	114	42.6	116	42.6	113	42.6	114	42.6	115	42.6
				74	12.8	79	14	89	16.5	73	11.6	77	12.4	83	13.9	74	10.8	75	11.2	79	12.1	74	10.5	75	10.8	78	11.4
			5 ACH	125	49	125	49	134	49	125	49	126	49	130	49	124	49	125	49	127	49	124	49	125	49	126	49
				80	12.9	85	14.1	96	16.6	80	11.7	83	12.5	89	14	79	10.9	82	11.3	85	12.2	80	10.6	81	10.9	84	11.5
		60% shading	3 ACH	101	36.2	102	36.2	108	36.2	100	36.2	101	36.2	104	36.2	99	36.2	100	36.2	102	36.2	99	36.2	100	36.2	101	36.2
				61	10.9	66	12.1	76	14.6	61	9.7	64	10.4	70	12	61	8.9	62	9.3	66	10.2	61	8.6	62	8.9	65	9.5
			4 ACH	112	42.6	113	42.6	119	42.6	111	42.6	112	42.6	115	42.6	111	42.6	111	42.6	113	42.6	110	42.6	111	42.6	112	42.6
				68	11	72	12.2	83	14.7	67	9.8	70	10.5	76	12.1	67	9	69	9.4	72	10.3	67	8.7	68	9	71	9.6
			5 ACH	123	49	125	49	130	49	122	49	123	49	126	49	122	49	122	49	124	49	122	49	122	49	123	49
				74	11.1	79	12.3	89	14.8	73	9.9	76	10.6	83	12.2	73	9.1	75	9.5	78	10.4	73	8.8	74	9.1	77	9.7
		80% shading	3 ACH	99	36.2	100	36.2	104	36.2	97	36.2	99	36.2	101	36.2	95	36.2	97	36.2	98	36.2	96	36.2	96	36.2	98	36.2
				55	9.1	60	10.4	70	12.9	55	7.9	58	8.7	63	10.2	54	7.1	56	7.6	59	8.4	54	6.8	56	7.1	58	7.7
			4 ACH	110	42.6	111	42.6	115	42.6	108	42.6	110	42.6	112	42.6	108	42.6	108	42.6	110	42.6	107	42.6	108	42.6	108	42.6
				61	9.2	66	10.5	76	13	61	8	64	8.8	70	10.3	61	7.2	62	7.7	66	8.5	61	6.9	62	7.2	64	7.8
			5 ACH	121	49	122	49	126	49	119	49	121	49	123	49	118	49	119	49	121	49	118	49	119	49	119	49
				68	9.3	72	10.6	82	13.1	67	8.1	70	8.9	76	10.4	67	7.3	69	7.8	72	8.6	67	7	68	7.3	70	7.8
	Ordinary double glazing	40% shading	3 ACH	102	36.2	104	36.2	110	36.2	101	36.2	103	36.2	107	36.2	101	36.2	102	36.2	104	36.2	101	36.2	102	36.2	103	36.2
				66	11.8	71	13.1	82	15.6	65	10.6	69	11.4	76	12.9	66	9.8	68	10.3	72	11.1	66	9.5	68	9.8	70	10.4
			4 ACH	113	42.6	115	42.6	121	42.6	112	42.6	114	42.6	117	42.6	112	42.6	113	42.6	115	42.6	112	42.6	113	42.6	114	42.6
				72	11.9	77	13.2	88	15.7	72	10.7	75	11.5	82	13	72	9.9	74	10.4	78	11.2	72	9.6	73	9.9	76	10.5
			5 ACH	124	49	126	49	132	49	123	49	125	49	128	49	123	49	124	49	126	49	123	49	124	49	125	49
				78	12	83	13.3	94	15.8	78	10.8	81	11.6	88	13.1	78	10	80	10.5	83	11.3	78	9.7	79	10	82	10.6
		60% shading	3 ACH	100	36.2	101	36.2	107	36.2	99	36.2	100	36.2	103	36.2	98	36.2	99	36.2	101	36.2	98	36.2	98	36.2	100	36.2
				60	10.2	65	11.5	75	14	60	9	63	9.8	69	11.3	60	8.2	61	8.5	64	9.3	60	7.9	61	8.1	63	8.6
			4 ACH	111	42.6	113	42.6	118	42.6	110	42.6	111	42.6	114	42.6	109	42.6	110	42.6	112	42.6	108	42.6	109	42.6	111	42.6
				66	10.3	71	11.6	81	14.1	66	9.1	69	9.9	75	11.4	66	8.3	67	8.6	70	9.4	66	8	67	8.2	69	8.7
			5 ACH	122	49	124	49	129	49	121	49	122	49	125	49	119	49	121	49	123	49	119	49	119	49	122	49
				72	10.4	77	11.7	87	14.2	72	9.2	75	10	81	11.5	72	8.4	76	8.7	76	9.5	72	8.1	73	8.3	75	8.8
		80% shading	3 ACH	97	36.2	99	36.2	104	36.2	97	36.2	97	36.2	100	36.2	96	36.2	96	36.2	98	36.2	96	36.2	96	36.2	97	36.2
				55	8.7	59	9.9	69	12.4	54	7.5	57	8.2	63	9.8	54	6.7	56	7.1	59	8	54	6.3	55	6.6	57	7.2
			4 ACH	109	42.6	110	42.6	115	42.6	107	42.6	108	42.6	111	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	108	42.6
				61	8.8	65	10	75	12.5	60	7.6	63	8.3	69	9.9	60	6.8	62	7.2	65	8.1	60	6.4	61	6.7	64	7.3
			5 ACH	120	49	122	49	126	49	118	49	119	49	122	49	117	49	119	49	119	49	117	49	118	49	119	49
				67	8.9	72	10.1	81	12.6	67	7.7	69	8.4	75	10	66	6.9	68	7.3	71	8.2	66	6.5	67	6.8	70	7.4
	Double low-e glazing	40% shading	3 ACH	99	36.2	101	36.2	106	36.2	98	36.2	100	36.2	103	36.2	97	36.2	97	36.2	100	36.2	97	36.2	97	36.2	98	36.2
				59	10	64	11.2	74	13.7	59	8.8	61	9.5	68	11.1	58	8	60	8.4	64	9.3	58	7.6	60	7.9	63	8.5
			4 ACH	110	42.6	112	42.6	117	42.6	109	42.6	11	42.6	114	42.6	108	42.6	108	42.6	111	42.6	108	42.6	108	42.6	109	42.6
				65	10.1	70	11.3	80	13.8	65	8.9	68	9.6	74	11.2	65	8.1	66	8.5	70	9.4	65	7.7	66	8	68	8.6
			5 ACH	121	49	123	49	128	49	120	49	122	49	124	49	119	49	119	49	122	49	119	49	119	49	121	49
				71	10.2	76	11.4	86	13.9	71	9	74	9.7	80	11.3	71	8.2	72	8.6	76	9.5	71	7.8	72	8.1	74	8.7
		60% shading	3 ACH	97	36.2	99	36.2	102	36.2	96	36.2	97	36.2	100	36.2	96	36.2	96	36.2	97	36.2	96	36.2	96	36.2	96	36.2
				55	8.8	59	9.8	67	11.9	55	7.6	57	8.3	62	9.6	54	6.8	56	7.1	58	7.7	55	6.5	55	6.7	57	7.1
			4 ACH	108	42.6	110	42.6	114	42.6	108	42.6	108	42.6	111	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	107	42.6
				61	8.9	65	9.9	73	12	61	7.7	63	8.4	68	9.7	61	6.9	62	7.2	64	7.8	61	6.6	62	6.8	63	7.2
			5 ACH	119	49	121	49	125	49	118	49	119	49	122	49	118	49	118	49	119	49	118	49	118	49	118	49
				67	9	71	10	79	12.1	67	7.8	70	8.5	75	9.8	67	7	68	7.3	70	7.9	67	6.7	68	6.9	69	7.3
		80% shading	3 ACH	96	36.2	99	36.2	102	36.2	96	36.2	96	36.2	99	36.2	97	36.2	96	36.2	96	36.2	96	36.2	97	36.2	96	36.2
				52	7.9	56	9.1	66	11.6	51	6.7	54	7.5	60	9	51	5.9	53	6.3	56	7.2	51	5.6	52	5.9	55	6.5
			4 ACH	107	42.6	110	42.6	113	42.6	107	42.6	107	42.6	110	42.6	107	42.6	107	42.6	107	42.6	106	42.6	107	42.6	107	42.6
				58	8	63	9.2	72	11.7	57	6.8	60	7.6	66	9.1	57	6	59	6.4	62	7.3	57	5.7	58	6	61	6.6
			5 ACH	118	49	121	49	124	49	118	49	118	49	121	49	118	49	118	49	118	49	118	49	118	49	118	49
				64	8.1	69	9.3	78	11.8	64	6.9	67	7.7	72	9.2	63	6.1	65	6.5	68	7.4	63	5.8	65	6.1	67	6.7
	Double low-e + solar protection glazing	40% shading	3 ACH	96	36.2	99	36.2	102	36.2	96	36.2	96	36.2	99	36.2	97	36.2	96	36.2	96	36.2	96	36.2	97	36.2	96	36.2
				52	8.2	56	9.4	66	11.9	51	7	54	7.8	60	9.3	51	6.2	53	6.6	56	7.5	51	5.9	52	6.2	55	6.8
			4 ACH	107	42.6	110	42.6	113	42.6	107	42.6	107	42.6	110	42.6	107	42.6	107	42.6	107	42.6	106	42.6	107	42.6	107	42.6
				58	8.3	62	9.5	72	12	57	7.1	60	7.9	66	9.4	57	6.3	59	6.7	62	7.6	57	6	58	6.3	61	6.9
			5 ACH	118	49	121	49	124	49	117	49	118	49	121	49	118	49	118	49	118	49	118	49	118	49	118	49
				64	8.4	69	9.6	78	12.1	64	7.2	66	8	72	9.5	63	6.4	65	6.8	68	7.7	63	6.1	65	6.4	67	7
		60% shading	3 ACH	96	36.2	96	36.2	97	36.2	94	36.2	96	36.2	96	36.2	95	36.2	95	36.2	96	36.2	95	36.2	95	36.2	95	36.2
				49	7.1	50	7.6	54	8.5	48	6.1	50	6.5	52	7.1	49	5.5	50	5.7	51	6	49	5.2	50	5.4	51	5.6
			4 ACH	107	42.6	106	42.6	107	42.6	105	42.6	107	42.6	106	42.6	105	42.6	105	42.6	107	42.6	105	42.6	106	42.6	105	42.6
				55	7.2	57	7.7	60	8.6	55	6.2	56	6.6	58	7.2	55	5.5	56	5.8	57	6.1	55	5.3	56	5.5	57	5.7
			5 ACH	117	49	117	49	118	49	116	49	117	49	117	49	115	49	115	49	118	49	116	49	116	49	116	49
				61	7.3	63	7.8	66	8.7	61	6.3	62	6.7	64	7.3	61	5.6	61	5.9	63	6.2	61	5.4	62	5.6	63	5.8
		80% shading	3 ACH	96	36.2	96	36.2	101	36.2	95	36.2	96	36.2	97	36.2	95	36.2	95	36.2	96	36.2	95	36.2	95	36.2	96	36.2
				49	7.2	53	8.5	63	11	48	6.1	51	6.8	57	8.3	48	5.2	49	5.7	53	6.5	48	4.9	49	5.2	51	5.8
			4 ACH	107	42.6	107	42.6	112	42.6	106	42.6	107	42.6	108	42.6	105	42.6	105	42.6	107	42.6	106	42.6	106	42.6	106	42.6
				55	7.3	59	8.6	69	11.1	54	6.2	57	6.9	63	8.4	54	5.3	56	5.8	59	6.6	54	5	55	5.3	57	5.9
			5 ACH	118	49	118	49	123	49	117	49	118	49	119	49	116	49	115	49	118	49	116	49	116	49	118	49
				61	7.4	66	8.7	75	11.2	61	6.3	63	7	69	8.5	60	5.4	62	5.9	65	6.7	60	5.1	61	5.4	64	6

Table B9: Terraced house: West orientation and medium glazing area (WWR 30%)

Orientation				West																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Medium glazing area (WWR 30%)	Single glazing	40% shading	3 ACH	116	36.2	119	36.2	124	36.2	115	36.2	117	36.2	121	36.2	115	36.2	116	36.2	118	36.2	115	36.2	115	36.2	117	36.2
				89	18.3	94	19.5	105	21.8	89	17.2	92	17.9	99	19.3	90	16.4	92	16.8	95	17.6	90	16.1	91	16.4	94	17
			4 ACH	127	42.6	130	42.6	135	42.6	126	42.6	128	42.6	131	42.6	126	42.6	127	42.6	129	42.6	126	42.6	126	42.6	128	42.6
				95	18.4	100	19.6	111	21.9	95	17.3	98	18	105	19.4	96	16.5	98	16.9	101	17.7	96	16.2	97	16.5	100	17.1
			5 ACH	138	49	141	49	146	49	137	49	139	49	142	49	137	49	138	49	140	49	137	49	138	49	139	49
				101	18.5	106	19.7	117	22	101	17.4	104	18.1	111	19.5	101	16.6	103	17	107	17.8	102	16.3	103	16.6	106	17.2
		60% shading	3 ACH	107	36.2	110	36.2	116	36.2	106	36.2	108	36.2	112	36.2	106	36.2	107	36.2	110	36.2	106	36.2	107	36.2	109	36.2
				75	14.5	79	15.7	89	18	74	13.4	77	14.1	83	15.5	74	12.6	76	13	80	13.8	74	12.3	76	12.6	78	13.2
			4 ACH	118	42.6	121	42.6	127	42.6	117	42.6	119	42.6	123	42.6	117	42.6	118	42.6	120	42.6	117	42.6	118	42.6	119	42.6
				81	14.6	86	15.8	95	18.1	80	13.5	83	14.2	89	15.6	80	12.7	82	13.1	86	13.9	80	12.4	82	12.7	84	13.3
			5 ACH	129	49	132	49	138	49	128	49	130	49	134	49	128	49	129	49	131	49	128	49	129	49	130	49
				87	14.7	92	15.9	102	18.2	87	13.6	90	14.3	96	15.7	87	12.8	88	13.2	92	14	87	12.5	88	12.8	90	13.4
		80% shading	3 ACH	101	36.2	103	36.2	107	36.2	101	36.2	102	36.2	104	36.2	100	36.2	101	36.2	102	36.2	100	36.2	100	36.2	101	36.2
				61	11.1	66	12.3	75	14.6	61	10	64	10.7	69	12.1	61	9.2	62	9.6	65	10.4	60	8.9	62	9.2	64	9.8
			4 ACH	112	42.6	114	42.6	118	42.6	112	42.6	113	42.6	115	42.6	111	42.6	112	42.6	113	42.6	111	42.6	111	42.6	112	42.6
				68	11.2	72	12.4	81	14.7	67	10.1	70	10.8	75	12.2	67	9.3	68	9.7	71	10.5	67	9	68	9.3	70	9.9
			5 ACH	123	49	125	49	129	49	123	49	124	49	126	49	122	49	123	49	124	49	122	49	123	49	123	49
				74	11.3	78	12.5	87	14.8	73	10.2	76	10.9	81	12.3	73	9.4	75	9.8	78	10.6	73	9.1	74	9.4	76	10
	Ordinary double glazing	40% shading	3 ACH	113	36.2	116	36.2	120	36.2	113	36.2	114	36.2	118	36.2	112	36.2	113	36.2	116	36.2	112	36.2	113	36.2	115	36.2
				85	16.6	91	17.8	102	20.1	86	15.5	90	16.2	97	17.6	87	14.8	89	15.2	93	16	88	14.5	89	14.7	92	15.3
			4 ACH	124	42.6	127	42.6	131	42.6	124	42.6	125	42.6	129	42.6	123	42.6	124	42.6	126	42.6	123	42.6	124	42.6	125	42.6
				91	16.7	97	17.9	108	20.2	92	15.6	96	16.3	103	17.7	93	14.9	95	15.3	99	16.1	93	14.6	95	14.8	98	15.4
			5 ACH	135	49	138	49	142	49	135	49	136	49	139	49	134	49	135	49	137	49	134	49	135	49	136	49
				98	16.8	103	18	114	20.3	98	15.7	101	16.4	108	17.8	99	15	101	15.4	105	16.2	99	14.7	100	14.9	103	15.5
		60% shading	3 ACH	105	36.2	108	36.2	113	36.2	105	36.2	107	36.2	110	36.2	105	36.2	106	36.2	108	36.2	105	36.2	105	36.2	106	36.2
				72	13.2	77	14.4	88	16.7	72	12.1	76	12.8	82	14.2	73	11.3	74	11.7	78	12.5	73	11	74	11.2	77	11.7
			4 ACH	116	42.6	119	42.6	124	42.6	116	42.6	118	42.6	121	42.6	116	42.6	117	42.6	119	42.6	116	42.6	116	42.6	117	42.6
				78	13.3	83	14.5	94	16.8	78	12.2	81	12.9	88	14.3	79	11.4	80	11.8	84	12.6	79	11.1	80	11.3	82	11.8
			5 ACH	127	49	130	49	135	49	127	49	129	49	132	49	127	49	128	49	130	49	127	49	127	49	128	49
				85	13.4	89	14.6	100	16.9	85	12.3	88	13	94	14.4	85	11.5	86	11.9	90	12.7	85	11.2	86	11.4	88	11.9
		80% shading	3 ACH	100	36.2	102	36.2	106	36.2	100	36.2	100	36.2	103	36.2	98	36.2	100	36.2	101	36.2	98	36.2	98	36.2	100	36.2
				60	10.3	64	11.4	74	13.7	60	9.1	62	9.8	68	11.3	59	8.4	61	8.8	64	9.6	59	8.1	61	8.3	63	8.9
			4 ACH	111	42.6	113	42.6	117	42.6	111	42.6	112	42.6	114	42.6	109	42.6	111	42.6	112	42.6	109	42.6	109	42.6	111	42.6
				66	10.4	71	11.5	80	13.8	66	9.2	69	9.8	74	11.4	66	8.5	67	8.9	70	9.7	66	8.2	67	8.4	69	9
			5 ACH	122	49	124	49	128	49	122	49	123	49	125	49	121	49	122	49	123	49	120	49	121	49	122	49
				73	10.5	77	11.6	86	13.9	72	9.3	75	9.9	80	11.5	72	8.6	73	9	77	9.8	72	8.3	73	8.5	75	9.1
	Double low-e glazing	40% shading	3 ACH	104	36.2	107	36.2	113	36.2	104	36.2	106	36.2	109	36.2	104	36.2	105	36.2	107	36.2	104	36.2	104	36.2	106	36.2
				71	13	76	14.2	87	16.5	71	11.9	74	12.6	81	14	72	11.1	74	11.5	78	12.3	72	10.8	74	11.1	76	11.6
			4 ACH	115	42.6	118	42.6	123	42.6	115	42.6	117	42.6	120	42.6	115	42.6	116	42.6	118	42.6	115	42.6	115	42.6	117	42.6
				77	13.1	82	14.3	93	16.6	77	12	80	12.7	87	14.1	78	11.2	80	11.6	84	12.4	78	10.9	80	11.2	82	11.7
			5 ACH	126	49	129	49	134	49	126	49	128	49	131	49	126	49	127	49	129	49	126	49	126	49	128	49
				83	13.2	88	14.4	99	16.7	83	12.1	87	12.8	93	14.2	84	11.3	86	11.7	89	12.5	84	11	85	11.3	88	11.8
		60% shading	3 ACH	101	36.2	102	36.2	106	36.2	100	36.2	101	36.2	103	36.2	100	36.2	101	36.2	102	36.2	100	36.2	100	36.2	101	36.2
				63	10.6	66	11.6	75	13.5	62	9.5	65	10.1	70	11.3	63	8.8	64	9.1	67	9.8	63	8.5	64	8.7	65	9.1
			4 ACH	112	42.6	113	42.6	117	42.6	111	42.6	112	42.6	115	42.6	111	42.6	112	42.6	113	42.6	111	42.6	111	42.6	112	42.6
				69	10.7	73	11.7	81	13.6	69	9.6	71	10.2	76	11.4	69	8.9	70	9.2	73	9.9	69	8.6	70	8.8	71	9.2
			5 ACH	123	49	124	49	128	49	122	49	123	49	126	49	122	49	123	49	124	49	122	49	122	49	123	49
				75	10.8	79	11.8	87	13.7	75	9.7	77	10.3	82	11.5	75	9	76	9.3	79	10	75	8.7	76	8.9	77	9.3
		80% shading	3 ACH	97	36.2	100	36.2	104	36.2	96	36.2	98	36.2	100	36.2	96	36.2	97	36.2	98	36.2	96	36.2	96	36.2	97	36.2
				55	8.8	60	10	69	12.3	55	7.7	58	8.4	63	9.8	55	6.9	56	7.3	59	8.2	55	6.6	56	6.9	58	7.5
			4 ACH	108	42.6	111	42.6	114	42.6	108	42.6	108	42.6	111	42.6	107	42.6	107	42.6	109	42.6	107	42.6	107	42.6	108	42.6
				62	8.9	66	10.1	75	12.4	61	7.8	64	8.5	69	9.9	61	7	62	7.4	66	8.3	61	6.7	62	7	64	7.6
			5 ACH	121	49	122	49	125	49	119	49	119	49	122	49	118	49	118	49	120	49	118	49	118	49	119	49
				68	9	72	10.2	81	12.5	67	7.9	70	8.6	75	10	67	7.1	69	7.5	72	8.4	67	6.8	68	7.1	70	7.7
	Double low-e + solar protection glazing	40% shading	3 ACH	104	36.2	100	36.2	104	36.2	97	36.2	99	36.2	101	36.2	96	36.2	97	36.2	98	36.2	96	36.2	97	36.2	97	36.2
				70	13.1	61	10.7	70	13.1	56	8.4	59	9.1	65	10.6	56	7.7	58	8.1	61	8.9	56	7.4	57	7.7	59	8.2
			4 ACH	115	42.6	111	42.6	115	42.6	108	42.6	110	42.6	112	42.6	108	42.6	108	42.6	110	42.6	107	42.6	108	42.6	108	42.6
				76	13.2	67	10.8	76	13.2	63	8.5	65	9.2	71	10.7	62	7.8	64	8.2	67	9	62	7.5	63	7.8	66	8.3
			5 ACH	126	49	122	49	126	49	119	49	121	49	123	49	119	49	119	49	121	49	118	49	119	49	119	49
				83	13.3	74	10.9	83	13.3	69	8.6	71	9.3	77	10.8	69	7.9	70	8.3	73	9.1	69	7.6	70	7.9	72	8.4
		60% shading	3 ACH	96	36.2	97	36.2	100	36.2	96	36.2	96	36.2	98	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2	96	36.2
				52	8.2	55	9	61	10.5	52	7.2	54	7.7	58	8.6	52	6.5	53	6.8	56	7.4	52	6.3	53	6.5	55	6.9
			4 ACH	107	42.6	108	42.6	111	42.6	106	42.6	107	42.6	108	42.6	107	42.6	107	42.6	107	42.6	107	42.6	107	42.6	107	42.6
				59	8.3	61	9.1	67	10.6	58	7.3	60	7.8	64	8.7	59	6.6	60	6.9	62	7.5	59	6.4	59	6.6	61	7
			5 ACH	118	49	120	49	122	49	117	49	118	49	119	49	118	49	117	49	118	49	118	49	118	49	118	49
				65	8.4	68	9.2	73	10.7	65	7.4	67	7.9	70	8.8	65	6.7	66	7	68	7.6	65	6.5	66	6.7	67	7.1
		80% shading	3 ACH	96	36.2	97	36.2	101	36.2	96	36.2	96	36.2	98	36.2	95	36.2	94	36.2	96	36.2	95	36.2	95	36.2	96	36.2
				50	7.7	54	8.9	63	11.2	49	6.6	52	7.3	57	8.7	49	5.8	51	6.2	54	7	49	5.5	50	5.8	53	6.4
			4 ACH	106	42.6	108	42.6	112	42.6	107	42.6	106	42.6	108	42.6	105	42.6	107	42.6	107	42.6	105	42.6	105	42.6	107	42.6
				56	7.8	60	9	69	11.3	56	6.7	58	7.4	64	8.8	55	5.9	57	6.3	60	7.1	55	5.6	56	5.9	59	6.5
			5 ACH	117	49	118	49	123	49	117	49	117	49	119	49	115	49	118	49	117	49	115	49	115	49	118	49
				63	7.9	67	9.1	75	11.4	62	6.8	64	7.5	70	8.9	61	6	63	6.4	66	7.2	61	5.7	63	6	65	6.6

Table B10: Terraced house: West orientation and high glazing area (WWR 45%)

