Department of Mechanical Engineering

Passive Housing Design in a Tropical Climate

by

Chayakorn Kunajitpimol

Supervisor: Dr. Paul Strachan

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Abstract

Passive House refers to the specific construction standard for residential building as solution of demand energy saving. The concepts of a passive house building are to keep the conventional life style of occupants and to make a comfortable and healthy environment inside the dwelling during the winter and the summer, but with a much reduced energy use.

The passive house design has been widespread in Europe and the United States, especially in Germany which is the original country of passive house design. The passive house is normally designed for a mild and warm climate, not a tropical climate.

Therefore, this project studied the passive housing design in a tropical climate by selecting case studies in Thailand. This research focused on cooling and utilised passive cooling strategies and the passive house standard approaches to cool down the house. The research also examined the efficiency of passive house in a tropical climate and identified the most significant parameters of passive housing design.

The tool used in this research was the Passive House Planning Package 2007 (PHPP). This software was created by the Passive House Institute in Germany specifically for the design of a passive house. In this research, there were 2 important case studies that were developed from a simplified model in Thailand. One of the case studies followed the passive house standard, especially cooling set point temperature of 25°C. The other case study set the cooling set point temperature at 28°C - a comfortable temperature for Thai people. Both case studies followed other requirements for the passive house standard. The results of this research were assessed and compared with other examples of passive houses in a hot and humid climate.

Many factors were found to affect the performance of a passive house. The findings of this research showed the features of the passive house model that have most influence on building performance in a tropical climate –shading, ventilation rate and insulation level– in terms of the most important factors that were assessed - thermal comfort, useful cooling demand and primary energy use. The results obtained were analysed and compared with those from common dwellings constructed in Thailand.

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It has been a very long and difficult journey to get to this point but it was worthwhile. There are a few people I would like to thank:

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Chapter 1: Introduction

1.1 Research Background

The passive house is a new construction designed to reduce energy consumption in households. It is quite well known in central Europe (especially Germany and Austria) as there are more than 8,000 passive houses in central Europe, which had to be designed to fit the local climate and environment in each area (IEEA, 2007). The insulation, ventilation and window designs are the main options of passive house and there are limitations in each area to be considered.

- The local building condition
- The specific climatic condition

Therefore, each region has a specific passive house solution under consideration. In addition, the passive house is defined by the Passive House Institute as an energy-efficient building with year-round comfort and good indoor environmental conditions without the use of active space heating or cooling systems (Passive House Institute, n.d.). While occupants in passive house feel comfortable in the internal temperature, and that buildings also have high indoor air quality during each season. Lifestyle of people living in passive houses may not be changed and the performance of passive houses and typical houses are not essentially different (Feist, 2004).

The passive house has become widespread as: it consumes twenty times less energy than traditional models, reducing energy consumption. Moreover, the concept of passive houses using ultra thick insulation, complex doors and windows depends upon each local climate. In cold climates, the passive house is covered with an airtight shell so that the heat cannot escape and the cold air cannot seep in. However, the passive house can be warmed not only by sun but also by the heat from household appliances and even from occupants' bodies.

The goal of passive houses is to create a comfortable house without excessive energy demand. Inside, these houses have slightly different gestalts than conventional houses. The air outside flows into passive houses through high efficiency particulate mechanical ventilation units before entering the rooms. In the case of passive houses in mild climate temperatures, air temperature inside and outside is not the same and the cement floor of the basements are not cold either.

This project researches the passive houses in the tropical climate that consume a high cooling energy demand. The tropical outdoor environment has been regarded as important as the indoor one in the lives of the populace, which is remarkably evident in the architecture of the region (Ossen et al, 2008). In this context, the tropical region has overheated the outdoor environment, which, in turn, affects the perceived uncomfortable indoor temperature; thus, putting a huge pressure on energy demand in cities.

Normally, the local climate affects the indoor environment in many buildings, especially temperature. In the tropical climate, a building is overheated by the sun through the building entrances and windows during the day. Therefore, there is high cooling energy consumption. The passive housing design can decrease this consumption and make the occupants feel comfortable with the indoor environment, subject to passive housing design strategies and passive cooling strategies.

1.2 Scope and Limitation

The scope of this study is to evaluate the effectiveness of passive houses in the tropical climate by using the case study of residential buildings in Thailand. The main focus is determine the design parameters to achieve this goal and use the Passive House Planning Package 2007 software (PHPP) to design and conduct simulations. The selected case study was previously used for the typical small dwelling in Thailand in research about low energy buildings in the tropical area. Hence, the main objective of this project is to assess the effectiveness of the passive house in the tropical climate and discover the most critical areas that influence the results.

This study used the PHPP software to design a passive house for the tropical climate. Thus, the limitations of this project are based on the limitations of this software. The chapter two reviews the basics of the PHPP software.

1.3 Research Significance

It is expected that the results of this study would show the effectiveness of passive houses in the tropical climate and demonstrate that the proper design of passive houses helps reduce heat in the residential buildings in Thailand. Furthermore, the most important features of passive houses are energy efficiency and comfortable indoor environment. Therefore, the findings of this research enable and provide building designers with several options in selecting an appropriate tropical passive house to achieve a balance between these two features. Finally, this research assesses the critical areas that the most affect the outcome, including:

- Windows and doors
- Ventilation
- Shading
- Building environment
- Insulation and thermal bridge
- Airtight

Chapter 2: Literature review

2.1 Passive house design

2.1.1 What is the passive house standard?

In the chapter one, the definition of a passive house was discussed. This section explains more details of passive houses. The passive house standard is required for the construction of passive houses and it can be met by using several design strategies, construction methods and technologies, which are relevant to any type of building. However, various passive house standards are used in many countries but this project used a typical standard as defined by The Passive House Institute (PHI, 2008).

The passive house standard is a specific construction standard for creating buildings with good and comfortable conditions in each season, whilst limiting traditional space heating and active cooling. Generally, this construction includes: optimising the insulation level with minimal thermal bridge, very low air leakage through the building, use of passive solar and internal gains and good indoor air quality by using a mechanical ventilation system.

There are four main requirements to achieve the passive house standard.

- Specific space heating demand (SSHD) < 15 kWh/(m^2a)
- Specific cooling demand (SCD) < 15kWh/(m^2a)
- Specific Primary Energy demand (SSPD) < 120 kWh/(m^2a) including electrical appliances (Vestre et al, 2008).
- Additionally, the air leakage test result must not exceed 0.6 air change per hour using 50 Pa over-pressurisation and under-pressurisation. If joints at building envelops, window frames and walls are not sealed this leads to air leakage and uncontrolled penetration of heat. The structure of air-tightness and minimal thermal bridge is also highly recommended for the passive house and a mechanical heat recovery ventilation system is required to supply fresh air in the house as well

2.1.2 The design strategies used to achieve passive houses.

In Central Europe, the passive house is quite well known. There are a variety of strategies used to achieve this goal such as installed insulation, air tightness, avoiding thermal bridging and passive solar gain. Hence the passive house is built under these eight principles:

I. **Super insulation.** A passive house is particularly well insulated around all building exterior shells, including underground.

II. **Airtight construction.** A traditional home loses up to 40 % of its heat through ventilation (fans, leaks, draft). A passive house needs to be airtight. This is tested for the blower door and on post-construction processes (Maine Passive House, n.d.).

III. **Mechanical ventilation.** The fresh air outside is brought into the house while the stale air inside is blown out through the central ventilation system.

IV. **Heat recovery.** The outgoing warm air passes side by side with the incoming cold air, separated by a creative membrane system. In summer, this works in reverse by cooling the incoming hot air (Maine Passive House, n.d.).

V. **Highly insulated windows.** Passive houses usually have triple pane windows with low e glazing and argon gas is contained in the insulated frame.

VI. **Passive solar gains.** Normally, most windows are located on Southern coverage and fewer with Northern coverage so solar gain is maximized. To avoid overheating in summer, planned shading and window glazing are essential.

VII. **Avoiding thermal bridges.** A thermal bridge is the break of thermal insulation surrounding the house. In traditional homes this would include all framing members. As the insulation layer surrounding the house is increased, it is possible that thermal bridges would lead to massive heat losses and make the super insulation less effective (Maine Passive House, n.d.).

VIII. **Computer modelling.** A useful program is implemented to design passive houses, the PHPP software creating by The Passive Housing Institute (Maine Passive House, n.d.).

Following are the basic features and details that distinguish passive house construction (PassivhausUK, 2007).

Compact form and good insulation	U-values of all components of external housing envelopes are insulated to less than 0.15 W/m^{2}K
Southern orientation and shade considerations	In the conventional house, some consideration is given with regard to North or South orientation, but the improved energy savings resulting from passive site design are often overlooked. While, the use of solar energy is a significant factor in the design of passive houses and its use depends on each region's climate.
Building element junction	Linear thermal transmittance < 0.01 W/mK.
Energy efficiency window glazing and frames	Windows (glazing and frames combined) should have U-values not exceeding 0.8 W/ m^{2}K with solar heat-gain coefficient around 50%. For double super glazing, U-values must not exceed than 0.75.
Building environmental air-tightness	Air leakage through unsealed joints must be less than 0.6 times the house volume per hour
Passive preheating of fresh air	Fresh air may be brought into the house by an underground air duct that exchanges heat with the soil.
Hygienic ventilation	Fresh air demand as requirement should be 30 m^3/h/person, extract from any damp room and controls l/m/h, more in any wet room.
Highly efficient heat recovery from exhaust air using air to air heat exchanger	Most observable heat in the exhaust air is transferred to incoming fresh air (heat recovery > 80%).
Latent heat recovery	Max heat load 10 W/m^2 and a compact heat pump unit is used for exhaust air.
Air heating on extreme day	Fresh air temperature >= 8 degrees and a subsoil heat exchanger is used as a fresh air pre-heating option.
Hot water supply using regenerative energy sources	Solar collectors or heat pumps provide energy for hot water

Energy saving household appliances	Low energy stoves, fridges, washers and dryers are necessary in passive housing design. The ventilation fans < 0.4 Wh/ m^3.

Table 1: Principle Features and Details of Passive House (PassivhausUK, 2007)

However, the passive house's design depends upon the climate region of the house location. Thus, not all of the methods of this design may be used in a house. While some types of design need all aforesaid features in the passive house (such as insulation and using energy saving household appliances). In case of passive houses in hot climates, the design will be focused on passive cooling design by using shading, insulation, ventilation. This will still use the passive housing standards to achieve the goal.

2.1.3 The elements of passive house.

After designing, the passive house the elements of the passive house should be similar to the following details:

- Air quality in the passive house is fresh and very clean because a ventilation system and good air quality are provided. About 0.3 air exchanges/hr (ACH) are recommended; otherwise, air may become stale (excessive carbon dioxide, flushing of indoor air pollutants) and dry (less than 40% humidity).
- Insulation has high R-values that lead to no outside wall, which are colder than other walls.
- There is more space on the room wall because it does not have radiators.
- Bedroom windows can be cracked slightly to improve different inside temperature in the building.
- The temperature inside building is homogenous; it is impossible to have a single bedroom in which the temperature is different from the other rooms in the house.
- When ventilation and heating is turned off, the temperature changes very slowly.
- Opening windows and doors for a short time has a very limited effect.
- Air inside the passive house has more moisture than other standard houses due to a lack of ventilation cold air.

2.2 Low energy design in the tropical climate

Generally, in the tropical climate, cooling is the main energy consumption for most people. There is also a high amount of solar radiation in the hot and humid climate; Hence, the passive cooling design feature can be used.

2.2.1 Construction details

The construction design is one solution to reduce energy demand in a house, and to make the occupants feel happy in the comfortable environment. The main climatic factors affecting human comfort and relevant to construction are:

- Extremely different ambient air temperatures during the day and night and between summer and winter
- Humidity and precipitation
- Solar radiation
- Air movement and wind

The main points to take into consideration when designing energy saving houses in hot climates are:

- Minimizing heat gain during daytime and maximizing heat loss at night in the hot season.
- Reducing internal heat gain in the hot season.
- Optimising the building structure (especially thermal storage and time lag).
- Controlling air circulation.

With reference solar radiation, the building is a source of maximizing heat gain. A common way of cooling is to minimize the incident solar radiation of the building, by using shading. If the ambient temperature is higher than the room temperature, heat will enter the building by convection due to unwanted ventilation. Therefore, elements of construction including the roof, wall, floor and opening must be discussed.

2.2.1.1 Roof design for passive house strategy

The roof should be closely fixed and its material should insulate the building from the extreme humidity and heat the climate. It should also create shading around the building and protect the exterior wall from solar radiation.

Pitched or sloping roofs are recommended and the materials should not be metals like aluminium, zinc and copper because they have high conductivity and there is a problem of corrosion by sulphur dioxide in the atmosphere. The construction of the second roofs and facades with several inches of gap between primary and secondary surfaces allows airflow around the primary building. This is very important as it can protect heating from sunlight and direct heating from outside surfaces

I. Roof solar shading

External devices can control the amount of solar radiation entering room, reduce a huge cooling load and improve indoor thermal comfort and solar radiation.

II. Roof solar reflection

The roof colour affects its ability to reflect solar radiation. However, if the long wave is emitted higher then heat flux transmitted into the building is reduced significantly. In addition, with highly absorptive roofs, the difference between surface and ambient air temperature may be as high as 50 degree Celsius. With less absorptive roofs such as white paint, the difference is only 10 degree Celsius; so the cool roof is more effective in reducing cooling energy use (Ossen et al, 2008).

III. Roof thermal insulation

Good insulation of a roof in the tropical climate takes into account the thickness, insulation materials and insulation colours. Typically, insulation thickness in a tropical climate is around 5 cm for the red and blue roof; so, for the medium colour, thickness value should be about 8 cm. For the type of insulation, polystyrene rather than mineral wool is typically used in the tropical climate. Although mineral wool is reasonably inexpensive, it does not work very well as it can lose its thermal properties when absorbing ambient humidity (Ossen et al, 2008).

IV. Summary

The performance of a roof depends upon the different level of thermal mass, insulation, the geometry of the ceiling, the external colour and ventilation. All of these factors can reduce the cooling energy requirements and degree of discomfort in the building. The use of insulation in the ceiling is also the most effective element of roof development. Indeed, in the higher mass cases, this is unhelpful as the super insulation prevents heat dissipation at night.

2.2.1.2 Wall design for passive house strategy

In hot climates, the protection required against the outdoor temperature and humidity is quite significant so the wall design is essential for low energy strategies. It allows for passive control of indoor conditions by managing the transmission of external outdoor temperature. Consequently, construction materials such as concrete, brick, cement, block and other solid materials with a high thermal mass are inappropriate to build with in hot climates.

The high-thermal mass materials generally absorb heat from solar radiation at a much slower rate than light weight materials like timber and steel. Light weight materials absorb heat faster and, cool down quickly. The construction wall should be appropriate to local climate.

I. Wall solar shading

In the hot climate, there is a high level of solar radiation. One way to prevent this entering the house is by solar shading the walls. The impact of solar protection walls is less significant than solar protection windows (Ossen et al, 2008). In addition, orientations of walls affect the indoor temperature as Southern and Northern surfaces normally receive less solar radiation than Eastern and Western surfaces.

II. Wall solar reflection

This reflection can avoid solar gains. Reflective insulation is the most effective means of improving room performance. The surface colour influences the absorbability; in a tropical climate with high solar radiation, white is highly recommended for the surfaces. The reflective white surface provides the best performance and it minimizes the need for insulation. However, for solar protection in darker colours, it is recommended to have thicker insulation.

III. Wall thickness

Wall thickness can determine comfort in a house; rooms with thicker walls are likely to be more comfortable. Temperatures in houses that have wall thickness ranges between 125 mm and 500 mm, which shows that rooms with thicker walls tend to be more comfortable (particularly in hot and humid climates). Generally, houses with thick walls on the lower floors offer a more comfortable environment than those on upper floors due to solar gain in the roof (Fuad, 1996).

Thermal transmission depends upon the thermal properties and thicknesses of the materials. Lower-value thermal conductivity has less thermal transmission. Low-mass materials such as wood are considered suitable for free-running operations in hot and humid climates as the indoor temperature decreases significantly in the evening when the wind usually dies down. The high mass building cools down more slowly during the night which is a cause of discomfort during sleep. In conclusion, free-running operations (if assisted by ventilation at night) for any high mass building can be more comfortable than low-mass one (Ossen et al 2008).

IV. Wall thermal insulation

Wall insulation is a good, commonly used strategy. The thermal mass of enclosing envelope is a parameter mostly related to the thickness and type of construction materials used. It is able to delay heat transfer through the building structure over a period of time. Moreover, insulation materials focusing on high temperatures have higher thermal conductivity and therefore higher envelop cooling load in different degrees, depending on the type of insulation material.

A higher thermal conductivity in insulation materials offers lower thermal resistance; thus the thickest insulation materials is required to achieve optimum thermal insulation. In fact, the thickness of insulation is an important aspect of the design since thick insulation materials can reduce the space of the building.

The thermal performance of a building environment is determined by the thermal properties of material used in its construction by absorbability and emission of solar heat and overall u-value of the corresponding components including insulation. Furthermore, the placement of insulation materials within building component should be close to the entrance of heat flow to achieve the best performance. However, in practice, it is common to use insulation inside or between wall cavities.

V. Summary

Conduction, convection and radiation affect a building's walls. Solar radiation penetrating through the building surface can be converted to heat by absorption and transmission with conductors. The conduction thermal transmission occurs from air outside the building to the external surface of wall, and from the internal surface of the wall to air inside the building. This contributes to a significant amount of heat gain from the outside to the building by conduction through the wall and air leakage, as the inner building area has a lower temperature.

The insulation thickness can reduce the energy demand and it is essential to optimize the suitable insulation material and thickness to have an economical cooling load system.

2.2.1.3 Floor design for passive house strategy

The modification of air temperature, humidity, solar radiation and air movement is necessary in this strategy. The strategy also depends upon the climatic condition. The landscape elements, including various types of hard and soft materials, can absorb the radiation and act as thermal insulation.

I. Ground surface treatment

In hot and humid climates, the surface temperature of concrete can reach as high as 55 degrees Celsius while the surface of metal can reach over 70 degrees Celsius (Ossen et al, 2008). In addition, the ground surface needs to be designed to reduce heat collector surfaces and the paved surface can absorb and re-radiate great quantities of heat. Paving should be covered by grass and shaded by some elements and trees. The colour of a paved surface affects to the level of heat absorption and re-radiation; lighter colours are preferred with rough surface in the horizontal and vertical as it can reduce heat absorption and re-radiation.

Another way to reduce direct heat gain in the building is by open wooden or aluminium structures. This can let breezes through the building. Plants like vines can also help cooling.

II. Ground thermal insulation.

In summer and mainly during the day, the ground temperature is lower than ambient air temperature. If some building parts are inserted, the building can lose some heat to the land in case of low level of insulation.

An experiment was conducted to compare two types of floor: the first one consisted of timber, and another one consisted of concrete slab. The explanation for better performance of ground type came from their direct linkage to the ground mass, which acted as a heat sink to the floor above. The simulation of un-insulated timber floor assumed a fully encircled perimeter. For both free running and conditioned operations, concrete slab performed better as a ground floor (Ossen et al, 2008).

When using insulation for on-ground floors, it decreases performance in both timber and concrete slabs. Thus, the insulation increases the separation between the room and the ground mass.

III. Natural solar shade.

Shading by trees is a very useful method for cooling the ambient hot air and protecting the building from solar radiation. The solar radiation is absorbed by leaves that mainly utilise it for photosynthesis and evaporative heat loss.

Heat emitted by solar radiation is stored in fluid by plants. The best place to plant some shading trees is by the windows that receive the most sunshine during peak hours in the hottest months. Normally, windows and walls at the West and East side of a building receive more sunshine than the North and South about 50% more (Ossen et al, 2008).

Trees should be planted at positions determined by lines from the centres of windows on the western and eastern walls near the position of the sun (Ossen et al, 2008). Furthermore, a main benefit of using vines and creepers in the passive cooling strategy is their ability to cover a large portion of a building in a short period of time.

As a result, this advantage can be successfully supplemented during the period by planting trees and shrubs in the landscape. This is also useful for areas with limited ground space.

IV. Summary

The overheating of solar radiation can be solved by using low absorbing or reflective surface materials. The building size and materials also affect the internal thermal comfort of a building. The colour of surfaces is also significant because it affects the material's ability to absorb solar radiation. Using trees to shade and protect against solar radiation is one strategy of passive cooling that can be applied to passive houses in hot and humid climates.

2.2.1.4 Opening design for passive house strategy

In a conventional house, windows need to be located at the certain point to create good ventilation. Thus, the opening windows can drop heat and humidity but also increase the inside temperature via solar penetration.

The windows on the western and eastern wings and walls usually receive high overheat solar radiation so they should have the most significant shading. Moreover, any unwanted heat gain from solar radiation in the morning and afternoon should be reduced by protecting the surfaces and windows facing to the West and East.

Planting trees around the dwelling is one option of these strategies to protect against the solar gain from outside and to control the temperature inside. In addition, the simple way to reduce the heat gain of the building is to fix some windows to face the prevailing breeze. One factor used in determining the construction of any tropical building is solar shade.

I. Solar shade

In a hot and humid climate, solar radiation is a predominant factor that should be considered for house protection. As a result, shading is highly required in this climate to prevent solar heat gain. The primary design strategy implies that shading potential is to reduce solar heat gained through wall openings. This strategy can be achieved by two options: natural devices and sun control devices.

The natural shading strategy is a way of shading the building by the orientation of the sun and the growing of plants. Moreover, another way is to exclude the useless solar radiation's transmission into the building. The design, fixed location, effectiveness in terminating the direct sun and operational system are installed in sun control devices that can be divided into two types: internal and external solar shading devices.

a) Internal devices

Internal devices can control solar radiation and can be categorized into two types. Solar shading devices (such as blinds, louvers, drapers and screens) that protect against solar radiation, and special glazing for windows. Internal shading devices are less effective than external shading ones since the former allow solar radiation to hit the vertical surface of the house. They also let heat penetrate to a building (Ossen et al, 2008).

b) External devices

External devices can be used to decrease unnecessary solar heat and they are more effective since they cut off the solar radiation before it reaches the vertical surface of the building. The heat reduction presents the best result by preventing unwanted heat, rather than removing it as blocked heat then dissipating to the outside air. External devices can be separated into two types: vertical and horizontal.

The external devices are typically structural projections in the form of cantilevered, floor, walls and shading devices using light weight materials. The performance of operable devices is better than fixed ones in preventing unwanted heat as it can be adjusted to the sun's movement and shading needs. Furthermore, fixed devices are maintenance free whereas operable devices need frequent maintenance to keep them in good condition.

Canopies and awnings are other types of external horizontal solar shading devices and, are typically used for high solar altitudes. The material's properties such as thermal and optical transmittance, colour, geometry and fixing position affect the efficiency of these devices. The angle of canopy and awning is quite important as well because it can reduce active cooling consumption in the house. However, there are certain limitations of installed external projection. Mostly, the limitations of installation were based on structural and architectural reasons regarding energy implication.

II. **Summary**.

Windows facing the East and the West should be protected by suitable wide horizontal shading devices such as verandas, eaves and pergolas. Vertical shading devices or windows should be small and placed high on the wall under the eave. External shading devices are preferred to internal shading devices due to their effectiveness.

2.2.1.5.1 Glazing

Building a passive house requires highly effective windows. The type of glazing and frame will depend upon the local climate. In many cases, selecting an advanced glazing system will create a cascade of benefits and savings. There are many types of window glazing suitable for a passive house. These have different properties according to the kind of glazing technology. See the brief explanation of glazing technology properties below.

- Visible transmittance: this is the percentage of visible light that can pass through. The visible transmittance of glazing appears clear, provides sufficient daylight and keeps views unchanged, but it can lead to a glare problem. However, glazing with low visible transmittance is best used in highly glare sensitive situation but it does have an issue with gloom under some weather conditions (Anon, n.d.).
- Visible reflectance: this indicates to what percentage the light striking the glazing and is reflected. Most visible reflectance glazing consists of both outside reflectance and inside reflectance. However, an interior problem that can occur is that the high reflectance also brings low transmittance (Anon, n.d.).
- Solar heat gain coefficient (SHGC) or G-value: this is the indicator of solar heat gain and, generally, the range is between 0.9 and 0.1 (lower value means low solar gain). These indices are dimensionless gain numbers between 0 and 1 that show the total heat transfer from sun radiation.

- U-value: this measures of heat transfer through the glazing because of different temperatures in the interior and exterior. It indicates the rate of heat flow, so a low value is better. This property is necessary to reduce cooling load in hot and humid climate and decrease heating load in the mild climate as well. Usually, windows have a U-value in the range of 0.8 to 1.1 W/m^2K, while R-values range from 0.9 to 0.3 m^2K/W (Anon, 1994).
- Spectral selectivity: this refers to the ability of glazing materials to respond to different wave lengths of solar, and energy, admit visible light and refuse invisible infrared heat. Spectrally selective glazing is generally used for special absorbing tints and coatings.
- Glazing colour: this affects the appearance of views and interior finishes for example, bronze will dull a blue sky. Glazing colour is also a main determinant of the external appearance of the building's frontage.

Therefore, a passive house should contain suitable window glazing. There are several types of glazing to help control heat loss and gain. The advanced glazing includes double and triple-pane windows with low emissivity coating (low-e). Normally, double or triple glazing is used in a passive house. A further option is low-e glazing.

Low-e glazing has special coatings that reduce heat transfer through windows. The coatings are thin and almost invisible; they consist of metal oxide or semiconductor films. Generally, air spaces within windows reduce heat flow between the panes of glass.