Orientation				West																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
High glazing area (WWR 45%)	Single glazing	40% shading	3 ACH	133	36.2	136	36.2	144	36.2	133	36.2	135	36.2	140	36.2	133	36.2	135	36.2	137	36.2	134	36.2	134	36.2	136	36.2
				116	25.3	122	26.3	133	28.5	117	24.2	120	24.9	127	26.2	118	23.5	120	23.9	124	24.6	118	23.2	120	23.5	122	24
			4 ACH	143	42.6	146	42.6	154	42.6	143	42.6	145	42.6	150	42.6	143	42.6	145	42.6	147	42.6	144	42.6	144	42.6	146	42.6
				122	25.4	127	26.4	138	28.6	123	24.3	126	25	133	26.3	124	23.6	126	24	129	24.7	124	23.3	125	23.6	128	24.1
			5 ACH	153	49	157	49	164	49	154	49	156	49	160	49	154	49	155	49	158	49	154	49	155	49	157	49
				128	25.5	133	26.5	144	28.7	129	24.4	132	25.1	139	26.4	129	23.7	131	24.1	135	24.8	130	23.4	131	13.7	134	24.2
		60% shading	3 ACH	118	36.2	121	36.2	126	36.2	118	36.2	119	36.2	122	36.2	117	36.2	118	36.2	120	36.2	117	36.2	118	36.2	119	36.2
				91	19.4	96	20.5	105	22.6	91	18.3	94	19	100	20.3	91	17.6	93	18	96	18.7	91	17.4	92	17.6	95	18.1
			4 ACH	129	42.6	132	42.6	137	42.6	129	42.6	130	42.6	133	42.6	129	42.6	129	42.6	131	42.6	128	42.6	129	42.6	130	42.6
				97	19.5	102	20.6	111	22.7	97	18.4	100	19.1	106	20.4	97	17.7	99	18.1	102	18.8	97	17.5	98	17.7	101	18.2
			5 ACH	140	49	143	49	148	49	140	49	141	49	144	49	139	49	140	49	142	49	139	49	140	49	141	49
				104	19.6	108	20.7	118	22.8	103	18.5	106	19.2	112	20.5	103	17.8	105	18.2	108	18.9	103	17.6	104	17.8	107	18.3
		80% shading	3 ACH	105	36.2	106	36.2	111	36.2	104	36.2	105	36.2	108	36.2	103	36.2	104	36.2	106	36.2	103	36.2	104	36.2	105	36.2
				68	13.4	72	14.5	81	16.6	68	12.3	70	13.3	76	14.3	68	11.6	69	12	72	12.7	67	11.4	68	11.6	71	12.1
			4 ACH	116	42.6	117	42.6	122	42.6	115	42.6	116	42.6	119	42.6	115	42.6	115	42.6	117	42.6	114	42.6	115	42.6	116	42.6
				75	13.5	79	14.6	87	16.7	74	12.4	77	13.4	82	14.4	74	11.7	75	12.1	78	12.8	74	11.5	75	11.7	77	12.1
			5 ACH	127	49	128	49	133	49	126	49	127	49	129	49	126	49	126	49	128	49	125	49	126	49	127	49
				81	13.6	85	14.7	93	16.8	80	12.5	83	13.5	88	14.5	80	11.8	81	12.2	84	12.9	80	11.6	81	11.8	83	11.2
	Ordinary double glazing	40% shading	3 ACH	129	36.2	133	36.2	140	36.2	130	36.2	132	36.2	136	36.2	130	36.2	131	36.2	133	36.2	130	36.2	131	36.2	132	36.2
				112	22.6	118	23.6	129	25.8	114	21.5	117	22.2	124	23.5	115	20.8	117	21.2	121	21.9	115	20.5	117	20.8	120	21.3
			4 ACH	139	42.6	143	42.6	150	42.6	140	42.6	142	42.6	146	42.6	140	42.6	141	42.6	143	42.6	140	42.6	141	42.6	142	42.6
				118	22.7	123	23.7	134	25.9	119	21.6	123	22.2	129	23.6	120	20.9	122	21.3	126	22	121	20.6	122	20.9	125	21.4
			5 ACH	150	49	154	49	161	49	150	49	153	49	157	49	151	49	152	49	154	49	151	49	152	49	153	49
				124	22.8	129	23.8	140	26	125	21.7	128	22.3	135	23.7	126	21	128	21.4	132	22.1	126	20.7	128	21	130	21.5
		60% shading	3 ACH	115	36.2	118	36.2	123	36.2	115	36.2	116	36.2	120	36.2	114	36.2	115	36.2	117	36.2	114	36.2	115	36.2	116	36.2
				88	17.3	93	18.4	103	20.5	89	16.3	92	16.9	98	18.2	89	15.5	91	15.9	95	16.7	90	15.3	91	15.5	93	16
			4 ACH	126	42.6	129	42.6	134	42.6	126	42.6	127	42.6	130	42.6	125	42.6	126	42.6	128	42.6	125	42.6	126	42.6	127	42.6
				94	17.4	99	18.5	109	20.6	95	16.4	98	17	104	18.3	95	15.6	97	16	101	16.8	95	15.4	97	15.6	99	16.1
			5 ACH	137	49	140	49	145	49	137	49	138	49	141	49	136	49	137	49	139	49	136	49	137	49	138	49
				100	17.5	105	18.6	115	20.7	101	16.5	104	17.1	110	18.4	101	15.7	103	16.1	106	16.8	101	15.5	102	15.7	105	16.2
		80% shading	3 ACH	103	36.2	105	36.2	110	36.2	103	36.2	104	36.2	107	36.2	102	36.2	103	36.2	105	36.2	102	36.2	103	36.2	104	36.2
				67	11.9	71	13	80	15.2	67	10.9	69	11.5	75	12.8	66	10.2	68	10.5	71	11.3	66	9.9	67	10.2	70	10.7
			4 ACH	114	42.6	116	42.6	121	42.6	114	42.6	115	42.6	117	42.6	113	42.6	114	42.6	115	42.6	113	42.6	114	42.6	115	42.6
				73	12	77	13.1	86	15.3	73	11	75	11.6	81	12.9	73	10.3	74	10.6	77	11.4	73	10	74	10.3	76	10.8
			5 ACH	125	49	127	49	132	49	125	49	126	49	128	49	124	49	125	49	127	49	124	49	125	49	126	49
				79	12.1	84	13.2	92	15.4	79	11.1	82	11.7	87	13	79	10.4	80	10.7	83	11.5	79	10.1	80	10.4	82	10.9
	Double low-e glazing	40% shading	3 ACH	114	36.2	116	36.2	123	36.2	113	36.2	115	36.2	119	36.2	113	36.2	114	36.2	117	36.2	113	36.2	114	36.2	115	36.2
				88	16.7	93	17.8	104	19.9	89	15.7	92	16.3	99	17.6	90	15	92	15.3	96	16.1	91	14.7	92	14.9	95	15.5
			4 ACH	125	42.6	127	42.6	133	42.6	124	42.6	126	42.6	130	42.6	124	42.6	125	42.6	127	42.6	124	42.6	125	42.6	126	42.6
				94	16.8	99	17.9	110	20	95	15.8	98	16.4	105	17.7	96	15.1	98	15.4	101	16.2	96	14.8	97	15	100	15.6
			5 ACH	136	49	139	49	144	49	135	49	137	49	141	49	135	49	136	49	138	49	135	49	136	49	137	49
				100	16.9	105	18	115	20.1	101	15.9	104	16.5	110	17.8	101	15.2	103	15.5	107	16.3	102	14.9	103	15.1	106	15.7
		60% shading	3 ACH	105	36.2	108	36.2	113	36.2	105	36.2	107	36.2	110	36.2	105	36.2	106	36.2	108	36.2	105	36.2	106	36.2	107	36.2
				73	13.3	78	14.4	88	16.5	73	12.2	76	12.9	82	14.2	74	11.5	76	11.9	79	12.6	74	11.2	75	11.5	78	12
			4 ACH	116	42.6	119	42.6	124	42.6	116	42.6	118	42.6	121	42.6	116	42.6	117	42.6	119	42.6	116	42.6	117	42.6	118	42.6
				79	13.4	84	14.5	94	16.6	79	12.3	82	13	88	14.3	80	11.6	81	12	85	12.7	80	11.3	81	11.6	84	12.1
			5 ACH	127	49	130	49	135	49	127	49	129	49	132	49	127	49	128	49	130	49	127	49	128	49	129	49
				85	13.5	90	14.6	99	16.7	85	12.4	88	13.1	94	14.4	86	11.7	87	12.1	91	12.8	86	11.4	87	11.7	89	12.2
		80% shading	3 ACH	100	36.2	101	36.2	105	36.2	99	36.2	100	36.2	102	36.2	98	36.2	99	36.2	101	36.2	98	36.2	98	36.2	100	36.2
				60	9.8	64	10.8	73	13	59	8.7	62	9.4	67	10.7	59	8	61	8.4	64	9.1	59	7.7	60	8	63	8.5
			4 ACH	111	42.6	112	42.6	116	42.6	110	42.6	111	42.6	114	42.6	109	42.6	110	42.6	112	42.6	109	42.6	109	42.6	111	42.6
				66	9.9	70	10.9	79	13.1	66	8.8	68	9.5	74	10.8	65	8.1	67	8.5	70	9.2	65	7.8	67	8.1	69	8.6
			5 ACH	122	49	123	49	127	49	121	49	122	49	125	49	121	49	122	49	123	49	120	49	121	49	122	49
				72	10	76	11	85	13.2	72	8.9	74	9.6	80	10.9	72	8.2	73	8.6	76	9.3	72	7.9	73	8.2	75	8.7
	Double low-e + solar protection glazing	40% shading	3 ACH	101	36.2	103	36.2	106	36.2	100	36.2	101	36.2	104	36.2	100	36.2	101	36.2	102	36.2	100	36.2	100	36.2	101	36.2
				63	11.2	67	12.3	76	14.5	63	10.2	65	10.8	71	12.2	63	9.5	64	9.9	67	10.6	63	9.2	64	9.5	66	10
			4 ACH	112	42.6	114	42.6	117	42.6	111	42.6	112	42.6	115	42.6	111	42.6	112	42.6	113	42.6	111	42.6	111	42.6	112	42.6
				69	11.3	73	12.4	82	14.6	69	10.3	71	10.9	77	12.3	69	9.6	70	10	73	10.7	69	9.3	70	9.6	72	10.1
			5 ACH	123	49	125	49	128	49	123	49	123	49	126	49	122	49	123	49	124	49	122	49	122	49	123	49
				75	11.4	80	12.5	88	14.7	75	10.4	78	11	83	12.4	75	9.7	76	10.1	79	10.8	75	9.4	76	9.7	78	10.2
		60% shading	3 ACH	99	36.2	100	36.2	104	36.2	97	36.2	99	36.2	101	36.2	97	36.2	98	36.2	99	36.2	97	36.2	97	36.2	98	36.2
				57	9.7	61	10.8	70	12.9	57	8.6	59	9.3	65	10.6	57	7.9	58	8.3	61	9	57	7.7	58	7.9	60	8.4
			4 ACH	110	42.6	111	42.6	115	42.6	108	42.6	110	42.6	112	42.6	108	42.6	108	42.6	111	42.6	108	42.6	108	42.6	109	42.6
				63	9.8	68	10.9	76	13	63	8.7	66	9.4	71	10.7	63	8	64	8.4	67	9.1	63	7.8	64	8	66	8.5
			5 ACH	121	49	122	49	126	49	119	49	121	49	123	49	119	49	119	49	122	49	119	49	119	49	120	49
				70	9.9	74	11	82	13.1	69	8.8	72	9.5	77	10.8	69	8.1	71	8.5	73	9.2	69	7.9	70	8.1	72	8.6
		80% shading	3 ACH	96	36.2	99	36.2	101	36.2	96	36.2	97	36.2	99	36.2	96	36.2	96	36.2	99	36.2	97	36.2	96	36.2	96	36.2
				52	8.1	56	9.2	64	11.3	51	7.1	54	7.7	59	9	51	6.3	52	6.7	55	7.5	51	6.1	52	6.3	54	6.8
			4 ACH	107	42.6	110	42.6	112	42.6	107	42.6	107	42.6	110	42.6	107	42.6	107	42.6	108	42.6	107	42.6	107	42.6	107	42.6
				58	8.2	62	9.3	70	11.4	58	7.2	60	7.8	65	9.1	57	6.4	59	6.8	62	7.6	57	6.2	58	6.4	60	6.9
			5 ACH	118	49	121	49	123	49	117	49	118	49	121	49	117	49	117	49	119	49	118	49	118	6.5	117	49
				65	8.3	68	9.4	76	11.5	64	7.3	66	7.9	71	9.2	63	6.5	65	6.9	68	7.7	64	6.3	64	6.5	66	7

Table B11: Detached house: North orientation and low glazing area (WWR 15%)

Orientation				North											
Wall, roof insulation				25 mm			50 mm			100 mm			150 mm		
Exterior absorptivity				0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9
Low glazing area (WWR 15%)	Single glazing	40% shading	2 ACH	111 29.8	117 29.8	130 29.8	110 29.8	114 29.8	122 29.8	110 29.8	112 29.8	116 29.8	109 29.8	110 29.8	114 29.8
				84 22.4	95 24.8	116 29.5	85 20.5	91 22	105 25	85 19.1	89 20	98 21.7	86 18.6	89 19.2	95 20.4
			3 ACH	121 35.9	127 35.9	139 35.9	120 35.9	124 35.9	131 35.9	119 35.9	122 35.9	125 35.9	119 35.9	121 35.9	123 35.9
				91 22.5	101 24.9	122 29.6	90 20.6	97 22.1	111 25.1	91 19.2	95 20.1	103 21.8	92 18.7	94 19.3	101 20.5
			4 ACH	131 42	138 42	148 42	130 42	134 42	141 42	130 42	132 42	136 42	130 42	131 42	134 42
				97 22.6	107 25	128 29.7	96 20.7	103 22.2	117 25.2	97 19.3	101 20.2	109 21.9	97 18.8	100 19.4	106 20.6
		60% shading	2 ACH	101 29.8	106 29.8	119 29.8	99 29.8	103 29.8	111 29.8	98 29.8	101 29.8	106 29.8	98 29.8	100 29.8	104 29.8
				69 18	78 20.3	97 25.1	68 16	73 17.5	86 20.5	67 14.7	71 15.5	79 17.2	67 14.1	70 14.7	75 15.9
			3 ACH	111 35.9	116 35.9	129 35.9	110 35.9	113 35.9	121 35.9	108 35.9	111 35.9	116 35.9	108 35.9	110 35.9	113 35.9
				75 18.1	84 20.4	103 25.2	74 16.1	79 17.6	92 20.6	73 14.8	77 15.6	84 17.3	73 14.2	76 14.8	81 16
			4 ACH	122 42	126 42	139 42	120 42	123 42	132 42	119 42	121 42	126 42	119 42	120 42	124 42
				81 18.2	90 20.5	109 25.3	80 16.2	85 17.7	98 20.7	79 14.9	83 15.7	90 17.4	79 14.3	82 14.9	87 16.1
		80% shading	2 ACH	94 29.8	98 29.8	108 29.8	93 29.8	95 29.8	100 29.8	92 29.8	93 29.8	96 29.8	91 29.8	93 29.8	95 29.8
				55 14.3	63 16.6	80 21.4	53 12.4	58 13.9	69 16.8	52 11	55 11.8	62 13.6	52 10.4	54 11	59 12.2
			3 ACH	104 35.9	109 35.9	118 35.9	103 35.9	106 35.9	110 35.9	102 35.9	103 35.9	106 35.9	101 35.9	103 35.9	105 35.9
				61 14.4	69 16.7	87 21.5	59 12.5	64 14	75 16.9	58 11.1	61 11.9	68 13.7	58 10.5	60 11.1	65 12.3
			4 ACH	114 42	119 42	128 42	113 42	116 42	120 42	112 42	114 42	117 42	112 42	113 42	115 42
				67 14.5	75 16.8	93 21.6	65 12.6	70 14.1	81 17	64 11.2	67 12	74 13.8	64 10.6	66 11.2	71 12.4
	Ordinary double glazing	40% shading	2 ACH	108 29.8	114 29.8	128 29.8	107 29.8	111 29.8	120 29.8	107 29.8	109 29.8	115 29.8	107 29.8	108 29.8	113 29.8
				81 20.3	91 22.7	112 27.4	81 18.4	88 19.9	102 22.9	83 17	87 17.9	96 19.6	84 16.4	87 17.1	94 18.3
			3 ACH	118 35.9	124 35.9	136 35.9	117 35.9	121 35.9	128 35.9	116 35.9	118 35.9	123 35.9	116 35.9	118 35.9	121 35.9
				87 20.4	97 22.8	118 27.5	87 18.5	94 20	108 23	88 17.1	93 18	101 19.7	89 16.5	93 17.2	99 18.4
			4 ACH	128 42	135 42	146 42	128 42	131 42	138 42	127 42	129 42	133 42	127 42	128 42	131 42
				93 20.5	102 22.9	124 27.6	93 18.6	99 20.1	113 23.1	94 17.2	98 18.1	107 19.8	95 16.6	98 17.3	105 18.5
		60% shading	2 ACH	99 29.8	104 29.8	117 29.8	98 29.8	101 29.8	109 29.8	97 29.8	99 29.8	104 29.8	97 29.8	99 29.8	102 29.8
				66 16.3	75 18.7	96 23.4	65 14.4	71 15.9	85 18.9	65 13	69 13.9	77 15.6	66 12.4	69 13	74 14.3
			3 ACH	109 35.9	114 35.9	127 35.9	108 35.9	111 35.9	119 35.9	107 35.9	109 35.9	114 35.9	107 35.9	108 35.9	112 35.9
				72 16.4	81 18.8	102 23.5	71 14.5	77 16	91 19	71 13.1	75 14	83 15.7	72 12.5	75 13.1	80 14.4
			4 ACH	120 42	124 42	137 42	118 42	121 42	130 42	117 42	120 42	124 42	117 42	119 42	122 42
				78 16.5	87 18.9	107 23.6	77 14.6	83 16.1	96 19.1	77 13.2	81 14.1	89 15.8	78 12.6	80 13.2	86 14.5
		80% shading	2 ACH	93 29.8	97 29.8	107 29.8	92 29.8	94 29.8	99 29.8	91 29.8	92 29.8	95 29.8	90 29.8	92 29.8	93 29.8
				53 13	61 15.4	80 20.1	52 11.1	57 12.6	69 15.6	51 9.7	54 10.6	61 12.3	51 9.1	53 9.7	58 11
			3 ACH	103 35.9	107 35.9	117 35.9	101 35.9	105 35.9	109 35.9	101 35.9	102 35.9	105 35.9	100 35.9	102 35.9	104 35.9
				59 13.1	67 15.5	86 20.2	58 11.2	63 12.7	75 15.7	57 9.8	60 10.7	67 12.4	57 9.2	59 9.8	64 11.1
			4 ACH	113 42	118 42	128 42	112 42	115 42	120 42	111 42	113 42	116 42	111 42	112 42	114 42
				66 13.2	74 15.6	92 20.3	64 11.3	69 12.8	81 15.7	63 9.9	66 10.8	73 12.4	63 9.3	65 9.9	70 11.2
	Double low-e glazing	40% shading	2 ACH	98 29.8	104 29.8	116 29.8	97 29.8	101 29.8	109 29.8	97 29.8	99 29.8	104 29.8	97 29.8	99 29.8	102 29.8
				66 16	75 18.3	96 23.1	66 14.1	72 15.5	86 18.5	67 12.7	70 13.5	79 15.2	68 12.1	71 12.7	77 13.9
			3 ACH	109 35.9	114 35.9	126 35.9	107 35.9	111 35.9	119 35.9	107 35.9	109 35.9	114 35.9	107 35.9	109 35.9	112 35.9
				72 16.1	81 18.4	102 23.2	72 14.2	78 15.6	91 18.6	72 12.8	76 13.6	85 15.3	73 12.2	76 12.8	82 14
			4 ACH	119 42	124 42	137 42	118 42	121 42	130 42	117 42	120 42	124 42	117 42	119 42	122 42
				78 16.2	87 18.5	108 23.3	78 14.3	84 15.7	97 18.7	78 12.9	82 13.7	90 15.4	79 12.3	82 12.9	88 14.1
		60% shading	2 ACH	95 29.8	98 29.8	111 29.8	93 29.8	96 29.8	103 29.8	93 29.8	94 29.8	98 29.8	92 29.8	93 29.8	96 29.8
				57 13.4	66 15.7	86 20.4	56 11.4	62 12.9	75 15.9	56 10	60 10.9	67 12.6	56 9.5	59 10.1	65 11.3
			3 ACH	105 35.9	109 35.9	121 35.9	104 35.9	106 35.9	113 35.9	103 35.9	104 35.9	107 35.9	102 35.9	103 35.9	105 35.9
				63 13.5	72 15.8	91 20.5	62 11.5	68 13	81 16	62 10.1	66 11	73 12.7	62 9.6	65 10.2	70 11.4
			4 ACH	116 42	119 42	131 42	114 42	116 42	123 42	113 42	115 42	118 42	113 42	114 42	116 42
				69 13.6	78 15.9	97 20.6	68 11.6	74 13.1	87 16.1	68 10.2	71 11.1	79 12.8	68 9.7	71 10.3	76 11.5
		80% shading	2 ACH	90 29.8	95 29.8	104 29.8	89 29.8	92 29.8	96 29.8	89 29.8	90 29.8	93 29.8	89 29.8	90 29.8	91 29.8
				49 11.2	57 13.6	75 18.3	48 9.3	53 10.8	65 13.7	47 7.9	50 8.7	57 10.5	47 7.3	49 7.9	54 9.1
			3 ACH	100 35.9	105 35.9	114 35.9	100 35.9	102 35.9	106 35.9	100 35.9	100 35.9	103 35.9	100 35.9	100 35.9	101 35.9
				55 11.3	63 13.7	81 18.4	54 9.4	11 10.9	71 13.8	53 8	56 8.8	63 10.6	53 7.4	55 8	60 9.2
			4 ACH	111 42	115 42	124 42	110 42	112 42	117 42	110 42	111 42	114 42	110 42	110 42	112 42
				61 11.4	69 13.8	87 18.5	60 9.5	65 11	76 13.9	59 8.1	62 8.9	69 10.7	59 7.5	61 8.1	66 9.3
	Double low-e + solar protection glazing	40% shading	2 ACH	92 29.8	96 29.8	106 29.8	91 29.8	93 29.8	99 29.8	90 29.8	91 29.8	94 29.8	90 29.8	91 29.8	93 29.8
				52 12	60 14.4	79 19.1	51 10.1	56 11.6	68 14.6	50 8.7	53 9.6	60 11.3	50 8.1	52 8.7	58 9.9
			3 ACH	102 35.9	106 35.9	116 35.9	100 35.9	103 35.9	108 35.9	100 35.9	101 35.9	104 35.9	100 35.9	101 35.9	103 35.9
				58 12.1	66 14.5	85 19.2	57 10.2	62 11.7	74 14.7	56 8.8	59 9.7	66 11.4	56 8.2	58 8.8	63 10
			4 ACH	112 42	117 42	127 42	111 42	114 42	119 42	110 42	112 42	115 42	110 42	111 42	113 42
				64 12.2	72 14.6	91 19.3	63 10.3	68 11.8	80 14.8	62 8.9	65 9.8	72 11.5	62 8.3	64 8.9	69 10.1
		60% shading	2 ACH	90 29.8	94 29.8	103 29.8	89 29.8	91 29.8	96 29.8	89 29.8	90 29.8	92 29.8	89 29.8	89 29.8	91 29.8
				48 10.8	56 13.2	74 17.9	47 8.9	52 10.4	63 13.4	46 7.5	49 8.4	56 10.1	46 7	48 7.6	53 8.8
			3 ACH	100 35.9	104 35.9	113 35.9	100 35.9	101 35.9	106 35.9	99 35.9	100 35.9	102 35.9	99 35.9	99 35.9	101 35.9
				54 10.9	62 13.3	80 18	53 9	58 10.5	69 13.5	52 7.6	55 8.5	62 10.2	52 7.1	54 7.7	59 8.9
			4 ACH	110 42	115 42	123 42	110 42	112 42	117 42	110 42	110 42	113 42	110 42	110 42	111 42
				60 11	69 13.4	86 18.1	59 9.1	64 10.6	75 13.6	58 7.7	61 8.6	68 10.3	58 7.2	60 7.8	65 9
		80% shading	2 ACH	90 29.8	92 29.8	100 29.8	89 29.8	90 29.8	95 29.8	88 29.8	89 29.8	91 29.8	88 29.8	88 29.8	90 29.8
				45 9.8	53 12.2	70 16.9	43 7.9	48 9.4	59 12.4	42 6.5	45 7.4	52 9.1	42 6	44 6.6	49 7.8
			3 ACH	100 35.9	102 35.9	110 35.9	99 35.9	100 35.9	105 35.9	99 35.9	99 35.9	100 35.9	99 35.9	99 35.9	99 35.9
				51 9.9	59 12.3	76 17	50 8	54 9.5	65 12.5	48 6.6	51 7.5	58 9.2	48 6.1	50 6.7	55 7.9
			4 ACH	110 42	113 42	120 42	110 42	110 42	115 42	109 42	110 42	111 42	109 42	109 42	110 42
				57 10	65 12.4	82 17.1	56 8.1	60 9.6	71 12.6	55 6.7	57 7.6	64 9.3	54 6.2	56 6.8	61 8

Table B12: Detached house: North orientation and medium glazing area (WWR 25%)

			Orientation	North											
			Wall, roof insulation	25 mm			50 mm			100 mm			150 mm		
			Exterior absorptivity	0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9
Medium glazing area (WWR 25%)	Single glazing	40% shading	2 ACH	141 29.8	148 29.8	163 29.8	141 29.8	145 29.8	155 29.8	141 29.8	144 29.8	150 29.8	142 29.8	143 29.8	148 29.8
				131 34	142 36.2	163 40.6	132 32.2	139 33.6	153 36.4	134 30.9	138 31.7	146 33.3	134 30.4	137 30.9	143 32.1
			3 ACH	149 35.9	156 35.9	171 35.9	149 35.9	154 35.9	163 35.9	150 35.9	152 35.9	158 35.9	150 35.9	152 35.9	156 35.9
				137 34.1	148 36.3	169 40.7	138 32.3	145 33.7	159 36.5	139 31	143 31.8	152 33.4	140 30.5	143 31	149 32.2
			4 ACH	159 42	166 42	180 42	159 42	164 42	172 42	160 42	162 42	167 42	160 42	162 42	165 42
				143 34.2	153 36.4	175 40.8	144 32.4	151 33.8	164 36.6	145 31.1	149 31.9	157 33.5	146 30.6	149 31.1	154 32.3
		60% shading	2 ACH	119 29.8	124 29.8	137 29.8	118 29.8	121 29.8	129 29.8	117 29.8	119 29.8	123 29.8	117 29.8	118 29.8	121 29.8
				96 26	106 28.2	126 32.6	96 24.2	102 25.6	115 28.4	96 22.9	99 23.7	107 25.3	96 22.4	99 23	104 24.1
			3 ACH	129 35.9	134 35.9	146 35.9	128 35.9	131 35.9	137 35.9	127 35.9	129 35.9	132 35.9	127 35.9	128 35.9	130 35.9
				102 26.1	112 28.3	131 32.7	102 24.3	108 25.7	120 28.5	102 23	105 23.8	113 25.4	102 22.5	104 23.1	110 24.2
			4 ACH	139 42	145 42	155 42	138 42	142 42	148 42	138 42	140 42	143 42	137 42	139 42	141 42
				108 26.2	118 28.4	137 32.8	108 24.4	114 25.8	126 28.6	108 23.1	111 23.9	119 25.5	108 22.6	110 23.2	115 24.3
		80% shading	2 ACH	102 29.8	105 29.8	116 29.8	100 29.8	102 29.8	109 29.8	99 29.8	100 29.8	103 29.8	99 29.8	99 29.8	101 29.8
				67 19.3	75 21.6	92 26	66 17.5	71 18.9	82 21.7	65 16.3	68 17.1	74 18.7	64 15.7	66 16.3	71 17.4
			3 ACH	112 35.9	115 35.9	126 35.9	110 35.9	112 35.9	118 35.9	109 35.9	110 35.9	113 35.9	109 35.9	110 35.9	111 35.9
				73 19.4	81 21.7	99 26.1	72 17.6	77 19	88 21.8	71 16.4	74 17.2	80 18.8	70 15.8	73 16.4	77 17.5
			4 ACH	122 42	125 42	137 42	121 42	123 42	129 42	120 42	121 42	123 42	119 42	120 42	122 42
				79 19.5	87 21.8	105 26.2	78 17.7	83 19.1	94 21.9	77 16.5	80 17.3	86 18.9	76 15.9	79 16.5	83 17.6
	Ordinary double glazing	40% shading	2 ACH	136 29.8	143 29.8	159 29.8	136 29.8	141 29.8	153 29.8	139 29.8	143 29.8	149 29.8	141 29.8	143 29.8	147 29.8
				124 30	135 32.2	158 36.7	127 28.2	134 29.6	150 32.4	131 26.9	135 27.8	144 29.4	133 26.4	136 27	143 28.1
			3 ACH	144 35.9	151 35.9	166 35.9	145 35.9	149 35.9	160 35.9	145 35.9	150 35.9	156 35.9	148 35.9	150 35.9	154 35.9
				130 30.1	141 32.3	163 36.8	132 28.3	139 29.7	155 32.5	136 27	141 27.9	150 29.5	138 26.5	141 27.1	148 28.2
			4 ACH	154 42	161 42	176 42	155 42	159 42	168 42	155 42	157 42	164 42	156 42	158 42	163 42
				136 30.2	147 32.4	169 36.8	138 28.4	145 29.8	160 32.6	141 27.1	146 28	155 29.6	144 26.6	147 27.2	153 28.3
		60% shading	2 ACH	115 29.8	120 29.8	134 29.8	114 29.8	117 29.8	127 29.8	114 29.8	116 29.8	122 29.8	114 29.8	116 29.8	120 29.8
				92 22.9	102 25.1	122 29.5	92 21.1	99 22.5	112 25.3	94 19.8	97 20.6	106 22.2	95 19.3	97 19.8	103 21
			3 ACH	125 35.9	130 35.9	143 35.9	124 35.9	127 35.9	135 35.9	123 35.9	125 35.9	130 35.9	123 35.9	124 35.9	128 35.9
				98 23	108 25.2	128 29.6	98 21.2	104 22.6	118 25.4	99 19.9	103 20.7	111 22.3	100 19.4	103 19.9	109 21.1
			4 ACH	135 42	141 42	152 42	135 42	138 42	145 42	134 42	136 42	140 42	133 42	135 42	138 42
				104 23.1	113 25.3	134 29.7	104 21.3	110 22.7	124 25.5	105 20	109 20.8	117 22.4	106 19.5	109 20	114 21.2
		80% shading	2 ACH	99 29.8	103 29.8	115 29.8	98 29.8	99 29.8	107 29.8	97 29.8	98 29.8	102 29.8	96 29.8	97 29.8	100 29.8
				65 16.9	73 19.1	91 23.6	63 15.1	69 16.5	80 19.3	63 13.8	66 14.6	73 16.2	63 13.3	65 13.9	70 15
			3 ACH	109 35.9	112 35.9	125 35.9	108 35.9	110 35.9	117 35.9	107 35.9	108 35.9	112 35.9	106 35.9	107 35.9	110 35.9
				71 17	79 19.2	97 23.7	70 15.2	75 16.6	86 19.4	69 13.9	72 14.7	79 16.3	69 13.4	71 14	76 15.1
			4 ACH	120 42	123 42	135 42	119 42	120 42	128 42	118 42	119 42	122 42	117 42	118 42	120 42
				77 17.1	85 19.3	103 23.8	76 15.3	81 16.7	92 19.5	75 14	78 14.8	85 16.4	75 13.5	77 14.1	82 15.2
	Double low-e glazing	40% shading	2 ACH	115 29.8	120 29.8	136 29.8	114 29.8	119 29.8	129 29.8	116 29.8	119 29.8	124 29.8	116 29.8	118 29.8	123 29.8
				93 22	103 24.3	125 28.7	94 20.2	101 21.6	116 24.4	98 19	102 19.8	111 21.4	100 18.4	103 19	110 20.1
			3 ACH	125 35.9	129 35.9	144 35.9	123 35.9	128 35.9	136 35.9	124 35.9	127 35.9	132 35.9	125 35.9	126 35.9	130 35.9
				98 22.1	109 24.4	131 28.8	100 20.3	107 21.7	122 24.5	103 19.1	108 19.9	117 21.5	106 18.5	109 19.1	115 20.2
			4 ACH	135 42	140 42	154 42	134 42	137 42	146 42	134 42	137 42	142 42	134 42	136 42	140 42
				104 22.2	115 24.5	136 28.9	106 20.4	113 21.8	127 24.6	108 19.2	113 20	122 21.6	110 18.6	114 19.2	120 20.3
		60% shading	2 ACH	103 29.8	109 29.8	120 29.8	102 29.8	106 29.8	113 29.8	102 29.8	104 29.8	108 29.8	102 29.8	103 29.8	106 29.8
				73 17.4	82 19.6	102 24	73 15.6	79 17	93 19.8	74 14.3	78 15.1	86 16.7	75 13.7	78 14.3	84 15.4
			3 ACH	112 35.9	118 35.9	129 35.9	112 35.9	116 35.9	122 35.9	112 35.9	114 35.9	118 35.9	112 35.9	113 35.9	116 35.9
				79 17.5	88 19.7	108 24.1	79 15.7	85 17.1	98 19.9	80 14.4	84 15.2	92 16.8	81 13.8	84 14.4	90 15.5
			4 ACH	123 42	129 42	140 42	122 42	126 42	133 42	122 42	124 42	128 42	122 42	124 42	126 42
				85 17.6	94 19.8	114 24.2	85 15.8	91 17.2	104 20	86 14.5	89 15.3	97 16.9	87 13.9	89 14.5	95 15.6
		80% shading	2 ACH	94 29.8	98 29.8	109 29.8	93 29.8	96 29.8	102 29.8	92 29.8	94 29.8	96 29.8	92 29.8	93 29.8	95 29.8
				56 13.5	64 15.7	82 20.1	55 11.7	61 13.1	72 15.9	55 10.4	58 11.2	65 12.8	55 9.8	57 10.4	62 11.5
			3 ACH	105 35.9	108 35.9	119 35.9	103 35.9	106 35.9	111 35.9	102 35.9	104 35.9	106 35.9	102 35.9	103 35.9	105 35.9
				62 13.6	70 15.8	88 20.2	61 11.8	67 13.2	78 16	61 10.5	64 11.3	71 12.9	61 9.9	63 10.5	68 11.6
			4 ACH	115 42	119 42	129 42	114 42	116 42	122 42	113 42	114 42	117 42	113 42	114 42	115 42
				68 13.7	76 15.9	94 20.3	67 11.9	73 13.3	84 16.1	67 10.6	70 11.4	77 13	67 10	69 10.6	74 11.7
	Double low-e + solar protection glazing	40% shading	2 ACH	97 29.8	101 29.8	113 29.8	96 29.8	98 29.8	106 29.8	95 29.8	96 29.8	101 29.8	94 29.8	95 29.8	99 29.8
				62 14.8	70 17	89 21.4	61 13	66 14.4	78 17.2	61 11.7	64 12.5	72 14.1	61 11.2	63 11.7	69 12.9
			3 ACH	107 35.9	110 35.9	123 35.9	106 35.9	107 35.9	115 35.9	105 35.9	106 35.9	110 35.9	104 35.9	105 35.9	108 35.9
				68 14.9	76 17.1	95 21.5	67 13.1	72 14.5	84 17.3	66 11.8	70 12.6	77 14.2	67 11.3	69 11.8	75 13
			4 ACH	118 42	121 42	133 42	116 42	118 42	126 42	115 42	116 42	121 42	115 42	116 42	119 42
				74 15	82 17.2	101 21.6	73 13.2	78 14.6	90 17.4	72 11.9	76 12.7	83 14.3	73 11.4	75 11.9	80 13.1
		60% shading	2 ACH	93 29.8	97 29.8	107 29.8	92 29.8	95 29.8	100 29.8	91 29.8	93 29.8	95 29.8	91 29.8	92 29.8	94 29.8
				54 12.6	62 14.9	80 19.3	53 10.9	58 12.3	70 15.1	53 9.6	56 10.4	62 12	53 9	55 9.6	60 10.7
			3 ACH	103 35.9	107 35.9	117 35.9	102 35.9	105 35.9	110 35.9	101 35.9	103 35.9	105 35.9	101 35.9	102 35.9	104 35.9
				61 12.7	68 15	86 19.4	59 11	64 12.4	76 15.2	59 9.7	62 10.5	68 12.1	59 9.1	61 9.7	65 10.8
			4 ACH	114 42	118 42	128 42	113 42	115 42	120 42	112 42	113 42	116 42	112 42	113 42	114 42
				67 12.8	74 15.1	92 19.5	65 11.1	70 12.5	81 15.3	65 9.6	68 10.6	74 12.2	65 9.2	67 9.8	71 10.9
		80% shading	2 ACH	90 29.8	94 29.8	102 29.8	89 29.8	91 29.8	96 29.8	89 29.8	90 29.8	92 29.8	89 29.8	89 29.8	91 29.8
				48 10.9	55 13.1	72 17.5	46 9.1	51 10.5	62 13.3	46 7.8	48 8.6	54 10.2	45 7.3	47 7.9	52 9
			3 ACH	100 35.9	104 35.9	111 35.9	100 35.9	101 35.9	106 35.9	99 35.9	100 35.9	102 35.9	99 35.9	100 35.9	100 35.9
				54 11	61 13.2	78 17.6	52 9.2	57 10.6	68 13.4	52 7.9	54 8.7	60 10.3	51 7.4	53 8	58 9.1
			4 ACH	110 42	114 42	122 42	110 42	111 42	116 42	110 42	110 42	113 42	110 42	110 42	111 42
				60 11.1	67 13.3	84 17.7	59 9.3	63 10.7	74 13.5	58 8	61 8.8	66 10.4	57 7.5	59 8.1	64 9.2

Table B13: Detached house: North orientation and high glazing area (WWR 35%)

Orientation				North																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
High glazing area (WWR 35%)	Single glazing	40% shading	2 ACH	180	29.8	187	29.8	203	29.8	181	29.8	186	29.8	196	29.8	182	29.8	185	29.8	191	29.8	183	29.8	185	29.8	189	29.8
				187	48.3	197	50.3	218	54.4	188	46.6	195	47.9	209	50.5	190	45.4	194	46.2	202	47.7	191	45	194	45.5	199	46.5
			3 ACH	187	35.9	194	35.9	210	35.9	188	35.9	193	35.9	203	35.9	189	35.9	192	35.9	198	35.9	189	35.9	191	35.9	196	35.9
				193	48.4	203	50.4	224	54.5	194	46.7	201	48	214	50.6	196	45.5	200	46.3	207	47.8	196	45.1	199	45.6	205	46.6
			4 ACH	196	42	203	42	219	42	197	42	201	42	211	42	197	42	200	42	206	42	198	42	200	42	204	42
				199	48.5	209	50.5	230	54.6	200	46.8	206	48.1	220	50.7	201	45.6	205	46.4	213	47.9	202	45.2	205	45.7	210	46.7
		60% shading	2 ACH	141	29.8	147	29.8	160	29.8	141	29.8	145	29.8	153	29.8	140	29.8	143	29.8	148	29.8	140	29.8	142	29.8	146	29.8
				131	34.8	140	36.9	159	41	130	33.2	136	34.5	148	37.1	130	32	134	32.7	141	34.2	131	31.5	133	32	138	33.1
			3 ACH	149	35.9	156	35.9	168	35.9	149	35.9	153	35.9	161	35.9	149	35.9	151	35.9	156	35.9	149	35.9	151	35.9	154	35.9
				137	34.9	146	37	165	41.1	136	33.3	142	34.6	154	37.2	136	32.1	140	32.8	147	34.3	136	31.6	139	32.1	144	33.2
			4 ACH	159	42	166	42	178	42	159	42	163	42	171	42	159	42	161	42	166	42	159	42	160	42	164	42
				143	35	152	37.1	171	41.2	142	33.4	148	34.7	160	37.3	142	32.2	146	32.9	153	34.4	137	31.7	145	32.2	150	33.3
		80% shading	2 ACH	109	29.8	115	29.8	126	29.8	108	29.8	112	29.8	119	29.8	107	29.8	109	29.8	113	29.8	107	29.8	109	29.8	111	29.8
				82	25.1	90	27.2	106	31.3	80	23.5	85	24.8	96	27.4	79	22.3	82	23.1	88	24.5	79	21.8	81	22.4	85	23.4
			3 ACH	119	35.9	125	35.9	135	35.9	118	35.9	121	35.9	128	35.9	117	35.9	119	35.9	123	35.9	117	35.9	118	35.9	121	35.9
				88	25.2	96	27.3	112	31.4	87	23.6	91	24.9	102	27.5	86	22.4	88	23.2	94	24.6	85	21.9	87	22.5	91	23.5
			4 ACH	130	42	135	42	146	42	129	42	132	42	139	42	128	42	130	42	134	42	127	42	129	42	132	42
				94	25.3	102	27.4	118	31.5	93	23.7	98	25	108	27.6	92	22.5	94	23.3	100	24.7	91	22	93	22.6	97	23.6
	Ordinary double glazing	40% shading	2 ACH	173	29.8	181	29.8	199	29.8	177	29.8	182	29.8	193	29.8	180	29.8	183	29.8	189	29.8	181	29.8	183	29.8	188	29.8
				178	42.1	189	44.2	212	48.3	183	40.5	190	41.8	204	44.4	187	39.3	191	40	200	41.5	189	38.8	192	39.3	199	40.4
			3 ACH	180	35.9	188	35.9	205	35.9	183	35.9	189	35.9	199	35.9	187	35.9	190	35.9	196	35.9	188	35.9	190	35.9	194	35.9
				184	42.2	194	44.3	218	48.4	188	40.6	195	41.9	210	44.5	192	39.4	197	40.1	205	41.6	194	38.9	197	39.4	203	40.5
			4 ACH	189	42	196	42	214	42	191	42	197	42	208	42	195	42	198	42	204	42	196	42	198	42	202	42
				189	42.3	200	44.4	223	48.5	193	40.7	201	42	215	44.6	198	39.5	202	40.2	210	41.7	200	39	203	39.5	209	40.6
		60% shading	2 ACH	136	29.8	143	29.8	157	29.8	136	29.8	140	29.8	150	29.8	137	29.8	139	29.8	145	29.8	137	29.8	139	29.8	144	29.8
				124	30.1	134	32.1	155	36.2	126	28.4	133	29.7	146	32.3	128	27.3	132	28	140	29.5	129	26.8	132	27.3	137	28.4
			3 ACH	145	35.9	151	35.9	165	35.9	145	35.9	149	35.9	158	35.9	145	35.9	148	35.9	153	35.9	145	35.9	147	35.9	151	35.9
				130	30.2	140	32.2	161	36.3	132	28.5	138	29.8	151	32.4	134	27.4	137	28.1	145	29.6	135	26.9	137	27.4	143	28.5
			4 ACH	154	42	161	42	174	42	155	42	159	42	167	42	155	42	157	42	162	42	155	42	157	42	160	42
				136	30.3	146	32.3	166	36.4	137	28.6	144	29.9	157	32.5	139	27.5	143	28.2	151	29.7	140	27	143	27.5	148	28.6
		80% shading	2 ACH	106	29.8	112	29.8	123	29.8	106	29.8	109	29.8	116	29.8	105	29.8	107	29.8	111	29.8	105	29.8	107	29.8	110	29.8
				78	21.4	86	23.4	104	27.6	77	19.8	83	21	94	23.6	77	18.6	80	19.3	87	20.8	77	18.1	79	18.6	84	19.7
			3 ACH	116	35.9	122	35.9	133	35.9	115	35.9	119	35.9	126	35.9	115	35.9	117	35.9	121	35.9	115	35.9	116	35.9	119	35.9
				84	21.5	92	23.5	110	27.7	83	19.9	89	21.1	100	23.7	83	18.7	86	19.4	93	20.9	83	18.2	85	18.7	90	19.8
			4 ACH	127	42	132	42	143	42	126	42	130	42	137	42	125	42	128	42	132	42	125	42	127	42	130	42
				90	21.6	99	23.6	116	27.8	89	20	95	21.2	106	23.8	89	18.8	92	19.5	99	21	89	18.3	91	18.8	96	19.9
	Double low-e glazing	40% shading	2 ACH	137	29.8	144	29.8	161	29.8	139	29.8	145	29.8	155	29.8	143	29.8	146	29.8	153	29.8	144	29.8	147	29.8	152	29.8
				127	29.6	138	31.7	161	35.8	131	28	139	29.3	153	31.9	136	26.8	141	27.5	150	29	139	26.3	143	26.8	149	27.9
			3 ACH	146	35.9	152	35.9	168	35.9	146	35.9	152	35.9	162	35.9	150	35.9	153	35.9	158	35.9	151	35.9	153	35.9	158	35.9
				133	29.7	143	31.8	166	35.9	137	28.1	144	29.4	159	32	142	26.9	146	27.6	154	29.1	144	26.4	147	26.9	154	28
			4 ACH	156	42	162	42	176	42	156	42	160	42	171	42	158	42	161	42	167	42	160	42	162	42	166	42
				139	29.8	179	31.9	171	36	142	28.2	149	29.5	164	32.1	147	27	151	27.7	160	29.2	149	26.5	152	27	159	28.1
		60% shading	2 ACH	116	29.8	120	29.8	135	29.8	115	29.8	119	29.8	128	29.8	116	29.8	119	29.8	123	29.8	117	29.8	118	29.8	122	29.8
				94	21.7	103	23.8	123	27.9	95	20.1	102	21.4	115	24	98	18.9	102	19.7	110	21.1	99	18.4	102	19	108	20
			3 ACH	125	35.9	130	35.9	143	35.9	124	35.9	128	35.9	137	35.9	124	35.9	127	35.9	132	35.9	125	35.9	127	35.9	130	35.9
				100	21.8	109	23.9	129	28	101	20.2	107	21.5	121	24.1	103	19	107	19.8	115	21.2	104	18.5	107	19.1	113	20.1
			4 ACH	136	42	141	42	153	42	135	42	138	42	146	42	135	42	137	42	142	42	135	42	136	42	140	42
				106	21.9	115	24	135	28.1	106	20.2	113	21.6	126	24.2	109	19.1	113	19.9	120	21.3	110	18.6	113	19.2	118	20.2
		80% shading	2 ACH	99	29.8	103	29.8	114	29.8	97	29.8	100	29.8	107	29.8	96	29.8	98	29.8	102	29.8	96	29.8	98	29.8	101	29.8
				65	16.1	73	18.1	90	22.2	64	14.4	70	15.7	81	18.3	64	13.2	68	14	74	15.5	65	12.7	67	13.3	72	14.3
			3 ACH	109	35.9	112	35.9	124	35.9	107	35.9	110	35.9	117	35.9	106	35.9	108	35.9	112	35.9	106	35.9	107	35.9	110	35.9
				71	16.2	79	18.2	96	22.3	70	14.5	76	15.8	87	18.4	70	13.3	73	14.1	80	15.6	70	12.8	73	13.4	77	14.4
			4 ACH	119	42	123	42	134	42	118	42	120	42	128	42	117	42	118	42	123	42	117	42	118	42	121	42
				77	16.3	85	18.3	102	22.4	76	14.6	82	15.9	93	18.5	76	13.4	79	14.2	86	15.7	76	12.9	79	13.5	83	14.5
	Double low-e + solar protection glazing	40% shading	2 ACH	103	29.8	109	29.8	119	29.8	103	29.8	106	29.8	113	29.8	102	29.8	104	29.8	108	29.8	102	29.8	104	29.8	106	29.8
				74	18.2	82	20.2	101	24.3	73	16.5	79	17.8	92	20.4	74	15.4	77	16.1	85	17.6	75	14.9	77	15.4	83	16.5
			3 ACH	113	35.9	119	35.9	129	35.9	112	35.9	116	35.9	123	35.9	112	35.9	114	35.9	118	35.9	112	35.9	114	35.9	116	35.9
				80	18.3	88	20.3	107	24.4	79	16.6	85	17.9	97	20.5	80	15.5	83	16.2	91	17.7	80	15	83	15.5	88	16.6
			4 ACH	123	42	129	42	140	42	123	42	127	42	133	42	123	42	125	42	129	42	123	42	124	42	127	42
				86	18.4	94	20.7	113	24.5	85	16.7	91	18	103	20.6	86	15.6	89	16.3	97	17.8	86	15.1	88	15.6	94	16.7
		60% shading	2 ACH	97	29.8	100	29.8	112	29.8	96	29.8	98	29.8	105	29.8	95	29.8	96	29.8	100	29.8	95	29.8	96	29.8	98	29.8
				62	14.6	70	16.7	87	20.8	61	13	66	14.3	77	16.9	61	11.8	64	12.6	71	14	61	11.3	63	11.9	68	12.9
			3 ACH	108	35.9	110	35.9	122	35.9	106	35.9	108	35.9	115	35.9	105	35.9	106	35.9	110	35.9	105	35.9	106	35.9	108	35.9
				68	14.7	76	16.8	93	20.9	67	13.1	72	14.4	83	17	67	11.9	70	12.7	77	14.1	67	11.4	69	12	74	13
			4 ACH	118	42	121	42	132	42	117	42	119	42	125	42	116	42	117	42	120	42	116	42	116	42	118	42
				74	14.8	82	16.9	99	21	73	13.2	78	14.5	89	17.1	73	12	76	12.8	82	14.2	73	11.5	75	12.1	80	13.1
		80% shading	2 ACH	91	29.8	96	29.8	103	29.8	90	29.8	93	29.8	97	29.8	90	29.8	91	29.8	94	29.8	90	29.8	90	29.8	92	29.8
				51	12.1	58	14.1	74	18.2	50	10.4	55	11.7	64	14.3	49	9.2	52	10	58	11.5	49	8.8	51	9.3	55	10.3
			3 ACH	101	35.9	106	35.9	113	35.9	100	35.9	103	35.9	107	35.9	100	35.9	101	35.9	104	35.9	100	35.9	100	35.9	102	35.9
				57	12.2	64	14.2	80	18.3	56	10.5	61	11.8	70	14.4	55	9.3	58	10.1	64	11.6	55	8.9	57	9.4	61	10.4
			4 ACH	112	42	116	42	123	42	111	42	114	42	118	42	110	42	112	42	115	42	110	42	111	42	113	42
				64	12.3	70	14.3	86	18.4	62	10.6	67	11.9	76	14.5	61	9.4	64	10.2	70	11.7	61	9	63	9.5	67	10.5

Table B14: Detached house: South orientation and low glazing area (WWR 15%)