When applied inside, the low-e glazing with double-pane window is placed at the outer surface of inner pane of glass to reflect heat back into the living space during the summer season (Anon, 1994). In cooling-dominated climates the coating is typically located on the inner face of the exterior pane to reflect heat out of the building (National Research Council Canada, 2009).

A low-e layer has low thermal emissivity. This coating reduces thermal radiation between inner and outer panes. Moreover, the gas in the gap is changed from normal air to s noble gas like Argon or Krypton as they have lower heat conductivity (PHI, 2006).

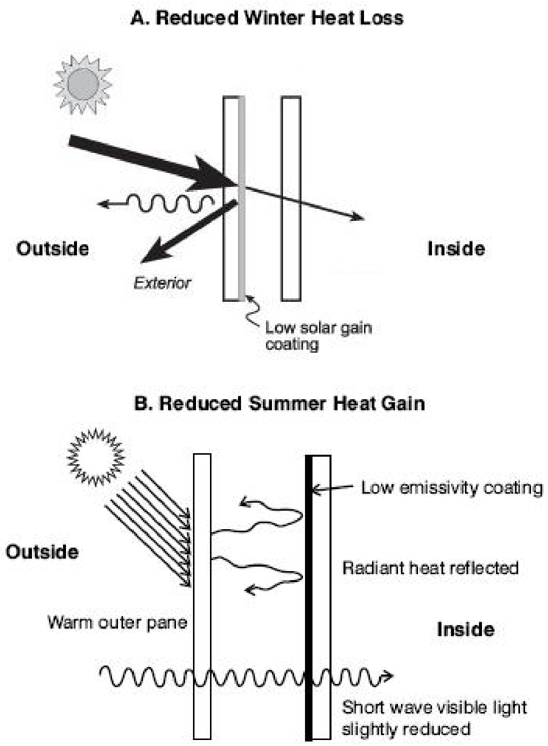
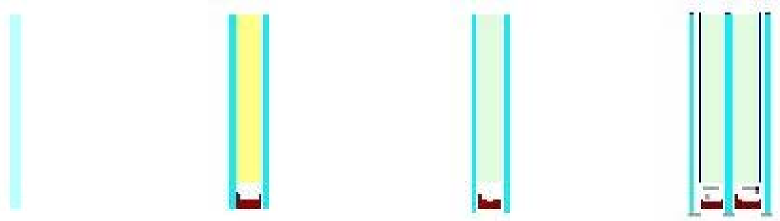


Figure 1 : Low-e Glazing Reduce Heat Transfer (ANON, 1994).



Type	Single	Double	Double low-e (Argon)	Triple low-e (Argon)
U-value (W/m^2K)	5.6	2.8	1.2	0.65
Internal Surface temperature (-10 degree out and 20 degree in)	-1.8 C	9.1 C	15.3 C	17.5 C
Solar transmittance	0.92	0.8	0.62	0.48

Table 2: Type of Windows (Bansal et al, 1994)

Double-pane low-e glazing shows a higher surface temperature (16 degrees on average). The poor insulation of conventional frames should be improved in a passive house; double glazing has been suggested in new constructions. There is an air gap between two panes and the heat loss coefficient is reduced to 2.8 W/ m^2K; hence nearly half the losses are saved compared to single glazing.

In a tropical climate, the amount of solar radiation of opening windows is affected by the location of the windows and weather condition. The reflective coat of glazing is suitable for hot climates and reflective coatings are commonly used to reduce the transmission of sunlight through window glass. Although they typically block more light than heat, reflective coatings when applied to a tint or clear glass can also slow the transmission of heat. However, the surrounding surface receiving solar radiation directly can be reflected this increases the effective collector area of wind. The reflectivity of surfaces is given below (PHI, 2006)

Perfect mirror	100 %
Green gas surface	15-30%
Sandy floors	15-40%
Brick floors	30%
New snow-covered surfaces	80-90%
Old snow-covered surfaces	40-70%
Concrete	30-50%
Dry grass	22-42%
Polished aluminium	75-95%
Silver backed glass	88-90%
Aluminised mylar	60-80%
Polished stainless steel	60-80%
White porcelain enamel	70-77%

Table 3: Reflectivity Percentage of Materials (Bansal et al, 1994)

In different climates the interior surface temperature should be of the same comfort level but the required U-value will be different. Moreover, the level of insulation in building components is well matched to the quality of windows suitable for passive houses. The advantage of passive house window is not only decreased heat loss and gain but also increased thermal comfort (Bansal et al, 1994).

2.2.1.6 Thermal bridge.

A thermal bridge refers to the materials or assembly of materials in a building envelop in which heat is transferred at a significant rate, due to higher thermal conductivity through the surrounding materials. Junctions between windows or doors and wall, wall and floor, and wall and roof should be designed carefully to avoid thermal bridges. A thermal bridge causes to increasing heat looses or gains depending on the seasonal climates but, in the case of hot climates, it causes heat gain through the structure (SEI, 2007).

A construction free of thermal bridges is highly recommended for the passive house located in a tropical climate. Heat can transfer from the higher temperature to the lower temperature between all junctions of building so thermal bridge effect should be avoided. Normally, the extra heat flows have negative values and there are linear thermal bridge heat loss coefficients (ψ) that should be greater than 0.01 W/mK. This parameter refers to exterior dimensions from the given interior reference dimensions (PHI, 2007).

$$\psi = \frac{Q_{2Dim} - Q_{1Dim}}{l \times \Delta\vartheta} \quad (2.1)$$

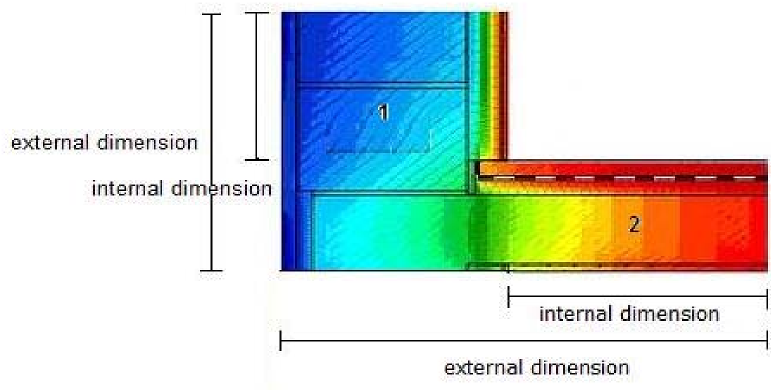


Figure 2: Thermal Bridge (PHI, 2007).

Q_{2Dim} : Heat flow

$\Delta\vartheta$: Temperature difference between the exterior and interior

$$Q_{1Dim} = \sum A_i U_i \Delta\vartheta_i \quad (2.2)$$

U_i : U-value of building assemblies

A_i : Building element area number " i "

2.2.2 Ventilation.

Ventilation is a powerful strategy to cool a passive house in the tropical climate and it has two goals:

- To remove heat from house
- To provide air movement in the house to cool the occupant (Anon, 2000).

There are many types of ventilation that can be used in passive house in the tropical climate, especially natural ventilation (to which a cross ventilation option may be added). This strategy is suitable to the tropical climates, but, sometimes the breeze brings heat from outside through the building, so it needs to be designed in the appropriate period and direction. In addition, mechanical ventilation is often used to cool the building but this is not strictly passive.

Natural ventilation relies upon the breeze in the summer to create air movement in the house. This is quite effective as the main objective of a passive house in the tropical climate is to avoid overheating of the indoor temperature by keeping it at least lower than outdoor temperature. However, the positions and types of window affect the ventilation system in the house.

The house windows on both the windward and leeward sides must be open to increase the air flow. If there is no air exit, the house will become pressurized- the opened windows of the house become another obstacle for the wind.

Cross ventilation is one method appropriate the tropical climates. In this method, windows are fixed at both sides of a room causing air flow across the space. The windows on the windward side of the building are opened less than windows on the leeward side. This ventilation is based on natural ventilation principles and is also based on the requirement of fresh, comfortable indoor air. Therefore, it is recommended that rooms with two external walls should have windows on both sides with the distance between the windows as long as possible, in order to maximize the potential of cross ventilation. It is recommended that the window size on the East and West sides should be reduced (Anon, 2000).

A fan is an optional mechanical ventilation device used to cool air inside the building; a ceiling fan does not remove heat but generates breezes passing, an occupant and helps reduce body heat efficiently. Fans should be fixed throughout the house, not only the master bedroom or family rooms, where family members in.

When there is no air flowing into the house, fans are required to pull some air from outside to cool the inside. The air in a hot room is removed and exhausted through a vent in the attic while the fan pulls in a cooler air supply through the window.

The one main aspect of having good air ventilation in a building is improved indoor air quality. There are also several types of mechanical ventilation units to get the fresh air coming in during cooling and heating the coming air that can improve the air quality. Heat recovery ventilation unit (HRV) and energy recovery ventilation unit (ERV) are one kind of heat and air exchanger of ventilation system.

HRV provides fresh air and improves climate control while saving energy by reducing heating and cooling requirement. ERV is also closely related but they transfers the humidity level of the exhaust air to the intake air. The difference between them is that HRVs are ideal for colder climates and keep the home supplied with a steady flow of fresh outdoor air, while ERVs are used in warmer climates and high humidity environments. It also recuperates the energy trapped in moisture, which improves overall recovery efficiency.

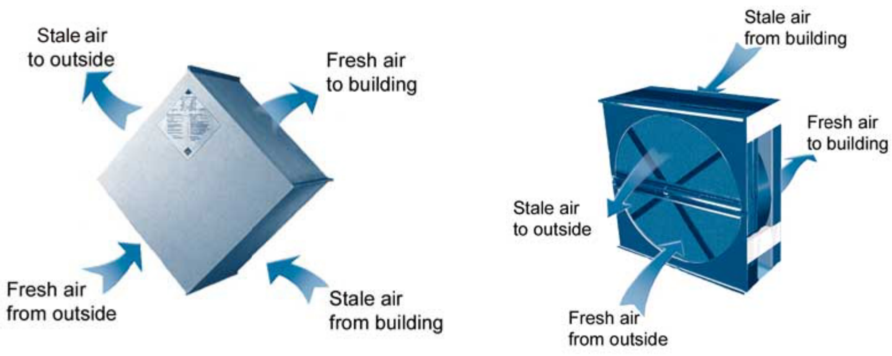


Figure3: HRV (left) & ERV (right) Operation Diagram. (Carol A., 2009)

In a passive house, this is more than sufficient for comfort cooling during summer without resorting to air conditioning. In more extreme hot climates a very small air to air micro heat pump in reverse (air conditioner) on an air inlet of air conditioner after the HRV heat exchanger has dumped heat to the outside air will suffice.

Finally, attic and roof ventilations reduce the roof and ceiling temperature; saving some cooling costs and ensuring the longevity of the roof. The figure below shows the variety of ventilation types. However, attic ventilators do not consume as much electricity as they would save air conditioning costs and are recommended only in cases when the required ventilation cannot be met by passive means.

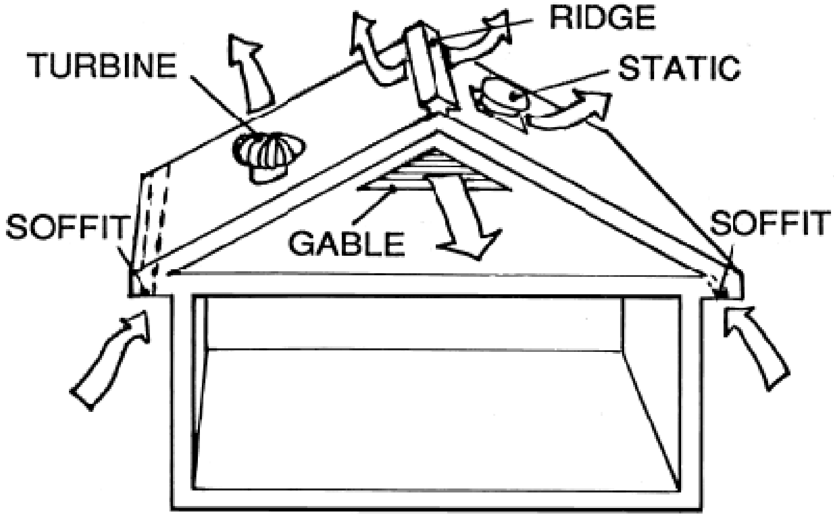


Figure4: Ventilation Operation (ANON, 2000)

The vent area needs to be separated equally between the low outlet at the eave or soffit and the high outlet at the roof ridge or gable. The most effective ventilation strategy is to combine continuous ridge and soffit. The amount of ventilation required depends upon the amount of moisture entering the attic and its floor area.

It should be noted that without a mechanical ventilation system in the building, one can only try to use the strategy of opening windows for at least 5 or 10 minutes at a time and the function of a ventilation system is to supply fresh air in the right amount into the living space. The basic solution is an exhaust fan that can extract stale and humid air from kitchens and bathrooms.

Fresh air should be supplied to the living room, bedroom, and studying room in the passive house; so this air can be used for heat distribution. This type of fresh air will work only for buildings with low heat requirements. However, the defining condition for passive houses is that they need to use quite smart energy saving solutions for building services.

2.3 PHPP software

Passive house planning package (PHPP) is the software used to design passive houses. The Passive House Institute said that this software can be used worldwide. This software package is based on a series of interlinked Microsoft Excels data sheets, allowing building designs to be verified against the passive housing standard.

The verification requires specific and detailed data about designs, materials and components to be input into the PHPP spreadsheets. The passive house id also built in relation to the climate data spreadsheet. Some principle worksheets are listed below, along with the main function.

- Climate data: it is possible to choose the climate to which the passive house is designed with significant impact on the U-value, which is required to achieve the annual heat or cooling demand. The users can either define the climate data by themselves or use a standard or regional climate in this software.
- Verification: this sheet relates to the overall evaluation of the building, including space heating and cooling requirements, specific primary energy requirements and the heating and cooling loads. The user can see at a glance on this sheet whether the building can be certified as a passive house or not.
- U-value: this sheet enables the assessor to specify the construction of all the opaque materials (i.e. excluding the windows) and the elements of the building envelope, for the purposes of calculating the U-value of those elements. The worksheet requires the input of the lambda value of the building materials, their thickness and the proportion of insulation occupied by structure elements.
- Windows: the orientation and size of all windows are input into this sheet along with the U-values of the glasses and frames.
- Annual heat requirement: this value is calculated by subtracting heat losses through transmission and ventilation from the total solar and internal heat gains. However, in a tropical climate this worksheet is not important but instead relates to cooling worksheet. That is the verification of the useful cooling energy demand, if there is active cooling.

- Heating load & cooling load: the building's heating and cooling loads are based on an energy balance calculation. For cooling load, the energy balance of internal and solar loads, and transmission and ventilation losses or gains, indicates the cooling capacity required to maintain a passive house with an extremely low cooling demand.

PHPP software is very complicated and detailed. The verification page is available to check whether the required data has met with passive house standards or not, such as space heating and space cooling requirements. If the value cannot meet the requirements, the building would likely need to be modified.

2.3.1 The methodology of PHPP software

As discussed previously, there are principle worksheets used in PHPP software and some calculations are required. Examples of these are shown below:

2.3.1.1 U-value

This worksheet is like a tool for calculating the overall heat transfer coefficients of building elements. It is not appropriate for building elements with metal penetrations. The U-value can be found by using the thermal resistance equation below:

$$U = \frac{1}{R_{si}+R_1+R_2+\cdots+R_n+R_{se}} \qquad (2.3)$$

R_{si} , R_{se} : Thermal resistance at interior and exterior surfaces (m^2K/W).

$R_1 \ldots R_2$: Thermal resistance of individual construction layers, 1…n (m^2K/W).

In this software used the thickness and thermal conductivity of different materials to calculate the thermal resistance: $R_i = d_i / \lambda_i$

d_i : thickness of material (m.)

λ_i : thermal conductivity (W/mK.)

In one section building area, there is only one U-value. Hence if the building assembly has different types of layers, it also determines the value of each section. In the PHPP, there are default values for the thermal resistance of the interior, exterior and below ground exterior surfaces, depending upon the direction of heat flow. All of these values are used to calculate the U-value.

Direction of Heat Flow			
	Upward	Horizontal	Downward
R_{si} (m^2K/W) : Thermal resistance of the interior surface	0.1	0.13	0.17
R_{se} (m^2K/W) : Thermal resistance of exterior surface		0.04	
R_{se} (m^2K/W) : Thermal resistance of below ground exterior surface		0	

Table 4: Surface Thermal Resistance (PHI, 2007)

The outside surface-facing adjacent to the air space would not be considered in the U-value calculation when this assembly has good ventilation, so the thermal resistance of the exterior surface has the same value as the interior surface (PHI, 2007).

2.3.1.2. Windows

Heat losses and gains of windows are one key factor impacting the energy balance in passive houses, so it should be calculated carefully. The window areas, window U-value, solar radiation through glazing and the matching reduction factors can be determined with this worksheet.

I. Solar radiation and window direction.

The calculation of solar radiation depends upon the angular deviation from the reference direction and the angle of inclination. In this case, North is the reference direction of these angles. Thus, the deviation clockwise from North (ϕ) is measured as an angle in the horizontal plane and the following table is a list of ϕ values as a reference.

North	0°
North East	45°
East	90°
South East	135°
South	180°
South West	225°
West	270°
North West	315°

Table 5: Definition of Solar Azimuth, ϕ from The North-South Line (PHI, 2007)

The angle of incidence is also required for the calculation of total radiation. This is the angle between the normal to window surface and the zenith; a vertically installed window has a ϴ value of 90°, for windows on a flat roof the value would be 0°. The solar gain for each window is calculated by using ϕ and ϴ (PHI, 2007).

II. Window Installation.

The window does not only include the frame and glazing but also the connection to the façade. Additionally, the glazing itself has spacers. These junctions lead to thermal bridge effects so these are the weakest thermal points of the window. However, thermal bridge effects can be reduced by using insulating spacers and insuring the best installation. This effect can be shown by the thermal bridge heat loss coefficients of the spacer (ψ_{spacer}) and the installation ($\psi_{installation}$) (PHI, 2007).

The window's U-value is calculated by using glazing, frame, the spacer and the installation.

$$U_{Window} = {}^{1}/_{A_{window}} \cdot [U_{Glazing} . A_{Glazing} + U_{Frame} . A_{Glazing} + l_{Glazing} . \psi_{spacer} + l_{window} \psi_{installation}] \quad (2.4)$$

A_{Window} : total window area (rough opening)

$A_{Glazing}$: total glazing area

A_{Frame} : total window frame area

$U_{Glazing}$: glazing U-value

U_{Frame} : window frame U-value

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$l_{Glazing}$: glazing perimeter (installation edge)

l_{Window} : window frame perimeter (installation edge)

ψ_{Window} : thermal bridge heat loss coefficient of the glazing edge seal.

$\Psi_{Installation}$: thermal bridge heat loss coefficient of the installation.

III. Reduction factors for solar gain

The reduction factors are determined by using shading and window details and they are used in the heating load and cooling load worksheet. The following formula is the reduction factor equation.

$$r = r_{shading} \cdot r_{dirt} \cdot r_{incidence\ angle} \cdot r_{frame} \tag{2.5}$$

$r_{shading}$ = reduction factor considering the degree of shading from neighbouring buildings, tree and overhangs. This value can be precisely determined in the shading worksheet.

r_{dirt} = reduction factor considering dirty windows. The standard value is 0.95.

$r_{incidence\ angle}$ = reduction factor considering the reduced energy transmittance due to non-vertical radiation. The standard value is 0.85.

r_{frame} = reduction factor considering the opaque part of the window.

In this case, calculating the shading reduction factor depends upon the window geometry, shading elements, orientation of the window and the time of the year. The shading factor is calculated with the following formula.

$$r_{shading} = r_H \cdot r_R \cdot r_o \cdot r_{ot} \tag{2.6}$$

r_H = shading by row of houses directly in front of the considered window

r_R = shading by reveals or other vertical elements.

r_o = shading by horizontal elements above the window such as balcony

r_{ot} = other shading by user defined and 100 % for no additional shading.

2.3.1.3 Annual heating and cooling demand

In PHPP software, this section is quite significant as it affects all other sections that involve this result. The domestic heating and cooling demand depends upon the balance of heat losses and heat gains, following PHPP calculations. The following diagram shows the formula used for the energy balance in a household. The result of this section can be used to calculate heating and cooling load in a building.

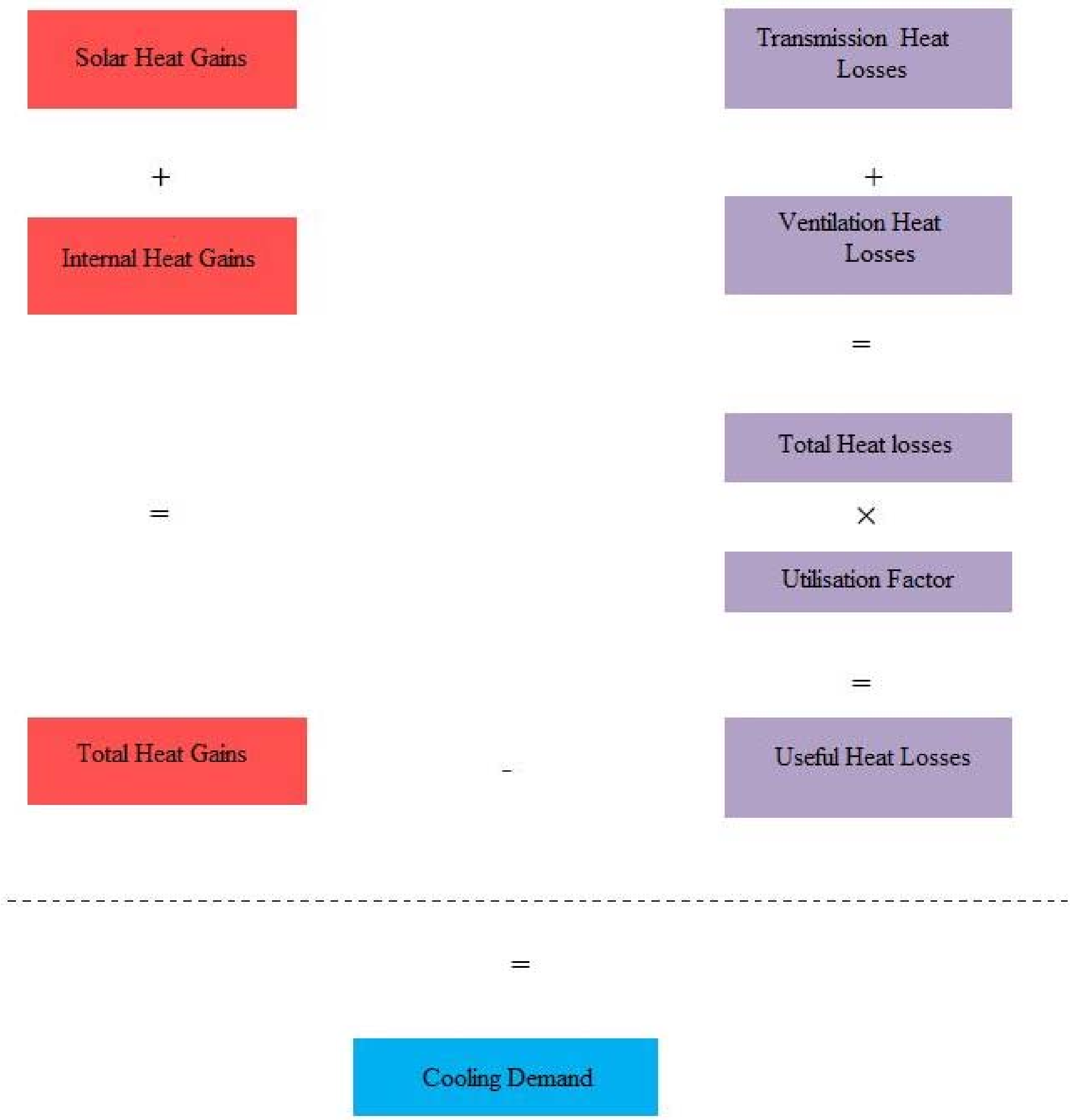

Figure 5: Energy Balance Diagram (PHI, 2007)

2.3.1.3.1 Heat losses

The annual heat losses can be divided into two sections: transmission heat losses; and ventilation heat losses. Both are calculated to find out the total annual heat demand.

I. Transmission heat losses

Transmission heat losses can be determined in every building assembly of heat exchanging envelope (such as windows, ceilings and floors) by using this formula.

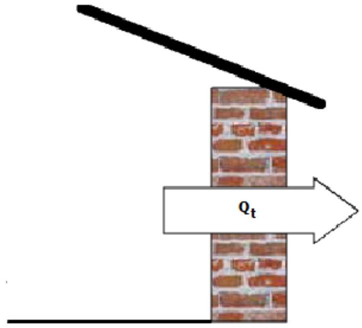

Figure 6: Transmission Heat Losses (Toolbox, 2005)

$$Q_T = A.U.f_T.G_T \qquad (2.7)$$

A : building element areas. The exterior dimensions of the insulated building envelope are used and this data can be generated in the area worksheet.

U : building element U-value

f_t : reduction factor for reduced temperature difference

G_t : temperature difference time integral

For transmission losses, the window quality plays an important role. In the design of passive houses, a comfortable interior temperature must be obtained without an additional heat source. If the windows are located at the South and are only shaded modestly, they can contribute solar heat to the room rather than lose it by transmission. There are several factors affecting the U-value of windows: glazing quality, frame of window, quality of spacers and installation and the glass to frame ratio (PHI, 2007).

There are heat losses in the joins of building envelops, so thermal bridges already exist in the calculated transmission heat losses. When using exterior dimensions to determine the heat loss coefficients of geometrical thermal bridges, these results are normally negative values. Hence these heat losses are overestimated if using this basic calculation method (PHI, 2007).