Orientation				South																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Low glazing area (WWR 15%)	Single glazing	40% shading	2 ACH	111	29.8	117	29.8	131	29.8	110	29.8	114	29.8	123	29.8	109	29.8	111	29.8	117	29.8	109	29.8	111	29.8	115	29.8
				85	21.6	95	24	117	28.8	85	19.7	92	21.2	106	24.2	86	18.3	90	19.2	98	20.9	87	17.7	90	18.4	96	19.6
			3 ACH	121	35.9	127	35.9	139	35.9	120	35.9	124	35.9	131	35.9	119	35.9	121	35.9	125	35.9	119	35.9	120	35.9	123	35.9
				91	21.7	101	24.1	123	28.9	91	19.8	98	21.2	111	24.3	92	18.4	96	19.3	104	21	92	17.8	95	18.5	101	19.7
			4 ACH	131	42	138	42	148	42	131	42	134	42	141	42	130	42	132	42	136	42	130	42	131	42	134	42
				97	21.8	107	24.2	128	29	97	19.9	104	21.2	117	24.4	98	18.5	101	19.4	110	21.1	98	17.9	101	18.6	107	19.8
		60% shading	2 ACH	101	29.8	106	29.8	119	29.8	99	29.8	103	29.8	111	29.8	99	29.8	101	29.8	106	29.8	99	29.8	100	29.8	104	29.8
				69	17.9	78	19.9	98	24.6	68	15.6	74	17.1	87	20.1	68	14.2	71	15	79	16.8	68	13.6	71	14.2	76	15.4
			3 ACH	111	35.9	116	35.9	129	35.9	109	35.9	113	35.9	121	35.9	108	35.9	111	35.9	116	35.9	108	35.9	110	35.9	114	35.9
				75	18	84	20	104	24.7	74	15.7	80	17.2	93	20.2	74	14.3	77	15.1	85	16.9	74	13.7	77	14.3	82	15.5
			4 ACH	121	42	127	42	139	42	120	42	123	42	132	42	119	42	121	42	126	42	119	42	121	42	124	42
				81	18.1	90	20.1	110	24.8	80	15.8	86	17.3	99	20.3	80	14.4	83	15.2	91	17	80	13.8	82	14.4	88	15.6
		80% shading	2 ACH	94	29.8	98	29.8	108	29.8	93	29.8	96	29.8	100	29.8	92	29.8	93	29.8	96	29.8	91	29.8	93	29.8	95	29.8
				55	14.2	63	16.5	81	21.3	53	12.2	58	13.7	70	16.7	52	10.8	55	11.7	62	13.4	52	10.3	54	10.9	59	12.1
			3 ACH	104	35.9	109	35.9	118	35.9	103	35.9	106	35.9	110	35.9	102	35.9	103	35.9	106	35.9	101	35.9	103	35.9	105	35.9
				61	14.3	69	16.6	87	21.4	59	12.3	65	13.8	76	16.8	58	10.9	61	11.8	68	13.5	58	10.4	60	11	65	12.2
			4 ACH	114	42	119	42	128	42	113	42	116	42	120	42	112	42	114	42	117	42	112	42	113	42	115	42
				67	14.4	75	16.7	93	21.5	65	12.4	71	13.9	82	16.9	64	11	67	11.9	74	13.6	64	10.5	66	11.1	71	12.3
	Ordinary double glazing	40% shading	2 ACH	108	29.8	114	29.8	128	29.8	107	29.8	111	29.8	121	29.8	106	29.8	109	29.8	115	29.8	107	29.8	109	29.8	113	29.8
				81	19.6	91	22	113	26.7	82	17.7	88	19.2	103	22.2	83	16.3	88	17.1	97	18.9	85	15.7	88	16.3	94	17.5
			3 ACH	118	35.9	124	35.9	136	35.9	117	35.9	121	35.9	128	35.9	116	35.9	118	35.9	124	35.9	116	35.9	117	35.9	122	35.9
				87	19.7	97	22.1	119	26.8	87	17.8	94	19.3	109	22.3	89	16.4	93	17.2	102	19	90	15.8	94	16.4	100	17.6
			4 ACH	128	42	135	42	146	42	128	42	131	42	138	42	127	42	129	42	133	42	127	42	128	42	131	42
				93	19.8	103	22.2	125	26.8	93	17.9	100	19.4	114	22.4	95	16.5	99	17.3	108	19.1	96	15.9	99	16.5	105	17.7
		60% shading	2 ACH	99	29.8	104	29.8	117	29.8	97	29.8	102	29.8	110	29.8	97	29.8	100	29.8	104	29.8	97	29.8	99	29.8	102	29.8
				66	15.9	76	18.3	96	23	66	14	72	15.5	85	18.5	66	12.6	70	13.4	78	15.2	67	12	70	12.6	75	13.8
			3 ACH	109	35.9	114	35.9	127	35.9	107	35.9	111	35.9	119	35.9	107	35.9	109	35.9	114	35.9	107	35.9	109	35.9	112	35.9
				73	16	82	18.4	102	23.1	72	14.1	78	15.6	91	18.6	72	12.7	76	13.5	84	15.3	73	12.1	75	12.7	81	13.9
			4 ACH	120	42	125	42	137	42	118	42	122	42	130	42	117	42	120	42	125	42	117	42	119	42	123	42
				79	16.1	88	18.5	108	23.2	78	14.2	84	15.7	97	18.7	78	12.8	82	13.6	90	15.4	78	12.2	81	12.8	87	14
		80% shading	2 ACH	93	29.8	97	29.8	107	29.8	92	29.8	94	29.8	100	29.8	91	29.8	92	29.8	95	29.8	90	29.8	92	29.8	93	29.8
				53	12.9	62	15.3	80	20	52	11	57	12.5	69	15.5	51	9.6	55	10.4	61	12.2	51	9	54	9.6	58	10.8
			3 ACH	103	35.9	107	35.9	117	35.9	102	35.9	104	35.9	109	35.9	101	35.9	102	35.9	105	35.9	100	35.9	102	35.9	104	35.9
				60	13	68	15.4	86	20.1	58	11.1	63	12.6	75	15.6	57	9.7	61	10.5	67	12.3	57	9.1	60	9.7	64	10.9
			4 ACH	113	42	118	42	128	42	112	42	115	42	120	42	111	42	113	42	116	42	111	42	112	42	114	42
				66	13.1	74	15.5	92	20.2	64	11.2	70	12.7	81	15.7	63	9.8	67	10.6	73	12.4	63	9.2	66	9.8	70	11
	Double low-e glazing	40% shading	2 ACH	98	29.8	104	29.8	116	29.8	97	29.8	101	29.8	109	29.8	97	29.8	100	29.8	104	29.8	97	29.8	99	29.8	102	29.8
				66	15.5	76	17.9	97	22.7	66	13.6	72	15.1	86	18.1	67	12.2	71	13.1	80	14.8	68	11.6	71	12.2	77	13.4
			3 ACH	108	35.9	114	35.9	126	35.9	107	35.9	111	35.9	119	35.9	107	35.9	109	35.9	114	35.9	107	35.9	109	35.9	112	35.9
				72	15.6	82	18	102	22.8	72	13.7	78	15.2	92	18.2	73	12.3	77	13.2	85	14.9	74	11.7	77	12.3	83	13.5
			4 ACH	119	42	124	42	137	42	117	42	122	42	129	42	117	42	120	42	124	42	118	42	119	42	122	42
				78	15.7	88	18.1	108	22.9	78	13.8	84	15.3	98	18.3	79	12.4	82	13.3	91	15	79	11.8	82	12.4	88	13.6
		60% shading	2 ACH	95	29.8	98	29.8	111	29.8	93	29.8	96	29.8	103	29.8	92	29.8	94	29.8	98	29.8	92	29.8	93	29.8	96	29.8
				57	13.1	66	15.5	86	20.2	56	11.2	62	12.7	75	15.7	56	9.8	60	10.6	68	12.4	57	9.2	60	9.8	65	11
			3 ACH	105	35.9	108	35.9	121	35.9	104	35.9	106	35.9	113	35.9	103	35.9	104	35.9	108	35.9	102	35.9	103	35.9	105	35.9
				63	13.2	72	15.6	92	20.3	62	11.3	68	12.8	81	15.8	62	9.9	66	10.7	74	12.5	63	9.3	65	9.9	71	11.1
			4 ACH	115	42	119	42	131	42	114	42	116	42	123	42	113	42	115	42	118	42	113	42	114	42	116	42
				69	13.3	78	15.7	98	20.4	68	11.4	74	12.9	87	15.9	68	10	72	10.8	79	12.6	69	9.4	71	10	77	11.2
		80% shading	2 ACH	90	29.8	95	29.8	104	29.8	89	29.8	92	29.8	96	29.8	89	29.8	90	29.8	93	29.8	89	29.8	90	29.8	91	29.8
				49	11.1	57	13.5	76	18.3	48	9.2	53	10.7	65	13.7	47	7.8	50	8.7	57	10.4	47	7.2	49	7.8	54	9.1
			3 ACH	100	35.9	105	35.9	114	35.9	100	35.9	102	35.9	106	35.9	100	35.9	100	35.9	103	35.9	100	35.9	100	35.9	101	35.9
				55	11.2	63	13.6	82	18.4	54	9.3	59	10.8	71	13.8	53	7.8	56	8.8	63	10.5	53	7.3	55	7.9	60	9.2
			4 ACH	111	42	116	42	124	42	110	42	112	42	117	42	110	42	111	42	114	42	110	42	110	42	112	42
				61	11.3	69	13.7	88	18.5	60	9.4	65	10.9	77	13.9	59	7.9	62	8.9	69	10.6	59	7.4	61	8	66	9.3
	Double low-e + solar protection glazing	40% shading	2 ACH	92	29.8	96	29.8	106	29.8	90	29.8	93	29.8	99	29.8	90	29.8	91	29.8	94	29.8	90	29.8	90	29.8	92	29.8
				52	11.8	60	14.2	79	19	51	9.9	56	11.4	68	14.4	50	8.5	53	9.4	61	11.1	50	7.9	53	8.5	58	9.7
			3 ACH	102	35.9	106	35.9	116	35.9	100	35.9	103	35.9	108	35.9	100	35.9	101	35.9	104	35.9	100	35.9	100	35.9	103	35.9
				58	11.9	66	14.3	85	19.1	57	10	62	11.5	74	14.5	56	8.6	59	9.5	66	11.2	56	8	58	8.6	64	9.8
			4 ACH	112	42	117	42	127	42	111	42	114	42	119	42	110	42	112	42	115	42	110	42	111	42	113	42
				64	12	72	14.4	91	19.2	63	10.1	68	11.6	80	14.6	62	8.7	65	9.6	72	11.3	62	8.1	64	8.7	69	9.9
		60% shading	2 ACH	90	29.8	94	29.8	103	29.8	89	29.8	91	29.8	96	29.8	89	29.8	90	29.8	92	29.8	89	29.8	89	29.8	91	29.8
				48	10.7	56	13.1	74	17.9	47	8.8	52	10.3	63	13.3	46	7.4	49	8.3	56	10	46	6.8	48	7.4	53	8.6
			3 ACH	100	35.9	104	35.9	113	35.9	100	35.9	101	35.9	106	35.9	99	35.9	100	35.9	102	35.9	100	35.9	99	35.9	101	35.9
				55	10.8	62	13.2	80	18	53	8.9	59	10.4	69	13.4	52	7.5	55	8.4	62	10.1	52	6.9	54	7.5	59	8.7
			4 ACH	110	42	115	42	124	42	110	42	112	42	117	42	110	42	110	42	113	42	110	42	110	42	111	42
				61	10.9	69	13.3	86	18.1	59	9	64	10.5	75	13.5	58	7.6	61	8.5	68	10.2	58	7	60	7.6	65	8.8
		80% shading	2 ACH	90	29.8	92	29.8	100	29.8	89	29.8	90	29.8	95	29.8	88	29.8	89	29.8	91	29.8	89	29.8	88	29.8	90	29.8
				45	9.8	53	12.2	70	17	43	7.9	48	9.4	59	12.4	42	6.5	45	7.4	52	9.1	42	5.9	44	6.6	49	7.8
			3 ACH	100	35.9	102	35.9	110	35.9	99	35.9	100	35.9	105	35.9	99	35.9	100	35.9	100	35.9	99	35.9	99	35.9	99	35.9
				51	9.9	59	12.3	76	17.1	50	8	54	9.5	65	12.5	49	6.6	52	7.5	58	9.2	48	6	50	6.7	55	7.9
			4 ACH	110	42	113	42	121	42	110	42	110	42	115	42	109	42	110	42	111	42	109	42	109	42	110	42
				57	10	65	12.4	82	17.2	56	8.1	60	9.6	71	12.6	55	6.7	58	7.6	64	9.3	54	6.1	56	6.8	61	8

Table B15: Detached house: South orientation and medium glazing area (WWR 25%)

Orientation				South																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Medium glazing area (WWR 25%)	Single glazing	40% shading	2 ACH	143	29.8	150	29.8	166	29.8	143	29.8	148	29.8	158	29.8	144	29.8	146	29.8	153	29.8	144	29.8	146	29.8	151	29.8
				134	33.2	145	35.5	167	39.9	136	31.4	143	32.9	157	35.7	137	30.2	142	31	150	32.6	138	29.6	141	30.2	147	31.3
			3 ACH	151	35.9	158	35.9	173	35.9	151	35.9	156	35.9	165	35.9	152	35.9	154	35.9	160	35.9	152	35.9	154	35.9	158	35.9
				140	33.3	151	35.6	173	40	142	31.5	148	33	162	35.8	143	30.3	147	31.1	155	32.7	144	29.7	147	30.3	153	31.4
			4 ACH	161	42	168	42	182	42	161	42	165	42	175	42	161	42	164	42	170	42	161	42	163	42	168	42
				146	33.4	156	35.7	179	40.1	147	31.6	154	33.1	168	35.8	149	30.4	153	31.2	161	32.8	150	29.8	153	30.4	158	31.5
		60% shading	2 ACH	120	29.8	125	29.8	139	29.8	119	29.8	122	29.8	131	29.8	118	29.8	120	29.8	125	29.8	118	29.8	119	29.8	123	29.8
				99	25.3	108	27.5	128	32	98	23.5	104	24.9	117	27.7	98	22.2	102	23	109	24.7	98	21.7	101	22.3	106	23.4
			3 ACH	130	35.9	135	35.9	147	35.9	129	35.9	132	35.9	139	35.9	128	35.9	130	35.9	133	35.9	128	35.9	129	35.9	131	35.9
				105	25.4	114	27.6	134	32.1	104	23.6	110	25	123	27.8	104	22.3	108	23.1	115	24.7	104	21.8	107	22.4	112	24.5
			4 ACH	140	42	146	42	157	42	139	42	143	42	149	42	139	42	141	42	144	42	138	42	140	42	142	42
				111	25.5	120	27.7	140	32.2	110	23.7	116	25.1	129	27.9	110	22.4	114	23.2	121	24.8	110	21.9	113	22.5	118	24.6
		80% shading	2 ACH	102	29.8	105	29.8	117	29.8	100	29.8	102	29.8	109	29.8	99	29.8	100	29.8	104	29.8	99	29.8	99	29.8	102	29.8
				68	19.3	76	21.5	93	26	66	17.5	71	18.9	82	21.7	65	16.2	68	17	74	18.6	65	15.7	67	16.3	71	17.4
			3 ACH	112	35.9	115	35.9	127	35.9	110	35.9	112	35.9	119	35.9	109	35.9	110	35.9	113	35.9	109	35.9	110	35.9	111	35.9
				74	19.4	82	21.6	99	26.1	72	17.6	77	19	88	21.8	71	16.3	74	17.1	80	18.7	71	15.8	73	16.4	77	17.5
			4 ACH	122	42	125	42	137	42	121	42	123	42	129	42	120	42	121	42	124	42	119	42	120	42	122	42
				80	19.5	88	21.7	105	26.2	78	17.7	83	19.1	94	21.9	77	16.4	80	17.2	87	18.8	77	15.9	79	16.5	83	17.6
	Ordinary double glazing	40% shading	2 ACH	137	29.8	145	29.8	162	29.8	138	29.8	144	29.8	155	29.8	142	29.8	145	29.8	151	29.8	143	29.8	145	29.8	150	29.8
				128	29.4	139	31.6	161	36.1	131	27.6	138	29	153	31.8	135	26.3	139	27.1	148	28.7	137	25.7	140	26.3	147	27.4
			3 ACH	146	35.9	153	35.9	169	35.9	146	35.9	152	35.9	162	35.9	149	35.9	152	35.9	158	35.9	150	35.9	152	35.9	156	35.9
				133	29.5	144	31.7	167	36.2	136	27.7	143	29.1	159	31.9	140	26.4	145	27.2	154	28.8	142	25.8	145	26.4	152	27.5
			4 ACH	156	42	163	42	177	42	156	42	161	42	171	42	158	42	161	42	167	42	159	42	161	42	165	42
				139	29.6	150	31.8	173	36.3	142	27.8	149	29.2	164	32	146	26.5	150	27.3	159	28.9	147	25.9	151	26.4	157	57.6
		60% shading	2 ACH	116	29.8	121	29.8	136	29.8	115	29.8	119	29.8	129	29.8	115	29.8	118	29.8	124	29.8	116	29.8	118	29.8	122	29.8
				94	22.2	104	24.5	125	28.9	95	20.4	101	21.9	115	24.7	96	19.1	100	20	108	21.6	97	18.6	100	19.2	106	20.3
			3 ACH	126	35.9	131	35.9	144	35.9	125	35.9	128	35.9	137	35.9	124	35.9	127	35.9	132	35.9	124	35.9	126	35.9	130	35.9
				100	22.3	110	24.6	130	29	100	20.5	107	22	120	24.8	102	19.2	106	20.1	114	21.7	103	28.7	106	19.3	111	20.4
			4 ACH	136	42	142	42	154	42	136	42	139	42	147	42	135	42	137	42	142	42	134	42	136	42	140	42
				106	22.4	116	24.7	136	29.1	106	20.6	113	22.1	126	24.9	107	19.3	111	20.2	119	21.8	108	28.8	111	19.4	117	20.5
		80% shading	2 ACH	99	29.8	103	29.8	115	29.8	98	29.8	100	29.8	108	29.8	97	29.8	98	29.8	103	29.8	96	29.8	97	29.8	101	29.8
				65	16.8	74	19.1	92	23.5	64	15.1	69	16.5	81	19.3	64	13.8	67	14.6	74	16.2	64	13.2	66	13.8	71	14.9
			3 ACH	109	35.9	113	35.9	125	35.9	108	35.9	110	35.9	118	35.9	107	35.9	108	35.9	112	35.9	106	35.9	107	35.9	110	35.9
				71	16.9	80	19.2	98	23.6	70	15.2	75	16.6	87	19.4	70	13.9	73	14.7	80	16.3	70	13.3	72	13.9	77	15
			4 ACH	120	42	123	42	135	42	119	42	120	42	128	42	117	42	118	42	123	42	117	42	118	42	121	42
				77	17	86	19.3	104	23.7	76	15.3	82	16.7	93	19.5	76	14	79	14.8	85	16.3	75	13.4	78	14	83	15.1
	Double low-e glazing	40% shading	2 ACH	115	29.8	122	29.8	137	29.8	116	29.8	121	29.8	130	29.8	117	29.8	120	29.8	126	29.8	118	29.8	120	29.8	126	29.8
				95	21.6	105	23.8	127	28.3	97	19.8	104	21.2	119	24	101	18.5	105	19.3	114	20.9	103	18	106	18.5	113	19.7
			3 ACH	125	35.9	130	35.9	145	35.9	124	35.9	129	35.9	138	35.9	126	35.9	128	35.9	134	35.9	126	35.9	128	35.9	132	35.9
				101	21.7	111	23.9	133	28.4	103	19.9	110	21.3	124	24.1	106	18.6	110	19.4	120	21	108	18.1	112	18.6	118	19.8
			4 ACH	136	42	141	42	155	42	135	42	139	42	148	42	135	42	138	42	143	42	136	42	138	42	141	42
				106	21.8	117	24	139	28.5	108	20	115	21.4	130	24.2	111	18.7	116	19.8	125	21.1	114	18.2	117	18.7	123	19.9
		60% shading	2 ACH	103	29.8	109	29.8	121	29.8	103	29.8	107	29.8	114	29.8	103	29.8	105	29.8	109	29.8	102	29.8	104	29.8	107	29.8
				74	16.9	84	19.2	104	23.6	75	15.1	81	16.6	94	19.4	76	13.8	80	14.7	88	16.3	77	13.3	80	13.9	86	15
			3 ACH	113	35.9	119	35.9	130	35.9	113	35.9	117	35.9	123	35.9	113	35.9	115	35.9	118	35.9	112	35.9	114	35.9	116	35.9
				80	17	90	19.3	110	23.6	81	15.2	87	16.7	100	19.5	82	13.9	86	14.8	94	16.4	86	13.4	86	14	91	15.1
			4 ACH	124	42	130	42	140	42	123	42	127	42	134	42	123	42	125	42	129	42	123	42	124	42	127	42
				86	17.1	96	19.4	116	23.7	86	15.3	93	16.8	106	19.6	87	14	91	14.9	99	16.5	88	13.5	91	14.1	97	15.2
		80% shading	2 ACH	97	29.8	100	29.8	112	29.8	95	29.8	97	29.8	105	29.8	94	29.8	95	29.8	100	29.8	94	29.8	95	29.8	98	29.8
				61	14.5	69	16.7	88	21.2	60	12.7	65	14.1	77	16.9	60	11.4	63	12.2	70	13.8	60	10.9	63	11.4	68	12.6
			3 ACH	107	35.9	110	35.9	122	35.9	105	35.9	107	35.9	115	35.9	104	35.9	105	35.9	109	35.9	104	35.9	105	35.9	107	35.9
				67	14.6	75	16.8	93	21.3	66	12.8	71	14.2	83	17	66	11.5	69	12.3	76	13.9	66	11	68	11.5	73	12.7
			4 ACH	117	42	120	42	132	42	116	42	118	42	125	42	115	42	116	42	120	42	115	42	115	42	118	42
				73	14.7	81	16.9	99	21.4	72	12.9	77	14.3	89	17.1	72	11.6	75	12.4	82	14	72	11.1	74	11.6	79	12.8
	Double low-e + solar protection glazing	40% shading	2 ACH	97	29.8	101	29.8	113	29.8	96	29.8	98	29.8	106	29.8	95	29.8	97	29.8	101	29.8	95	29.8	96	29.8	99	29.8
				62	14.6	71	16.8	90	21.3	62	12.8	67	14.2	79	17	62	11.5	65	12.3	72	13.9	62	11	65	11.5	70	12.7
			3 ACH	107	35.9	111	35.9	123	35.9	106	35.9	108	35.9	116	35.9	105	35.9	106	35.9	111	35.9	104	35.9	105	35.9	109	35.9
				68	14.7	77	16.9	96	21.4	68	12.9	73	14.3	85	17.1	68	11.6	71	12.4	78	14	68	11.1	70	11.6	76	12.8
			4 ACH	118	42	121	42	134	42	117	42	118	42	126	42	116	42	117	42	121	42	115	42	116	42	119	42
				74	14.8	83	17	102	21.5	74	13	79	14.4	91	17.2	74	11.7	77	12.5	84	14.1	74	11.2	76	11.7	81	12.9
		60% shading	2 ACH	94	29.8	97	29.8	108	29.8	92	29.8	95	29.8	100	29.8	92	29.8	93	29.8	95	29.8	91	29.8	92	29.8	94	29.8
				55	12.5	63	14.7	81	19.2	54	10.7	59	12.1	70	14.9	53	9.4	57	10.2	63	11.8	53	8.9	56	9.4	60	10.6
			3 ACH	104	35.9	107	35.9	117	35.9	102	35.9	105	35.9	110	35.9	102	35.9	103	35.9	105	35.9	101	35.9	102	35.9	104	35.9
				61	12.6	69	14.8	87	19.3	60	10.8	65	12.2	76	15	59	9.5	63	10.3	69	11.9	59	9	62	9.5	66	10.7
			4 ACH	114	42	118	42	128	42	113	42	116	42	120	42	112	42	114	42	116	42	112	42	113	42	115	42
				67	12.7	75	14.9	93	19.4	66	10.9	71	12.3	82	15.1	65	9.6	69	10.4	75	12	65	9.1	68	9.6	72	10.8
		80% shading	2 ACH	90	29.8	94	29.8	102	29.8	89	29.8	91	29.8	96	29.8	89	29.8	90	29.8	92	29.8	89	29.8	89	29.8	91	29.8
				48	10.9	55	13.1	72	17.6	47	9.1	51	10.5	62	13.3	46	7.8	49	8.6	55	10.2	45	7.3	48	7.8	52	9
			3 ACH	100	35.9	104	35.9	111	35.9	100	35.9	101	35.9	106	35.9	100	35.9	100	35.9	102	35.9	100	35.9	100	35.9	110	35.9
				54	11	61	13.2	78	17.7	53	9.2	55	10.6	68	13.2	52	7.9	55	8.7	61	10.3	52	7.4	54	7.9	58	9.1
			4 ACH	110	42	114	42	122	42	110	42	112	42	117	42	110	42	110	42	113	42	110	42	110	42	111	42
				60	11.1	68	13.3	84	17.8	59	9.3	63	10.7	74	13.1	58	8	61	8.8	67	10.4	58	7.5	60	8	64	9.2

Table B16: Detached house: South orientation and high glazing area (WWR 35%)

Orientation			South											
Wall, roof insulation			25 mm			50 mm			100 mm			150 mm		
Exterior absorptivity			0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9	0.3	0.5	0.9
High glazing area (WWR 35%) — Single glazing	40% shading	2 ACH	181 29.8	189 29.8	205 29.8	182 29.8	187 29.8	198 29.8	184 29.8	187 29.8	193 29.8	184 29.8	187 29.8	192 29.8
			189 45.6	199 47.7	221 51.8	191 43.9	197 45.2	211 47.8	193 42.7	197 43.5	205 45	194 42.2	197 42.7	202 43.8
		3 ACH	188 35.9	196 7	212 35.9	189 35.9	194 35.9	205 35.9	191 35.9	194 35.9	200 35.9	192 35.9	194 35.9	198 35.9
			195 45.7	205 47.7	226 51.9	196 44	203 45.3	217 47.9	198 42.8	202 43.6	210 45.1	199 42.3	202 42.8	208 43.9
		4 ACH	197 42	204 42	220 42	198 42	203 42	213 42	199 42	203 42	209 42	200 42	202 42	207 42
			201 45.8	211 47.8	232 52	202 44.1	209 45.4	48 48	204 42.9	208 43.7	216 45.2	205 42.4	208 42.9	213 44
	60% shading	2 ACH	141 29.8	148 29.8	161 29.8	141 29.8	145 29.8	153 29.8	141 29.8	143 29.8	148 29.8	141 29.8	143 29.8	146 29.8
			132 34.2	141 36.3	161 40.5	132 32.5	138 33.8	150 36.5	132 31.3	136 32.1	143 33.6	132 30.8	135 31.4	140 32.4
		3 ACH	150 35.9	156 35.9	169 35.9	150 35.9	154 35.9	161 35.9	149 35.9	152 35.9	156 35.9	150 35.9	151 35.9	154 35.9
			138 34.3	147 36.4	167 40.6	138 32.6	144 33.9	156 36.6	138 31.4	142 32.2	149 33.7	138 30.9	141 31.5	146 32.5
		4 ACH	160 42	166 42	178 42	159 42	163 42	171 42	159 42	162 42	166 42	159 42	161 42	164 42
			144 34.4	153 36.5	172 40.7	144 32.7	150 34	162 36.7	144 31.5	147 32.3	155 33.8	144 31	147 32.6	152 32.6
	80% shading	2 ACH	109 29.8	114 29.8	125 29.8	108 29.8	111 29.8	118 29.8	107 29.8	109 29.8	113 29.8	107 29.8	108 29.8	111 29.8
			81 24.5	89 26.5	106 30.7	80 22.8	85 24.1	95 26.7	79 21.6	82 22.3	88 23.9	79 21.1	81 21.6	85 22.7
		3 ACH	119 35.9	124 35.9	135 35.9	117 35.9	121 35.9	128 35.9	117 35.9	119 35.9	123 35.9	116 35.9	118 35.9	121 35.9
			88 24.6	95 26.6	112 30.8	86 22.9	91 24.2	101 26.8	85 21.7	88 22.4	94 24	85 21.2	87 21.7	91 22.8
		4 ACH	129 42	135 42	145 42	128 42	131 42	139 42	127 42	129 42	133 42	127 42	128 42	131 42
			94 24.7	102 26.7	118 30.9	92 23	97 24.3	107 26.9	91 21.8	94 22.5	100 24.1	91 21.3	93 21.8	97 22.9
Ordinary double glazing	40% shading	2 ACH	175 29.8	184 29.8	200 29.8	179 29.8	184 29.8	195 29.8	182 29.8	185 29.8	192 29.8	184 29.8	186 29.8	191 29.8
			181 39.7	192 41.8	214 46	185 38.1	193 39.4	207 42	190 36.9	194 37.6	203 39.1	192 36.4	195 36.9	201 38
		3 ACH	182 35.9	190 35.9	207 35.9	186 35.9	191 35.9	201 35.9	188 35.9	191 35.9	198 35.9	190 35.9	192 35.9	197 35.9
			186 39.8	197 41.9	220 46.1	191 38.2	198 39.5	212 42.1	195 37	199 37.7	208 40	197 36.5	200 37	207 38.1
		4 ACH	190 42	199 42	215 42	194 42	199 42	209 42	196 42	199 42	205 42	198 42	200 42	204 42
			192 39.9	203 42	225 46.2	196 38.3	203 39.6	218 42.2	200 37.1	205 37.8	213 40.1	203 36.6	206 37.1	212 38.2
	60% shading	2 ACH	137 29.8	143 29.8	158 29.8	137 29.8	141 29.8	151 29.8	138 29.8	141 29.8	147 29.8	138 29.8	141 29.8	146 29.8
			126 29.5	136 31.6	157 35.8	128 27.9	134 29.2	148 31.8	130 26.7	134 27.4	142 28.9	131 26.2	134 26.7	140 27.8
		3 ACH	145 35.9	152 35.9	166 35.9	146 35.9	150 35.9	159 35.9	146 35.9	148 35.9	154 35.9	146 35.9	148 35.9	153 35.9
			132 29.6	142 31.7	162 35.9	133 28	140 29.3	153 31.9	135 26.8	139 27.5	147 29	137 26.2	139 26.8	145 27.9
		4 ACH	155 42	161 42	175 42	155 42	159 42	168 42	156 42	158 42	163 42	156 42	158 42	162 42
			138 29.7	148 31.8	168 26	139 28.1	146 29.4	159 32	141 26.9	145 27.6	153 29.1	142 26.3	145 26.9	151 28
	80% shading	2 ACH	106 29.8	112 29.8	122 29.8	105 29.8	109 29.8	116 29.8	105 29.8	107 29.8	111 29.8	105 29.8	106 29.8	109 29.8
			78 20.8	86 22.9	104 27.1	77 19.1	82 20.4	94 23.1	77 17.9	80 18.7	87 20.2	77 17.4	79 18	84 19
		3 ACH	116 35.9	122 35.9	132 35.9	115 35.9	119 35.9	126 35.9	115 35.9	117 35.9	121 35.9	115 35.9	116 35.9	119 35.9
			84 20.9	92 23	110 27.2	83 19.2	88 20.5	100 23.2	83 18	86 18.8	93 20.3	83 17.5	85 18.1	90 19.1
		4 ACH	126 42	132 42	143 42	126 42	129 42	136 42	125 42	127 42	131 42	125 42	127 42	130 42
			90 21	98 23.1	116 27.3	89 19.3	94 20.6	106 23.3	89 18.1	92 18.9	98 20.4	89 17.6	91 18.2	96 19.2
Double low-e glazing	40% shading	2 ACH	137 29.8	145 29.8	161 29.8	141 29.8	146 29.8	156 29.8	144 29.8	147 29.8	154 29.8	146 29.8	149 29.8	153 29.8
			129 28.1	140 30.1	162 34.3	134 26.4	141 27.7	155 30.3	139 25.2	143 25.9	152 27.5	142 24.7	145 25.2	151 26.3
		3 ACH	146 35.9	153 35.9	168 35.9	148 35.9	153 35.9	163 35.9	150 35.9	154 35.9	160 35.9	152 35.9	155 35.9	159 35.9
			134 28.2	145 30.2	167 34.4	139 26.5	146 27.8	161 30.4	144 25.3	148 26	157 27.6	147 24.8	150 25.3	156 26.4
		4 ACH	156 42	162 42	177 42	157 42	162 42	171 42	159 42	162 42	168 42	160 42	163 42	167 42
			140 28.3	151 30.3	173 34.5	144 26.6	151 27.9	166 30.5	149 25.4	153 26.1	162 27.6	152 24.9	155 25.4	161 26.5
	60% shading	2 ACH	115 29.8	121 29.8	135 29.8	115 29.8	120 29.8	129 29.8	117 29.8	119 29.8	124 29.8	117 29.8	119 29.8	122 29.8
			95 21.4	104 23.5	125 27.7	96 19.7	103 21	116 23.7	99 18.5	103 19.3	111 20.8	101 18	104 18.6	109 19.6
		3 ACH	125 35.9	130 35.9	144 35.9	124 35.9	129 35.9	137 35.9	125 35.9	128 35.9	133 35.9	126 35.9	127 35.9	131 35.9
			101 21.5	110 23.6	130 27.8	102 19.8	109 21.1	122 23.8	104 18.6	108 19.4	116 20.9	106 18.1	109 18.7	15 19.7
		4 ACH	136 42	140 42	153 42	135 42	138 42	147 42	135 42	137 42	142 42	135 42	137 42	141 42
			107 21.6	116 23.7	136 27.9	108 19.9	114 21.2	127 23.9	110 18.7	114 19.5	122 21	111 18.2	114 18.8	120 19.8
	80% shading	2 ACH	98 29.8	102 29.8	114 29.8	97 29.8	100 29.8	107 29.8	96 29.8	98 29.8	102 29.8	96 29.8	97 29.8	100 29.8
			65 15.7	73 17.8	90 21.9	64 14	69 15.3	81 18	64 12.8	67 13.6	74 15.1	64 12.3	67 12.9	72 13.9
		3 ACH	108 35.9	112 35.9	124 35.9	107 35.9	109 35.9	117 35.9	106 35.9	108 35.9	112 35.9	106 35.9	107 35.9	110 35.9
			71 15.8	79 17.9	96 22	70 14.1	75 15.4	87 18.1	70 12.9	73 13.7	80 15.2	70 12.4	73 13	77 14
		4 ACH	119 42	123 42	134 42	118 42	120 42	127 42	117 42	118 42	123 42	116 42	118 42	121 42
			77 15.9	85 18	102 22.1	76 14.2	81 15.5	92 18.2	76 13	79 13.8	86 15.3	76 12.5	78 13.1	83 14.1
Double low-e + solar protection glazing	40% shading	2 ACH	103 29.8	109 29.8	119 29.8	103 29.8	106 29.8	113 29.8	103 29.8	105 29.8	108 29.8	102 29.8	104 29.8	106 29.8
			74 17.5	83 19.6	101 23.8	74 15.9	80 17.2	92 19.8	75 14.7	79 15.4	86 16.9	76 14.2	78 14.7	84 15.8
		3 ACH	113 35.9	119 35.9	129 35.9	113 35.9	116 35.9	122 35.9	112 35.9	114 35.9	118 35.9	112 35.9	114 35.9	116 35.9
			80 17.6	89 19.7	107 23.9	80 16	86 17.3	98 19.9	81 14.8	84 15.5	92 17	81 14.3	84 14.8	89 15.9
		4 ACH	123 42	129 42	140 42	123 42	127 42	133 42	123 42	125 42	129 42	123 42	124 42	127 42
			86 17.7	95 19.8	113 24	86 16.1	92 17.4	103 20	86 14.9	90 15.6	97 17.1	87 14.4	90 14.9	95 16
	60% shading	2 ACH	97 29.8	101 29.8	112 29.8	96 29.8	98 29.8	105 29.8	95 29.8	96 29.8	100 29.8	95 29.8	96 29.8	99 29.8
			62 14.5	70 16.6	87 20.8	61 12.8	67 14.2	78 16.8	61 11.6	65 12.4	71 13.9	62 11.2	64 11.7	68 12.8
		3 ACH	107 35.9	110 35.9	122 35.9	106 35.9	108 35.9	115 35.9	105 35.9	106 35.9	110 35.9	105 35.9	105 35.9	108 35.9
			68 14.6	76 16.7	93 20.9	68 12.9	73 14.3	83 16.9	67 11.7	70 12.5	77 14	67 11.3	70 11.8	74 12.8
		4 ACH	118 42	121 42	132 42	117 42	118 42	125 42	116 42	117 42	121 42	115 42	116 42	119 42
			74 14.7	82 16.8	99 21	74 13	79 14.4	89 17	73 11.8	76 12.6	83 14.1	73 11.4	76 11.9	80 12.9
	80% shading	2 ACH	91 29.8	96 29.8	103 29.8	90 29.8	93 29.8	97 29.8	90 29.8	91 29.8	94 29.8	90 29.8	90 29.8	92 29.8
			51 11.9	58 14	74 18.2	50 10.3	54 11.6	64 14.2	49 9.1	52 9.8	58 11.3	49 8.6	51 9.1	55 10.2
		3 ACH	101 35.9	106 35.9	113 35.9	100 35.9	103 35.9	107 35.9	100 35.9	101 35.9	104 35.9	100 35.9	100 35.9	102 35.9
			57 12	64 14.1	80 18.3	56 10.4	60 11.7	70 14.3	55 9.2	58 9.9	64 11.4	55 8.7	57 9.2	61 10.3
		4 ACH	112 42	116 42	123 42	111 42	114 42	118 42	110 42	112 42	114 42	110 42	111 42	113 42
			63 12.1	70 14.2	86 18.4	62 10.5	67 11.8	76 14.4	61 9.3	64 10	70 11.5	61 8.8	63 9.3	67 10.4

Table B17: Detached house: East orientation and low glazing area (WWR 15%)

Orientation			East																							
Wall, roof insulation			25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity			0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Low glazing area (WWR 15%) – Single glazing	40% shading	2 ACH	114	29.8	120	29.8	131	29.8	113	29.8	117	29.8	124	29.8	113	29.8	115	29.8	118	29.8	113	29.8	114	29.8	116	29.8
			88	23.6	97	25.8	117	30.2	88	21.8	94	23.2	107	26	89	20.4	92	21.2	100	22.9	89	19.9	92	20.5	98	21.6
		3 ACH	123	35.9	130	35.9	140	35.9	123	35.9	127	35.9	133	35.9	123	35.9	125	35.9	128	35.9	123	35.9	124	35.9	126	35.9
			94	23.7	103	25.9	123	30.3	94	21.9	100	23.3	113	26.1	95	20.5	98	21.3	106	23	95	20	98	20.6	104	21.7
		4 ACH	134	42	140	42	150	42	133	42	137	42	144	42	133	42	135	42	139	42	133	42	134	42	137	42
			100	23.8	109	26	129	30.4	100	22	106	23.4	119	26.2	101	20.6	104	21.4	112	23.1	101	20.1	103	20.7	109	21.8
	60% shading	2 ACH	102	29.8	108	29.8	120	29.8	101	29.8	105	29.8	113	29.8	101	29.8	103	29.8	108	29.8	101	29.8	102	29.8	106	29.8
			71	18.6	80	20.8	98	25.2	70	16.8	76	18.1	88	20.9	70	15.4	74	16.2	81	17.8	70	14.9	73	15.5	78	16.6
		3 ACH	112	35.9	117	35.9	129	35.9	111	35.9	114	35.9	122	35.9	110	35.9	113	35.9	117	35.9	110	35.9	112	35.9	115	35.9
			77	18.7	86	20.9	104	25.3	76	16.9	82	18.2	94	21	76	15.5	80	16.3	87	17.9	76	15	79	15.6	84	16.7
		4 ACH	123	42	128	42	140	42	121	42	125	42	133	42	121	42	123	42	128	42	121	42	122	42	126	42
			83	18.8	92	21	110	25.4	82	17	88	18.3	99	21.1	82	15.6	86	16.4	93	18	82	15.1	85	15.7	90	16.8
	80% shading	2 ACH	94	29.8	99	29.8	107	29.8	93	29.8	96	29.8	100	29.8	92	29.8	94	29.8	97	29.8	92	29.8	93	29.8	95	29.8
			55	14.6	63	16.8	79	21.2	54	12.8	59	14.2	69	17	53	11.4	56	12.2	62	13.8	53	10.9	55	11.5	59	12.6
		3 ACH	104	35.9	109	35.9	117	35.9	103	35.9	106	35.9	110	35.9	102	35.9	104	35.9	107	35.9	102	35.9	103	35.9	105	35.9
			62	14.7	69	16.9	85	21.3	60	12.9	65	14.3	75	17.1	59	11.5	62	12.3	68	13.9	59	11	61	11.6	65	12.7
		4 ACH	115	42	119	42	127	42	114	42	117	42	121	42	113	42	115	42	117	42	113	42	114	42	116	42
			68	14.8	75	17	92	21.4	66	13	71	14.4	81	17.2	65	11.6	68	12.4	74	14	65	11.1	67	11.7	71	12.8
Ordinary double glazing	40% shading	2 ACH	110	29.8	116	29.8	129	29.8	110	29.8	114	29.8	121	29.8	109	29.8	111	29.8	117	29.8	109	29.8	110	29.8	115	29.8
			83	21.3	93	23.6	114	28	84	19.5	90	20.9	104	23.7	86	18.2	90	19	97	20.6	87	17.6	89	18.2	95	19.3
		3 ACH	120	35.9	126	35.9	137	35.9	120	35.9	123	35.9	130	35.9	119	35.9	121	35.9	125	35.9	119	35.9	120	35.9	123	35.9
			89	21.4	99	23.7	119	28.1	89	19.6	96	21	110	23.8	91	18.3	95	19.1	103	20.7	92	17.7	95	18.3	101	19.4
		4 ACH	130	42	137	42	147	42	130	42	134	42	140	42	130	42	132	42	135	42	130	42	131	42	133	42
			95	21.5	105	23.8	125	28.2	95	19.7	102	21.1	115	23.9	97	18.4	101	19.2	109	20.8	98	17.8	101	18.4	106	19.5
	60% shading	2 ACH	100	29.8	105	29.8	117	29.8	99	29.8	103	29.8	110	29.8	99	29.8	101	29.8	105	29.8	99	29.8	101	29.8	103	29.8
			68	16.8	77	19.1	96	23.5	68	15	73	16.4	86	19.2	68	13.7	72	14.5	79	16.1	69	13.1	71	13.7	76	14.8
		3 ACH	110	35.9	115	35.9	127	35.9	108	35.9	112	35.9	120	35.9	108	35.9	111	35.9	115	35.9	109	35.9	110	35.9	113	35.9
			74	16.9	83	19.2	102	23.6	74	15.1	79	16.5	92	19.3	74	13.8	78	14.6	85	16.2	75	13.2	77	13.8	82	14.9
		4 ACH	121	42	125	42	138	42	119	42	123	42	131	42	119	42	121	42	126	42	119	42	121	42	124	42
			80	17	89	19.3	108	23.7	80	15.2	85	16.6	98	19.4	80	13.9	84	14.7	91	16.3	80	13.3	83	13.9	88	15
	80% shading	2 ACH	93	29.8	97	29.8	106	29.8	92	29.8	95	29.8	99	29.8	91	29.8	93	29.8	95	29.8	91	29.8	92	29.8	94	29.8
			54	13.3	61	15.5	79	19.9	53	11.4	58	12.8	69	15.6	52	10.1	55	10.9	62	12.5	52	9.6	54	10.2	59	11.4
		3 ACH	103	35.9	107	35.9	116	35.9	102	35.9	105	35.9	109	35.9	101	35.9	103	35.9	105	35.9	101	35.9	102	35.9	104	35.9
			60	13.4	67	15.6	85	20	59	11.5	64	12.9	75	15.7	58	10.2	61	11	68	12.6	58	9.7	60	10.3	65	11.5
		4 ACH	114	42	118	42	127	42	113	42	115	42	119	42	112	42	113	42	116	42	112	42	113	42	115	42
			66	13.5	74	15.7	91	20.1	65	11.6	70	13	81	15.8	64	10.3	67	11.1	73	12.7	64	9.8	66	10.4	71	11.6
Double low-e glazing	40% shading	2 ACH	99	29.8	105	29.8	117	29.8	99	29.8	103	29.8	110	29.8	99	29.8	101	29.8	105	29.8	99	29.8	100	29.8	103	29.8
			68	16.6	76	18.8	96	23.2	67	14.7	74	16.1	86	18.9	68	13.4	72	14.2	80	15.8	70	12.9	72	13.4	78	14.6
		3 ACH	110	35.9	115	35.9	127	35.9	108	35.9	112	35.9	120	35.9	108	35.9	111	35.9	115	35.9	108	35.9	110	35.9	113	35.9
			74	16.7	82	18.9	102	23.3	73	14.8	79	16.2	92	19	74	13.5	78	14.3	86	15.9	75	13	78	13.5	83	14.7
		4 ACH	120	42	125	42	137	42	119	42	123	42	130	42	119	42	121	42	126	42	119	42	121	42	124	42
			80	16.8	88	19	107	13.4	79	14.9	85	16.3	98	19.1	80	13.6	84	14.4	91	16	81	13.1	84	13.6	89	14.8
	60% shading	2 ACH	96	29.8	99	29.8	110	29.8	94	29.8	96	29.8	103	29.8	93	29.8	94	29.8	98	29.8	93	29.8	94	29.8	96	29.8
			58	13.6	66	15.8	85	20.3	57	11.8	63	13.2	75	16	58	10.5	61	11.3	68	12.9	58	9.9	61	10.5	66	11.6
		3 ACH	106	35.9	109	35.9	120	35.9	104	35.9	106	35.9	113	35.9	103	35.9	105	35.9	108	35.9	103	35.9	104	35.9	106	35.9
			64	13.7	72	15.9	90	20.4	64	11.9	69	13.3	81	16.1	64	10.6	67	11.4	74	13	64	10	67	10.6	72	11.7
		4 ACH	116	42	120	42	131	42	115	42	117	42	124	42	114	42	115	42	119	42	114	42	115	42	117	42
			71	13.8	78	16	96	20.5	70	12	75	13.4	87	16.2	70	10.7	73	11.5	80	13.1	70	10.1	72	10.7	77	11.8
	80% shading	2 ACH	90	29.8	95	29.8	103	29.8	90	29.8	92	29.8	96	29.8	89	29.8	90	29.8	93	29.8	89	29.8	90	29.8	92	29.8
			49	11.3	57	13.5	74	17.9	48	9.5	53	10.8	64	13.6	48	8.1	51	8.9	57	10.5	48	7.6	50	8.1	54	9.3
		3 ACH	100	35.9	105	35.9	113	35.9	100	35.9	102	35.9	106	35.9	100	35.9	100	35.9	103	35.9	100	35.9	100	35.9	102	35.9
			55	11.4	63	13.6	80	18	54	9.6	59	10.9	70	13.7	54	8.2	57	9	63	10.6	54	7.7	56	8.2	60	9.4
		4 ACH	111	42	115	42	123	42	110	42	112	42	117	42	110	42	111	42	114	42	110	42	110	42	112	42
			62	11.5	69	13.7	86	18.1	60	9.7	65	11	76	13.8	60	8.3	63	9.1	69	10.7	60	7.8	62	8.3	66	9.5
Double low-e + solar protection glazing	40% shading	2 ACH	92	29.8	96	29.8	105	29.8	91	29.8	94	29.8	98	29.8	90	29.8	92	29.8	94	29.8	90	29.8	91	29.8	93	29.8
			52	12.1	60	14.4	77	18.8	51	10.3	56	11.7	67	14.5	51	9	54	9.8	61	11.4	51	8.4	53	9	58	10.1
		3 ACH	102	35.9	106	35.9	115	35.9	101	35.9	104	35.9	108	35.9	100	35.9	102	35.9	104	35.9	100	35.9	101	35.9	103	35.9
			58	12.2	66	14.5	83	18.9	57	10.4	62	11.8	73	14.6	57	9.1	60	9.9	66	11.5	57	8.5	59	9.1	64	10.2
		4 ACH	113	42	117	42	126	42	112	42	114	42	118	42	111	42	112	42	115	42	110	42	111	42	114	42
			64	12.3	72	14.6	89	19	63	10.5	68	11.9	79	14.7	63	9.2	66	10	72	11.6	63	8.6	65	9.2	70	10.3
	60% shading	2 ACH	90	29.8	94	29.8	102	29.8	89	29.8	91	29.8	96	29.8	89	29.8	90	29.8	92	29.8	89	29.8	89	29.8	91	29.8
			48	10.8	56	13	72	17.5	47	9	52	10.4	63	13.2	47	7.7	49	8.5	56	10.1	47	7.1	49	7.7	53	8.8
		3 ACH	100	35.9	104	35.9	112	35.9	100	35.9	101	35.9	106	35.9	99	35.9	100	35.9	103	35.9	99	35.9	99	35.9	101	35.9
			54	10.9	62	13.1	78	17.6	53	9.1	58	10.5	69	13.3	53	7.8	56	8.6	62	10.2	53	7.2	55	7.8	59	8.9
		4 ACH	110	42	115	42	122	42	110	42	112	42	117	42	110	42	110	42	113	42	110	42	110	42	112	42
			61	11	68	13.2	84	17.7	59	9.2	64	10.6	74	13.4	59	7.9	62	8.7	68	10.3	59	7.3	61	7.9	65	9
	80% shading	2 ACH	89	29.8	92	29.8	99	29.8	89	29.8	89	29.8	94	29.8	88	29.8	89	29.8	90	29.8	88	29.8	88	29.8	89	29.8
			45	9.8	52	12	68	16.4	43	7.9	48	9.3	58	12.1	43	6.6	45	7.4	51	9	42	6.1	44	6.6	49	7.8
		3 ACH	100	35.9	102	35.9	109	35.9	99	35.9	100	35.9	104	35.9	98	35.9	99	35.9	100	35.9	99	35.9	98	35.9	99	35.9
			51	9.9	58	12.1	74	16.5	49	8	54	9.4	64	12.2	49	6.7	51	7.5	57	9.1	48	6.2	50	6.7	55	7.9
		4 ACH	110	42	112	42	120	42	110	42	110	42	115	42	108	42	110	42	111	42	109	42	108	42	110	42
			57	10	64	12.2	80	16.6	56	8.1	60	9.5	70	12.3	55	6.8	57	7.6	63	9.2	54	6.3	56	6.8	61	8

Table B18: Detached house: East orientation and medium glazing area (WWR 25%)