If all building essentials are constructed to the standards and avoid heat losses from thermal bridges, then thermal bridge-free construction is achievable. In fact, the thermal bridge effects should be reduced as much as possible using thermal separation. There are different solutions for typical thermal bridge construction. The following formula is used to calculate the transmission heat losses and gains through a thermal bridge.

$$Q_T = l.\psi.f_T.G_t \qquad (2.8)$$

l : length of thermal bridge

ψ : thermal bridge heat coefficient (related to the exterior dimensions of the building elements)

f_t : reduction factor for reduced temperature difference

G_t : temperature difference time integral

II. Ventilation heat losses.

Ventilation heat loss is associated with air flow through the building by natural means, i.e. through small openings or cracks in the structure. The rate of ventilation (infiltration and escape) depends upon several factors, e.g. wind velocity and direction. The following formula calculates ventilation heat loss:

$$Q_v = n_v.V_{RAX}.c.G_t \qquad (2.9)$$

n_v : effective air exchange rate

V_{RAX} : reference volume of ventilation system (the occupied or usable area within residence)

c : specific heat capacity of air : 0.33 Wh/m^3K

G_t : temperature difference time integral.

The effective air exchange rate using heat recovery is calculated using the following formula:

$$n_V = n_{V,system}.(1 - \Phi_{HR}) + n_{infiltration} \quad (2.10)$$

$n_{v,\ system}$ = the average air exchange rate achieved through the ventilation system. The standard value for residences is 0.4 h^{-1} (PHI, 2007). However, a more accurate value can be determined in the ventilation worksheet of the PHPP software. If the average air rate exchange is not calculated in details, the program will use the standard value as the air exchange rate. This is tabulated below.

	Residential	Assisted Living	Administration	School	Other
Natural Ventilation	0.6	0.6	0.75	0.41	More accurate calculation required
Mechanical Ventilation	0.4	0.5	0.35	0.6	More accurate calculation required

Table 6: Typical Building Air Exchange Rate (PHI, 2007)

$n_{infiltration}$ = Infiltration air exchange rate caused by residual leakage through the airtight building envelope. Standard Value = 0.042 h^{-1}. This value corresponds to 50 Pa fan pressurisation test result of 0.6 h^{-1}, the highest value permitted for passive houses (PHI, 2007).

The total heat recovery efficiency of the heat recovery system is determined by this formula.

$$\Phi_{HR} = 1 - (1 - \eta_{eff})(1 - \eta_{SHX}) \quad (2.11)$$

Φ_{HR} : Total heat recovery efficiency of the system.

η_{eff} : The heat recovery efficiency of the system.

η_{SHX} : The efficiency of heat recovery in the subsoil heat exchanger.

Finally, the total heat loss can be determined by the sum of transmission heat losses and ventilation heat losses ($Q_L = Q_T + Q_v$).

2.3.1.3.2 Heat gains

I. Internal heat gain

The internal heat gains are the sum of heat generated from people and household appliances during a heating period. The internal heat gains are estimated for the standard living conditions and input as an overall value. However, an accurate calculation is necessary for a building so the formula below is used (PHI, 2007).

- 2.1 W/m^2 treated floor area for single-family, multifamily and row houses.
- 4.1 W/m^2 treated floor area for assisted living facilities
- 3.5 W/m^2 treated floor area for office and administration
- 2.8 W/m^2 treated floor area for schools

$$Q_I = \frac{E_{use}.V_1.V_2}{t} \quad (2.12)$$

Q_I : Internal heat gain

E_{use} : The useful energy demand

V_1 : Determines if the device is located inside or outside the thermal envelope

V_2 : The usability determines what fraction of the waste heat can be used in the building as an actual heat supply

t : The duration of operation service; normally it is 8760 hours.

II. Solar radiation

Solar heat gain is determined by using the following formula

$$Q_s = r.g.A_w.G \quad (2.13)$$

r : Reduction factor taking into account the frame to window area ratio, shading, dirt on the windows and the tilted incidence angle of radiation through the window.

g : Degree of solar radiation transmitted through glazing normal to the irradiated surface.

A_w : Window area

G : Total radiation also depends on the climate region.

The total heat gain is a sum of the interior heat sources and the solar gain during a heating period. Finally, the annual heating and cooling demand is the result of different value heat gains and heat losses. The specific annual heating and cooling demand can be determined by calculating the demand per usable area. The passive housing standard requires less than 15 kWh/m^{2}a each.

2.3.1.4. Cooling unit

This part focuses on the energy demand for space cooling and dehumidification used in tropical climates, and on the calculation of electricity consumption for household appliances in the building.

I. Energy demand for space cooling.

This calculation is based on monthly average values and it is difficult because the underlying processes are extremely non-linear. However, changes of moisture content in the building occur in timescales of months; short-term humidity variation can be compensated by storage effects as the dehumidification has a considerable impact on the energy demand.

There are four different processes aside from the latent energy. This section is computerised in the part of entire cooling demand (sensible and latent) that each air conditioning unit covers. The ventilation unit and the average moisture recovery rate during cooling and hot periods are required.

- Air cooling supply: In the climatic region, air cooling supply plays a role in keeping indoor temperature comfortable and the compressor normally runs at its full capacity until threshold temperature is reached. If the cooling coils of the air supply are controllable, this cycle operation should not be marked with a cross. The average temperature of the cooling surface at full capacity must be input.

- Recirculation cooling: This works in the conventional air-cooled unit. Air from the service room is drawn in by an extra ventilator, cooled down and blown back into the room.
- Surface cooling: There is no air conditioning so surface cooling can be checked off. The load not covered by air cooling can be met by surface cooling without condensation forming.
- Extra dehumidification: In a humid climate in the summer, this process is very important and all of the following data is required
  - Target value of room humidity: recommended value of 12 g/kg at a dew point of 17 degrees Celsius.
  - Source of moisture: the usual value is 2 g water/m^2/hr.
  - Moisture capacity of the building: this is related to the amount of water per square meter that the building can absorb per 1g/kg. This value depends upon the construction of the inner and outer building components. The typical value of this one is700 g/(g/kg)/m^2 (PHI, 2007).

II. Electricity consumption

Pursuant to the passive housing standard, the primary energy requirement must be less than 120 kWh/ m^2a (PHI, 2007). The electrical household appliances and all electrical systems are essential for future electrical demands. The primary energy requirement is calculated from the relevant conventional consumption and standard conditions. These conditions are assumed to be fixed values. The number of occupants, living areas and reference volume will also affect the electrical demand. The results of this section can be shown as specific electricity demand and non-electricity demand.

- Specific electricity demand recommended 18 kWh/ m^2a.
- Specific primary energy demand for household electricity recommended 50 kWh/ m^2a (PHI 2007).

The annual electricity demand is determined for every household service by using the formula below:

$$E_{el} = s.V_{norm}.f_{use}.h.G.f_{el} \tag{2.14}$$

s: Indicate if the considered appliance or service exists (1=Yes, 0=No Normally the value is 1 or 0 for a single house.

V_{norm}: The value from the energy efficiency label

f_{use}: Factor for correction of the standard energy consumption. The standard value is 1.

h: Frequency of use per year and per reference size

G: Reference quantity for "h" such as number of occupants, number of households, occupied area or air volume.

f_{el} : Electrical part of the energy service. In most instances this value is 1.

The specific electricity demand is calculated subject according to each treated floor area, divided by an annual electricity demand. However, energy from other sources aside from electricity (such as cooking using natural gas) are grouped together under primary energy and calculated separately from the electricity demand (PHI, 2007).

$$E_{other} = s.V_{norm}.f_{use}.h.G.f_{other}.(1 + V_{additional}).e_{sys}.(1 - f_{solar}) \tag{2.15}$$

f_{other} : 1- f_{el} : the part of energy service that is not provided by electricity.

$v_{additional}$: Relative additional useful energy demand due to exchange of non-electrical energy. The value may be negative.

e_{sys} : Insignificant performance ratio for useful energy produced from the used final energy.

f_{solar} : Solar thermal contribution.

The specific primary energy demand for every household service can be determined using the following formula:

$$e_{primary} = \frac{E_{el} \cdot p_{el} + E_{other} \cdot p_{other}}{A_{TFA}} \qquad (2.16)$$

p_{el}, p_{other}: primary energy factor

p_{el} = 2.7 kWh/kWh

$p_{natural\ gas}$ = 1.1 kWh/kWh

$p_{fuel\ oil}$ = 1.1 kWh/kWh

2.4 Climate data

Climatic conditions play a considerable role in heating and cooling load in a building, so the passive housing design needs to consider the climate data. The following is a list of parameters of climate data, as required by the PHPP software:

- Geometry of region. The PHPP software requires the latitude, longitude and altitude.
- Monthly outside temperatures
- Average monthly solar irradiation (horizontally and vertically) for the four main sky directions (kWh/m^2).
- Dew point temperatures. This parameter also invalidates the calculations for the cooling unit.
- Sky temperatures
- Ground temperatures. This parameter is not highly necessary
- Heating and cooling load. These should be climate data on the design day in summer and winter period. If no data is available, then no results are calculated in the heating and cooling load worksheets. Note that the irradiation data must be in W/m^2.

If users need to define climate data but the data for the particular climate is unavailable then the climate program 'Meteonorm' can be used to generate the needed monthly data for locations worldwide.

2.5 Case studies

The case studies shown below are in the warmer climates of Europe, so they showed strategies of passive cooling and for reducing cooling loads. However, the case study that looks most similar to the passive house strategies of tropical climates was Italy.

Case study	Spain	Portugal	Italy	France
House				
Type of house	Terraced spanish dwelling (3-4 bedrooms)	Single floor (2 bedrooms)		2 stories terraced house
Area (m^2)	100	110	120	
Climate : temperature (C)	Mediteranian climate : 23 degree in summer	High solar radiation : 30 degree in summer	Around 28 degree in summer	Mediteranian climate : 30 degree in summer
Strategies				
Ventilation	Mechanical ventilation to preheat air inlet and north space act as chimney at night	Used cross ventilation	natural and active ventilation at night	Mechanical ventilation
Glazing	High level in South Minimum glazing in North	Used double glazing		Double glazing
Thermal mass	Low inertia with brick and high inertia with low density ceramic block	Insulated 100 and 150 mm for exterior wall and roof	Insulated 10 cm for wall and 15 cm for roof	Insulated 15 cm for wall and 8 cm for roof
Shading		Used overhangs in south windows and venetian blinds in all windows	Used roof eaves and Persian shutter to reduce solar gain in all windows	Used exterior shading devices
Performance				
Heating (kWh/m2)	8.7	5.6	2.7	13.1
Cooling (kWh/m2)	7.9	3.7	9.6	10.6

Table 7: Case Study Comparison of Warm Climates in Europe (IEEA, 2007)

2.5.1 Case study in Italy.

The Italian case study has high envelope insulation, a lack of thermal bridges and active ventilation with heat recovery. The house is a South-facing end of terrace property with $120m^2$ net floor area. In addition, the Italian passive house adopts certain strategies, such as solar shading provided by roof eaves or Persian shutters to reduce solar gain through the windows. The natural night time ventilation strategy is supplemented with active cooling.

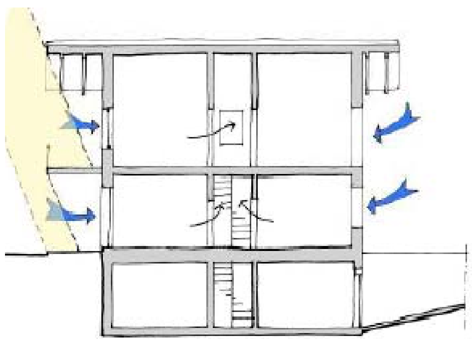

Figure7: Summer Strategy of Italian Passive House Case Study (IEEA, 2007)

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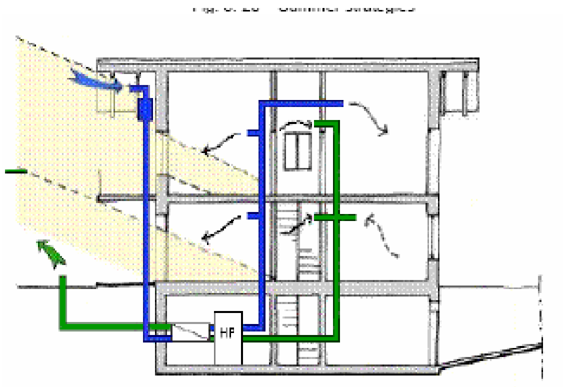


Figure 8: Winter Strategy of Italian Passive House Case Study (IEEA, 2007)

This house used two distinct strategies for winter and summer. The insulation is approximately 10 cm for the walls and 15 cm for the roof. In the summer, it minimised solar gain by using a highly insulated building shell and shaded windows. Natural and active ventilation are used at night to release solar heat gains and internal heat gains accumulated throughout the day from the building shell. Heat loss is reduced in winter through the highly insulated building shell and the elimination of thermal bridges. Active ventilation with heat recovery is provided by the exhausted air. Moreover, it allows solar gains by glazing 30% of the southern façade and reduces losses by limiting glazing on the northern facade (IEEA, 2007).

For the final issue, a well-insulated heavy structure provides the effective basis to cool the building's thermal mass during the night in the summer. Night time air passes through the building either by wind, natural buoyancy differences or by using the fan of an active ventilation system (IEEA, 2007).

In this case study, the maximum indoor temperature is around 30 degree Celsius. Although the night time ventilation strategy does work, the indoor temperature can be reduced by using small powered reversible heat pumps. The figure below shows the living room temperature in the summer by using passive cooling in Milan.

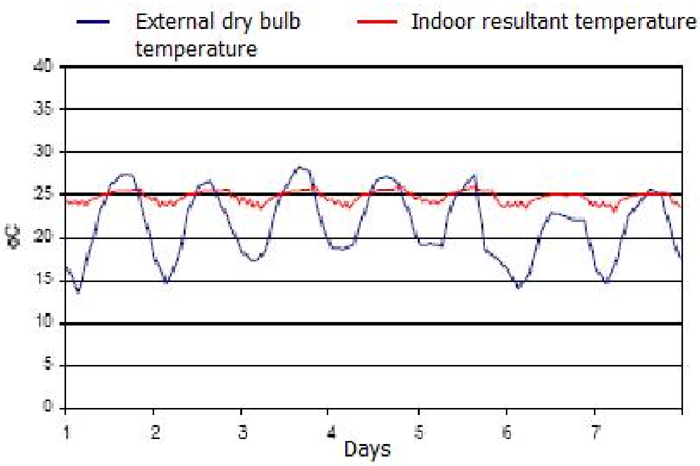


Figure 9: Living Room Temperature in Milan of an Italian Passive House Case Study (IEEA, 2007).

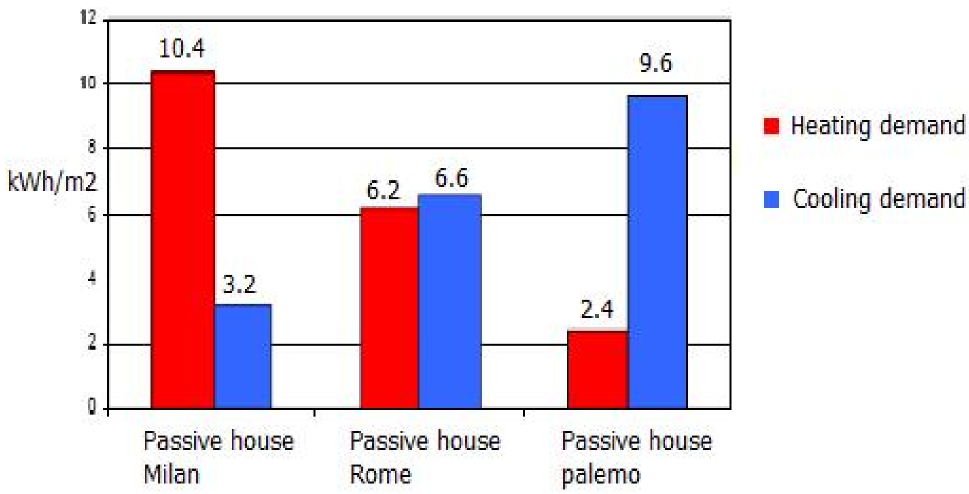


Figure 10: Heating and Cooling Energy Demands of an Italian Passive House (IEEA, 2007).

Figure 10 shows the heating and cooling demands of a passive house in Italy and they met the passive house standard requirement. However, the natural ventilation strategy in Palemo is less effective so some active cooling is required (IEEA, 2007).

Chapter 3: Methodology

The main objective of this research is to evaluate the effectiveness of passive houses in tropical climate thus there are three main stages objectives of this research to be achieved.

- Reviews and validation of selected building simulations used in PHPP software.
- Description of research method.
- Development of a simplified model using passive cooling and other strategies under the passive house standard condition.

3.1 Research design.

In order to achieve these objectives, the research design was divided into two sections. Firstly, a model for selecting typical buildings was designed and developed by using passive house design strategies. Therefore, they could be compared to find out which design strategies were the most efficient and the effectiveness of passive houses in tropical climates could also be evaluated.

The methodology of this research was to select the types of dwelling and location and then to prepare climate data for the PHPP and Meteonorm software, as recommended by the Passive House Institute. Finally, the passive house was designed by selecting the typical model and then the results were analysed. In order to obtain the passive housing design, two case studies were analysed. They could be separated by using standards of passive house conditions and the climate conditions. The passive house design in Case Study 1 was based on standards of passive houses in Europe under 25°C of cooling set point temperature, whereas Case Study 2 used 28°C of set point temperature as its comfortable temperature in Thailand (given as thermal comfort in Bangkok residential buildings: Rungsiraksa, 2006). The following diagram shows the research design of this project:

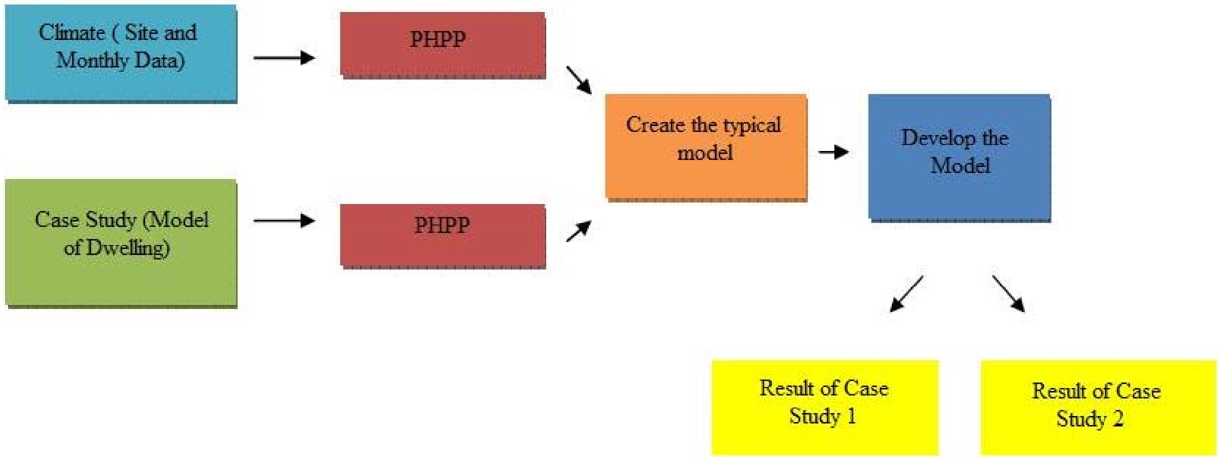


Figure11: Research Design Diagram

In order to accomplish the last objective (discovering the factor most essential to passive building design), each strategy was used to develop the typical model for a passive house. These were then compared to find which one was the most efficient.

3.2 Model.

Selecting a model is the first step and this project focuses on passive houses in the tropical climate. Hence, this research was conducted in Bangkok, Thailand (as this country is located in the tropical climate) and the dwelling type used in the simulation was a one-storey detached house with energy efficiency, which is commonly found in Thailand. In fact, this model was designed by The Ministry of Energy for Thailand. This plan has been promoted to people who desire to build a building with low energy consumption.

3.2.1 Data requirement.

There was a lot of model data required by the PHPP software, all of them affecting the passive house design. The required data is listed below:

- Construction details (usage area and size of house)
- Types and sizes of windows and frames
- Systems in house (the ventilation system and electrical household appliances)
- Neighbouring landscape (e.g. trees and neighbouring houses)
- House location
- Building materials

- The number of occupants

All of this data affects the performance of the house and this project selected an efficiency-based energy house in Thailand as a simplified model, as this house looked similar to general houses in Thailand. Areas surrounding this house have been planted with trees to shade the building. The materials used in this model are those commonly used in Thailand which would be discussed in the chapter four. In this research, the simplified model can be created using the PHPP software and then developed into a passive building.

3.2.2 Location of model.

The location of a model is quite significant as solar radiation can more or less pass through the house depending on the house orientation and the window locations. In this model, the entrance was at the North façade and there were trees around the house to protect it from sunlight. The location of this model was in a suburban area, so this could affect the ventilation system in the building. The size of the windows in each orientation was different as they were designed to reduce the heat gained from solar radiation. For example, there were big windows at the North due to less solar radiation in this direction. Consequently, this research necessarily dealt with the orientation of window installation.

3.3 Climate data

Climate data is a significant factor in reaching the research objectives, as this design depends upon the regional climate. The strategies used for passive building design were different for different climates. In this research, the Passive House Institute recommended the use of the Meteonorm Software as it indicates worldwide climate data.

3.3.1 Meteonorm Software.

Meteonorm is a global meteorological database and a tool to import climate data to the PHPP software. It is a comprehensive meteorological reference and calculation procedure for solar applications and system designs for any worldwide location.

The measured parameters of this tool are: monthly mean averages of global radiation, temperature, humidity, precipitation, wind speed and direction and sunshine duration. All of this data is continually updated by satellite data. This tool was created by the Meteotest Company, a private company in German that also provides other scientific knowledge about the weather. This tool has accurate climatic data and uses the same patterns and unit measurements as required by the climate data worksheet in PHPP, so it is suitable to use this tool with the PHPP software for this current study (Meteotest, 2002).

3.4 Identification of design passive house strategies

The methodology to develop the simplified model into a passive house model can be divided into two sections. The first involves the construction development, including exterior surfaces of the building, windows and landscape. The second section involves the ventilation and electrical systems in a building, as a healthy environment and comfortable interior temperature are significant factors for the occupants.

3.4.1 Construction detail

There are various types of passive housing design strategies and all of them could be used in this project. Some of these strategies are insulating, developing window glazing and frames and shading.

In consideration of the requirements of passive housing, insulating all of the external surfaces of a building was highly recommended in this design. Hence, this strategy was used in developing the simplified model into a passive housing model. However, there were some insulation conditions so the strategy could not be satisfactorily used to accomplish all of the passive house requirements. This design also depended upon the insulation materials chosen and their U-values were anlaysed in the PHPP. In addition, the exterior surface colour was considered and white or other special colours have always been used for their low absorption rate.

Ensuring a low U-value of the window glazing and frames is one option in this project. Moreover, additional shading is useful to reduce the cooling demands of a passive house. Low-e triple glazing is the best type of window glazing. Solar reduction is one effective shading factor and it can be improved by adding external shading devices and planting. Finally, avoiding the thermal bridge effect between the joints of a building is always necessary as it can prevent the hot outside breeze from entering the house and heating the interior, so the thermal bridge value of the building should not be more than 0.01 W/mK (under the passive housing standards).

3.4.2 Ventilation system

Another key strategy is using an installed ventilation system; this project used both mechanical and natural ventilation. Cooling units and heat recovery ventilation units were used to cool and bring fresh air into the building. However, the primary energy value needs to be considered. Furthermore, the air cooling, recirculation cooling, panel cooling and dehumidification can be used to make occupants feel more comfortable, although all of these mechanical ventilators need to be considered as they could force the primary energy consumption to exceed passive housing standards.

Natural ventilation and cross ventilation were both options in this study but it was highly recommended to use natural ventilation because of the higher outside temperature. Thus, cross ventilation could be used at night when the outdoor temperature became cooler, but this needed to be decided based on other factors as well.

For evaluating the most efficient strategy of designing a passive house model, the typical model structure was developed using each strategy. In addition, the result of each strategy was analysed. This can be separated into three sections: insulation, windows and shading and ventilation systems.

Chapter 4: System Description and Modelling of Typical Houses in Thailand

This chapter describes the climate data, construction details and method of modelling the case study of a typical house in Thailand. The performance of a simplified model consists of assessing the cooling demand, primary energy demand and indoor environment. This model is a basic model of passive housing development in a tropical climate.

4.1 Climate data in Thailand

An important input of the model is the climate data. This was obtained by using Meteonorm software. The climate data in this research was from Bangkok, Thailand in 2008, as the data was quite realistic and updated. The Meteonorm software collected the satellite data to update the climate record in each year and, as a result, is quite accurate. This software has different climate information for several areas in Thailand, such as Chiang Mai (located in the North of Thailand), whereas this research used Bangkok as the location for the case study because the residents of Bangkok mainly live there for working activities. Therefore, this provides a good opportunity to evaluate the effectiveness of passive houses for workers in the capital of Thailand. When comparing the Bangkok climate evidence of this software with ESP-r software that was modified by University of Strathclyde, the climate data of both applications had similar results, e.g. for the temperature and solar radiation. Therefore, there was no doubt about the accuracy of the input data. However, the reason behind using the Meteonorm software was that the other climatic data used in PHPP software were already prepared in Meteonorm, for example the data used in the heating and cooling calculation.