Orientation				East																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Medium glazing area (WWR 25%)	Single glazing	40% shading	2 ACH	148	29.8	155	29.8	168	29.8	148	29.8	153	29.8	161	29.8	149	29.8	152	29.8	156	29.8	149	29.8	151	29.8	155	29.8
				140	36.9	150	39	170	43.1	141	35.3	147	36.5	160	39.1	142	34	146	34.8	154	36.3	143	33.5	146	34.1	151	35.1
			3 ACH	156	35.9	163	35.9	176	35.9	157	35.9	161	35.9	169	35.9	158	35.9	160	35.9	165	35.9	158	35.9	160	35.9	163	35.9
				146	37	156	39.1	176	43.2	147	35.4	153	36.6	166	40	148	34.1	152	34.9	159	36.7	149	33.6	151	34.2	157	35.2
			4 ACH	166	42	173	42	186	42	17	42	171	42	179	42	167	42	170	42	175	42	168	42	169	42	173	42
				152	37.1	161	39.2	181	43.3	153	35.5	159	36.7	172	40.1	154	34.2	158	35	165	36.8	154	33.7	157	34.3	162	35.3
		60% shading	2 ACH	123	29.8	129	29.8	140	29.8	123	29.8	126	29.8	133	29.8	122	29.8	124	29.8	127	29.8	122	29.8	123	29.8	125	29.8
				102	27.5	111	29.5	130	33.6	102	25.8	108	27.1	120	29.7	102	24.6	106	25.3	113	26.8	103	24.1	105	24.6	110	25.6
			3 ACH	133	35.9	139	35.9	149	35.9	133	35.9	136	35.9	141	35.9	132	35.9	134	35.9	137	35.9	132	35.9	133	35.9	135	35.9
				108	27.6	117	29.6	135	33.7	108	25.9	114	27.2	125	29.8	108	24.7	112	25.4	118	26.9	109	24.2	111	24.7	116	25.7
			4 ACH	144	42	149	42	158	42	143	42	146	42	152	42	143	42	144	42	148	42	142	42	144	42	146	42
				114	27.7	123	29.7	141	33.8	114	26	120	27.3	131	29.9	114	24.8	118	25.5	124	27	114	24.3	117	14.8	122	25.8
		80% shading	2 ACH	103	29.8	106	29.8	117	29.8	101	29.8	103	29.8	110	29.8	100	29.8	101	29.8	105	29.8	100	29.8	101	29.8	103	29.8
				69	20.3	77	22.3	93	26.4	68	18.6	73	19.9	83	22.4	67	17.4	70	18.1	76	19.6	67	16.9	69	17.4	73	18.4
			3 ACH	113	35.9	116	35.9	126	35.9	112	35.9	113	35.9	119	35.9	111	35.9	112	35.9	114	35.9	110	35.9	111	35.9	112	35.9
				75	20.4	83	22.4	99	26.5	74	18.7	79	20	89	22.5	73	17.5	76	18.2	82	19.7	73	17	75	17.5	79	18.5
			4 ACH	123	42	126	42	137	42	122	42	124	42	130	42	121	42	122	42	125	42	121	42	121	42	123	42
				81	20.5	89	22.5	105	26.6	80	18.8	85	20.1	95	22.6	80	17.6	82	18.3	88	19.8	79	17.1	81	17.6	85	18.6
	Ordinary double glazing	40% shading	2 ACH	142	29.8	149	29.8	163	29.8	143	29.8	147	29.8	156	29.8	144	29.8	146	29.8	154	29.8	145	29.8	148	29.8	153	29.8
				132	32.6	142	34.7	163	38.8	134	31	141	32.2	155	34.8	138	29.7	142	30.5	150	32	140	29.2	143	29.8	149	30.8
			3 ACH	150	35.9	157	35.9	171	35.9	151	35.9	156	35.9	164	35.9	152	35.9	155	35.9	161	35.9	153	35.9	155	35.9	160	35.9
				138	32.7	148	34.8	169	38.9	140	31.1	146	32.3	161	34.9	143	29.8	147	30.6	156	32.1	145	29.3	148	29.9	154	30.9
			4 ACH	160	42	167	42	180	42	161	42	166	42	174	42	162	42	165	42	170	42	162	42	164	42	168	42
				144	32.8	154	34.9	174	39	146	31.2	152	32.4	166	35	148	29.9	153	30.7	161	32.2	150	29.4	153	30	159	31
		60% shading	2 ACH	119	29.8	124	29.8	137	29.8	118	29.8	121	29.8	130	29.8	117	29.8	120	29.8	126	29.8	118	29.8	121	29.8	124	29.8
				97	24.2	106	26.2	125	30.3	98	22.5	104	23.8	116	26.3	99	21.2	103	22	110	23.5	100	20.8	103	21.3	108	22.3
			3 ACH	129	35.9	134	35.9	145	35.9	128	35.9	131	35.9	139	35.9	128	35.9	129	35.9	134	35.9	127	35.9	129	35.9	133	35.9
				103	24.3	112	26.3	131	30.4	104	22.6	110	23.9	122	26.4	105	21.3	109	22.1	116	23.6	106	20.9	108	21.4	114	22.4
			4 ACH	140	42	145	42	155	42	139	42	142	42	148	42	138	42	140	42	144	42	138	42	139	42	142	42
				109	24.4	118	26.4	137	30.5	110	22.7	115	24	128	26.5	111	21.4	114	22.2	122	23.7	111	21	114	21.5	119	22.5
		80% shading	2 ACH	100	29.8	103	29.8	115	29.8	99	29.8	101	29.8	108	29.8	98	29.8	99	29.8	104	29.8	97	29.8	99	29.8	102	29.8
				67	17.7	74	19.7	91	23.8	66	16	71	17.3	81	19.9	65	14.8	68	15.5	75	17	65	14.3	68	14.8	72	15.8
			3 ACH	110	35.9	113	35.9	125	35.9	109	35.9	111	35.9	118	35.9	108	35.9	109	35.9	113	35.9	107	35.9	108	35.9	111	35.9
				73	17.8	80	19.8	97	23.9	72	16.1	77	17.4	87	20	71	14.9	74	15.6	81	17.1	71	14.4	74	14.9	78	15.9
			4 ACH	121	42	124	42	135	42	120	42	121	42	128	42	119	42	119	42	124	42	118	42	119	42	122	42
				79	17.9	86	19.9	103	24	78	16.2	83	17.5	93	20.1	77	15	80	15.7	86	17.2	77	14.5	80	15	84	16
	Double low-e glazing	40% shading	2 ACH	119	29.8	124	29.8	138	29.8	118	29.8	123	29.8	132	29.8	120	29.8	123	29.8	128	29.8	121	29.8	122	29.8	126	29.8
				98	23.6	107	25.7	127	29.8	100	22	106	23.2	120	25.8	103	20.7	107	21.5	115	23	104	20.2	108	20.8	114	21.8
			3 ACH	129	35.9	133	35.9	147	35.9	127	35.9	131	35.9	140	35.9	128	35.9	131	35.9	136	35.9	129	35.9	131	35.9	134	35.9
				104	23.7	113	25.8	133	29.9	105	22.1	112	23.3	125	25.9	108	20.8	112	21.6	121	23.1	110	20.3	113	20.9	119	21.9
			4 ACH	139	42	144	42	156	42	138	42	141	42	150	42	138	42	141	42	146	42	139	42	141	42	144	42
				109	23.8	119	25.9	139	30	111	22.2	117	23.4	130	26	113	20.9	117	21.7	126	23.2	115	20.4	118	21	124	22
		60% shading	2 ACH	105	29.8	111	29.8	121	29.8	105	29.8	108	29.8	114	29.8	105	29.8	107	29.8	110	29.8	105	29.8	106	29.8	109	29.8
				76	18.1	85	20.1	104	24.2	77	16.4	83	17.7	95	20.3	78	15.2	82	15.9	89	17.4	79	14.7	82	15.2	87	16.3
			3 ACH	115	35.9	121	35.9	131	35.9	115	35.9	118	35.9	124	35.9	115	35.9	116	35.9	120	35.9	115	35.9	116	35.9	118	35.9
				82	18.2	91	20.2	109	24.3	83	16.5	88	17.8	100	20.4	84	15.3	87	16	95	17.5	85	14.8	87	15.3	93	16.4
			4 ACH	125	42	131	42	141	42	125	42	129	42	135	42	125	42	127	42	131	42	125	42	126	42	129	42
				88	18.3	97	20.3	115	24.4	89	16.6	94	17.9	106	20.5	90	15.4	93	16.1	100	17.6	90	14.9	93	15.4	98	16.5
		80% shading	2 ACH	95	29.8	98	29.8	108	29.8	94	29.8	96	29.8	101	29.8	93	29.8	94	29.8	97	29.8	93	29.8	94	29.8	95	29.8
				57	13.9	65	15.9	81	20	56	12.2	61	13.5	72	16	56	11	59	11.7	66	13.2	56	10.5	59	11	63	12
			3 ACH	105	35.9	108	35.9	118	35.9	104	35.9	106	35.9	111	35.9	103	35.9	104	35.9	107	35.9	103	35.9	104	35.9	105	35.9
				63	14	71	16	87	20.1	63	12.3	67	13.6	78	16.1	62	11.1	65	11.8	71	13.3	62	10.6	65	11.1	69	12.1
			4 ACH	116	42	119	42	128	42	115	42	117	42	122	42	114	42	115	42	117	42	114	42	114	42	116	42
				69	14.1	77	16.1	93	20.2	69	12.4	73	13.7	84	16.2	68	11.2	71	11.9	77	13.4	68	10.7	70	11.2	75	12.2
	Double low-e + solar protection glazing	40% shading	2 ACH	98	29.8	102	29.8	113	29.8	97	29.8	99	29.8	106	29.8	96	29.8	98	29.8	102	29.8	95	29.8	97	29.8	100	29.8
				64	15.3	71	17.4	89	21.5	63	13.7	68	14.9	79	17.5	63	12.4	66	13.2	73	14.7	64	11.9	66	12.5	71	13.5
			3 ACH	108	35.9	111	35.9	123	35.9	107	35.9	109	35.9	116	35.9	105	35.9	107	35.9	111	35.9	105	35.9	107	35.9	110	35.9
				70	15.4	77	17.5	95	21.6	69	13.8	74	15	85	17.6	69	12.5	72	13.3	79	14.8	70	12	72	12.6	77	13.6
			4 ACH	119	42	122	42	133	42	117	42	119	42	127	42	116	42	118	42	122	42	116	42	117	42	120	42
				76	15.5	83	17.6	100	21.7	75	13.9	80	15.1	91	17.7	75	12.6	78	13.4	85	14.9	75	12.1	78	12.7	82	13.7
		60% shading	2 ACH	94	29.8	98	29.8	107	29.8	93	29.8	95	29.8	100	29.8	92	29.8	93	29.8	95	29.8	92	29.8	93	29.8	94	29.8
				56	12.8	63	14.9	79	19	55	11.2	59	12.4	70	15	54	9.9	57	10.7	63	12.2	54	9.4	57	10	61	11
			3 ACH	104	35.9	108	35.9	116	35.9	103	35.9	105	35.9	110	35.9	102	35.9	104	35.9	105	35.9	102	35.9	103	35.9	104	35.9
				62	12.9	69	15	85	19.1	61	11.3	65	12.5	76	15.1	60	10	63	10.8	69	12.3	60	9.5	63	10.1	67	11.1
			4 ACH	115	42	118	42	127	42	114	42	116	42	120	42	113	42	114	42	116	42	113	42	114	42	115	42
				68	13	75	15.1	91	19.2	67	11.4	71	12.6	82	15.2	66	10.1	69	10.9	75	12.4	66	9.6	68	10.2	73	11.2
		80% shading	2 ACH	90	29.8	93	29.8	100	29.8	89	29.8	91	29.8	95	29.8	89	29.8	90	29.8	92	29.8	89	29.8	89	29.8	91	29.8
				48	10.9	55	13	70	17.1	47	9.2	51	10.5	61	13.1	46	8	49	8.8	54	10.2	46	7.5	48	8.1	52	9.1
			3 ACH	100	35.9	104	35.9	110	35.9	100	35.9	101	35.9	106	35.9	99	35.9	100	35.9	102	35.9	99	35.9	99	35.9	101	35.9
				54	11	61	13.1	76	17.2	53	9.3	57	10.6	67	13.2	52	8.1	55	8.9	60	10.3	52	7.6	54	8.2	58	9.2
			4 ACH	110	42	114	42	121	42	110	42	111	42	116	42	110	42	110	42	113	42	110	42	110	42	111	42
				60	11.1	67	13.2	82	17.3	59	9.4	63	10.7	73	13.3	58	8.2	61	9	66	10.4	58	7.7	60	8.3	64	9.3

Table B19: Detached house: East orientation and high glazing area (WWR 35%)

Orientation				East																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
High glazing area (WWR 35%)	Single glazing	40% shading	2 ACH	187	29.8	194	29.8	208	29.8	188	29.8	193	29.8	202	29.8	190	29.8	192	29.8	197	29.8	190	29.8	192	29.8	196	29.8
				196	50.4	206	52.3	225	56	198	48.9	204	50	216	52.4	199	47.7	203	48.4	210	49.8	200	47.3	203	47.8	208	48.7
			3 ACH	195	35.9	202	35.9	215	35.9	196	35.9	200	35.9	209	35.9	197	35.9	105	35.9	204	35.9	197	35.9	199	35.9	203	35.9
				202	50.5	212	52.4	231	56.1	203	49	210	50.1	222	52.5	205	47.8	209	48.5	216	49.9	206	47.4	208	47.9	213	48.8
			4 ACH	205	42	211	42	224	42	205	42	209	42	218	42	206	42	208	42	213	42	206	42	208	42	211	42
				208	50.6	217	52.5	237	56.2	209	49.1	215	50.2	228	52.6	211	47.9	214	48.6	221	50	211	47.5	214	48	219	48.9
		60% shading	2 ACH	146	29.8	152	29.8	164	29.8	146	29.8	150	29.8	157	29.8	146	29.8	148	29.8	153	29.8	146	29.8	148	29.8	151	29.8
				137	37	145	38.8	163	42.6	137	35.4	142	36.6	153	38.9	137	34.3	140	35	147	36.3	137	33.9	139	34.3	144	35.3
			3 ACH	154	35.9	160	35.9	172	35.9	154	35.9	158	35.9	166	35.9	154	35.9	156	35.9	161	35.9	154	35.9	156	35.9	159	35.9
				143	37.1	151	38.8	169	42.7	143	35.5	148	36.7	159	39	143	34.4	146	35.1	153	36.4	143	34	145	34.4	150	35.4
			4 ACH	164	42	170	42	182	42	164	42	168	42	175	42	164	42	166	42	171	42	164	42	166	42	169	42
				149	37.2	157	38.9	175	42.8	149	35.7	154	36.8	165	39.1	149	34.5	152	35.2	158	36.5	149	34.1	151	34.5	156	35.5
		80% shading	2 ACH	112	29.8	117	29.8	127	29.8	111	29.8	114	29.8	121	29.8	111	29.8	113	29.8	116	29.8	111	29.8	112	29.8	115	29.8
				86	26.5	93	28.4	108	32.1	85	25	89	26.2	99	28.5	84	23.9	87	24.5	92	25.9	84	23.4	86	23.9	90	24.9
			3 ACH	122	35.9	127	35.9	137	35.9	121	35.9	124	35.9	131	35.9	120	35.9	122	35.9	126	35.9	120	35.9	122	35.9	124	35.9
				92	26.6	99	28.5	114	32.2	91	25.1	95	26.3	105	28.6	90	24	93	24.6	98	26	90	23.5	92	24	96	25
			4 ACH	132	42	137	42	147	42	131	42	135	42	141	42	131	42	133	42	137	42	131	42	132	42	135	42
				98	26.7	105	28.6	120	32.3	97	25.2	101	26.4	111	28.7	96	24.1	99	24.7	104	26.1	96	23.6	98	24.1	102	25.1
	Ordinary double glazing	40% shading	2 ACH	179	29.8	187	29.8	202	29.8	182	29.8	187	29.8	197	29.8	185	29.8	188	29.8	194	29.8	186	29.8	188	29.8	193	29.8
				186	44	196	45.9	217	49.6	190	42.5	197	43.7	210	46	194	41.4	198	42	206	43.4	196	40.9	199	41.4	204	42.4
			3 ACH	187	35.9	194	35.9	209	35.9	189	35.9	194	35.9	203	35.9	192	35.9	195	35.9	200	35.9	193	35.9	195	35.9	199	35.9
				191	44.1	201	46	223	49.7	195	42.6	202	43.8	215	46.1	199	41.5	203	42.1	211	43.5	201	41	204	41.5	209	42.5
			4 ACH	196	42	203	42	217	42	198	42	203	42	212	42	201	42	203	42	208	42	202	42	213	42	207	42
				197	44.2	207	46.1	228	49.8	201	42.7	207	43.9	221	46.2	205	41.6	208	42.2	216	43.6	206	41.1	214	41.6	215	42.6
		60% shading	2 ACH	140	29.8	147	29.8	159	29.8	141	29.8	145	29.8	153	29.8	142	29.8	144	29.8	148	29.8	142	29.8	144	29.8	147	29.8
				130	32	139	33.8	158	37.6	131	30.8	137	31.6	149	34	133	29.3	137	30	144	31.3	134	28.9	137	29.3	142	30.3
			3 ACH	149	35.9	155	35.9	167	35.9	149	35.9	154	35.9	161	35.9	150	35.9	153	35.9	157	35.9	151	35.9	152	35.9	155	35.9
				135	32.1	144	33.9	163	37.7	137	30.9	143	31.7	155	34.1	139	29.4	142	30.1	149	31.4	140	29	142	29.4	147	30.4
			4 ACH	159	42	165	42	177	42	159	42	163	42	171	42	160	42	162	42	167	42	160	42	162	42	165	42
				141	32.2	150	34	169	37.8	142	31	148	31.8	161	34.2	144	29.5	148	30.2	155	31.5	145	29.1	148	29.5	153	30.5
		80% shading	2 ACH	109	29.8	114	29.8	124	29.8	103	29.8	112	29.8	118	29.8	108	29.8	110	29.8	114	29.8	108	29.8	110	29.8	112	29.8
				82	22.6	89	24.5	105	28.2	81	21.1	86	22.3	96	24.6	81	20	84	20.6	90	22	81	19.5	83	20	88	20.9
			3 ACH	119	35.9	124	35.9	134	35.9	118	35.9	122	35.9	128	35.9	118	35.9	120	35.9	124	35.9	118	35.9	119	35.9	122	35.9
				88	22.7	95	24.6	111	28.3	87	21.2	92	22.4	102	24.7	87	20.1	90	20.7	96	22.1	87	19.6	89	20.1	94	21
			4 ACH	129	42	134	42	144	42	129	42	132	42	139	42	129	42	131	42	134	42	129	42	130	42	133	42
				94	22.8	101	24.7	117	28.4	93	21.3	98	22.5	108	24.8	93	20.2	96	20.8	102	22.2	93	19.7	95	20.2	100	21.1
	Double low-e glazing	40% shading	2 ACH	142	29.8	148	29.8	163	29.8	143	29.8	148	29.8	158	29.8	147	29.8	150	29.8	155	29.8	148	29.8	150	29.8	154	29.8
				132	30.8	142	32.6	163	36.4	136	29.2	143	30.4	156	32.8	141	28.1	145	28.8	153	30.1	143	27.7	146	28.1	152	29.1
			3 ACH	150	35.9	157	35.9	170	35.9	152	35.9	155	35.9	165	35.9	154	35.9	157	35.9	162	35.9	155	35.9	157	35.9	161	35.9
				138	30.9	148	32.7	168	36.5	142	29.3	148	30.5	162	32.9	146	28.2	150	28.9	158	30.2	148	27.8	151	28.2	157	29.2
			4 ACH	160	42	166	42	179	42	161	42	165	42	174	42	162	42	165	42	171	42	164	42	166	42	169	42
				144	31	153	32.8	174	36.6	147	29.4	154	30.6	167	33	151	28.3	155	29	163	30.3	153	27.9	156	28.3	162	29.3
		60% shading	2 ACH	118	29.8	123	29.8	136	29.8	117	29.8	122	29.8	130	29.8	119	29.8	121	29.8	126	29.8	120	29.8	121	29.8	125	29.8
				97	22.9	106	24.7	124	28.5	98	21.3	104	22.5	117	24.9	101	20.2	104	20.9	112	22.3	102	19.8	105	20.2	110	21.2
			3 ACH	128	35.9	133	35.9	144	35.9	127	35.9	130	35.9	139	35.9	127	35.9	130	35.9	135	35.9	128	35.9	130	35.9	133	35.9
				103	23	112	24.8	130	28.6	104	21.4	110	22.6	122	25	106	20.3	110	21	117	22.4	108	19.9	110	20.3	115	21.3
			4 ACH	139	42	143	42	154	42	138	42	140	42	148	42	137	42	139	42	144	42	138	42	139	42	143	42
				109	23.1	118	24.9	136	28.7	110	21.5	116	22.7	128	25.1	112	20.4	116	21.1	123	22.5	113	20	116	20.4	121	21.4
		80% shading	2 ACH	99	29.8	104	29.8	114	29.8	98	29.8	101	29.8	108	29.8	98	29.8	100	29.8	104	29.8	98	29.8	99	29.8	102	29.8
				67	16.8	74	18.6	90	22.4	67	15.2	72	16.4	82	18.8	67	14.1	70	14.8	76	16.1	67	13.7	69	14.1	74	15.1
			3 ACH	110	35.9	113	35.9	124	35.9	108	35.9	111	35.9	118	35.9	108	35.9	110	35.9	114	35.9	108	35.9	109	35.9	112	35.9
				73	16.9	80	18.7	96	22.5	73	15.3	77	16.5	88	18.9	73	14.2	76	14.9	82	16.2	73	13.8	75	14.2	80	15.2
			4 ACH	120	42	124	42	134	42	119	42	121	42	128	42	118	42	120	42	124	42	118	42	120	42	122	42
				79	17	86	18.8	102	22.6	79	15.4	83	16.6	94	19	79	14.3	82	15	88	16.3	79	13.9	81	14.3	85	15.3
	Double low-e + solar protection glazing	40% shading	2 ACH	105	29.8	110	29.8	120	29.8	105	29.8	108	29.8	114	29.8	105	29.8	107	29.8	110	29.8	105	29.8	106	29.8	108	29.8
				76	18.6	84	20.4	101	24.2	76	17	81	18.2	93	20.5	77	15.9	81	16.6	87	17.9	78	15.4	80	15.9	85	16.9
			3 ACH	115	35.9	120	35.9	130	35.9	114	35.9	118	35.9	124	35.9	115	35.9	116	35.9	120	35.9	115	35.9	116	35.9	118	35.9
				82	18.7	90	20.5	107	24.3	82	17.1	87	18.3	99	20.6	83	16	86	16.7	93	18	84	15.5	86	16	90	17
			4 ACH	125	42	131	42	140	42	125	42	128	42	135	42	125	42	127	42	130	42	125	42	126	42	129	42
				88	18.8	96	20.6	113	24.4	88	17.2	93	18.4	104	20.7	89	16.1	92	16.8	99	18.1	89	15.6	92	16.1	96	17.1
		60% shading	2 ACH	98	29.8	101	29.8	111	29.8	97	29.8	99	29.8	105	29.8	96	29.8	97	29.8	101	29.8	95	29.8	97	29.8	99	29.8
				63	15	70	16.9	86	20.6	63	13.5	67	14.6	78	17	63	12.3	65	13	72	14.4	63	11.9	65	12.4	69	13.3
			3 ACH	108	35.9	111	35.9	121	35.9	107	35.9	108	35.9	115	35.9	106	35.9	107	35.9	111	35.9	106	35.9	106	35.9	109	35.9
				69	15.1	76	17	92	20.7	69	13.6	73	14.7	83	17.1	69	12.4	71	13.1	77	14.5	69	12	71	12.5	75	13.4
			4 ACH	119	42	121	42	132	42	118	42	119	42	126	42	117	42	117	42	121	42	116	42	117	42	120	42
				75	15.2	82	17.1	98	20.8	75	13.7	79	14.8	89	17.2	75	12.5	77	13.2	83	14.6	75	12.1	77	12.6	81	13.5
		80% shading	2 ACH	92	29.8	95	29.8	102	29.8	91	29.8	93	29.8	97	29.8	90	29.8	92	29.8	94	29.8	90	29.8	91	29.8	93	29.8
				52	12.2	58	14.1	72	17.9	51	10.7	55	11.9	64	14.2	50	9.6	53	10.3	58	11.6	50	9.1	52	9.6	56	10.6
			3 ACH	102	35.9	106	35.9	112	35.9	101	35.9	103	35.9	107	35.9	100	35.9	102	35.9	104	35.9	100	35.9	101	35.9	103	35.9
				58	12.3	64	14.2	78	18	57	10.8	61	12	70	14.3	56	9.7	59	10.4	64	11.7	56	9.2	58	9.7	62	10.7
			4 ACH	112	42	116	42	122	42	111	42	114	42	118	42	111	42	112	42	115	42	111	42	112	42	113	42
				64	12.4	70	14.3	84	18.1	63	10.9	67	12.1	76	14.4	62	9.8	65	10.5	70	11.8	62	9.3	64	9.8	68	10.8

Table B20: Detached house: West orientation and low glazing area (WWR 15%)

Orientation				West																							
Wall, roof insulation				25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity				0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Low glazing area (WWR 15%)	Single glazing	40% shading	2 ACH	111	29.8	117	29.8	130	29.8	110	29.8	114	29.8	123	29.8	110	29.8	112	29.8	118	29.8	110	29.8	112	29.8	116	29.8
				86	21.8	96	23.9	117	28.4	87	20.2	93	21.6	107	24.3	88	19.1	92	19.8	101	21.4	89	18.6	93	19.2	98	20.3
			3 ACH	121	35.9	127	35.9	139	35.9	120	35.9	124	35.9	132	35.9	120	35.9	121	35.9	127	35.9	119	35.9	121	35.9	125	35.9
				92	21.9	102	24	123	28.5	93	20.3	99	21.7	112	24.4	94	19.2	98	19.9	106	21.5	95	18.7	98	19.3	104	20.4
			4 ACH	132	42	137	42	149	42	131	42	134	42	141	42	130	42	132	42	136	42	130	42	131	42	135	42
				98	22	108	24.1	128	28.6	99	20.4	105	21.8	118	24.5	100	19.3	103	20	112	21.6	101	18.8	104	19.4	110	20.5
		60% shading	2 ACH	100	29.8	106	29.8	118	29.8	99	29.8	103	29.8	111	29.8	99	29.8	101	29.8	106	29.8	99	29.8	101	29.8	104	29.8
				69	17.4	78	19.7	97	24.2	69	15.5	74	16.9	87	19.8	69	14.3	72	15.1	80	16.8	69	13.8	72	14.4	77	15.5
			3 ACH	110	35.9	116	35.9	128	35.9	109	35.9	113	35.9	121	35.9	109	35.9	111	35.9	116	35.9	109	35.9	111	35.9	114	35.9
				75	17.5	84	19.8	103	24.3	75	15.6	80	17	92	19.9	75	14.4	78	15.2	85	16.9	75	13.9	77	14.5	83	15.6
			4 ACH	121	42	126	42	138	42	119	42	123	42	131	42	119	42	122	42	126	42	119	42	121	42	124	42
				81	17.6	90	19.9	109	24.4	81	15.7	86	17.1	98	20	81	14.5	84	15.3	91	17	81	14	83	14.6	89	15.7
		80% shading	2 ACH	94	29.8	98	29.8	107	29.8	92	29.8	95	29.8	99	29.8	92	29.8	93	29.8	96	29.8	91	29.8	92	29.8	94	29.8
				54	13.9	62	16.2	79	20.7	53	12	58	13.8	69	16.4	52	10.7	55	11.5	61	13.2	52	10.1	54	10.7	59	11.9
			3 ACH	104	35.9	108	35.9	117	35.9	102	35.9	105	35.9	109	35.9	102	35.9	103	35.9	106	35.9	101	35.9	102	35.9	104	35.9
				61	14	68	16.3	85	20.8	59	12.1	64	13.9	75	16.5	58	10.8	61	11.6	67	13.3	58	10.2	60	10.8	65	12
			4 ACH	114	42	119	42	127	42	113	42	116	42	120	42	112	42	114	42	117	42	112	42	113	42	115	42
				67	14.1	74	16.4	91	20.9	65	12.2	70	14	81	16.6	64	10.9	67	11.7	73	13.4	64	10.3	66	10.9	71	12.1
	Ordinary double glazing	40% shading	2 ACH	108	29.8	114	29.8	128	29.8	107	29.8	111	29.8	121	29.8	107	29.8	111	29.8	116	29.8	109	29.8	111	29.8	114	29.8
				82	19.8	92	21.9	113	26.4	83	18.2	90	19.6	104	22.3	86	17.1	90	17.8	99	19.4	88	16.6	91	17.2	97	18.3
			3 ACH	118	35.9	124	35.9	136	35.9	117	35.9	121	35.9	129	35.9	117	35.9	119	35.9	125	35.9	117	35.9	119	35.9	123	35.9
				88	19.9	98	22	119	26.5	89	18.3	95	19.7	110	22.4	92	17.2	96	17.9	104	19.5	93	16.7	96	17.3	102	18.4
			4 ACH	128	42	134	42	146	42	128	42	131	42	139	42	127	42	129	42	134	42	127	42	129	42	132	42
				94	20	104	22.1	125	26.6	95	18.4	101	19.8	115	22.5	97	17.3	101	18	110	19.6	99	16.8	102	17.4	108	18.5
		60% shading	2 ACH	98	29.8	104	29.8	116	29.8	98	29.8	101	29.8	109	29.8	98	29.8	100	29.8	104	29.8	98	29.8	99	29.8	102	29.8
				66	15.8	76	18	95	22.6	66	13.9	72	15.3	85	18.2	67	12.8	71	13.6	79	15.1	68	12.3	71	12.9	76	14
			3 ACH	109	35.9	114	35.9	126	35.9	107	35.9	111	35.9	119	35.9	107	35.9	110	35.9	114	35.9	107	35.9	109	35.9	112	35.9
				72	15.9	82	18.1	101	22.7	72	14	78	15.4	91	18.3	73	12.9	77	13.7	84	15.2	74	12.4	76	13	82	14.1
			4 ACH	119	42	124	42	136	42	118	42	122	42	129	42	118	42	120	42	124	42	118	42	119	42	123	42
				79	16	88	18.2	107	22.8	78	14.1	84	15.5	97	18.4	79	13	82	13.8	90	15.3	79	12.5	82	13.1	88	14.2
		80% shading	2 ACH	92	29.8	97	29.8	106	29.8	91	29.8	94	29.8	99	29.8	91	29.8	92	29.8	95	29.8	90	29.8	91	29.8	93	29.8
				53	12.7	61	14.9	78	19.5	52	10.8	57	12.2	68	15.1	51	9.4	54	10.3	61	11.9	51	8.9	54	9.5	58	10.6
			3 ACH	102	35.9	107	35.9	116	35.9	101	35.9	104	35.9	108	35.9	101	35.9	102	35.9	105	35.9	100	35.9	101	35.9	103	35.9
				59	12.8	67	15	84	19.6	58	10.9	63	12.3	74	15.2	57	9.5	60	10.4	67	12	57	9	60	9.6	64	10.7
			4 ACH	113	42	117	42	126	42	112	42	115	42	119	42	111	42	113	42	115	42	111	42	112	42	114	42
				65	12.9	73	15.1	90	19.7	64	11	69	12.4	80	15.3	63	9.6	66	10.5	73	12.1	63	9.1	66	9.7	70	10.8
	Double low-e glazing	40% shading	2 ACH	98	29.8	104	29.8	115	29.8	97	29.8	101	29.8	108	29.8	98	29.8	100	29.8	104	29.8	98	29.8	99	29.8	102	29.8
				66	15.4	75	17.7	95	22.2	66	13.7	73	15.1	86	17.8	68	12.6	72	13.4	81	14.9	70	12.1	73	12.7	79	13.8
			3 ACH	108	35.9	114	35.9	125	35.9	107	35.9	111	15.2	118	35.9	107	35.9	110	35.9	113	35.9	107	35.9	109	35.9	111	35.9
				72	15.5	81	17.8	101	22.3	72	13.8	79	15.2	92	17.9	74	12.7	78	13.5	86	15	75	12.2	78	12.8	84	13.9
			4 ACH	119	42	124	42	136	42	118	42	122	42	129	42	118	42	120	42	124	42	118	42	119	42	122	42
				78	15.6	87	17.9	107	22.4	78	13.9	85	15.3	97	18	79	12.8	83	13.6	91	15.1	81	12.3	83	12.9	90	14
		60% shading	2 ACH	94	29.8	98	29.8	109	29.8	93	29.8	95	29.8	103	29.8	92	29.8	94	29.8	98	29.8	92	29.8	93	29.8	96	29.8
				57	13	65	15.2	84	19.8	56	11.1	62	12.5	74	15.4	57	9.8	60	10.6	68	12.2	57	9.3	60	9.9	66	11
			3 ACH	105	35.9	108	35.9	119	35.9	103	35.9	105	35.9	112	35.9	102	35.9	104	35.9	107	35.9	102	35.9	103	35.9	105	35.9
				63	13.1	71	15.3	90	19.9	62	11.2	68	12.6	80	15.5	63	9.9	66	10.7	74	12.3	63	9.4	66	10	71	11.1
			4 ACH	115	42	119	42	130	42	114	42	116	42	123	42	113	42	114	42	118	42	113	42	114	42	116	42
				69	13.2	78	15.4	96	20	68	11.3	74	12.7	86	15.6	69	10	72	10.8	79	12.4	69	9.5	72	10.1	77	11.2
		80% shading	2 ACH	90	29.8	94	29.8	103	29.8	89	29.8	92	29.8	96	29.8	89	29.8	90	29.8	92	29.8	89	29.8	90	29.8	91	29.8
				49	10.9	56	13.2	74	17.8	47	9.1	53	10.5	64	13.4	47	7.7	50	8.5	57	10.2	47	7.2	49	7.7	54	8.9
			3 ACH	100	35.9	104	35.9	113	35.9	100	35.9	102	35.9	106	35.9	100	35.9	100	35.9	103	35.9	100	35.9	100	35.9	101	35.9
				55	11	62	13.3	80	17.9	54	9.2	59	10.6	70	13.5	53	7.8	56	8.6	63	10.3	53	7.3	55	7.8	60	9
			4 ACH	111	42	115	42	123	42	110	42	112	42	117	42	110	42	110	42	113	42	110	42	110	42	112	42
				61	11.1	68	13.4	86	18	60	9.3	65	10.7	75	13.6	59	7.9	62	8.7	68	10.4	59	7.4	61	7.9	66	9.1
	Double low-e + solar protection glazing	40% shading	2 ACH	91	29.8	96	29.8	105	29.8	90	29.8	93	29.8	98	29.8	90	29.8	91	29.8	93	29.8	90	29.8	90	29.8	92	29.8
				51	11.7	59	14	77	18.5	50	9.8	55	11.2	67	14.1	50	8.5	53	9.3	60	10.9	50	7.9	53	8.5	58	9.7
			3 ACH	101	35.9	106	35.9	115	35.9	100	35.9	103	35.9	108	35.9	100	35.9	101	35.9	104	35.9	100	35.9	100	35.9	102	35.9
				58	11.8	65	14.1	83	18.6	56	9.9	61	11.3	73	14.2	56	8.6	59	9.4	66	11	56	8	59	8.6	64	9.8
			4 ACH	112	42	116	42	125	42	111	42	114	42	118	42	110	42	112	42	114	42	110	42	111	42	113	42
				64	11.9	71	14.2	89	18.7	63	10	68	11.4	79	14.3	62	8.7	65	9.5	72	11.1	62	8.1	64	8.7	69	9.9
		60% shading	2 ACH	90	29.8	94	29.8	102	29.8	89	29.8	91	29.8	95	29.8	89	29.8	90	29.8	92	29.8	89	29.8	89	29.8	91	29.8
				48	10.6	55	12.8	72	17.4	47	8.7	51	10.1	62	13	46	7.3	49	8.2	56	9.8	46	6.8	48	7.4	53	8.5
			3 ACH	100	35.9	104	35.9	112	35.9	100	35.9	101	35.9	106	35.9	99	35.9	100	35.9	102	35.9	100	35.9	100	35.9	101	35.9
				54	10.7	62	12.9	78	17.5	53	8.8	58	10.2	68	13.1	52	7.4	55	8.3	61	9.9	52	6.9	54	7.5	59	8.6
			4 ACH	110	42	114	42	122	42	110	42	111	42	116	42	110	42	110	42	113	42	110	42	110	42	111	42
				60	10.8	68	13	84	17.6	59	8.9	64	10.3	74	13.2	58	7.5	61	8.4	67	10	58	7	60	7.6	65	8.7
		80% shading	2 ACH	89	29.8	92	29.8	99	29.8	89	29.8	89	29.8	94	29.8	89	29.8	89	29.8	90	29.8	89	29.8	89	29.8	89	29.8
				44	9.7	52	11.9	68	16.5	43	7.8	48	9.2	58	12.1	42	6.4	45	7.3	51	8.9	42	5.9	44	6.5	48	7.6
			3 ACH	100	35.9	102	35.9	109	35.9	99	35.9	100	35.9	104	35.9	99	35.9	99	35.9	100	35.9	99	35.9	100	35.9	99	35.9
				51	9.8	58	12	74	16.6	49	7.9	54	9.3	64	12.2	48	6.5	51	7.4	57	9	48	6	50	6.6	54	7.7
			4 ACH	110	42	112	42	120	42	110	42	110	42	115	42	110	42	110	42	111	42	109	42	110	42	110	42
				57	9.9	64	12.1	80	16.7	55	8	60	9.4	70	12.3	54	6.6	57	7.5	63	9.1	54	6.1	56	6.7	60	7.8

Table B21: Detached house: West orientation and medium glazing area (WWR 25%)

Orientation			West																							
Wall, roof insulation			25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity			0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
Medium glazing area (WWR 25%) – Single glazing	40% shading	2 ACH	145	29.8	153	29.8	168	29.8	146	29.8	152	29.8	162	29.8	149	29.8	152	29.8	158	29.8	150	29.8	152	29.8	156	29.8
			139	35.1	150	37.1	171	41	141	33.6	148	34.9	162	37.4	144	32.6	148	33.3	157	34.7	146	32.2	149	32.7	154	33.7
		3 ACH	154	35.9	161	35.9	175	35.9	154	35.9	159	35.9	169	35.9	156	35.9	159	35.9	165	35.9	157	35.9	159	35.9	163	35.9
			145	35.2	155	37.2	176	41.1	147	33.7	154	35	168	37.5	150	32.7	154	33.4	162	34.8	151	32.3	154	32.8	160	33.8
		4 ACH	164	42	170	42	184	42	164	42	169	42	178	42	165	42	168	42	173	42	166	42	168	42	172	42
			151	35.3	161	37.3	182	41.2	153	33.8	159	35.1	174	37.6	156	32.8	160	33.5	168	34.9	157	32.4	160	32.9	165	33.9
	60% shading	2 ACH	120	29.8	125	29.8	139	29.8	119	29.8	123	29.8	132	29.8	119	29.8	122	29.8	127	29.8	119	29.8	121	29.8	125	29.8
			101	25.6	110	27.8	129	32	101	24.1	107	25.3	119	27.9	101	23	105	23.8	112	25.2	102	22.6	104	23.1	110	24.1
		3 ACH	130	35.9	135	35.9	147	35.9	129	35.9	132	35.9	140	35.9	129	35.9	130	35.9	135	35.9	128	35.9	130	35.9	133	35.9
			107	25.7	116	27.9	135	32.1	106	24.2	112	25.4	125	28	107	23.1	111	23.8	118	25.3	108	22.7	110	23.2	115	24.2
		4 ACH	141	42	146	42	157	42	140	42	143	42	150	42	139	42	141	42	145	42	139	42	140	42	143	42
			113	25.8	122	28	140	32.2	112	24.3	118	25.5	131	28.1	113	23.2	117	23.9	124	25.4	114	22.8	116	23.3	121	24.3
	80% shading	2 ACH	101	29.8	104	29.8	116	29.8	100	29.8	102	29.8	109	29.8	99	29.8	100	29.8	104	29.8	98	29.8	99	29.8	102	29.8
			68	19	75	21.2	92	25.4	67	17.3	71	18.6	82	21.3	66	16	69	16.8	75	18.4	66	15.5	68	16.1	72	17.2
		3 ACH	111	35.9	114	35.9	126	35.9	110	35.9	112	35.9	119	35.9	109	35.9	110	35.9	113	35.9	109	35.9	109	35.9	111	35.9
			74	19.1	82	21.3	98	25.5	73	17.4	77	18.7	88	21.4	72	16.1	75	16.9	81	18.5	72	15.6	74	16.2	78	17.3
		4 ACH	122	42	125	42	136	42	121	42	122	42	129	42	120	42	121	42	124	42	119	42	120	42	122	42
			80	19.2	88	21.4	104	25.6	79	17.5	84	18.8	94	21.5	78	16.2	81	17	87	18.6	78	15.7	80	16.3	84	17.4
Ordinary double glazing	40% shading	2 ACH	140	29.8	148	29.8	164	29.8	144	29.8	148	29.8	159	29.8	146	29.8	150	29.8	157	29.8	149	29.8	151	29.8	156	29.8
			132	31.2	144	33.2	165	37.2	137	29.8	144	31	159	33.5	142	28.7	146	29.4	155	30.9	145	28.3	148	28.8	154	29.8
		3 ACH	148	35.9	155	35.9	171	35.9	151	35.9	156	35.9	165	35.9	153	35.9	156	35.9	163	35.9	155	35.9	157	35.9	162	35.9
			138	31.3	149	33.3	171	37.3	142	29.9	149	31.1	164	33.6	147	28.8	151	29.5	160	31	150	28.4	153	28.9	159	29.9
		4 ACH	158	42	165	42	180	42	160	42	164	42	174	42	162	42	165	42	171	42	163	42	165	42	170	42
			144	31.4	155	33.4	177	37.4	148	30	155	31.2	169	33.7	152	28.9	157	29.6	165	31.1	155	28.5	158	29	164	30
	60% shading	2 ACH	113	29.8	122	29.8	136	29.8	116	29.8	121	29.8	129	29.8	118	29.8	120	29.8	125	29.8	118	29.8	120	29.8	123	29.8
			96	22.6	105	24.6	126	28.9	97	21.2	104	22.4	117	25	100	20.1	103	20.9	112	22.3	101	19.7	104	20.2	110	21.2
		3 ACH	126	35.9	131	35.9	144	35.9	125	35.9	129	35.9	138	35.9	126	35.9	128	35.9	133	35.9	126	35.9	128	35.9	132	35.9
			102	22.7	111	24.7	131	29	103	21.3	109	22.5	122	25.1	105	20.2	109	21	117	22.4	106	19.8	109	20.3	115	21.3
		4 ACH	137	42	141	42	154	42	136	42	139	42	148	42	135	42	138	42	143	42	136	42	138	42	142	42
			108	22.8	117	24.8	137	29.1	109	21.4	115	22.6	128	25.2	111	20.3	115	21.1	122	22.5	112	19.9	115	20.4	120	21.4
	80% shading	2 ACH	99	29.8	103	29.8	114	29.8	97	29.8	100	29.8	109	29.8	96	29.8	98	29.8	103	29.8	96	29.8	98	29.8	101	29.8
			65	16.6	73	18.7	90	23	64	14.9	70	16.2	81	18.9	64	13.6	67	14.4	74	15.9	64	13.1	67	13.6	71	14.7
		3 ACH	109	35.9	112	35.9	124	35.9	108	35.9	110	35.9	117	35.9	106	35.9	108	35.9	112	35.9	106	35.9	107	35.9	110	35.9
			71	16.7	79	18.8	96	23.1	70	15	76	16.3	87	19	70	13.7	73	14.5	80	16	70	13.2	73	13.7	77	14.8
		4 ACH	120	42	123	42	134	42	118	42	120	42	128	42	117	42	118	42	123	42	117	42	118	42	121	42
			77	16.8	85	18.9	102	23.2	77	15.1	82	16.4	93	19.1	76	13.8	79	14.6	86	16.1	76	13.3	79	13.8	83	14.9
Double low-e glazing	40% shading	2 ACH	116	29.8	123	29.8	137	29.8	118	29.8	122	29.8	132	29.8	119	29.8	123	29.8	129	29.8	122	29.8	124	29.8	128	29.8
			97	22.5	107	24.5	129	28.5	100	21.1	107	22.3	121	24.8	105	20	109	20.7	118	22.2	108	19.6	111	20.1	118	21.1
		3 ACH	125	35.9	132	35.9	145	35.9	126	35.9	131	35.9	139	35.9	127	35.9	130	35.9	136	35.9	128	35.9	131	35.9	135	35.9
			103	22.6	113	24.6	134	28.6	106	21.2	113	22.4	127	24.9	110	20.1	114	20.8	123	22.3	113	19.7	116	20.2	123	21.2
		4 ACH	136	42	142	42	155	42	136	42	140	42	149	42	137	42	139	42	145	42	138	42	140	42	144	42
			109	22.7	119	24.7	140	28.7	111	21.3	118	22.5	132	25	115	20.2	120	20.9	128	22.4	118	19.8	121	20.3	128	21.3
	60% shading	2 ACH	104	29.8	109	29.8	121	29.8	103	29.8	107	29.8	114	29.8	103	29.8	105	29.8	110	29.8	103	29.8	105	29.8	109	29.8
			75	17.1	84	19.2	104	23.4	76	15.5	82	16.7	95	19.3	78	14.4	82	15.1	90	16.6	79	14	82	14.5	88	15.5
		3 ACH	113	35.9	119	35.9	129	35.9	113	35.9	117	35.9	123	35.9	113	35.9	115	35.9	118	35.9	113	35.9	114	35.9	117	35.9
			81	17.2	90	19.3	109	23.5	82	15.6	88	16.8	101	19.4	84	14.5	87	15.2	95	16.7	85	14.1	88	14.6	94	15.6
		4 ACH	124	42	130	42	139	42	124	42	127	42	133	42	124	42	125	42	129	42	123	42	125	42	127	42
			87	14.3	96	19.4	115	23.6	88	15.7	94	16.9	106	19.5	89	14.6	93	15.3	101	16.8	91	14.2	93	14.7	99	15.7
	80% shading	2 ACH	94	29.8	98	29.8	108	29.8	93	29.8	95	29.8	101	29.8	92	29.8	93	29.8	97	29.8	92	29.8	93	29.8	95	29.8
			56	13.2	64	15.3	81	19.6	56	11.5	61	12.8	72	15.5	56	10.2	59	11	65	12.5	56	9.7	58	10.2	63	11.3
		3 ACH	104	35.9	108	35.9	118	35.9	103	35.9	105	35.9	111	35.9	102	35.9	104	35.9	106	35.9	102	35.9	103	35.9	105	35.9
			62	13.3	70	15.4	87	19.7	62	11.6	67	12.9	78	18.1	62	10.3	65	11.1	71	12.6	62	9.8	64	10.3	69	11.4
		4 ACH	115	42	118	42	128	42	114	42	116	42	121	42	113	42	114	42	117	42	113	42	114	42	115	42
			69	13.4	76	15.5	93	19.8	68	11.7	73	13	83	18.2	68	10.4	71	11.2	77	12.7	68	9.9	70	10.4	74	11.5
Double low-e + solar protection glazing	40% shading	2 ACH	96	29.8	101	29.8	112	29.8	95	29.8	98	29.8	106	29.8	95	29.8	97	29.8	101	29.8	95	29.8	96	29.8	99	29.8
			62	14.7	70	16.8	89	21.1	62	13	67	14.3	79	17	62	11.8	66	12.5	73	14	63	11.4	66	11.9	71	12.9
		3 ACH	107	35.9	110	35.9	122	35.9	105	35.9	108	35.9	116	35.9	105	35.9	107	35.9	111	35.9	105	35.9	106	35.9	109	35.9
			68	14.8	76	16.9	94	21.2	68	13.1	73	14.4	85	17.1	68	11.9	72	12.6	79	14.1	69	11.5	71	12	76	13
		4 ACH	118	42	121	42	133	42	116	42	118	42	126	42	115	42	117	42	121	42	115	42	116	42	119	42
			75	14.9	82	17	100	21.3	74	13.2	79	14.5	91	17.2	74	12	77	12.7	85	14.2	75	11.6	77	12.1	82	13.1
	60% shading	2 ACH	93	29.8	97	29.8	106	29.8	92	29.8	94	29.8	100	29.8	91	29.8	93	29.8	95	29.8	91	29.8	92	29.8	94	29.8
			55	12.4	62	14.6	79	18.8	54	10.7	59	12.1	69	14.7	54	9.5	57	10.2	63	11.8	54	8.9	56	9.5	61	10.6
		3 ACH	103	35.9	107	35.9	116	35.9	102	35.9	105	35.9	109	35.9	101	35.9	103	35.9	105	35.9	101	35.9	102	35.9	104	35.9
			61	12.5	68	14.7	85	18.9	60	10.8	65	12.2	75	14.8	60	9.6	62	10.3	69	11.9	60	9	62	9.6	66	10.7
		4 ACH	114	42	118	42	127	42	113	42	115	42	120	42	112	42	113	42	116	42	112	42	113	42	114	42
			67	12.6	74	14.8	91	19	66	10.9	71	12.3	81	14.9	66	9.7	68	10.4	75	12	66	9.1	68	9.7	72	10.8
	80% shading	2 ACH	90	29.8	93	29.8	100	29.8	89	29.8	91	29.8	95	29.8	89	29.8	90	29.8	92	29.8	89	29.8	89	29.8	90	29.8
			48	10.7	54	12.8	70	17.1	46	9	51	10.3	61	13	46	7.7	48	8.5	54	10	45	7.2	47	7.7	51	8.8
		3 ACH	100	35.9	103	35.9	110	35.9	100	35.9	101	35.9	106	35.9	100	35.9	99	35.9	102	35.9	99	35.9	100	35.9	100	35.9
			54	10.8	61	12.9	76	17.2	52	9.1	57	10.4	67	13.1	52	7.8	54	8.6	60	10.1	52	7.3	53	7.8	57	8.9
		4 ACH	110	42	114	42	121	42	110	42	111	42	116	42	110	42	110	42	113	42	110	42	110	42	111	42
			60	10.9	67	13	82	17.3	58	9.2	63	10.5	73	13	58	7.9	60	8.7	66	10.2	58	7.4	60	7.9	63	9

Table B22: Detached house: West orientation and high glazing area (WWR 35%)