Thailand has three seasons in a year, namely summer, rainy and winter. The summer period in Thailand is between March and June and the rainy season is from July to October. The period from November until February is the winter season. The average temperature in Thailand is around 29 degrees Celsius.

Location: Latitude [°] = 13.730 North Longitude [°] = 100.500 East

Minimum monthly outdoor temperature: 26.4 °C

Maximum monthly outdoor temperature: 30.2 °C

Daily temperature swing in summer = 6.8

Average relative humidity = 71%

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Heating load (W/m^2)		Cooling load (W/m^2)
													Weather 1	Weather 2	Radiation
Ambient temp (°C)	27.9	27.9	29.7	30.2	29.3	29.3	28.8	29.1	28.6	28.6	27.4	26.4	21.6	26.3	31.4
North solar radiation (kWh/m^2 month)	33.0	34.0	37.0	42.0	62.0	64.0	60.0	45.0	34.0	38.0	31.0	31.0	56	15	56
East solar radiation (kWh/m2 month)	77.0	73.0	91.0	90.0	85.0	77.0	73.0	78.0	72.0	71.0	77.0	76.0	109	16	126
South solar radiation (kWh/m2 month)	128.0	102.0	86.0	57.0	50.0	48.0	47.0	49.0	58.0	85.0	118.0	140.0	118	17	86
West solar radiation (kWh/m2 month)	76.0	77.0	85.0	84.0	87.0	73.0	75.0	72.0	64.0	75.0	77.0	80.0	87	16	113
Global solar radiation (kWh/m2 month)	144.0	144.0	172.0	168.0	161.0	144.0	146.0	140.0	128.0	137.0	140.0	147.0	183	30	227
Dew point (°C)	19.7	22.1	23.3	24.2	24.8	24.1	23.7	23.7	23.7	24.1	23.8	21.7			
Sky temp (°C)	17.2	18.8	19.8	20.7	20.8	20.7	20.6	20.5	20.5	20.5	20.0	16.6			
Ground temp (°C)	29.8	29.8	29.9	30.1	30.3	30.5	30.6	30.6	30.5	30.3	30.1	29.9	29.8	29.8	30.6
Relative humidity (%)	68.9	66.5	69.8	68.2	71.1	76.6	72.4	75.4	76.4	81.0	68.0	57.7			

Table 8: Climate Conditions in Thailand

Table 8 shows the climate data of Bangkok, Thailand in 2008 by using Meteonorm software. All of these figures are the monthly average values. However, it can be noticed that on the right-hand side of this table, three columns indicated heating load of Weather1 and Weather2 and cooling load. The figures in these columns are normally used as the climate conditions are calculated in the cooling and heating load worksheet in the PHPP software.

The heating load and cooling load data includes the design temperature in different situations, ground design temperature and radiation in the different directions. All of this data was generated by using dynamic simulation and was used to find the maximum cooling and heating load in the PHPP software. There were 2 situations in the heating load column defined by the PHPP manual:

- Weather 1 is on a cold but sunny winter day with a cloudless sky (high pressure weather situation).
- Weather 2 is on a moderately cold but overcast day with minimal solar radiation.

As can be seen, the temperatures of the cooling load and heating load were different because, in the cooling load condition. The maximum cooling load during the heating period had to be determined to keep the house cool following cooling load climate data. Hence, all of the climate data was based on the maximum data in the heating period. On the other hand, the climate records of the heating load condition were based on the data from winter days in 2 situations to find out the maximum heating load of the model in the PHPP software. As all monthly climate input as Table8, PHPP can plot the graph as shown in Figure 12, demonstrating the relationship of monthly climate data with different parameters from the Meteonorm software.

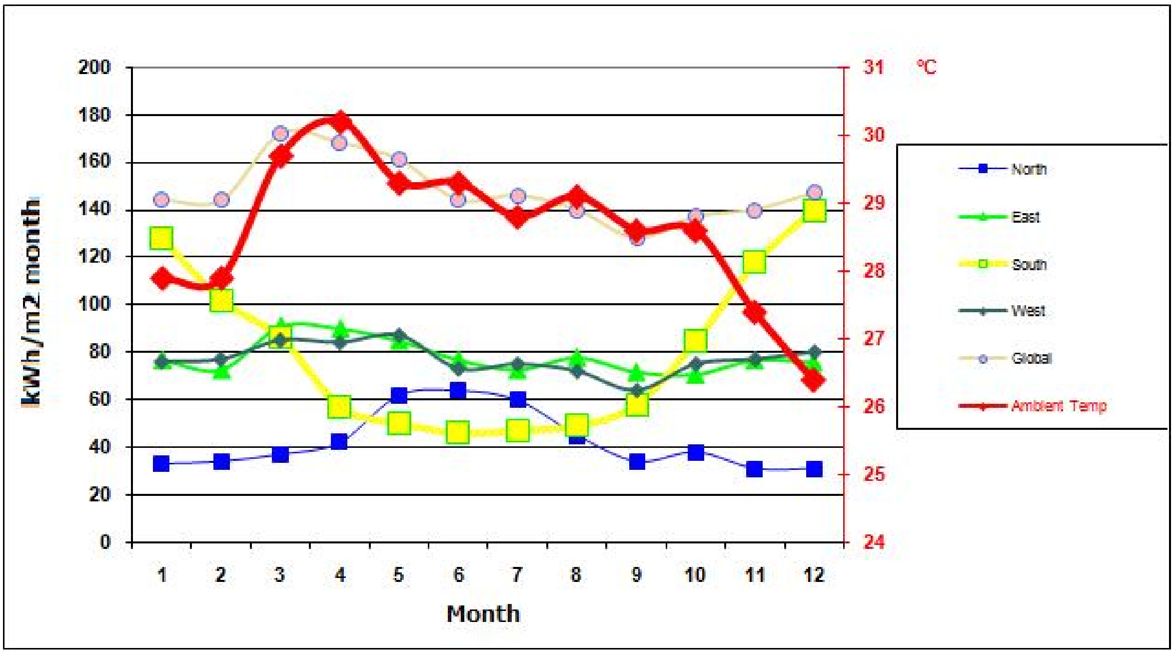


Figure 12: Monthly Ambient Temperature and Solar Radiation Graph

4.2 Construction of a typical house

This section describes the construction details of a typical model as used in this research. It includes the model location and structure of building. This research selected this particular housing model from the Department of Alternative Energy Development and Efficiency, Ministry of Energy in Thailand. The reason for choosing this model was that it was guaranteed by the Ministry of Energy and it looked like a common house in Thailand - it was proven that around 78% of Thais live in this type of detached house (National Statistical Office of Thailand, 2004). Another factor was that this model is a low energy building and it applies some strategies to reduce energy consumption; hence it was a better way to compare and improve the typical model to a passive house model. In fact, there are several types of low energy efficiency house but this model was selected as it was the most simple detached house model.

The housing model consists of five main rooms, including two bedrooms, kitchen, living area and bathroom. In addition, the building model's construction and performance are described in this chapter.

4.2.1 Building structure

This model consists of around 67 m^2 of usable floor area and the building is 6.08 m. high. The main elements of this model include a roof, walls and a floor. Each of these elements has different insulation layers and construction materials; the role of each element differs (e.g. in regards to solar radiation acceptance) so all of the materials were selected according to the area.

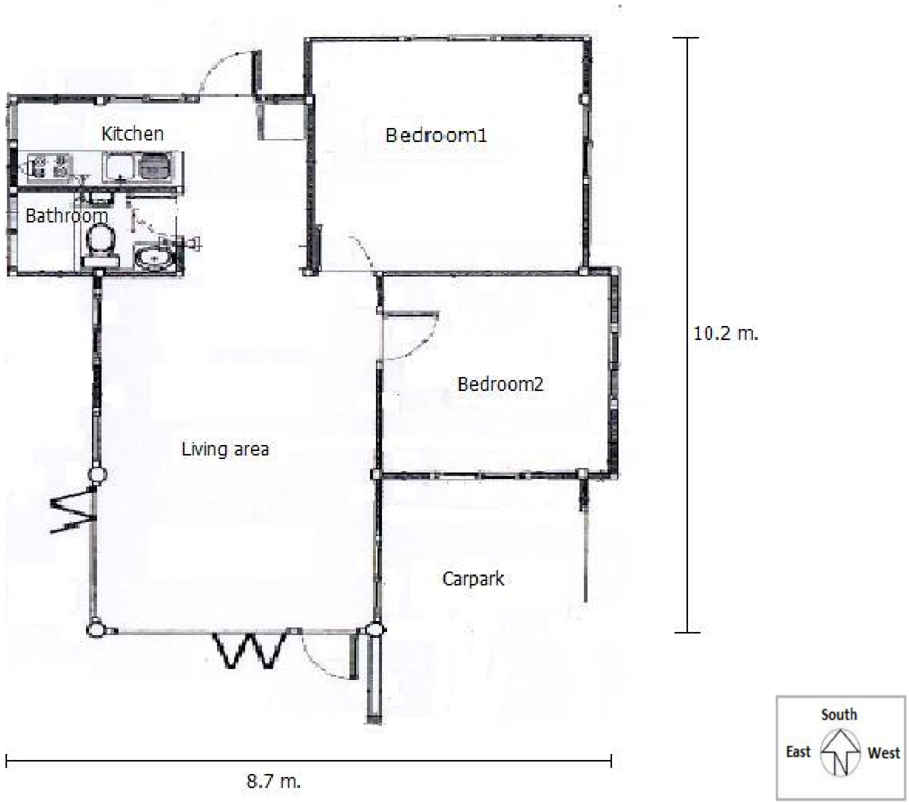


Figure13: Floor Plan of Typical Housing Model (Department of Alternative Energy Development and Efficiency, n.d.)

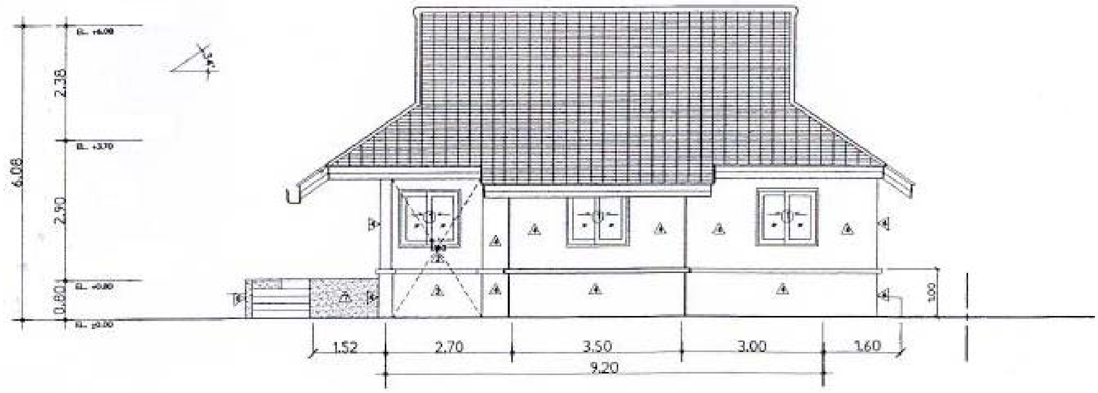


Figure14: Typical House Model in West View (Department of Alternative Energy Development and Efficiency, n.d.)

The external surface area of this model can be separated into four groups: floor, exterior wall, windows and roof. In addition, all of these (excluding floor area) are in the interior air against ambient air zone. The floor is also in the interior air against the ground zone. The zones can indicate the temperatures difference between outside ambient air and building elements. The following table shows the overall area of the building elements.

Building elements	Area (m^2)
Exterior wall	115
Roof	127.5
Floor	66.35
Window (North)	6.2
Window (East)	6.78
Window (South)	2.64
Window (West)	3.96

Table 9: Area of Building Elements

Normally, the exterior wall consists of three layers: exterior plaster coat, autoclaved aerated concrete lightweight block (AAC) and interior plaster coat. Their thicknesses are completely different and the AAC lightweight block is the thickest. Due to the elements of this exterior surface, it can be noticed that there is no wall insulation in this model. However, the roof is insulated by gypsum board with aluminium foil and fibre in the flat ceiling and the fibre insulation is thicker. Finally, the ground floor of the simplified model is usually assembled with some concrete as the main material and some parquets are used to cover the concrete to make it more visually appealing. However, concrete has high thermal conductivity so it leads to a high U-value of the overall ground floor. This can affect the transmission losses and gains in the model, which in turn affects the cooling demand. Actually, most of these building assemblies lead to a change in transmission heat losses and gains and cooling demand. If there is a low U-value in the building assemblies, this can reduce the heat transfer by conduction through the building elements.

Overall	Exterior wall	Roof	Ground floor
U-value (W/m^2K)	0.552	0.166	1.153
Width (cm)	22	26.2	35

Table 10: U-value of Building Elements

This table shows the U-values and width of each building element in the typical house model. The materials used in each construction layer were based on common materials and structures used in Thailand that were provided in the housing plan of the selected low energy model. The U-values of each material were based on the default value that was given by PHPP manual. Therefore, the results of Table 10 were determined by the PHPP software and they affect the cooling demand of the case study.

The colour coating the exterior surface in this model is a special colour with a low absorption rate and the thermal bridge has different values in the different areas. In order to control heating and cooling balance in the dwelling, thermal bridge effects should be avoided. The overall length of thermal bridge in this model was around 112 m. The heat losses from thermal bridges were represented by the linear thermal transmittance (ψ) and, in this simplified model, that value was -0.231 W/mK. The cause of the negative value of thermal transmittance (ψ) was because there was an interior dimension ψ -value less than the total heat flow of the 2 adjacent areas in that joint. Therefore, when the ψ-value in each area became negative, the total would be negative as well. This value depended upon the difference between the outdoor and indoor temperatures, U-values and thickness of building elements including exterior wall, roof and ground floor.

This model comprised of three different sizes of window installed around this area. There were four big windows and one small on the northern side of the building. In the opposite direction, two small windows were set. Three small windows were installed at the West direction. At the East side, there were three big windows and a small one; half of the small one with a louver. The location of the windows is necessary for calculating the heat gains through the house and will be explained in the next section.

The selection of the type of window glazing and frame relates to the transmission losses and gains and solar heat gains in the model. Usually, the kind of window glazing in Thailand is a single glazing pane with a high U-value around 5.8 W/ m^2K. Window frames are normally wooden, PVC and metal, yet in this case wooden and metal frames were used for the different types of window. The U-values of the wooden and metal frames were 2.5 W/ m^2K and 5.5 W/ m^2K. All of these values were default values provided by PHPP and based on the average value of the materials. The high U-value of the glazing and frame led to high transmission heat gains of fabric elements. Thermal bridging of the glazing edges should be considered as well but it depends on the type of window frame. The following table shows the window performance in the typical model.

Window area orientation	Window area (m^2)	U-value (W/ m^2K)	Cooling Degree Hours (kKh/a)	Transmission gains (kWh/a)
North	6.2	4.71	4	116
East	6.78	4.76	4	129
South	2.64	5.32	4	56
West	3.96	5.89	4	93
Total or Average value for all windows	**19.6**	**5.05**	**4**	**394**

Table 11: Window Performance of Typical House Model

As can be seen in this table, the transmission heat gains entered this model due to the high U-value of the windows and the glazing. It can be noted that the U-values in the western direction were the highest but the transmission gains value was not maximum, while the areas of window glazing at the East side had the greatest value and also the highest transmission gains value. In addition, the transmission heat gains depended upon the internal and external temperatures that were determined in the cooling degree hour values. The cooling degree hours are the quantitative indices to reflect the amount of energy needed to cool the building. It was discovered by the total monthly cooling degree hours based on the climate condition and the cooling set point temperature at 28°C. This set point temperature is the Thai comfort temperature, as provided at the 23rd public research conference on passive and low energy architecture in Switzerland 2006 (Rungsiraksa, 2006). In fact, there are two types of cooling degree hours in PHPP software: cooling degree hours of the exterior surfaces and cooling degree hours of the ground. The cooling degree hours used in individual windows was the exterior surface cooling degree hours. Moreover, U-values of all the window area orientations were based on the materials of the window glazing and frames, and the area of them. This value was an important parameter in the varied transmission gains of the building.

4.2.2 Building location

The location of a building is quite significant as it affects the level of solar radiation the house receives. Thus, shading design is an essential form of protection in the tropical climate, due to the high level of solar radiation in this region.

The front facade of this model faced the North orientation, hence a shading strategy should be considered as it reduces heat gain by solar radiation value that varies energy demand of the house. In this project, four shading strategies were used: shading by a row of objects, shading by window reveal, shading by cantilevered elements and additional shading elements, such as balcony railings, deciduous trees or similar.

With regards to shading, this simplified model only used two strategies. Trees were planted on the northern and eastern sides to shade the big windows in both directions. The efficiency of this type of shading depends upon the height of the shading objects, the transparent window areas and the horizontal distance. In addition, the overhang of the roof was designed to shade the windows. In the summer, interior shading devices were added into this model by using white roller blinds. Thus, the percentage of the reduction factor in the summer decreased and the reduction factors in each direction could be calculated to prevent the heat gain by solar radiation using PHPP.

Window area orientation	Reduction Factor for solar radiation	Average global radiation (kWh/ m^2a)	G-value (%)	Heat Gains Solar Radiation (kWh/a)
North	0.07	511	87	189
East	0.10	940	87	535
South	0.14	966	87	311
West	0.09	925	87	298
Total or Average value for all windows	**0.10**	**3342**	**87**	**1333**

Table 12: Shading Performance of Typical House Model

It can be seen that solar heat gains depend upon all of the parameters in Table 12 and the areas of the windows. Moreover, PHPP could determine these results with the products of all the parameters, consisting of global radiation, window areas, G-values and reduction factors. The G-value is the coefficient of the permeability of total solar radiation energy stated as a percentage (%), a lower percentage representing less solar gain. The G-value was based on the materials of the selected frames. The global radiation also depends on the climate conditions in each region.

According to the above table, the reduction factor is the indices of the percentage of solar radiation through the windows. If the reduction factor is high, there is a high heat gain value. This is determined by factors like shading, dirty windows, the reduced energy transmittance and portion of glazing. It can be noticed that the heat gain value in the northern direction was lowest because of the minimum value of reduction factors for solar radiation and the amount of global radiation. This means that the windows at the northern site had proper shading but the eastern direction received the highest heat gain due to the high rate of global radiation and large window areas in that direction. If there was a high value of overall heat gain, the useful cooling demand would be higher as well.

4.3 Ventilation System

This simplified model had normal ventilation systems that were often utilised in Thailand, such as natural and cross ventilation. Air conditioners have typically been used to cool houses. This model used natural ventilation and cross ventilation during the day time and at night the cooling units were operated. As the use of air conditioners is common in Thailand, the electricity consumption is particularly high in the summer season.

Regarding the operations of the ventilation systems, the individual volumes were set at $30m^3/h$ per person for the residential area on the supply air requirement. As it influences the air quality hygiene in the building, this value would be changed as well. In schools and day care centres, 15 to 20 m^3/h per child has proven to be sufficient and the exact dimensions depend on the ages of the children and the type of application. Moreover, gyms need a ventilation of 60 m^3/h as the highest degree of user activity. This project assumed that there were two adults in this house; therefore the supply air requirement was 60 m^3/h for all the living areas. The exhaust air room consisting of the kitchen, shower room and toilet had a different air requirement. The kitchen required $60m^3/h$ and the shower and toilet rooms needed $20m^3/h$ each. The overall extract air requirement was $100m^3/h$. Therefore, the maximum design air flow rate was $100m^3/h$ to cover the supply and extract air requirement. All of the supply and exhaust air requirement values in each room (or per person) were default values provided by the PHPP as giving a room good air quality. These values were based on the requirement of DIN 1946, part 6. In order to attain a hygienic air quality, the average air change rate should be equal or exceed the passive housing standard of 0.3 h^{-1}. Moreover, the average air change rate using the standard values of operation and the maximum design air flow rate to get a good indoor air quality was 0.46 h^{-1}; over 0.3 h^{-1} was the average rate required to meet the passive housing standard. Thus, the average exchange rate of this building should be nearly 0.46 h^{-1}.

This simplified model did not integrate heat recovery ventilation since it has not been commonly used in Thailand. The operation of the ventilation systems in this model can be divided into two periods: natural and cross ventilation during the day and cooling ventilation at night. In the case of cross ventilation and natural ventilation, they were optimised with 0.62 h^{-1} air change rate so this building could achieve good interior air quality. The ventilation was designed to have windows open around 50% of the time during the day and not opened at all at night when the air conditioners were turned on. However, the opening width of windows also affects the cooling demand so windows were not opened wide during the day due to the higher outside temperature. Therefore, PHPP determined the daily average air change rate at day time was 0.62 h^{-1}. Both types of natural and cross ventilation are related to the ventilation transmission parameter that affects the ventilation heat gains. If the frequency of overheating at 28 °C, which is the comfortable temperature for Thai people in residential buildings, achieved a high percentage, then additional ventilation is required for cooling. Therefore, this simplified case study needed to add cooling units as the frequency of overheating was 100%. All of the ventilation systems influenced the ventilation heat gains and added to the values of cooling demand.

Although this model uses natural and cross ventilation systems, the temperature inside the building was still high so the occupants felt uncomfortable. Additional cooling units were required to make occupants feel satisfied in that environment so air supply cooling, dehumidification, recirculation cooling and panel cooling were required.

This dwelling was installed with recirculation cooling and dehumidification to improve the comfortable atmosphere. The recirculation cooling is the conventional air cooling unit and mainly runs with recirculated air. The air from the building service room was drawn in via an extra ventilator, cooled down and blown back into the room. There are 2 target values of the useful cooling demand: sensible and latent loads. The sensible load of this model was 80 kWh/ m^2a, and 39 kWh/ m^2a for the latent load. Recirculation cooling was utilised to reduce the sensible and latent loads. It generated 80 kWh/ m^2a for the sensible load and 25.2 kWh/ m^2a for the latent load. Dehumidification produced 13.9 kWh/ m^2a to fulfil the remaining latent load.

In addition, the heat pump in reverse system was applied to cool this building and work with all cooling units in the package unit. The heat pump in reverse system worked as an air conditioner; in the cooling mode, the heat pump evaporated a refrigerant in the indoor coil. As the liquid evaporated, it pulled heat from inside to outside. After the gas was compressed, it passed into the outdoor coil and condensed, releasing the heat outside. Moreover, the COP of the air conditioner used in this typical model was around 4.5, based on the ideal specification provided by the manufacturer (Alto) and the range was given by PHPP.

In conclusion, the ventilation system of this typical model used natural and cross ventilation during the day and cooling units at night, in order to provide the occupants with a more comfortable sleeping environment.

4.4 Household appliances

All the cooling unit systems led to an increase in the primary energy values and internal heat gains, especially dehumidification. Furthermore, energy demand is also related to electricity appliances, e.g. washing machines without domestic hot water, fridges, lighting, small appliances and the cooling heat pump. Typical houses in Thailand use high efficiency electrical appliances, particularly class A^{+} or A^{++}, to save energy.

The electricity load is highly dependent upon the number of occupants and other conditions. The following table shows the electricity consumption and description of various electrical appliances in a typical house. This research assumed the following electrical household appliances were used: washing machine, refrigerator and air conditioner (all Class A++ high energy efficiency appliances, as normally used in Thailand). The electricity demands of all the appliances were based on the specifications provided by each manufacturer. For the lighting, small appliances and consumer electronic appliances, their default values were based on the PHPP software.

Electrical Application	Brand and model	Electricity demand of appliances / COP
Washing machine	Zanussi (ZWF12080W)	0.86 (kWh/use)
Refrigerator	Smeg (FAB28RNE)	0.59 (kWh/day)
Lighting		11 (W)
Consumer electronic appliances		80 (W)
Small appliances		50 (W)
Air condition	Alto (AS-H22Y)	4.5 (COP)

Table 13: Description and Electricity Demand of Electrical Appliances

Electrical Application	Primary Energy (kWh/m^2a)
Washing machine	2.07
Refrigerator	7.35
Lighting	2.5
Consumer electronic appliances	3.4
Small appliances	3.85
Heat pump	71.5
Total	**90.67**

Table14: Primary Energy of All Electrical Appliances

Table 14 did not include cooking energy because Thai people mostly use gas as the energy source; it could be estimated at 3.9 kWh/m^2a. All of these results were from the calculation of annual energy demand of all electrical household appliances and the frequency of energy usage in this house. The frequency of the usages was based on the average values for each household appliance in the PHPP software. It can be noticed that the heat pump had the highest value among of all the appliances. The total primary energy value could not be more than 120 kWh/m^2a to comply with the standard passive house requirement. With the added primary energy of gas cooking, the overall primary energy was around 94.6 kWh/m^2a.

This section only described the structure and the systems in this model. The next section will explain and discuss the typical house performance in this case study.

4.5 Typical house performance

This section describes the performance of this model, including comfort parameters, construction values, cooling demand and the primary energy value. All of these parameters were influenced by building design, as previously discussed.

4.5.1 Comfort parameter

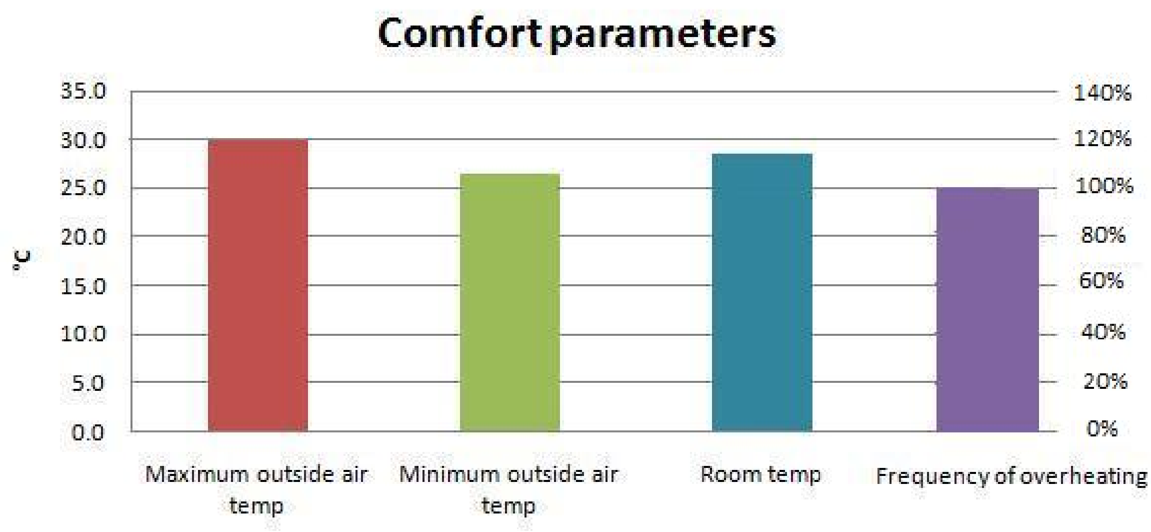


Figure 15: Comfort Parameters Graph of Typical House Model

This typical model has a set point temperature of 28°C, as this temperature was found to be comfortable for Thai people (Rungsiraksa, 2006). This is a practical performance for houses in Thailand. Comfort temperature is calculated from the average air temperature and the mean radiant temperature, which was based on EN ISO 13790 (the standard energy performance for buildings). There were not huge differences between the maximum and minimum outside temperatures and the room temperature. However, the frequency of overheating in the summer was based on the comfort temperature of 28°C without mechanical ventilation, which has a high rate, so it could make people feel uncomfortable. As a result, a cooling unit system was desired.

The main issues making occupants feel uncomfortable in this case study were the heat gains by conduction in fabric elements and the solar heat gain in different directions. Moreover, the annual solar heat gain was approximately 2373 kWh and the transmission heat gains were around 2092 kWh, so there were significant heat gains in this model. In order to achieve a comfortable internal environment, super insulation and shading were required to improve the comfort parameters.

4.5.2 Cooling load

This section provides the maximum cooling load as a result of the energy balance of internal and solar heat loads and the ventilation and transmission loads for the design day (an extremely hot day during the time period). The cooling load represents a daily average of the cooling capacity required to keep a house cool. The use of daily average values supposes that building mass can buffer the fluctuations of the internal and solar loads during the day.

This model had 18.8 W/ m^2 of maximum cooling load and this figure was significantly high when compared with the standard of passive housing at 10 W/ m^2. This means that a typical house in Thailand required a maximum cooling load of 18.8 W/ m^2 to keep the house at a comfortable temperature during the hottest day. Moreover, the transmission heat loads of the fabric elements influenced the cooling load considerably so it should be redesigned. Otherwise, the primary energy value would be higher due to an increased cooling consumption.

4.5.3 Cooling demand

The cooling consumption depends upon various parameters. Cooling consumption usually depends on the balance of heat losses and gains. It is influenced by the building construction and any systems equipped in the house. The following figure presents the annual heating energy balance. This was derived from the PHPP calculations for solar radiation, cooling demand and outdoor temperature.

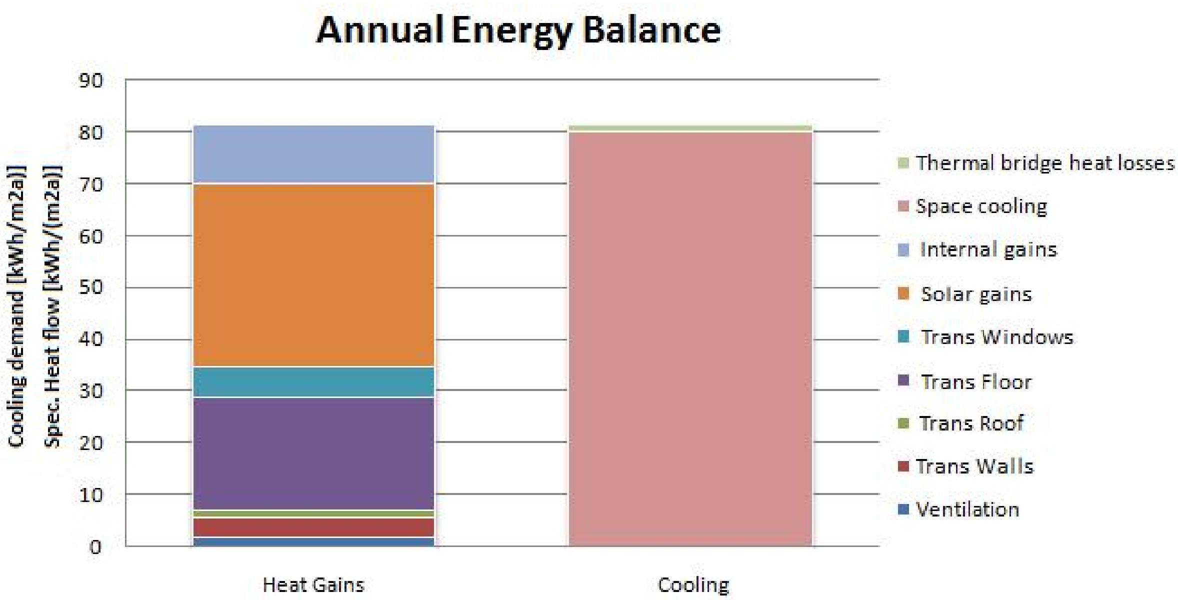


Figure 16: Annual Energy Balance Graph of Typical House Model

Figure 16 shows the energy balance between heat gains and cooling demand in this typical model. Heat gains include solar gains, internal gains, ventilation gains and heat gains of all the building elements. As can be seen, heat gains from the building elements consisted of windows, floors, roof and walls while the majority of transmission heat gains came from floor areas and its value was around 22 kWh/m^2a. While the highest contributing factor of total heat gains was solar gains (35.4 kWh/m^2a) there was also a high amount of global radiation in this climate. Thus, this building's shading did not adequately prevent the solar gains. The internal heat gains played the important role as well. The total heat gain in this building was around 80 kWh/m^2a.

In order to make the inside temperature comfortable the cooling demand should be higher or equal to the total heat gain, so the cooling demand in this model should be around 80 kWh/m^2a. Thus, the cooling demand shown in Figure 16 could make the occupants feel satisfied with the temperature. However, this number was considerably higher than the passive house standard. Therefore, this house should be modified to reduce solar heat gain and transmission heat gains of all building elements by shading and increasing the insulation to be a passive house. Moreover, the internal heat gain also influenced the cooling demand, although few actions have been taken to change cooling demand when compared with other parameters. This was discovered by considering the useful energy of each appliance, the application period and the location of the household.

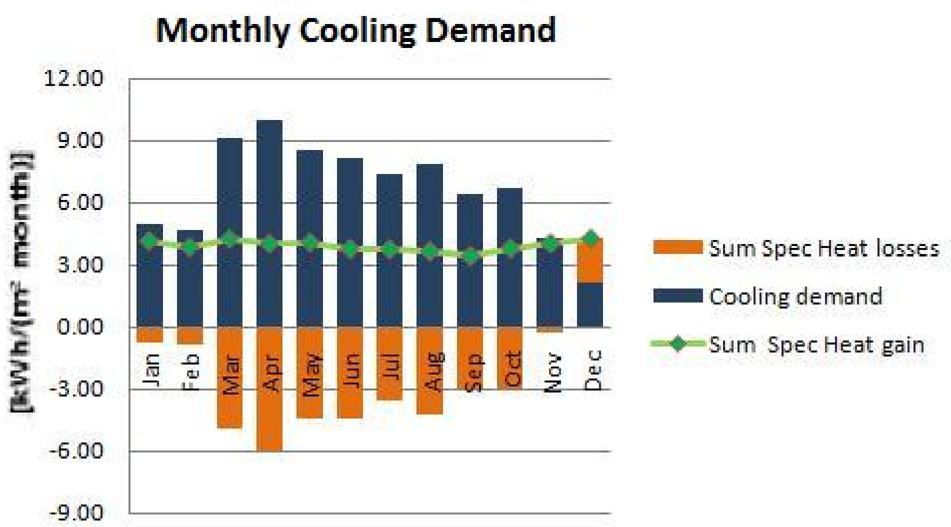


Figure 17: Monthly Cooling Demand of Typical House Model

According to the monthly energy balance graph, cooling demand was mostly required in April at 10 kWh/ m^2 per month, due to the climate conditions. In fact, April is in the summer season so all the building elements absorb and gain heat into the house. Whereas in December, the cooling demand is not as high; the number of heat losses in this month is the highest. It can be seen that almost all of monthly heat losses are negative, so heat gain leaking into the house caused the increasing cooling demand. It can be noticed that, during March to October, the specific heat losses had negative values. The reason why the cooling demand in these months is so high is because that period is in the summer and raining seasons, resulting in high external temperatures which then heat the house. However, the rate of heat gain did not fluctuate in the monthly periods but the lowest value is in September, due to the minimum amount of solar radiation.

Figure 18 indicates the monthly energy requirements for a typical house in Thailand. The cooling degree day rates follow the same trend as the cooling demands. The cooling degree day is the quantitative index designed to reflect the energy needed to cool the house. In the summer, April had the highest value of cooling degree days in line with the highest cooling demand, while the global solar radiation graph in that month was not the highest. Therefore, it can be concluded that cooling demand was not only affected by solar radiation but there were other related factors, such as absorption rate of the material, window emissivity and internal heat gain. The highest monthly energy requirement was in April at 13 kWh/m^2 Month; the lowest was in December (winter).

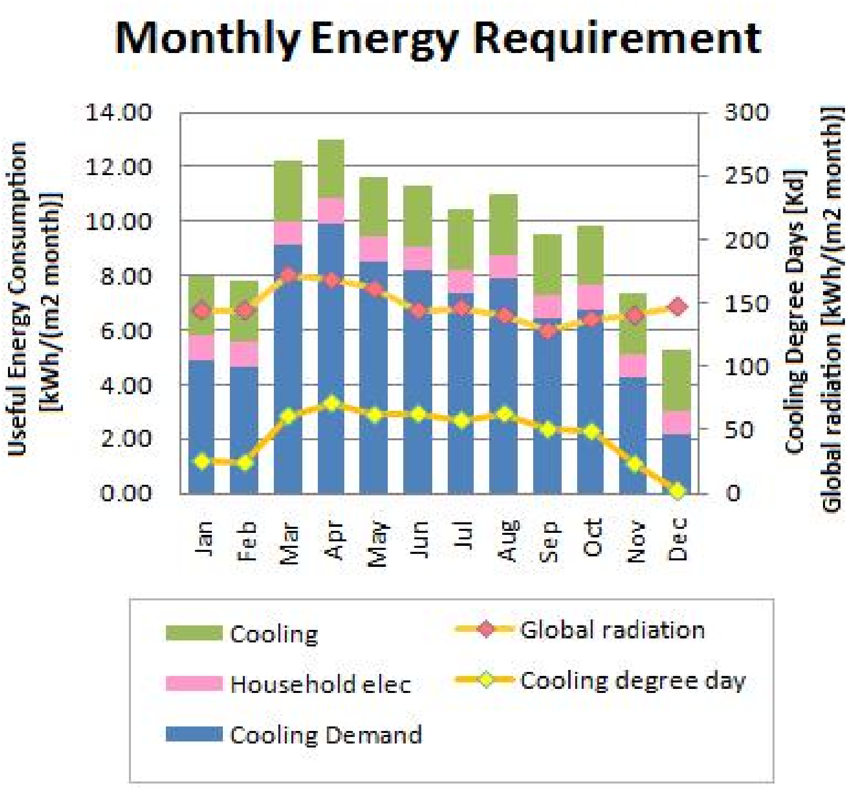


Figure 18: Monthly Energy Requirement of Typical House Model

4.5.4 Primary Energy value

The primary energy consumption in this case study can be divided into two groups: household electricity consumption and auxiliary electricity consumption for space cooling. In addition, the primary energy value of space cooling was related to the annual cooling demand and the specifications of the heat pump. In Figure 18, this graph shows the monthly overall energy consumption for this model. From this, it can be concluded that the majority of energy consumption was for the electricity consumption of space cooling because it required high cooling demand and this cooling unit consumed a high rate of electricity.

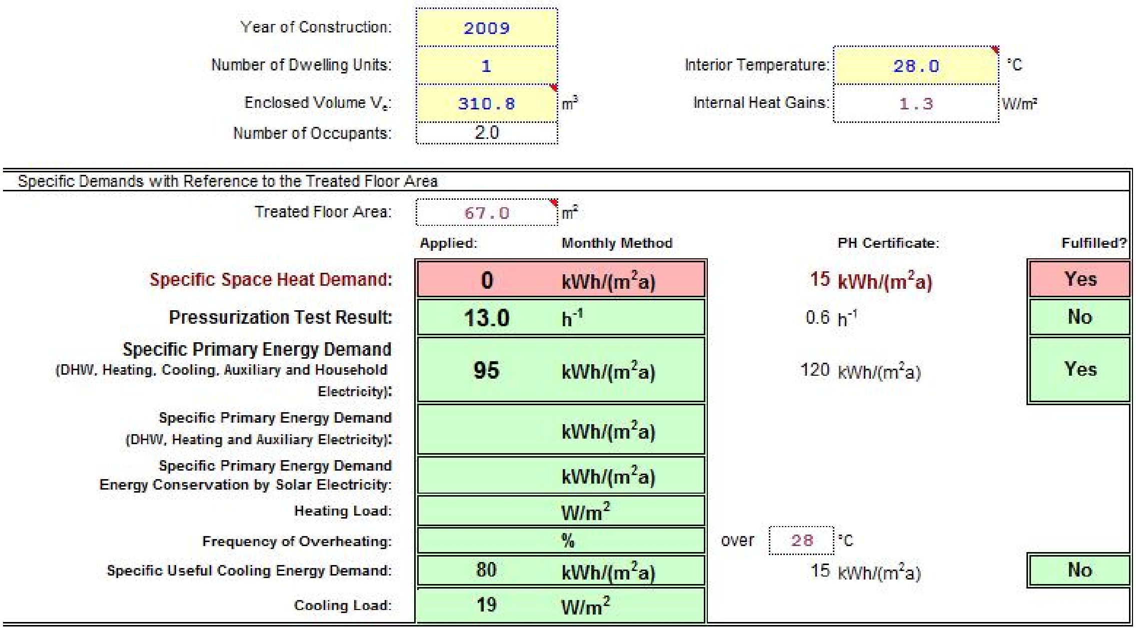
The PHPP calculated the primary value of this case study to be around 95 kWh/ m^2a, consisting of 71.5 kWh/ m^2a of space cooling, 7.1 kWh/ m^2a and 3.9 kWh/ m^2a of electrical household appliances and gas cooking, respectively. Moreover, there was 23.7kg/ m^2a of carbon emissions. To determine the primary energy consumption from final energy consumption values, the primary energy factors decided upon internationally and data used was 2.7 kWh/kWh for electricity and 1.1 kWh/kWh for natural gas. It can be concluded that the primary energy consumption is a result of the final energy consumption and it also affected the carbon emissions.

4.6 Summary

For the performance of a typical house in Thailand, it can be concluded that many of the required values were far from the passive house standard requirements. However, the weak points of this design can be modified to become a passive house. The main issues of this model were heat gains by conduction and solar heat gains due to climate condition but they can be reduced by some physical modifications. Moreover, the average air change rate at 50 Pa used the typical value of a general house at 13 h^{-1}. In fact, it did not influence to the cooling demand and load very much (Ridley et al, n.d.).

The following list shows the values of verification in the typical housing model in Thailand at 28 °C of comfort temperature.

- 80 kWh/ m^2a of cooling demand
- 95 kWh/ m^2a for primary energy consumption
- 19 W/ m^2 for cooling load
- 13 h^{-1} for pressurisation test result at 50 Pa
- 23.7 kWh/ m^2a of carbon emissions



Year of Construction:	2009			
Number of Dwelling Units:	1		Interior Temperature:	28.0 °C
Enclosed Volume V_e:	310.8	m^3	Internal Heat Gains:	1.3 W/m²
Number of Occupants:	2.0			

Specific Demands with Reference to the Treated Floor Area

	Applied:	Monthly Method	PH Certificate:	Fulfilled?
Treated Floor Area:	67.0	m^2		
Specific Space Heat Demand:	0	kWh/(m^2a)	15 kWh/(m^2a)	Yes
Pressurization Test Result:	13.0	h^{-1}	0.6 h^{-1}	No
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	95	kWh/(m^2a)	120 kWh/(m^2a)	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):		kWh/(m^2a)		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		kWh/(m^2a)		
Heating Load:		W/m^2		
Frequency of Overheating:		%	over 28 °C	
Specific Useful Cooling Energy Demand:	80	kWh/(m^2a)	15 kWh/(m^2a)	No
Cooling Load:	19	W/m^2		

Figure19: Verification Worksheet in PHPP Software of Typical House Model

The next chapter shows the evaluation results for passive houses in Thailand and how typical housing models could be modified.

Chapter 5: Results and Discussion of Passive Housing Model.

This chapter assesses the experiment and simulation of a passive housing model; the results were derived from the cooling demand, primary energy demand and indoor environment in the tropical climate. The results were presented in the graph of monthly cooling demand and in some figures. The development of the passive house design in the tropical climate depended upon certain main element designs (i.e. roof, floor, wall and opening). Ventilation systems also had to follow the passive house criteria. Finally, the interpretation of the passive house design in the tropical climate was discussed.

5.1 **Modified construction model**.

The performance of the simplified model in the chapter four needed to be modified to meet the following passive house standards:

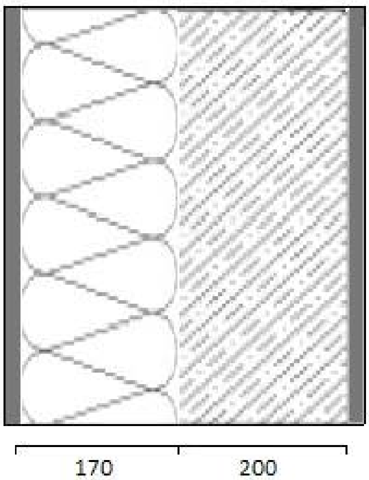
- 15 kWh/m^{2}a for cooling demand
- 10 W/m^2 for maximum cooling load
- 120 kWh/m^{2}a for primary energy value

A development of the building's construction was the first recommendation, as mentioned in the previous chapter, due to the high value of transmission and solar heat gains. After that, the ventilation system needed to be improved. In addition, the cooling set point temperature inside the passive house was 25°C, according to the passive house standard defined in the PHPP manual. Therefore, this section describes the improvement of building construction, including super insulation and window and shading.

5.1.1 Insulation

The building assemblies (consisting of roof, exterior walls and floor) could be insulated. In fact, if the U-value of each building element is very low, it could reduce the cooling demand. However, under the passive house standards, the U-value of the insulation in each building element does not have to exceed 0.15 W/m^{2}K.

In order to modify the building, the selected material should have a low thermal conductivity. The U-value also depended upon the thermal conductivity and thickness of materials. This model did not change any window sizes or the areas of the building elements. The location of the passive house model remained unchanged as well. The table below shows the materials used for developing this model with insulation strategy. Thermal bridges and the absorption rate of the house's exterior were also significant factors in achieving the standards of passive house. To comply with these standards, the U-values of the building assemblies needed to be as low as possible, between 0.1 W/m^{2}K and 0.15 W/m^{2}K. Thus, all selected materials of this passive house model were justified by the thermal conductivity of each material and the frequency of the materials' use in Thailand. The thermal conductivity of each material was derived from PHPP. The thickness of each layer of building element was designed in accordance with other Thai properties. The specification of the chosen materials was also widely used in the region. However, the main objective of these designs was to get a suitable U-value and thickness layer of building elements. U-values can be determined by inversing the sum of thermal resistance at the interior and exterior surfaces and the thermal resistances of the individual construction layers by PHPP. Moreover, the thermal resistance of individual construction layers was found by using the thickness and the thermal conductivity of the materials.

Building Elements	**Description**
	**Exterior Walls** Exterior plaster coat (10 mm.) AAC Lightweight blocks (200 mm.) Rigid Polyurethane Foam (170mm.) Interior plaster coat (10 mm.) U-value = 0.108 W/ m^{2}K.

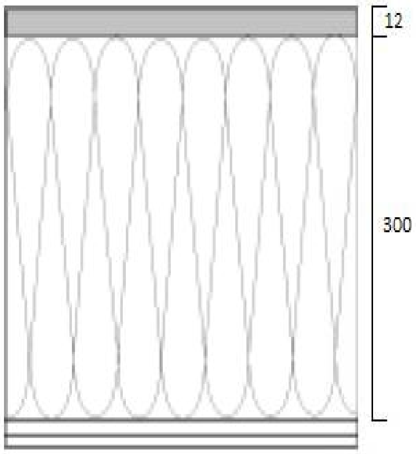
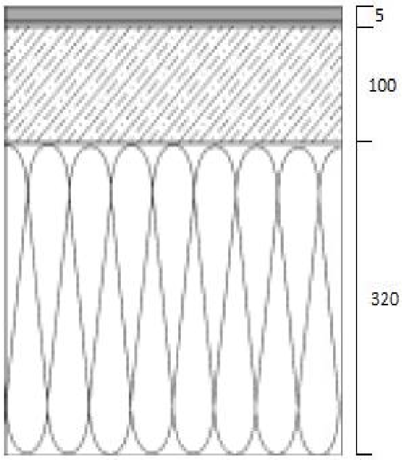
	**Roof** Gypsum board and Aluminium foil (12 mm.) Rigid Polyurethane Foam (300 mm.) U-value = 0.100 W/ m^2K.
	**Floor** Polystyrene Foam (270 mm.) Impact sound insulation (50 mm.) Concrete floor slab (100 mm.) Carpet (5mm.) U-value = 0.118 W/ m^2K.

Table 15: Standard Details of Thailand Passive House Envelopes

When increasing the insulation, the transmission heat gain of the building elements is less than in the typical house model case study, due to the decreased U-value. These values depended upon the area of each element, U-value and cooling degree hours. Table 16 showed the relationship between the areas of building elements, U-value and transmission heat gains. The cooling degree hours in this case could be divided into 2 types: exterior surfaces and ground surface due to differences in the outdoor temperature of each area. The cooling set point temperature was 25°C, under the passive housing standard. It led to high transmission heat gains that affected the cooling demand of the passive house. As can be seen in the Table 16, the windows had a high heat gain by conduction because of their high U-values. It can be concluded that transmission heat gains are the products of area, U-values and cooling degree hours.

Building element	Area (m^2)	U-value (W/ m^2K)	Cooling Degree Hours (kKh/a)	Transmission gains (kWh/a)
Exterior Wall	117.7	0.108	30	381
Roof	127.5	0.082	30	312
Floor	66.4	0.118	46	357
Windows	19.6	0.799	30	468
Thermal Bridge	112.1 (m.)	-0.021 (W/ mK)	30	- 69
Total	331.12	0.134		**1449**

Table 16: Transmission Losses of each Building Element at 25°C of Cooling Set Point Temperature

Moreover, this passive house model used the special colour for coating to reduce the absorption rate of the opaque area, as given by PHPP. However, the thermal bridge was one factor essential to designing the passive house. The passive house standard requires the thermal bridge heat losses coefficient (ψ) to not exceed 0.01 W/mK and, in this model, the thermal bridge was lower than the required value at -0.021 W/mK. This value is normally negative when using exterior dimensions because the interior dimension value is lower than the heat flow of adjacent areas. The thermal bridge also impacted the cooling demand of the passive house model because it led to the variation of transmission heat losses and gains.

5.1.2 Window & Shading

In the tropical climate, types of window glazing and frame and the shading strategy were significant options to protect the house from solar radiation, particularly as Thailand has a high global radiation value.

First of all, the type of window was modified from single pane to a low-e glazing that was suitable for any high solar radiation region, as it has a special coating to reduce heat transfer. The window glazing and frame were related to the transmission and solar heat gains. The window's U-value depended not only on the quality of the glazing, but also the quality of the frames, spacers, installation and the glass to frame ratio. The windows should be placed in the plane of the insulation layer, not in the plane of the masonry. In addition, the frame of the window was changed from wood and metal to the starz softline Iv92 material that was given in PHPP. This frame was selected because it has a low U-value and G-value. It was recommended to use in the passive house by the Passive House Institute. Normally, the U-value of low-e glazing in PHPP is around 0.51 W/ m^2K and the U-value of this frame is around 0.68 W/ m^2K. Pursuant to the regulations of passive house, the U-value of a window cannot exceed 0.8 W/ m^2K in order to protect a high value of window transmission heat gains, as it was related to window areas, U-values and the cooling degree hours. Table 17 presents the U-values of windows in each direction and the transmission heat gains under 25°C of cooling set point temperature, as computerised by PHPP.

Window area orientation	**Window area (m^2)**	**Window U-value (W/m^2K)**	**Cooling degree hours (kKh/a)**	**Transmission heat gains (kWh/a)**
North	6.2	0.79	30	147
East	6.78	0.8	30	163
South	2.64	0.8	30	63
West	3.96	0.8	30	95
Total or average value of all windows	19.58	0.8		468

Table 17: Window Performance of Passive House Model at 25°C of Cooling Set Point Temperature

According to the window performance table, the transmission heat gains were a product of the window's area, U-value and the cooling degree hours. All of the parameters in this table were calculated by PHPP. For example, the window U-value was the average U-value in each direction. The highest transmission heat gain was at the eastern orientation with the largest window area. When comparing the rates of transmission heat gains of the passive house and that of the simplified model, the passive house's value was higher. This means that the passive house had more heat gains through the window than the typical housing model although the average window U-values of passive house were lower than the based case model. Thus, cooling degree hours was the most important parameter for determining transmission heat gains. The transmission heat gain rates were one essential factor of the cooling demand variation, based on the cooling degree hours in each region.