Orientation				West																						
Wall, roof insulation			25 mm						50 mm						100 mm						150 mm					
Exterior absorptivity			0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9		0.3		0.5		0.9	
High glazing area (WWR 35%) – Single glazing	40% shading	2 ACH	187	29.8	195	29.8	210	29.8	190	29.8	195	29.8	204	29.8	192	29.8	194	29.8	200	29.8	193	29.8	194	29.8	198	29.8
			197	48.5	207	50.3	228	54	200	47.1	207	48.3	220	50.6	203	49.2	207	46.9	214	48.2	204	45.8	207	46.3	212	47.2
		3 ACH	194	35.9	202	35.9	217	35.9	197	35.9	201	35.9	211	35.9	199	35.9	201	35.9	207	35.9	199	35.9	201	35.9	205	35.9
			203	48.6	213	50.4	234	54.1	206	47.2	212	48.4	225	50.7	208	49.3	212	47	220	48.3	210	45.9	212	46.4	218	47.3
		4 ACH	203	42	210	42	225	42	205	42	210	42	219	42	207	42	210	42	215	42	208	42	210	42	213	42
			208	48.7	218	50.5	239	54.2	211	47.3	218	48.5	231	50.8	214	49.4	218	47.1	225	48.4	215	46	218	46.5	223	47.4
	60% shading	2 ACH	143	29.8	148	29.8	161	29.8	142	29.8	146	29.8	155	29.8	143	29.8	145	29.8	150	29.8	143	29.8	145	29.8	148	29.8
			134	34.8	143	36.6	162	40.3	135	33.5	141	34.6	153	36.9	136	32.5	139	33.2	146	34.5	136	32.1	139	32.6	144	33.5
		3 ACH	151	35.9	157	35.9	169	35.9	151	35.9	155	35.9	163	35.9	151	35.9	153	35.9	158	35.9	151	35.9	153	35.9	156	35.9
			140	34.9	149	36.7	168	40.4	141	33.6	147	34.7	159	37	142	32.6	145	33.3	152	34.6	142	32.2	145	32.7	149	33.6
		4 ACH	161	42	167	42	179	42	161	42	165	42	172	42	161	42	163	42	167	42	161	42	162	42	166	42
			146	35	155	36.8	174	40.5	146	33.7	152	34.8	164	37.1	147	32.7	151	33.4	158	34.7	148	32.3	150	32.8	155	33.7
	80% shading	2 ACH	110	29.8	115	29.8	125	29.8	109	29.8	112	29.8	118	29.8	108	29.8	110	29.8	114	29.8	108	29.8	109	29.8	112	29.8
			83	24.3	90	26.3	106	30.3	81	22.7	86	24	96	26.5	81	21.6	84	22.3	89	23.7	81	21.1	83	21.6	87	22.6
		3 ACH	119	35.9	125	35.9	135	35.9	118	35.9	122	35.9	128	35.9	118	35.9	120	35.9	124	35.9	118	35.9	119	35.9	122	35.9
			89	24.4	96	26.4	112	30.4	88	22.8	92	24.1	102	26.6	87	21.7	90	22.4	95	23.8	87	21.2	89	21.7	93	22.7
		4 ACH	130	42	135	42	145	42	129	42	132	42	139	42	128	42	130	42	134	42	128	42	130	42	132	42
			95	24.5	102	26.5	118	30.5	94	22.9	98	24.2	108	26.7	93	21.8	96	22.5	101	23.9	93	21.3	95	21.8	99	22.8
Ordinary double glazing	40% shading	2 ACH	182	29.8	189	29.8	205	29.8	185	29.8	191	29.8	202	29.8	191	29.8	194	29.8	200	29.8	193	29.8	195	29.8	199	29.8
			189	42.7	200	44.5	221	48.2	195	41.4	202	42.5	216	44.8	201	40.4	205	41.1	213	42.4	204	40	207	40.5	212	41.4
		3 ACH	188	35.9	196	35.9	211	35.9	192	35.9	197	35.9	207	35.9	197	35.9	200	35.9	206	35.9	199	35.9	201	35.9	205	35.9
			195	42.8	205	44.6	226	48.3	200	41.5	207	42.6	221	44.9	206	40.5	210	41.2	218	42.5	209	40.1	212	40.6	217	41.5
		4 ACH	197	42	204	42	219	42	200	42	205	42	215	42	204	42	207	42	213	42	206	42	208	42	213	42
			200	42.9	211	44.7	232	48.4	205	41.6	212	42.7	226	45	211	40.6	215	41.3	223	42.6	214	40.2	217	40.7	222	41.6
	60% shading	2 ACH	138	29.8	144	29.8	159	29.8	139	29.8	144	29.8	153	29.8	142	29.8	144	29.8	149	29.8	143	29.8	144	29.8	148	29.8
			129	30.4	138	32.3	158	35.9	131	29.1	138	30.3	150	32.6	134	28.2	138	28.8	146	30.1	136	27.8	139	28.2	144	29.2
		3 ACH	146	35.9	152	35.9	166	35.9	147	35.9	151	35.9	160	35.9	148	35.9	151	35.9	157	35.9	150	35.9	151	35.9	155	35.9
			135	30.5	144	32.4	164	36	137	29.2	143	30.4	156	32.7	140	28.3	144	28.9	151	30.2	141	27.9	144	28.3	150	29.3
		4 ACH	156	42	162	42	175	42	156	42	161	42	169	42	158	42	160	42	165	42	158	42	160	42	164	42
			140	30.6	150	32.5	169	36.1	142	29.3	149	30.5	162	32.8	145	28.4	149	29	157	30.3	147	28	150	28.4	155	29.4
	80% shading	2 ACH	107	29.8	112	29.8	122	29.8	106	29.8	110	29.8	116	29.8	106	29.8	108	29.8	112	29.8	106	29.8	107	29.8	110	29.8
			79	20.7	87	22.7	104	26.6	79	19.1	84	20.3	95	22.8	79	18.1	82	18.8	88	20.1	79	17.7	81	18.2	86	19.1
		3 ACH	117	35.9	122	35.9	132	35.9	116	35.9	119	35.9	126	35.9	116	35.9	118	35.9	121	35.9	116	35.9	117	35.9	120	35.9
			85	20.8	93	22.8	110	26.7	85	19.2	90	20.4	101	22.9	85	18.2	88	18.9	94	20.2	85	17.8	87	18.3	92	19.2
		4 ACH	127	42	132	42	142	42	127	42	130	42	136	42	126	42	128	42	132	42	126	42	128	42	130	42
			91	20.9	99	22.9	116	26.8	91	19.3	96	20.5	106	23	91	18.3	94	19	100	20.3	91	17.9	93	18.4	98	19.3
Double low-e glazing	40% shading	2 ACH	141	29.8	149	29.8	163	29.8	145	29.8	150	29.8	161	29.8	149	29.8	152	29.8	158	29.8	151	29.8	154	29.8	159	29.8
			134	29.8	144	31.6	165	35.2	139	28.4	146	29.6	160	31.9	146	27.5	150	28.1	158	29.5	149	27.1	152	27.6	158	28.5
		3 ACH	148	35.9	156	35.9	170	35.9	152	35.9	156	35.9	167	35.9	156	35.9	159	35.9	164	35.9	158	35.9	160	35.9	164	35.9
			139	29.9	149	31.7	170	35.3	144	28.5	151	29.7	165	32	151	27.6	155	28.2	163	29.6	154	27.2	157	27.7	163	28.6
		4 ACH	157	42	164	42	179	42	160	42	165	42	175	42	164	42	167	42	173	42	166	42	168	42	172	42
			144	30	155	31.8	176	35.4	150	28.6	156	29.8	171	32.1	156	27.7	160	28.3	168	29.7	159	27.3	162	27.8	168	28.7
	60% shading	2 ACH	115	29.8	122	29.8	134	29.8	117	29.8	121	29.8	129	29.8	118	29.8	120	29.8	125	29.8	123	29.8	126	29.8	125	29.8
			96	21.8	105	23.6	124	27.4	98	20.4	104	21.6	117	23.9	102	19.5	106	20.1	114	21.5	104	19.1	107	19.6	112	20.5
		3 ACH	125	35.9	130	35.9	143	35.9	125	35.9	129	35.9	137	35.9	126	35.9	128	35.9	133	35.9	127	35.9	128	35.9	132	35.9
			102	21.9	111	23.7	130	27.5	104	20.5	110	21.7	123	24	107	19.6	111	20.2	119	21.6	109	19.2	112	19.7	117	20.6
		4 ACH	136	42	140	42	153	42	135	42	139	42	147	42	136	42	139	42	143	42	137	42	138	42	141	42
			107	22	117	23.8	136	27.6	110	20.6	116	21.8	128	24.1	113	19.7	116	20.3	124	21.7	114	19.3	117	19.8	123	20.7
	80% shading	2 ACH	98	29.8	102	29.8	113	29.8	97	29.8	100	29.8	107	29.8	97	29.8	99	29.8	102	29.8	97	29.8	98	29.8	101	29.8
			65	15.6	73	17.5	89	21.5	65	14	70	15.2	81	17.7	65	12.9	68	13.6	75	15	66	12.5	68	13	73	13.9
		3 ACH	108	35.9	112	35.9	123	35.9	107	35.9	110	35.9	117	35.9	106	35.9	108	35.9	112	35.9	106	35.9	108	35.9	111	35.9
			71	15.7	79	17.6	95	21.6	71	14.1	76	15.3	87	17.8	71	13	74	13.7	81	15.1	72	12.6	74	13.1	78	14
		4 ACH	119	42	122	42	133	42	117	42	120	42	127	42	117	42	119	42	123	42	117	42	118	42	121	42
			77	15.8	85	17.7	101	21.7	77	14.2	82	15.4	92	17.9	77	13.1	80	13.8	56	15.2	77	12.7	80	13.2	84	14.1
Double low-e + solar protection glazing	40% shading	2 ACH	103	29.8	109	29.8	118	29.8	103	29.8	106	29.8	112	29.8	103	29.8	105	29.8	108	29.8	103	29.8	104	29.8	107	29.8
			74	17.6	83	19.6	100	23.6	75	16.2	81	17.3	92	19.8	76	15.2	80	15.9	86	17.2	76	14.9	79	15.3	85	16.3
		3 ACH	113	35.9	119	35.9	128	35.9	113	35.9	116	35.9	122	35.9	113	35.9	114	35.9	118	35.9	113	35.9	114	35.9	116	35.9
			80	17.7	89	19.7	106	23.7	81	16.3	87	17.4	98	19.9	82	15.3	85	16	92	17.3	83	15	85	15.4	90	16.4
		4 ACH	124	42	129	42	139	42	123	42	127	42	133	42	123	42	125	42	128	42	123	42	124	42	126	42
			86	17.8	95	19.8	112	23.8	87	16.4	92	17.5	104	20	88	15.4	91	16.1	98	17.4	89	15.1	91	15.5	96	16.5
	60% shading	2 ACH	97	29.8	100	29.8	111	29.8	96	29.8	98	29.8	104	29.8	95	29.8	96	29.8	100	29.8	95	29.8	96	29.8	98	29.8
			62	14.4	69	16.4	85	20.4	61	12.8	66	14.1	77	16.6	62	11.7	65	12.4	71	13.8	62	11.2	64	11.7	69	12.7
		3 ACH	107	35.9	109	35.9	120	35.9	106	35.9	107	35.9	114	35.9	105	35.9	106	35.9	110	35.9	104	35.9	105	35.9	108	35.9
			68	14.5	75	16.5	91	20.5	67	12.9	72	14.2	83	16.7	68	11.8	71	12.5	77	13.9	68	11.3	70	11.8	74	12.8
		4 ACH	118	42	120	42	131	42	116	42	118	42	125	42	116	42	116	42	120	42	115	42	116	42	119	42
			74	14.6	81	16.6	97	20.6	73	13	78	14.3	89	16.8	74	11.9	76	12.6	82	14	74	11.4	76	11.9	80	12.9
	80% shading	2 ACH	91	29.8	95	29.8	102	29.8	90	29.8	93	29.8	96	29.8	90	29.8	91	29.8	93	29.8	90	29.8	90	29.8	92	29.8
			51	11.8	57	13.8	72	17.7	50	10.2	54	11.4	63	13.9	49	9	52	9.7	57	11.2	49	8.6	51	9.1	55	10.1
		3 ACH	101	35.9	105	35.9	112	35.9	100	35.9	103	35.9	107	35.9	100	35.9	101	35.9	104	35.9	100	35.9	100	35.9	102	35.9
			57	11.9	63	13.9	78	17.8	56	10.3	60	11.5	69	14	55	9.1	58	9.8	63	11.3	55	8.7	57	9.2	61	10.2
		4 ACH	112	42	116	42	122	42	111	42	113	42	117	42	110	42	112	42	114	42	110	42	111	42	113	42
			63	12	70	14	84	17.9	62	10.4	66	11.6	75	14.1	61	9.2	64	9.9	69	11.4	61	8.8	63	9.3	67	10.3

Appendix C

QUESTIONNAIRE FOR PROFESSIONALS ON A PASSIVE HOUSE APPROACH FOR VIETNAMESE HOUSING

Information of the survey

Research Project Title: Low Energy Housing in The Hot Humid Climate of Vietnam: The Value of a Passive House Approach

The aims of the survey: To obtain experts' viewpoints about Passive House approach in Vietnam and about the pilot design guidance for Passive House dwellings. The data collected will be analysed for validating and improving the guidance for use as a valuable reference in future.

Participants: Experts and practitioners in the field of architecture and engineering (architects, engineers, builders, researchers)

Data protection: All information which is collected will be strictly confidential and anonymised in compliance with the Data Protection Act and ethical research guidelines and principles.

Contact details of researcher:

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School of Art, Design and Architecture

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Questionnaire Part 1

1. Do you think energy saving design has been currently paid adequate attention in Vietnam?

☐ Strongly agree ☐ Agree ☐ Neither ☐ Disagree ☐ Strongly disagree

2. How often do you apply design solutions to save energy for buildings?

☐ Always ☐ Often ☐ Half of the time ☐ Seldom ☐ Never

3. How difficult was it to look for energy-efficient design guidelines in Vietnam?

☐ Very easy ☐ Slightly easy ☐ Neither ☐ Slightly difficult ☐ Very difficult

4. How satisfied are you with current energy-efficient design guidelines in Vietnam?

☐ Very satisfied ☐ Satisfied ☐ Neutral ☐ Unsatisfied ☐ Very unsatisfied

5. Do you think there is a need for an energy-efficient design guideline for Vietnamese housing?

☐ Strongly agree ☐ Agree ☐ Neither ☐ Disagree ☐ Strongly disagree

6. Do you think naturally-ventilated buildings can satisfy thermal comfort and indoor air quality, considering the context of global warming and air pollution?

☐ Strongly agree ☐ Agree ☐ Neither ☐ Disagree ☐ Strongly disagree

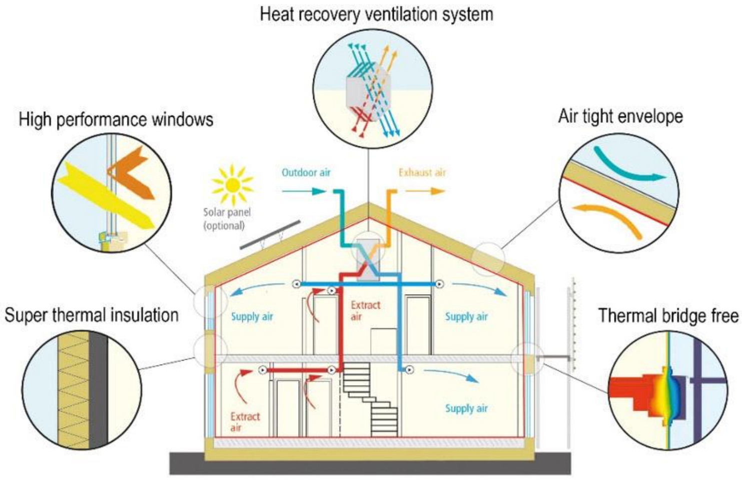
7. Do you think sealed buildings with energy-efficient mechanical ventilation could be an effectively alternative solution for naturally ventilated buildings?

☐ Strongly agree ☐ Agree ☐ Neither ☐ Disagree ☐ Strongly disagree

Introduction of the Passive House concept

Passive House development: The foundation of the Passive House concept was formally laid in the 1980s by Wolfgang Feist, a German who emerged as the father of Passive House movement. In 1989, Dr Feist built the first Passive House in Darmstadt, Germany, which saved 90% of energy consumption compared to the German Building Code of 1995. In 1996, Dr Feist established the Passive House Institute to research on Passive House. After that, many countries have founded their own Passive House organisation and have participated in the International Passive House Association. So far, with over 60,000 certificated Passive House buildings all over the world, the Passive House standard is seen the fastest growing sustainable standard in the world. Over the last decade, the interest in Passive House standard has spread from temperate to warmer regions in Southern Europe, America, China, UAE, and some other countries.

Passive House principles: Generally, Passive Houses require a high level of thermal insulation by applying high-performance windows and doors as well as well-insulated walls, ground floor and roofs. This helps to eliminate the thermal bridge and draughts and keep the indoor temperature at a stable comfortable state. Dealing with ventilation issues in such an airtight building fabric, a heat-recovery ventilation system (or energy recovery for warm regions) is used to supply the fresh air which is heated by the heat from the extracted stale air. This system replaces conventional air conditioners and can operate all year round if necessary with a minimum amount of energy consumption. This ventilation system can be combined with or separated from heating or cooling equipment.



Five basic principles of Passive House (Source: passiv.de)

A Passive House with MVHR ventilation system

Passive House benefits: As stated by Passive House Institute and proved in practice, the Passive House standard is "*A building standard that is truly energy efficient, comfortable, affordable and ecological at the same time*". The details are as follows:

- Save up to 90% of energy consumption compared to conventional buildings.
- Provide comfortable temperature all year round for occupants.
- Provide fresh air, healthy indoor environment.
- Extremely silent.
- Affordable in terms of buildings' life circle cost, although construction cost is little higher than conventional buildings (around 10% for European countries).

Potential applicability to Vietnam: Passive House approach could be a promising solution to deal with global warming, air and noise pollution, urban heat island and the lack of wind in cities. In Vietnam, although passive design techniques are common in both traditional and current architecture, Passive House is a completely new approach which can replace the common techniques of natural ventilation or hybrid methods in current buildings.

Questionnaire Part 2

8. How much do you know about Passive House concept (not passive design) before this survey?

☐ Well understood ☐ Basically understood ☐ Heard about ☐ Never heard about

9. What do you think about the benefits of Passive House buildings, especially about the indoor air quality and energy saving?

☐ Excellent ☐ Good ☐ Average ☐ Below average ☐ Poor

10. How interested are you in the application of Passive House approach to Vietnam?

☐ Extremely interested ☐ Very interested ☐ Moderately interested ☐ Slightly interested ☐ Not at all interested

11. Do you think how complicated is the application of Passive House principles?

☐ Extremely complicated ☐ Very complicated ☐ Moderately complicated ☐ Slightly complicated ☐ Not at all complicated

12. Construction cost of a Passive House building is higher than a conventional building, but the life circle cost could be equal or lower. So, do you think how important is the construction cost factor for the development of Passive House Vietnam?

☐ Extremely important ☐ Very important ☐ Moderately important ☐ Slightly important ☐ Not at all important

13. Closed Passive House buildings contrast with Vietnam traditional architecture which is open and naturally ventilated. Do you think how difficult will it be for the occupants to accept and adapt to Passive House buildings?

☐ Very easy ☐ Slightly easy ☐ Neither ☐ Slightly difficult ☐ Very difficult

14. Do you think Passive House approach needs to be researched and developed in Vietnam?

☐ Strongly agree ☐ Agree ☐ Neither ☐ Disagree ☐ Strongly disagree

15. Please let me know other issues you are still concerning about Passive House approach in Vietnam?

……

……

(Please read the attached design guidance before taking the following part)

Questionnaire Part 3

16. Is the presentation of this design guidance clear and easy to understand and apply?

☐ Strongly agree ☐ Agree ☐ Neither ☐ Disagree ☐ Strongly disagree

17. Do you think this guidance is a useful reference for designing Passive House dwellings in Vietnam?

☐ Strongly agree ☐ Agree ☐ Neither ☐ Disagree ☐ Strongly disagree

18. Overall, how satisfied are you with this guidance?

☐ Very satisfied ☐ Satisfied ☐ Neutral ☐ Unsatisfied ☐ Very unsatisfied

19. Please let me know your other opinions about this guidance:

……

……

Appendix D

A REFERENCE DESIGN GUIDANCE FOR DESIGNING PASSIVE HOUSE DWELLINGS IN HOT HUMID VIETNAM

(A sample version)

1. Introduction of the design guidance

This design guidance is based on a comprehensive study on the application of a Passive House approach for dwellings in Vietnam. The focus of that study is a parametric simulation of two housing models representing two typical housing types, terraced house and detached house. The study provided substantial data on energy demand of various housing design combinations, which were capitalised for the development of this tabular design guidance.

2. Contents of the design guidance

This guidance includes 21 tables showing the results on energy consumption of various housing design solutions that follow the Passive House approach. For the simplicity and ease to use, energy performances of design proposals were divided by different colours as follows:

Colour	Building category	Annual cooling + dehumidification demand (kWh/m^{2}a)
(dark green)	Passive House standard for Vietnam (very good)	≤ 55
(light green)	Passive House standard for Vietnam (good)	56 - 76
(yellow)	Low energy standard (high level)	≤ 55
(orange)	Low energy standard (medium level)	56 - 76
(dark red)	Low energy standard (low level)	77 - 91
(red)	Not energy efficiency	> 91 (or primary energy > 120)

3. The use of the guidance

This guidance can be used to:

- Choose reference Passive House design solutions.
- Evaluate the energy efficiency of housing design proposals built to the Passive House approach.

4. Annotations for building parameters in the guidance

The guidance covers a large range of design solutions which are important for a Passive House building including orientations; window area; glazing types; wall, roof insulation; exterior absorptivity (paint colour); solar shading and air tightness of the envelope.

Window area:

Based on the window to wall area ratio (%), the guidance covers 3 ratios as follows:

- Terraced house (2 external façades): small = 15%; medium = 30%; large = 45%
- Detached house (4 external façades): small = 15%; medium = 25%; large = 35%

Insulation layer of walls and roof:

For simplicity in the calculation and operation of the simulation software, the 220mm brick wall structure and the reinforced concrete roof remain the same, only the insulation thickness varies (the example here uses extruded polystyrene material (XPS)) to change thermal insulation level of walls and roofs. The respective U-values (W/(m^2K)) of selected cases are as follows:

- No insulation: wall U-value = 1.932; roof U-value = 3.244
- XPS insulation layer thickness of 25mm: wall U-value = 0.918; roof U-value = 1.137
- XPS insulation layer thickness of 50mm: wall U-value = 0.514; roof U-value = 0.576
- XPS insulation layer thickness of 100mm: wall U-value = 0.296; roof U-value = 0.316
- XPS insulation layer thickness of 150mm: wall U-value = 0.208; roof U-value = 0.218

The structure and materials of wall, roof may vary, but the same U-value should be ensured.

Exterior paint colour:

Material and colour of exterior surfaces are related to a building's absorption of solar radiation. Shiny surfaces absorb less radiation and vice versa. The guidance tables include 3 typical levels as follows:

- The paint colour is bright (white, light yellow, ...) = solar absorptivity of 0.3
- The paint colour is medium (blue, bright red ...) = solar absorptivity of 0.5
- The paint colour is dark (black, purple, dark brown ...) = solar absorptivity of 0.9

Shading for windows:

This is the combined value of various shading factors, including the buildings and surrounding trees; balconies, overhangs, curtains (automatically calculated in the PHPP software). Three typical levels of shading in the guidance are as follows:

- Good shading: reduce 80% of sunrays
- Medium shading: reduce 60% of sunrays
- Poor shading: reduce 40% of sunrays

The air tightness of the building envelope:

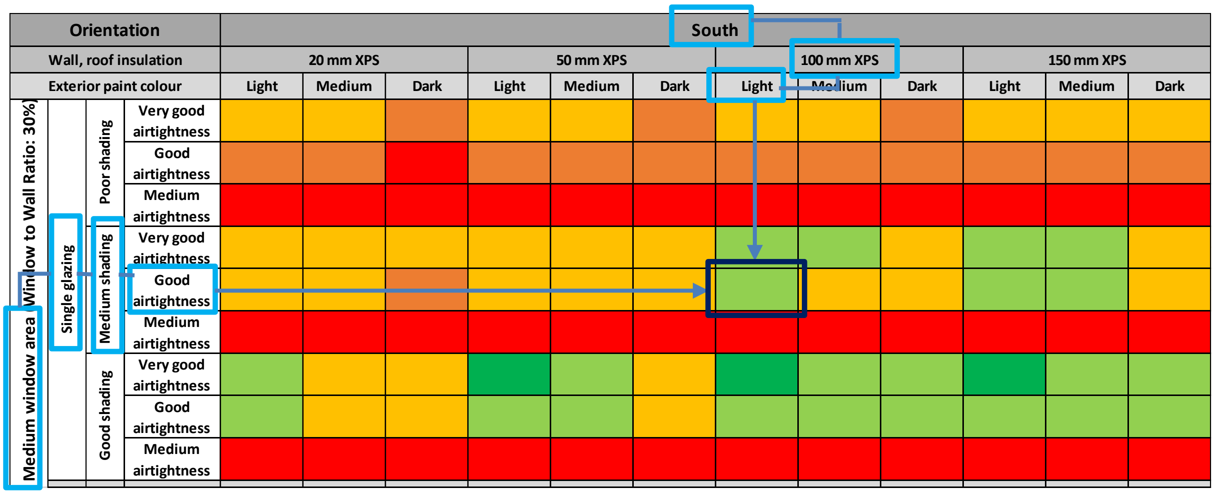
The original Passive House standard in Europe requires a very high air tightness (0.6 ACH under the condition of a pressure difference of 50 Pascals from atmospheric pressure) to prevent heat loss, requiring high quality building materials and construction techniques. However, in the context of Vietnam, the guidance proposes 3 higher levels of air tightness as follows:

- Very good air tightness = 3 ACH
- Good air tightness = 4 ACH
- Medium air tightness = 5 ACH

5. Guide to use

For example, a terraced house facing South has medium window area (Window to Wall Ratio: 30%) with single glazing; 100 mm XPS insulation layer for walls, roof; light paint colour for exterior surfaces; medium solar shading and a good air tight envelope.

According to the guidance (as shown in the below example), it is observed that the corresponding cell has light green colour which indicates that this housing design meets the Passive House standard for Vietnam (good level).



6. The design tables

Note that the design guidance includes 21 design tables. However, to avoid repetition, this sample guidance only presents an example design table for terraced housing. It could be referred to the result tables in Appendix B for the remaining 20 design tables.

(An example design table of the guidance for terraced housing)