The window did not only contain glazing and a frame, but the space between them and a connection to the facade were also essential because heat could get through these. Therefore, the thermal bridge in these areas should be low as much as possible. The thermal bridge effect can be decreased by using insulation spacers and assuring optimal installation. The value of the thermal bridge heat loss coefficient of the window installation ($\psi_{installation}$) and the thermal bridge heat loss coefficient at the glazing edge (ψ_{spacer}) were given in the frame specification in PHPP. In this case, starz softline Iv92 frames were used and the values of $\psi_{installation}$ and ψ_{spacer} were 0.04 W/mK and 0.03 W/mK, respectively. Both of them were factors for the selection of this frame and ensuring it was suitable for this model.

The solar heat gain was also a factor leading to the variation of the cooling demand. One method for preventing heat transfer to the house is using a shading strategy. In the Passive House Case Study, when shading was increased the cooling demand diminished in comparison to the basic case study.

In this passive house model, more trees were planted and window reveals were used to increase shading. Reveals can reduce the solar heat gains in the passive building because there will be a depth between the building façade and window, so the sunlight emitted through the window is less than normal. Moreover, the efficiency shading devices were selected due to their low shading reduction factor. This is defined as the percentage of sunlight getting through the window from the shading devices. Therefore, a 100% reduction factor means no shading and 0% means total shading. This model used a 20% shading reduction factor (also related to the solar radiation reduction factor) by using roller blinds. This figure was given by PHPP.

The definition of the solar radiation reduction factor is the percentage of solar radiation that can pass through the window. This parameter depends upon the frame to window area ratio shading, dirt on the windows and the tilted incidence angle of radiation through the window. If the reduction factor reaches a high percentage then the solar heat gain rate would be high as well, leading to an increased cooling demand. As discussed before, more trees were planted in the passive house. The type of tree should be perennial due to their high stems and leaves for good protection from sunlight. The high plants were set in the North as there were large windows at the northern orientation. On the western and eastern sides there should be some trees to shade the windows, but those trees should be of a medium height. Table 18 shows the window and shading performance of a passive house under the standard cooling set point temperature of 25°C.

Orientation of area	Reduction factor for solar radiation	G-value (%)	Global Radiation (kWh/ m^2a)	Solar heat gains (kWh/a)
North	0.005	52	511	8
East	0.01	52	940	41
South	0.02	52	966	25
West	0.01	52	925	17
Total or average value for all windows	**0.01**	**52**	**3342**	**91**

Table 18: Shading Performance of Passive House at 25°C of Cooling Set Point Temperature

Clearly, the solar radiation reduction factor in each orientation had a low value (around 0.01), indicating that was high protection by shading. The reduction factors of the modified model and typical house model were significantly different. The solar gain value was based on the window area, reduction factor, G-value and global radiation, all of which were determined by PHPP. In addition, the total solar gains of this model was 91 kWh/a, an almost 93% difference from the typical house model. This can be attributed to the increased shading, which affects the cooling demand.

Furthermore, one material that should not be ignored is the opaque area of building elements, such as the walls and window frames. These may have a high absorption rate and low reflection so conduct heat inside the house. In this case there was 318 kWh/a of solar heat gain in the opaque area and 1040 kWh/a for the typical housing model. Obviously, the rate of solar heat gain was completely different because the building components were changed, e.g. by adding an insulation layer. It could be concluded that there was a big difference for the transmission and solar heat gains between the basic case model and the modified model because the structure of the building was changed. All of these parameters led to an alteration in the cooling demand.

5.2 Ventilation.

In a passive house, the air quality should be high so occupants feel comfortable and healthy; hence the ventilation system is quite important. The air change rates for supply and extract air volumes are important and should be appropriate to the model. The climate condition is another important parameter to consider when designing the ventilation system for this modified model.

The fresh air coming in should be balanced with the air being exhausting. In addition, the passive house requires and air change rate of 30 m^3/h per person for a good quality air flow, as previously discussed. Therefore, the supply air requirement was around 60 m^3/h due to the estimated number of occupants. The exhaust air requirement was 100 m^3/h, calculated from the number and type of each room in the house. Only the kitchen, shower room and WC need an exhaust air system, while supply air systems are necessary for the living area and bedroom. Thus, the maximum air flow rate in this case study was 100 m^3/h to cover the supply and extract air requirements. All of these values were given by PHPP, following the requirement of DIN 1946, part 6, as discussed in the chapter four.

The ventilation system in this model was designed to exploit the mechanical ventilation including the heat recovery system because, in accordance with passive house regulations, it is recommended to optimise the mechanical ventilation. The mechanical ventilation was used alongside the natural ventilation during the day and with the cooling ventilation at night.

<u>Mechanical Ventilation</u>

In this modified model, the daily average air change rate was designed to have a suitable rate in the residential building. It was designed in the different operation system for the heat recovery ventilation in one day. The average air change rate was calculated using the maximum air flow rate and multiplication with maximum different factors, depending upon the types of operation. All of these factors were provided by PHPP, including 0.77 of standard operation, 0.54 of basic operation and 0.4 of minimum operation. The standard operation lasted 12 hours when the occupants had done their activities. The basic operation lasted 8 hours as they did not need to use high energy or sleeping. The minimum operation lasted 4 hours when no one stayed in the building. The average daily air change rate was around 0.38 h^{-1}, based on the maximum internal air flow rate of this case study. This air change rate is in the range of the passive house standards for indoor hygiene and it also affected the cooling demand. If the air change rate was designed to achieve a higher value of indoor air hygiene, useful cooling consumption could increase because there was a high outdoor temperature. Therefore, the designed daily air change rate was another parameter affecting the passive house's performance.

Regarding the heat recovery unit, the duct runs should be well insulated and as short as possible. The high efficiency ventilation unit could be installed either inside or outside the thermal envelope. On the other hand, it should remain as close as possible to the opening within the envelope as the heat losses from or to the duct have serious implications for the heat recovery efficiency.

In this case, the ventilation units consisted of the counter flow heat exchanger, the supply and exhaust ventilator, two integrated filters and a control to set the flow volumes. The installed central unit heat exchangers were from Paul Company (ATMOS 175 DC Model), as recommended by the Passive House Institute. Its efficiency was around 86 % and 0.3 Wh/m^3 of electric efficiency. This included 40 mm thick heat insulation with no thermal bridges. This machine was appropriate for this case study due to its high efficiency, suitable specification and better electricity saving.

Technical detail of heat recovery system (manufacturer's specification)

Dimensions:	1600×552×442 (H×W×D) [mm.]
Duct material:	Plastic
Ventilators:	2 EC radial fans with integrated electronic and constant flow character
Volume air flow:	50-300 m^3/h
Power consumption (entire system):	15-125 W.

The system was installed within the thermal envelop to protect heat transfer from or to the duct. It was unnecessary to have a long duct if it was set inside the thermal envelope, while heat recovery efficiency was not significantly by the addition or removal of a thermal envelope. Thus, it did not greatly affect the cooling consumption. The nominal lengths of duct were around 1.1 m. and 1.5 m of the supply and exhaust air ducts, respectively. The transmittance of both was 0.16 W/mK with the ambient air duct and 0.22 W/mK of the exhaust air duct. All of the specifications for the heat recovery unit were recommended in the passive house by PHPP. Their values were obtained using the PHPP calculation (PHI, 2007).

Natural ventilation

During the day time, the conventional ventilation by opening the windows was cost efficient and individually adjustable. The air exchange was powered by two different mechanisms: wind and temperature causing differences in density. In addition, there was natural ventilation in all rooms during the day. At least one window was opened in each room with a width of 0.05m to have an inside air flow. The temperature difference was around 4°C and the wind velocity was around 1m/s in the summer in these climate conditions. The reason for the slight opening width was so heat can be transferred through the gap directly due to the higher outside temperature. Therefore, the average air change rate of the natural ventilation in daytime was 0.22 h^{-1} - this value was supplied by PHPP. Normally, a passive house requires good interior air quality so the average air change rate should be over 0.3 h^{-1} to comply with the passive house standard. However, mechanical ventilation was used in addition to natural ventilation to help improve air quality so it reached the passive house standard.

Thus, during the day time HRV and natural ventilation simultaneously work together. There was a daily air exchange rate of around 0.38 h^{-1} of HRV and 0.22 h^{-1} of the natural ventilation. The HRV removed stale, polluted indoor air and replaced it with fresh outdoor air; at the same time, it recovered energy from inside before it was flushed outside. Hence, this ventilator could help improve inside air quality by avoiding the use of natural ventilation, as this kind of ventilation could transfer heat to inside. This mechanical ventilator can cool fresh air and bring it into the building as well.

Both mechanical and natural ventilation influence the ventilation heat gains of this building. This is related to the average air change rate, volume of the building and cooling degree days. In the case of a 25°C of cooling set point temperature, the ventilation heat gain was 450 kWh/a; a high amount. This kind of heat gain was one factor behind the cooling demand variation. The designs for the mechanical and natural ventilation were based on the frequency of overheating at the comfort temperature of 25°C in the hot period. As a result, there was 100% of overheating at 25°C, meaning the inside temperature was not comfortable for the occupants. Consequently, the occupants needed an active cooling system to make them more comfortable. However, adding an active cooling system led to an increase in the primary energy value of the passive house.

Cooling system

As previously discussed, natural ventilation was only used during the day and at night most windows were closed and the air conditioners were turned on instead, as the natural ventilation could not cool down the inside temperature at night (especially in the summer). It still made the occupants feel uncomfortable. However, a HRV was still operated with active cooling units in this passive house model. Their operation is discussed in this section.

The active cooling in this model was designed to deploy the heat pump, recirculation cooling and dehumidification to make the inside environment more comfortable. A tropical climate case study has a high percentage of relative humidity so dehumidification needed to be used to make the occupants feel satisfied. The set point for the maximum humidity ratio in the dehumidification was 16 g/kg, corresponding to a dew point of approximately 21°C as the suitable climate condition to make occupants comfortable. Additionally, the minimum temperature of the cooling coil surface was around 4°C and had a volume flow rate of 300m^3/h to create a sensible fraction to meet around 70% of the usual value. These values were default values recommended by PHPP. The heat pump installed in this building had an ideal COP of 4.5, the same as considered in the chapter four. This led to the variation of primary energy as well, due to the useful cooling demand variation. This packaged air conditioner worked at night alongside the HRV; the air entered the air conditioner after the HRV dumped heat to the air outlet. After that, the heat exchanger would suffice and the air conditioner worked to cool the building. Finally, the HRV also recovered energy from the air inside before it was flushed outside.

According to an exploitation of the active cooling unit, the factors helping to make a decision to select types of cooling unit were the sensible and latent loads in the building. As a result of a PHPP calculation for passive houses with 25°C set point temperatures, the sensible load was 45.8 kWh/m^{2}a and 34.7 kWh/m^{2}a for the latent load, so the recirculation cooling generated 45.8 kWh/m^{2}a and 15.9 kWh/m^{2}a for the sensible and latent loads, respectively. The remaining latent load was produced by the dehumidification. All of the active cooling operations affected the primary energy value, although it did not influence the useful cooling demand.

It can be concluded that the ventilation modifications in this passive house were the addition of the mechanical ventilation with a heat recovery unit, used alongside natural ventilation during the day and working with cooling units at night. The mechanical and natural ventilation systems caused a change of cooling demand. The comfortable feeling could be measured in the building. In addition, active cooling was integrated when the inside temperature made the occupants unsatisfied, so heat pump, recirculation cooling and dehumidification were operated in the packaged air conditioner. Most of the active cooling system did not alter the cooling demand but it affected the primary energy value and carbon emissions.

5.3 Household electrical appliances in the passive house model.

The electrical household appliances utilised in the passive house model were the same as those in the simplified case study. The reason for using the same model of electrical household appliances was their energy efficiency, Class A++. This was commonly adopted in Thailand so there was no reason to change it.

Consequently, the energy consumption of the electrical household appliances remained the same. There was a slight change in the energy consumption of the cooling unit because the useful cooling demand of the passive house model was lower than the basic case model. However, the model and specifications of the air conditioner was still the same as per the basic case model; its ideal COP was 4.5 and it was the alto-AS H22Y model. In addition, the HRV was integrated into the passive house model so this could directly influence the primary energy value and useful cooling demand. The model of HRV is the ATMOS-175DC by Paul Company that the Passive House Institute recommended.

All of the development criteria, including the development of the construction and the ventilation systems, used basic strategies to modify the building in the tropical climate. The performance of the passive house is discussed in the next section. Two case studies of this model criterion are shown in different cooling set point temperatures.

5.4 Performance of passive house case study 1.

This case study followed the criteria of passive house standards, particularly the cooling set point temperature at 25°C. It used all the structure modifications described in the previous section. This section shows the performance of a passive house with 25°C as the comfort temperature. The performance can be divided into four groups: comfort parameters, maximum cooling load, cooling demand and primary energy consumption.

5.4.1 Comfort parameters

The comfort parameters came from the inside temperature and the frequency of overheating at the comfort temperature. In this case, the comfort temperature was set at 25°C, the maximum temperature of passive house standards given in PHPP.

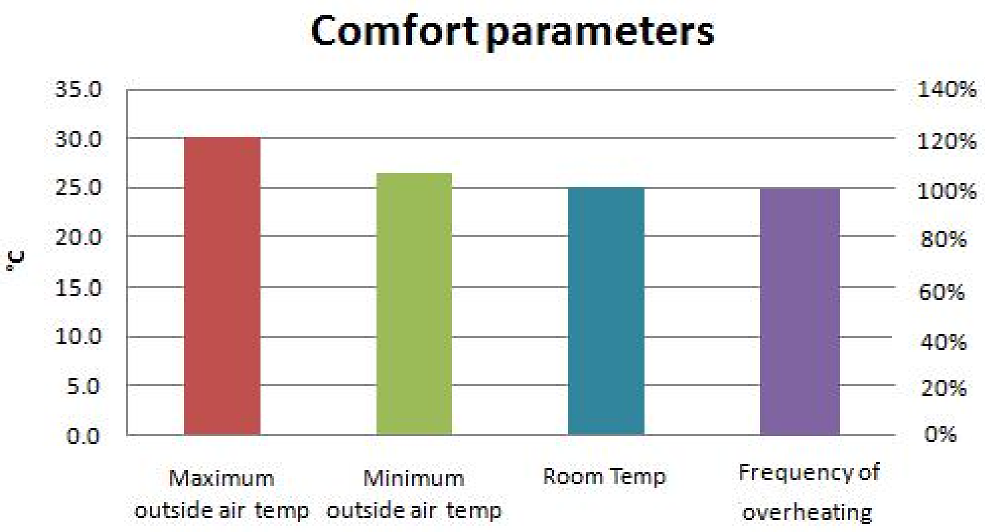


Figure 20: Comfort Parameters of Passive House Model Case Study 1

This graph presented the comfort parameters in this building. It could be noticed that both maximum outside temperature and minimum outside temperature were over the interior comfort temperature set point. Therefore, the cooling degree hours should be considered as they were directly affected by the temperature gap between the inside and outside temperatures. The transmission ventilation heat gains were important parameters in changing the useful cooling demand due to the variation of cooling degree hours. However, the building was modified to reduce the heat gains by conduction and solar gain, by the addition of shading and insulation.

As can be noticed in the next column, the frequency of overheating at 25°C was 100%; the inside room temperature was always over the cooling set point without the mechanical ventilation. As a result of the high frequency of overheating, active cooling units and mechanical ventilation were required to make the occupants feel comfortable in this passive house.

The active cooling units were required in this model to make the occupants satisfied. The recirculation cooling also generated the sensible and latent load. Furthermore, in the tropical climate there is a high percentage of humidity so dehumidification was also required to reduce the latent load in this building.

5.4.2 Cooling load

PHPP determined the maximum cooling load of this case study to be around 8.5 W/m^2. This value did not exceed the standard requirement of passive houses at 10 W/ m^2. Thus, this house needed a cooling rate of approximately 8.5 W/m^2 to achieve a comfortable temperature of 25°C during the hottest day in this climate. The main parameter correlating to the cooling load calculation was the transmission and internal heat loads, which were around 268 W and 154 W respectively.

There was a big difference in the comparison between the maximum cooling load of this case study and the typical house model: the cooling load of this case study was reduced by 53%. The following graph shows the comparison of all parameters affecting the cooling load determined by PHPP.

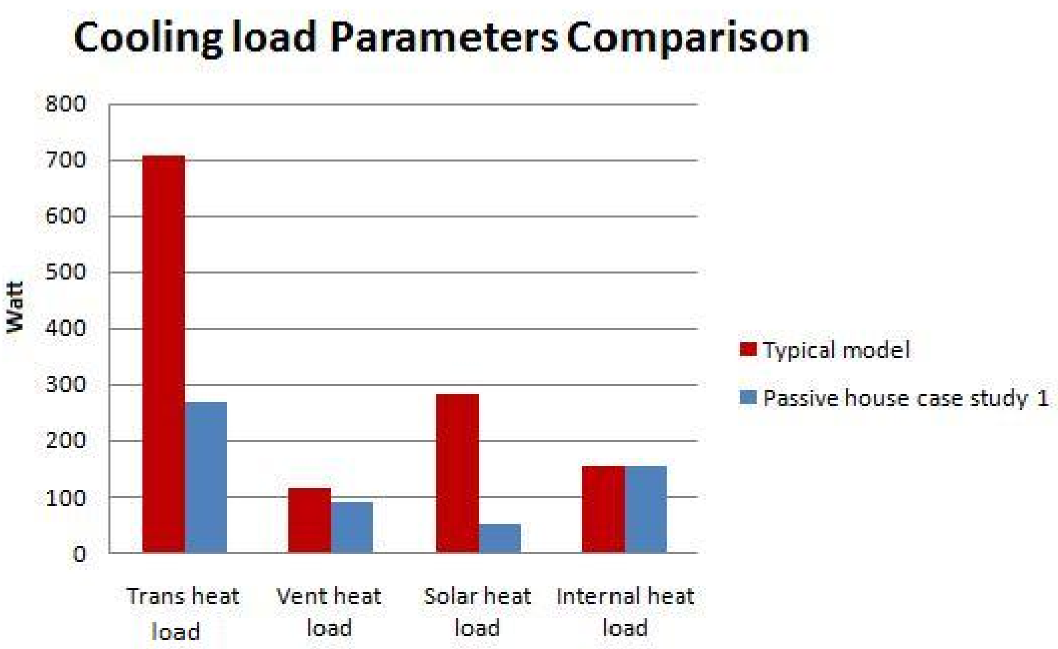


Figure 21: All Parameters of Cooling Load Comparison between Typical Model and Passive House Case Study 1

As shown above, the transmission heat load between simplified model and this case study was more than 50% different. The insulation strategy was successful in reducing these values. The shading strategy was also helpful in decreasing the solar heat load. The internal gains of both case studies were the same when there was no change of electrical household appliance usage, except the cooling units and mechanical ventilation. Furthermore, the internal heat load did not change so the cooling units and mechanical ventilation did not significantly affect the internal gain. One important aspect to be considered was the temperature differences between the exterior and interior set point temperatures as it was a key factor for all the parameters, especially transmission heat load. The variation of cooling load was also related to the cooling demand, as discussed in the next section.

5.4.3 Cooling demand

According to the passive house standards, the cooling demand should not exceed 15 kWh/m^{2}a and the maximum cooling load should not be over 10 W/m^2. Subject to the modification of the typical housing structure, the heat losses and heat gains were altered. Hence, the rate of cooling demand and cooling load were changed. Figure 22 shows the annual energy balance of this model and the typical model for comparison determined by PHPP.

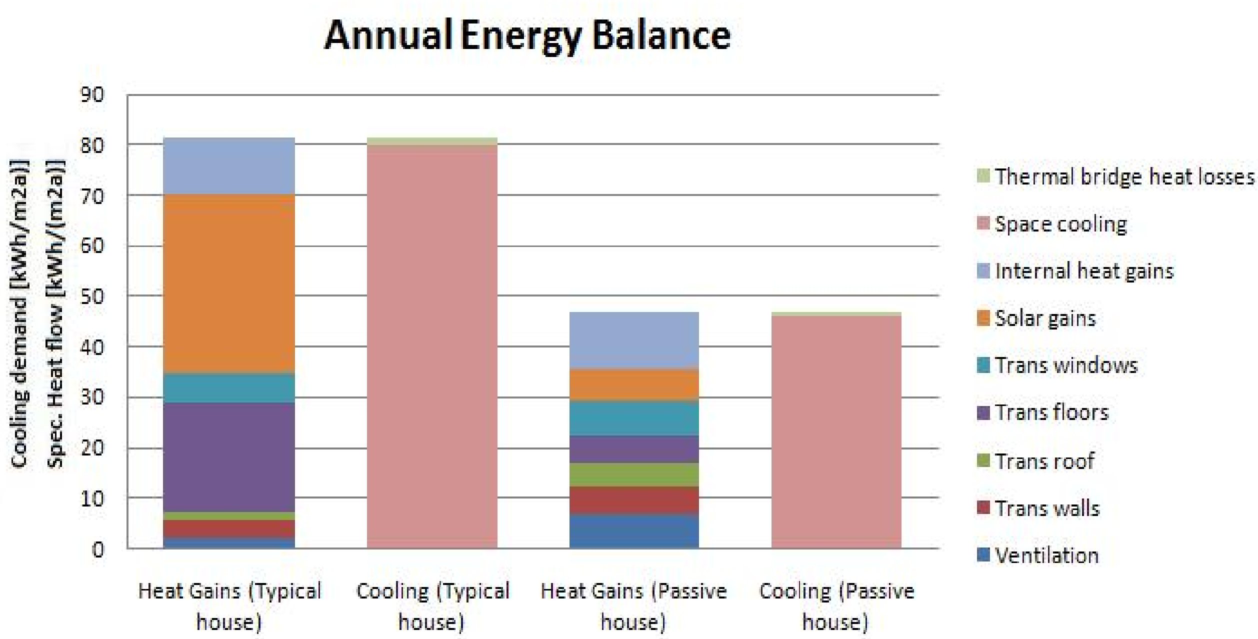


Figure 22: Annual Energy Balance Comparison of Passive House Case Study 1 and Typical House Model

As shown above, the rate of total heat gain in the passive house was reduced by 42% compared to the basic case model. The passive house modifications reduced solar heat gains by around 78% using the shading strategy. The addition of insulation significantly decreased the heat gain by conduction in the floor area by 70%. Other components of total heat gain increased moderately due to a big difference in the average annual cooling degree hours. The cooling set point temperature of this case study was at 25°C; a lower value than the set point temperature of the base model. The U-value and reduction factors of this case study decreased in comparison to the base model, as did the total heat gains. The ventilation heat gains increased, whereas the average air change rate in the passive house model decreased. Mechanical ventilation was added to the new model due to the growth of cooling degree hours. Thus, it could be concluded that the key parameters that varied the heat gains were the cooling degree hours, U-values and reduction factors for solar radiation.

Regarding the passive house heat gain, the cooling demand of this case study was considerably decreased to balance the energy. In order to maintain a comfortable environment inside the building, the cooling demand should be equal or over the total heat gain value in each case study. Therefore, the cooling demand of this Passive House Case Study was around 46 kWh/ m^2a, balancing the heat gain value.

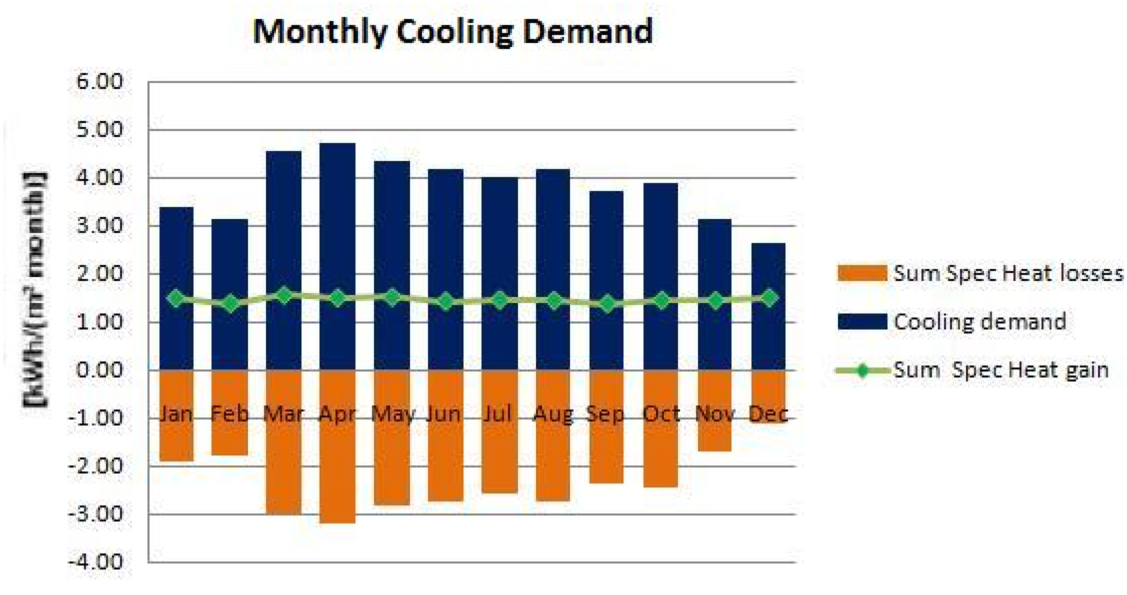


Figure 23: Monthly Cooling Demand of Passive House Case Study1

As per the monthly calculation method of PHPP, the results are shown as Figure 23. The useful cooling demand of the passive house was around 46 kWh/m^2a per year. This cooling demand did not meet the passive house standard requirement of 15 kWh/m^2a. When comparing this cooling consumption of the base case model and the Passive House Case Study, the cooling demand of the passive house was 42% less due to the heat gains reduction. According to the monthly cooling demand graph, April required the highest cooling demand (nearly 5 kWh/m^2 per month) as this month has the highest average temperatures. The lowest cooling consumption was in December with around 2.5 kWh/m^2 per month, due to the month being in the winter period. The monthly heat losses were negative; December had the highest heat losses whereas April had the lowest. This was correlated to the monthly cooling demand - it could be noticed that the trend of heat loss looked similar to the trend of cooling demand but in the inverse direction. Therefore, it could be said that heat losses was one of the main parameters affecting the cooling demand because the heat gains were quite stable. In this case, the heat gains consisted of solar gains and internal gains. Thus, the main parameter to vary the useful cooling demand was the negative heat losses, meaning they were some kind of heat gain. Thus, it seemed there were no heat losses in the Passive House Case Study but there were only heat gains to add on. Moreover, the months that had the lowest values of heat gains in the line graph were February and November because of the lowest internal heat gain in February and the lowest solar gain in November.

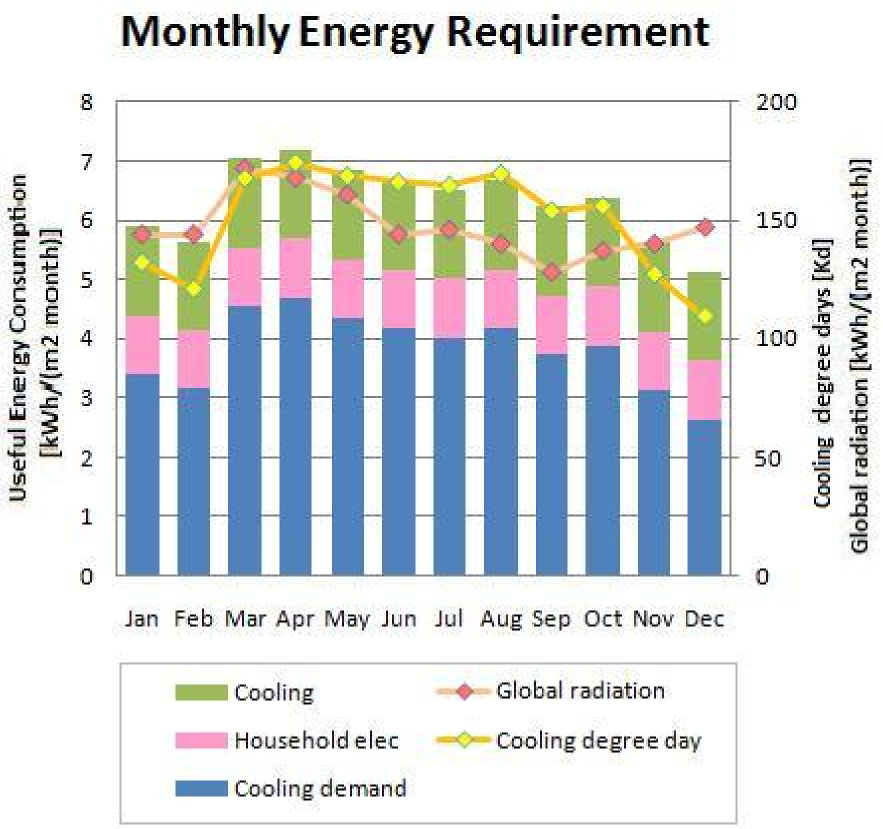


Figure 24: Monthly Energy Requirement of Passive House Case Study1

From the monthly energy requirement graph, it can be noticed that the trend of cooling degree days and cooling demand look similar. It could therefore be argued that the cooling degree days influenced the cooling demand rate. The cooling degree days are the amount of energy needed to cool down the building to the set point temperature. Consequently, the highest point of cooling degree day was in April as it was the period with the highest cooling demand. Conversely, December had the lowest cooling demand and the lowest point of cooling degree day. According to the electrical consumption of the household appliances and space cooling, both values did not vary much.

As previously discussed, the cooling demand of this case study was 46 kWh/ m^2a, exceeding the passive house standard for cooling demands at 15 kWh/ m^2a. Thus, this Passive House Case Study was not effective in this region even though other values met the requirements. This cooling demand was determined at the cooling set point of 25°C, based on the maximum standard for the passive house inside temperature. However, this comfortable temperature was quite low for Thai people so the next case study increased the cooling set point temperature of the building to an appropriate level for Thai occupants, in order to evaluate the effectiveness of passive houses in the tropical climate by developing this model further.

5.4.4 Primary energy

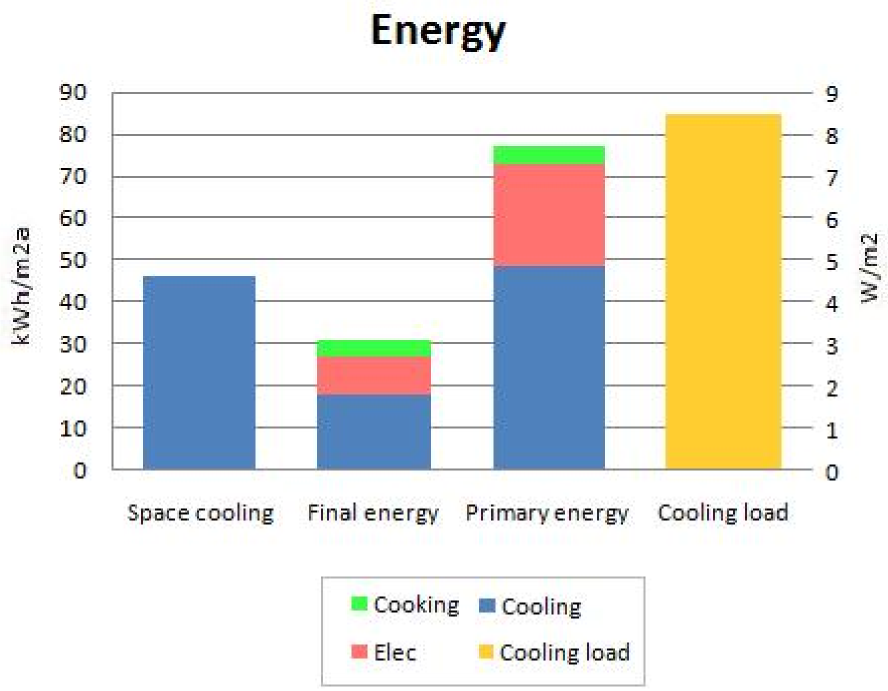


Figure 25: Energy Requirement of Passive House Case Study 1

Primary energy can be divided into three groups, namely the cooling unit, household electrical appliances and cooking. Figure 25 shows the annual energy consumption in this case study that was calculated by PHPP. The total annual primary energy consumption of this case study was 77 kWh/m^{2}a, meeting the standard requirements because it did not exceed 120 kWh/m^{2}a. In addition, the primary energy value was calculated from the final energy and primary energy factors that were determined by PHPP. The final energy is defined as the energy consumed by the occupants subject to the energy demand of appliances and the frequency of usage. The main factor affecting the final energy was the space cooling coming from the cooling unit at 18 kWh/m^{2}a. The remaining energy came from the household electrical appliances, requiring low energy, and gas cooking. The primary energy was higher than the final energy as the former was derived from the final energy demand and non-renewable primary energy factors with different fuel values. The primary energy factor was mentioned in the previous chapter. In addition, the primary value fraction of gas was lower than electricity so the primary value of cooking did not change too much from the final energy as shown in the graph.

As previously discussed, the final space cooling energy consumption was influenced by the annual useful cooling demand. If the annual cooling demand increased, the final energy for the space cooling would also increase. In this instance, the heat pump used for the space cooling had an ideal COP of around 4.5, the same model as used in the base case model. If this COP decreased, it would not influence the annual cooling demand but it would increase the primary value. However, mechanical ventilation (HRV) was added in this case study so the primary energy value was still lower than in the simplified case study. This means that there was little effect on the primary energy value and the main parameter varying the primary energy value was the final energy of the space cooling.

The primary energy value in this case study was determined as 48.3 kWh/m^{2}a for space cooling, 25 kWh/m^{2}a and 3.9 kWh/m^{2}a for electrical household appliances and cooking, respectively. Finally, it can be concluded that the primary energy did not influence other parameters, except carbon emissions, but it was affected by the annual cooling demand. In addition, there was around 19 kg/ m^{2}a of carbon emissions in one year.

5.4.5 Summary

This model was developed to meet the passive housing standard requirements. All of the conditions complied with the standards defined by the Passive House Institute, especially the maximum cooling set point temperature of 25°C. The results are shown below:

- 46 kWh/ m^{2}a of cooling demand
- 77 kWh/ m^{2}a for primary energy consumption
- 8.5 W/ m^2 for cooling load
- 0.6 h^{-1} for pressurisation test result
- 19.3 kWh/ m^{2}a of carbon emission

Year of Construction:	2009				
Number of Dwelling Units:	1		Interior Temperature:	25.0	°C
Enclosed Volume V_e:	310.8	m^3	Internal Heat Gains:	1.3	W/m^2
Number of Occupants:	1.9				

Specific Demands with Reference to the Treated Floor Area				
Treated Floor Area:	67.0 m^2			
	Applied:	**Monthly Method**	**PH Certificate:**	**Fulfilled?**
Specific Space Heat Demand:	0	$kWh/(m^2a)$	15 $kWh/(m^2a)$	Yes
Pressurization Test Result:	0.6	h^{-1}	0.6 h^{-1}	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	77	$kWh/(m^2a)$	120 $kWh/(m^2a)$	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):		$kWh/(m^2a)$		
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		$kWh/(m^2a)$		
Heating Load:	0	W/m^2		
Frequency of Overheating:		%	over 25 °C	
Specific Useful Cooling Energy Demand:	46	$kWh/(m^2a)$	15 $kWh/(m^2a)$	No
Cooling Load:	8	W/m^2		

Figure 26: Verification of passive house Case Study 1 at 25°C

As a result, it can be concluded that this model did not meet the passive house standard requirements as the cooling demand exceeded 15 kWh/m^2a. Therefore, this passive house was not effective in the tropical climate subject to all the passive house standard conditions, especially the maximum cooling set point temperature of 25°C. Regarding the modifications of this model, the heat gains were the main parameters of the cooling demand variation that could be reduced. Furthermore, the main issue of the missing requirement was the high value of cooling degree hours based on the climate condition; this could be enhanced by changing the cooling set point. Therefore, the next case study altered the cooling set point temperature to evaluate the efficiency of the passive house and the new cooling set point reasonable to the tropical climate conditions.

5.5 Performance of passive house Case Study 2.

As previously discussed, the passive house in Case Study 1 did not meet the requirements because the cooling set point temperature was set at the standard of passive house. There was still a big difference between the interior and exterior surface temperatures. However, in this case study the set point temperature was 28°C because this was found to be the comfortable temperature for Thai people, as mentioned in the 23rd conference on the passive and low energy architecture in Geneva, 2006 (Rungsiraks, 2006). The effectiveness of this model in the tropical climate should be assessed under the condition of the Thai comfortable temperature. All of the modifications still had the same criteria as in Case Study1.

In order to change the cooling set point temperature, the rates of all the parameters (such as the transmission and ventilation heat gains) were altered. These rates varied due to the alteration of cooling degree hours following the new set point temperature. The following sections explain the performance of the Passive House Case Study 2.

5.5.1 Comfort parameters

The comfort parameters in this case study were the same as the base model because the frequency of overheating at 28°C was still 100% without mechanical ventilation. The cooling set point of this case study was increased to 28°C, as indicated in the following graph.

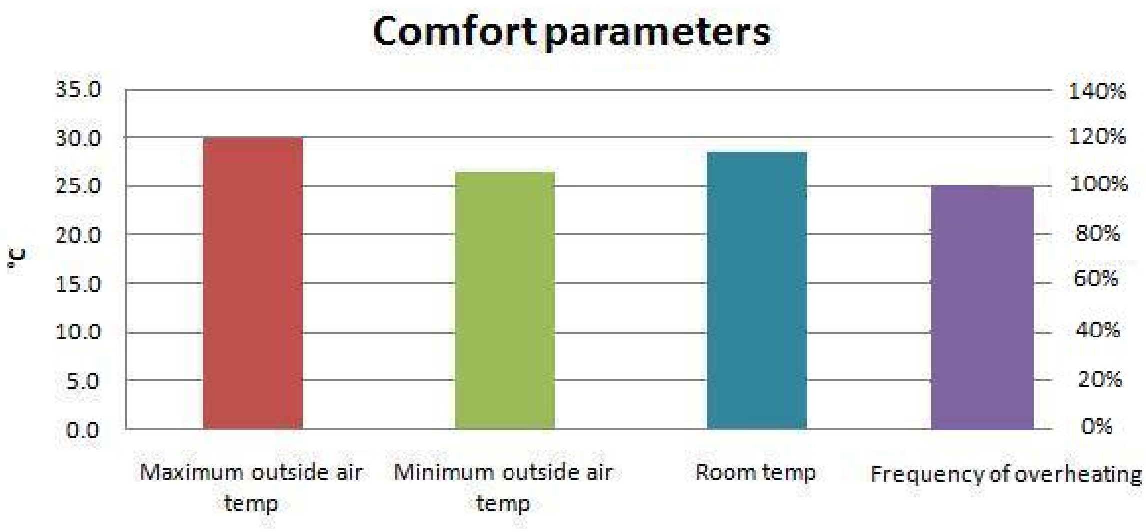


Figure 27: Comfort Parameters of Passive House Case Study2

The room temperature was higher than the minimum outside temperature, while this temperature was lower than the maximum ambient air temperature. So, it seems the number of heat gains could be reduced. The cause of reduction was the decrease in cooling degree hours due to the alteration in the cooling set point temperature.

Although the set point of this case study was changed, the frequency of overheating was still 100% due to the climatic conditions. Thus, it could be concluded that passive houses in the tropical climate should not only be designed with natural or cross ventilation in the building, but that mechanical ventilation and active cooling may be necessary to make the house more comfortable. In fact, the comfort parameters of this case study had the same result as the Typical House Case Study, due to the same frequency of overheating. The total heat gains were reduced compared with the typical house and Passive House Case Study 1. This is discussed in the following section.

The active cooling unit was one mechanism that could not be ignored as it made the occupants feel more comfortable. This case study implemented dehumidification and recirculation cooling units to reduce the latent and sensible loads. Moreover, there was a slight change of volume flow rate reduction in the recirculation cooling of this case study. This did not affect the cooling demand but it influenced the latent load generation of this unit. The operation of cooling units led to an increase in the primary energy of this case study, particularly the dehumidification when compared with no cooling unit integration. Although the primary energy value increased, it was still lower than the primary energy of the typical house model as this number depended upon the cooling demand. Therefore, it could be concluded that active cooling units were one factor to help occupants feel more comfortable, despite them increasing the primary energy.

5.5.2 Cooling load

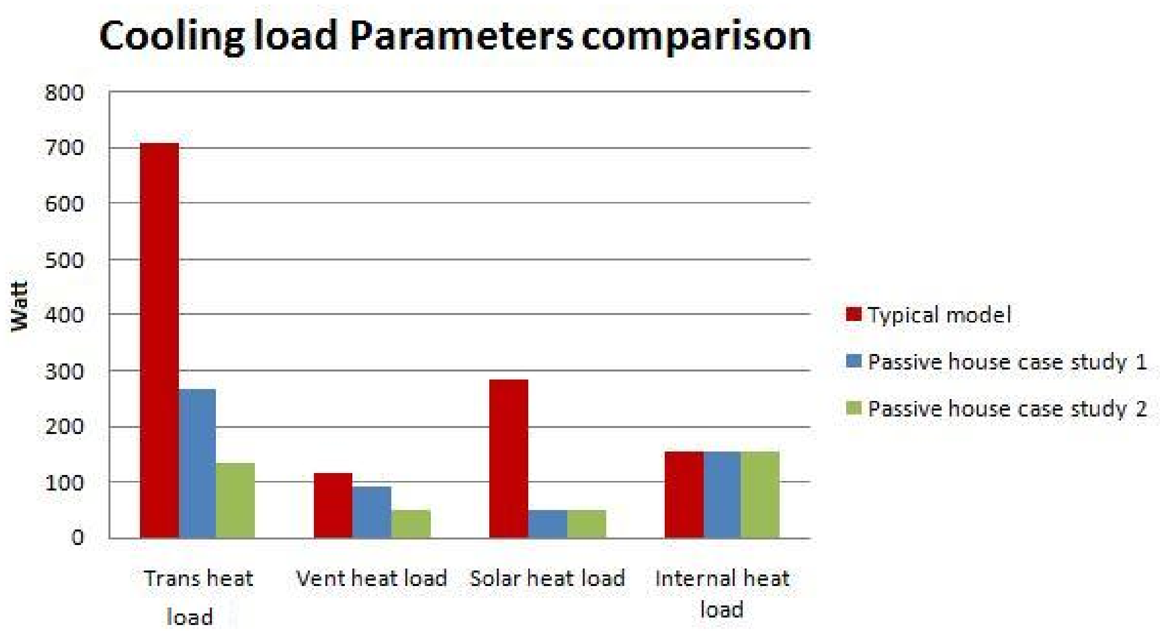


Figure 28: Cooling Load Comparison of three Case Studies

The maximum cooling load determined by PHPP for this case study was around 6 W/m^2, the lowest value of all the case studies. Thus, the building needed 6 W/ m^2 to cool the house enough to maintain the comfortable temperature during the hottest day. Figure 28 provides a comparison of the maximum cooling loads for the 3 case studies as calculated by PHPP. It can be noticed that the internal gains value remained the same as both previous case studies at around 154 Watts. However, the solar gains of the passive house case studies had the same values; a reduction of 82% compared to the typical house model. This was due to the addition of shading in the passive house models. The main parameter contributing to the solar heat load was the solar radiation that was unrelated to the cooling degree day.

Moreover, there were three levels of ventilation heat load. Case Study 2 had the lowest ventilation load at 51 W/m^2 due to the minimum daily average air change rate. Therefore, the breeze outside could not bring the heat transfer to the house as much as the Typical House Case Study. However, the different ventilation heat loads of the passive house case studies not only depends upon the average air change rate but also temperature differences. Therefore, it was clear that the set point directly affected the transmission heat loads and ventilation heat loads.

A key effect of the cooling load variation was in the transmission heat loads. The transmission heat loads of Case Study 2 were 80% less than in the Typical House Case Study and 50% less than the Passive House Case Study 1. This was influenced by the increased insulation layer on the exterior surface and a change of the inside comfort temperature set point to 28°C. The U-values of the building elements and temperature differences were directly influenced by the transmission heat load.

It can be concluded that this case study had the lowest cooling load because of the development of the building structure and ventilation systems. Although the structure of this case study had the same modifications as the Passive House Case Study 1, the set point of inside temperature was different. This Passive House Case Study had the temperature set point at 28°C. Thus, this is also one issue that could change the cooling load when compared with the Passive House Case Study 1. The cooling load of this case study did not exceed 10 W/ m^2, meeting the requirement of the passive house standards.

5.5.3 Cooling demand

According to the PHPP calculations, the results of the Passive House Case Study 1 cooling demand did not meet the standard requirements. Thus, for this case study, the cooling set point temperature was changed from the passive house standard of 25°C to the comfortable temperature for Thai people of 28°C before analysing the results. In this section, the Passive House Case Study 1 and Passive House Case Study 2 were compared to show the different results for the dissimilar set point temperatures. The following graph shows the annual energy balance.

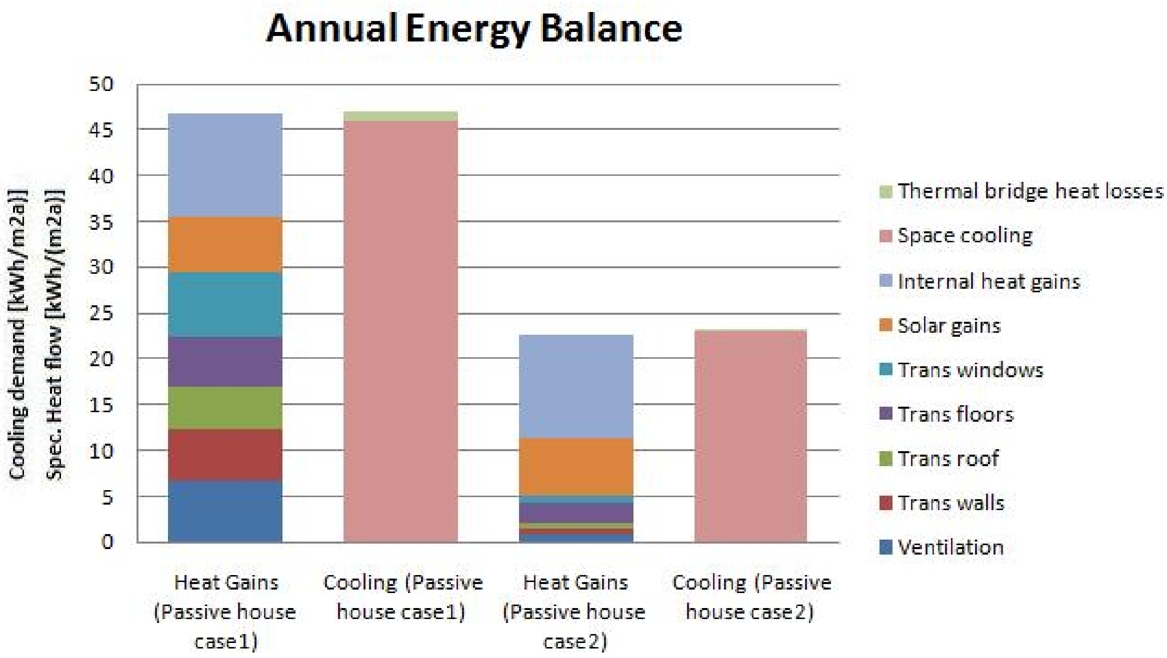


Figure 29: Annual Energy Balance of Passive House Case Study2

Both case studies had a solar gain of 6 kWh/m^{2}a as they used the same shading strategies. Similarly, both internal gains had the equivalent value of 11.4 kWh/m^{2}a since they operated on the same specifications of household appliances. In addition, the total heat gains by conduction of the Passive House Case Study 2 considerably decreased by 80% and the ventilation heat gains reduction by 88%. This was because the average monthly cooling degree hour was based on the cooling set point temperature, which was changed in Case Study 2.

In order to balance the energy, the cooling demand needed to be equal to the heat gain values. In Passive House Case Study 2, the cooling demand was around 23 kWh/m^{2}a in order to balance the total heat gains. As can be seen in Figure 30, the internal gain played an important role in the Passive House Case Study 2. Thus, the cooling demand of the Passive House Case Study 2 could be declining to meet the passive housing standard requirements by a decrease of internal heat gain. However, it was quite hard to cut the internal gains because all the electrical household appliances were equipped as necessary and they were also low energy efficiency appliances.

Nevertheless, the total heat gains of Passive House Case Study 2 were 50% less than the total heat gains of Passive House Case Study1. The main parameter of this reduction was the heat gains by conduction of all building elements, such as floor, roof and walls. The ventilation gain was also an important factor.

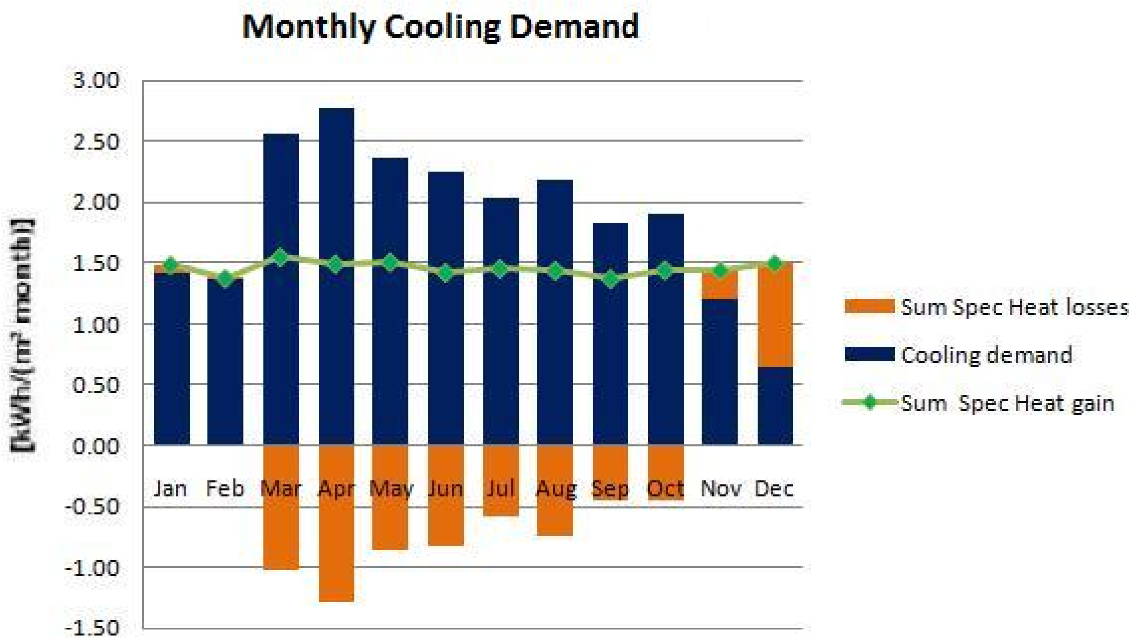


Figure 30: Monthly Cooling Demand of Passive House Case Study2

As per the monthly cooling demand graph calculated by PHPP, the highest value was in April with 2.8 kWh/m^2 per month, as it is in the hot season. Therefore, there was high solar radiation and cooling degree days in this period, leading to high heat gains based on the particular climate's conditions. The overall cooling demand of this Passive House Case Study was 23 kWh/m^{2}a and consequently did not meet the passive housing standard requirement. It could be noted that the trend of heat gain did not fluctuate so the cooling demand variation depended upon heat loss values that were negative in some periods. The negative values of heat losses were heat gains by conduction and ventilation to building. Therefore, the summer season had additional high heat gains by conduction and ventilation. Furthermore, the least monthly cooling demand was in December when the heat loss values were high and positive.

When comparing the monthly cooling demand of this case study with Case Study 1 under different set point temperatures, the monthly cooling demand of this study decreased by 50%. It can be concluded that the important parameter of this effect was the cooling degree days, while the other factors were constant in both case studies. Consequently, the cooling set point temperature was the important factor affecting the cooling demand.

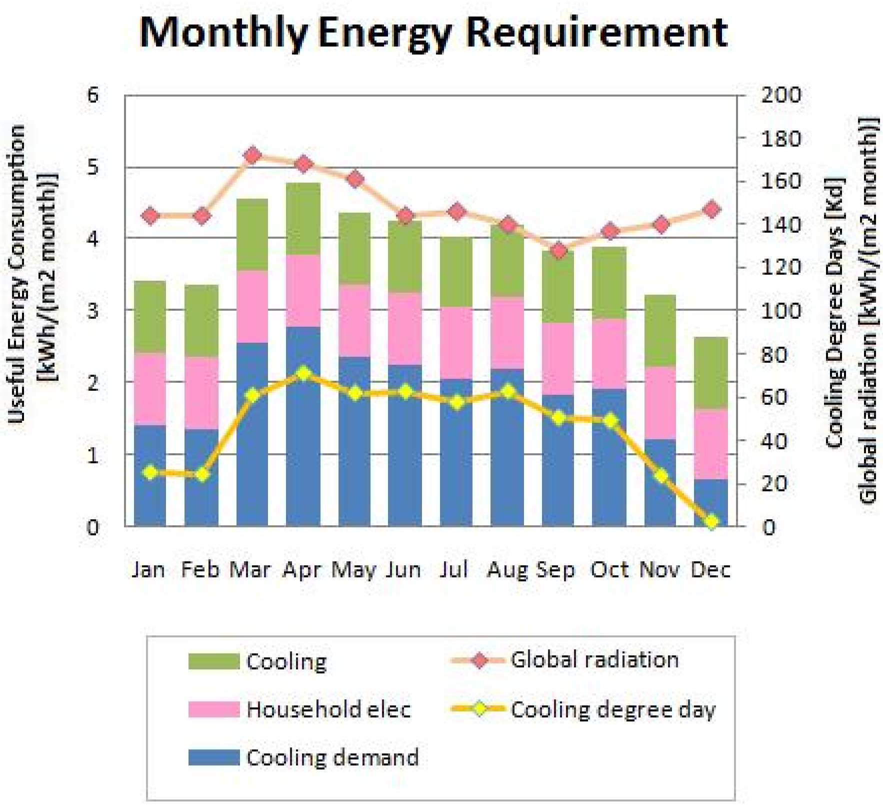


Figure 31: Monthly Energy Requirement of Passive House Case Study2

The monthly energy requirements for this case study included the cooling demand, electricity for household appliances and electricity for space cooling. The trend of cooling degree days appears similar to that of cooling demand since cooling degree days were an important affective factor to the cooling demand. In addition, the global radiation was related to the solar gain but did not correlate to cooling degree days. This was because the cooling degree days depended upon the cooling set point temperature and climate conditions.

Furthermore, the space cooling power decreased slightly when compared with the Passive House Case Study 1 because the cooling demand of Passive House Case Study 2 was less. However, the energy of the electrical household appliances was stable because the appliances were applied with the same specifications in all 3 case studies. However, mechanical ventilation was added in both passive house models, which slightly affected the energy of the household appliances.

5.5.4 Primary energy

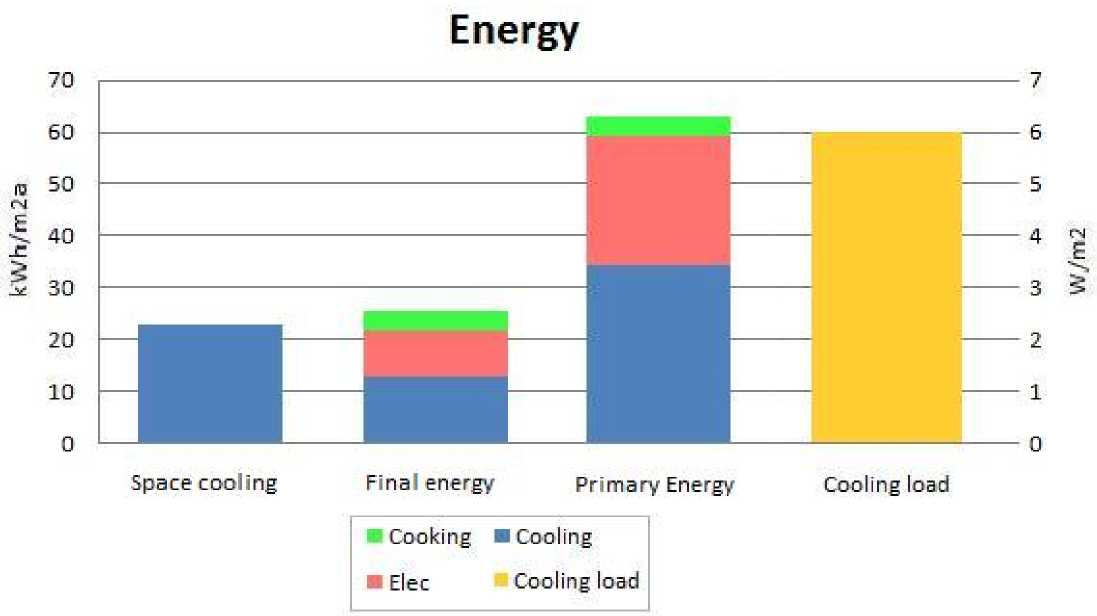


Figure 32: Energy Requirement of Passive House Case Study2

The primary energy values and final energy consist of energy from the cooling unit, household electrical appliances and cooking. All of these values were found using PHPP. In this case study, the primary value was around 63 kWh/m^{2}a so it met the passive housing standard requirement of 120 kWh/m^2. The cause of the reduction in primary energy was the decrease in cooling demand, as it did not need high cooling energy from cooling units.

The primary energy values depended upon the final energy values, as defined in the Passive House Case Study 1 section. However, the energy required for cooking and electrical household appliances did not change very much in the final energy and primary energy. In addition, the primary energy values affected the carbon emission value, which was around 16 kg/ m^{2}a.

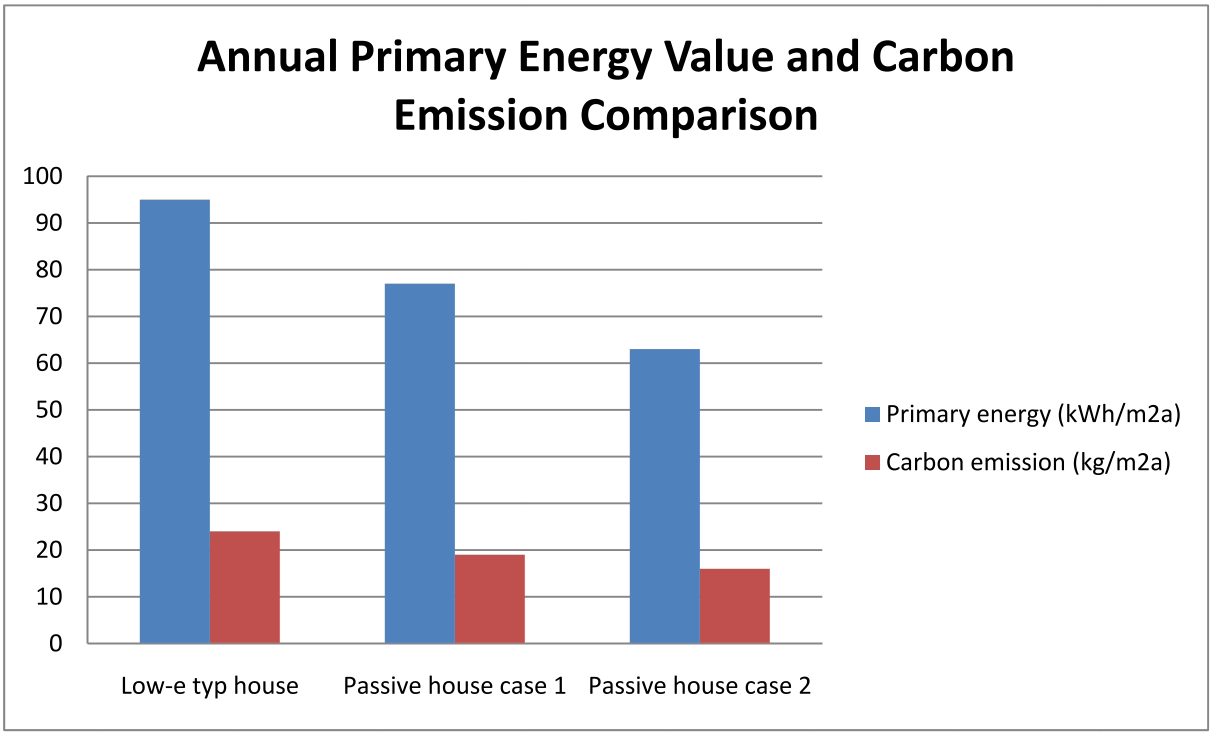


Figure 33: Annual Primary Energy and Carbon Emission Comparison three Case Studies

This graph illustrates the difference between the annual primary energy and carbon emissions of the three case studies (the simplified model, Passive House Case Study 1 and Passive House Case Study 2). All of these values were derived from PHPP. The blue column indicates the primary energy values; the Passive House Case Study 2 had the lowest value at around 63 kWh/ m^2a. The Passive House Case Study 2 saves the most primary energy - around 34% per year from the basic case model. Passive House Case Study 1 saved around 20% primary energy annually compared with the typical house. The annual carbon emission of Passive House Case Study 2 was reduced by 33% compared with the low energy house in Thailand, whereas Passive House Case Study 1 saved 20 %.

It could be concluded that this Passive House Case Study had the lowest primary energy value due to it having the lowest cooling demand of all three case studies. Moreover, the primary energy in this case was 63 kWh/ m^2a.

5.5.5 Summary

All the results of this case study were PHPP calculations and the building structure was modified from the typical house. However, the criteria of this modified model were the same as for Passive House Case Study 1; the only important parameter that was changed was the cooling set point temperature. The temperature was changed from the 25°C used in Passive House Case Study 1 to 28°C, as this was considered the comfortable temperature for Thai people (Rungsiraksa, 2006). Thus, the results of this case study are as follows:

- 23 kWh/ m^{2}a of cooling demand
- 63 kWh/ m^{2}a for primary energy consumption
- 6 W/ m^2 for cooling load
- 0.6 h^{-1} for pressurisation test result
- 16 kWh/ m^{2}a of carbon emission

Year of Construction:	2009				
Number of Dwelling Units:	1		Interior Temperature:	28.0	°C
Enclosed Volume V_e:	310.8	m³	Internal Heat Gains:	1.3	W/m²
Number of Occupants:	1.9				

Specific Demands with Reference to the Treated Floor Area

	Applied:	Monthly Method	PH Certificate:		Fulfilled?
Treated Floor Area:	67.0	m²			
Specific Space Heat Demand:	0	kWh/(m²a)	15	kWh/(m²a)	Yes
Pressurization Test Result:	0.6	h⁻¹	0.6	h⁻¹	Yes
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	63	kWh/(m²a)	120	kWh/(m²a)	Yes
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):		kWh/(m²a)			
Specific Primary Energy Demand Energy Conservation by Solar Electricity:		kWh/(m²a)			
Heating Load:		W/m²			
Frequency of Overheating:		%	over 28	°C	
Specific Useful Cooling Energy Demand:	23	kWh/(m²a)	15	kWh/(m²a)	No
Cooling Load:	6	W/m²			

Figure 34: Verification of Passive House Case Study 2 at 28°C

It can be concluded that this cooling demand did not meet the passive housing standard because it was over 15 kWh/ m^{2}a, whilst the other results did meet the requirements. Thus, this passive house model was not effective in a tropical climate, although this cooling demand nearly approached the passive house standard requirements. The climate condition was one important parameter impacting all of these results. However, when comparing the cooling demand, primary energy value and carbon emissions with the typical house model, it successfully decreased the household energy consumption in the tropical climate.

The next section discusses the most effective factor of passive housing design to reduce household energy consumption. These factors include insulation, shading, window glazing and frames and the ventilation system. All of these will be compared to show their relative effectiveness in passive house design.

5.6 Effective factors for passive housing design

This section examines the most affective factors of passive housing modification. This simulation was placed on the typical housing model and the passive housing model in Case Study 2 because both used the same cooling set point temperature. This experiment utilised the PHPP software as a tool to design and determine all of the results. This simulation can be divided into three parts: insulation, windows and shading and ventilation.

For the methodology of this experiment, the simplified model was modified to become a passive house model by developing only one part. The other parts were still based on the basic case model criteria. Thus, the most efficient factor of this passive house modification in the tropical climate can be assessed.

5.6.1 Construction

Normally, the development of construction includes integrated insulation, change of window glazing and frame and increased of shading. This case used the typical low energy efficiency house as a basic case model and each part was modified individually while the other sections remained based on the simplified model.

5.6.1.1 Insulation

The first recommendation of the Passive House Institute for developing a building into a passive house was to add insulation to the exterior surfaces of the building elements (roof, walls and floor). The following table presents a list of the U-value and thickness for each building assembly of the typical house and passive house model. All of these values were calculated by PHPP and based on the passive house and typical house models, as per the previous discussion.

Building Assemblies	U-value of typical model (W/m^2K)	Thickness of typical model (cm.)	U-value of passive house model case 2 (W/m^2K)	Thickness of passive house model case 2 (cm.)
Exterior Walls	0.552	22	0.108	39
Roof	0.166	26.2	0.100	31.2
Ground Floor	1.153	35	0.118	42.5

Table 19: U-values and Thickness of Building Assemblies of Typical House Model and Passive House Model

This table shows the U-value and thickness of each building assembly in the typical housing and passive housing models. After adding the insulation layer to the exterior surfaces, the typical model has the same criteria as Passive House Case Study 2. Meanwhile, the types of window, shading and ventilation systems were still the same as the typical model. The cooling demand was reduced from 80 kWh/ m^2a to 50 kWh/ m^2a compared to the simplified model, as shown in Figure 35. Moreover, the maximum cooling load and primary value moderately fell to 13 W/ m^2 and 75 kWh/ m^2a respectively, while the frequency of overheating at 28°C was still the same (100%).

In order to assess the effectiveness of the insulation strategy, this simulation needed to vary the U-value under the standard of passive housing. The U-value of exterior surfaces according to the passive house standard needed to be in the range of 0.1 to 0.15 W/m^2K. Thus, the U-values of the this model varied in a range of passive housing standard U-values. PHPP determined the results of the cooling demand, cooling load and primary energy value. Consequently, all of these results were not significantly different due to the small possible range of passive house standard U-values.

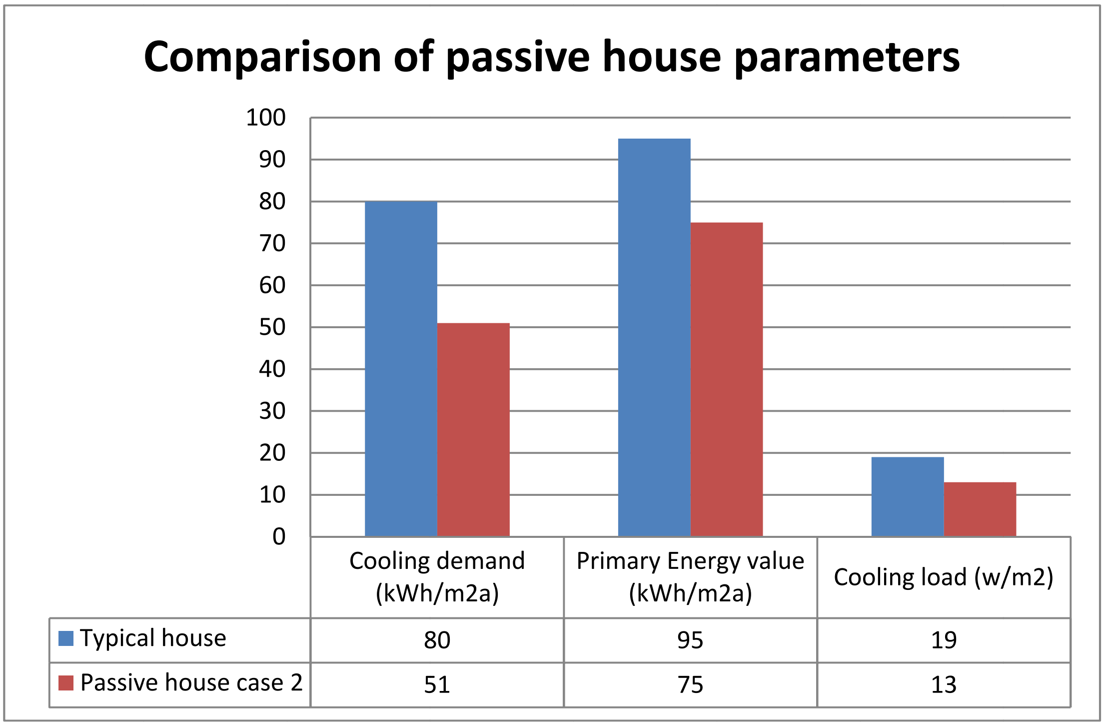


Figure 35: Passive House Parameters Comparison Following Insulation Strategy of Passive House Case Study 2

It can be seen that the integrated insulation significantly influenced the passive house modification. As shown above, the cooling demand declined by 36% and the primary energy value reduction by 21%. There was only 5% difference in the cooling demands between the maximum and minimum U-value variations and only 3% primary value alteration. Finally, adding insulation was one important strategy to optimise in passive house modifications in the tropical climate.

5.6.1.2 Window & Shading

This section would examine the effectiveness of window and shading strategy in the passive house modification. A typical house in Thailand has single glazed windows and a metal or wood frame, as previously discussed. To evaluate the efficiency of the windows and the shading strategy in this scenario, the types of glazing and frame were changed with the increase of shading under the criteria of Passive House Case Study 2.

To evaluate the potential of the windows and shading strategy, the types of glazing and frame were altered while shading and other strategies remained the same, as per the simplified model. Afterwards, the shading was added according to the Passive House Case Study 2 standards, whereas the window frames and glazing and other strategies were based on the typical house model criteria. This was done to prove the efficiency of shading. Finally, shading and windows were modified as Passive House Case Study 2 criteria and then the competence of both was estimated.

Table 20 shows the data of the window and shading norms in the simplified model and Passive House Case Study 2. All of these results were certain conditions from PHPP calculations and the data was provided by PHPP as well

Orientation of window area	U-value of typical house (W/m^2K)	G-value of typical house (%)	Reduction factor for solar radiation of typical house	U-value of passive house case study 2 (W/m^2K)	G-value of passive house case study 2 (%)	Reduction factor for solar radiation of passive house case study 2
North	4.71	87	0.07	0.79	52	0.005
East	4.97	87	0.10	0.8	52	0.01
South	5.32	87	0.14	0.8	52	0.02
West	5.89	87	0.09	0.8	52	0.01
Average	5.10	87	0.10	0.8	52	0.01

Table 20: Window Performance of Typical House Model and Passive Houses following Window and Shading Strategy

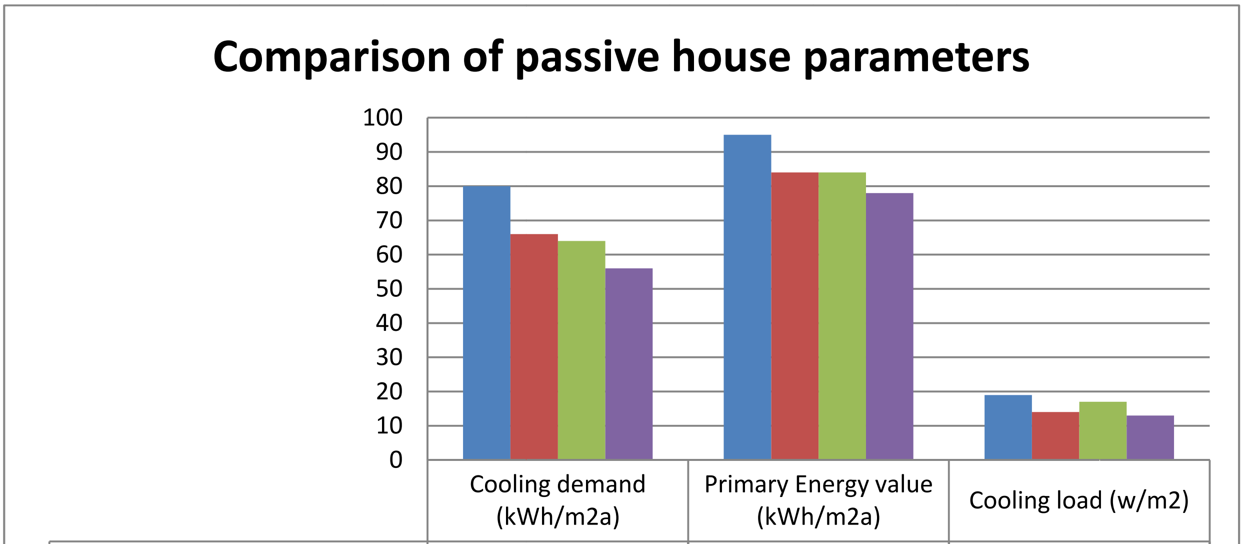
As per the previous discussion, the types of window glazing and frame were changed from single plane glazing and metal and wood frames to low-e glazing and Starz softline Iv92 frames, pursuant to the Passive House Case Study 2. The U-values of single glazing was 0.58 W/m^2K, 2.5 W/m^2K and 5.5 W/m^2K of wood and metal frames, respectively, while the U-value of the low-e glazing was 0.51 W/m^2K and 0.68 W/m^2K of the passive housing frame. All of this data was given by PHPP and the results of the window development were determined by this tool as well. Consequently, cooling demand was moderately reduced to 66 kWh/m^2a. There was a slight decrease of primary energy to 84 kWh/m^2a and 14 W/m^2 of cooling load, as shown in Figure 36. The cause of this reduction was the lower U-value from changing the glazing and frame types, which led to a decrease in the window heat gains by conduction. However, the frequency of overheating at 28°C was still 100% without mechanical ventilation.

Aside from the window modifications depending on the Passive House Case Study 2 criteria, the type of window glazing varied between double and triple glazing to assess the differences between the commonly used passive house glazing methods. As a result, the cooling demand after using the double glazing declined slightly by 8% and by 18% with triple glazing compared to the basic case model.

It can be concluded, with regards to the window glazing and frame strategy, that cooling demand decreased moderately by 20% with the low-e glazing used in Passive House Case Study 2. While the cooling demand under the double and triple glazing conditions was slightly lower; around 8% and 18% respectively. Therefore, the U-values of the window glazing and frames were important factors in developing a passive house.

For the shading strategy, some shading was increased under the Passive House Case Study 2 criteria while the window modification was optimised; consequently, the amount of solar radiation was considerably reduced due to the sunlight protection. The G-value decreased due to a change of window frames (as shown in Table 20) that led to a solar heat gains reduction as well. As indicated by the results of the PHPP computerisation, the cooling demand after adopting the window and shading strategy fell by 30% while the primary energy value declined by 20% (as illustrated in Figure 36) when compared with the typical house.

However, only applying the shading strategy led to a cooling demand reduction of 20% and a primary energy reduction of 12%. The following graph shows the comparison of the passive house parameters under the change of window and shading conditions.



	Cooling demand (kWh/m2a)	Primary Energy value (kWh/m2a)	Cooling load (w/m2)
Typical house	80	95	19
Window strategy under Passive house case 2	66	84	14
Shading strategy under passive house case 2	64	84	17
Window and shading strategy under passive house case 2	56	78	13

Figure 36: Passive House Parameters Comparison Following Window and Shading Strategy of Passive House Case Study 2

It could be concluded that adopting window and shading strategy could reduce cooling demand around 30% that was a significant reduction. In addition, using only window strategy could decrease cooling demand by 20% that was the same as applying only shading strategy in the Passive House Case Study 2. While other parameters did not vary a lot in this condition, so it could be said that this strategy was effective for passive house development as it could radically reduce solar heat gains and window transmission heat gains that were the important factors of cooling demand.

5.6.2 Ventilation system

The ventilation was a complex system in the passive housing model. It was also a parameter in creating a comfortable interior environment. To evaluate the potential of a ventilation system under the passive house modification, the ventilation of the basic case model was developed to match that of Passive House Case Study 2. The development of this system can be divided into two parts: natural ventilation and mechanical ventilation. All of these results were based on PHPP computerisation and ventilation system designs drawn from the Simplified Model and Passive House Case Study 2.

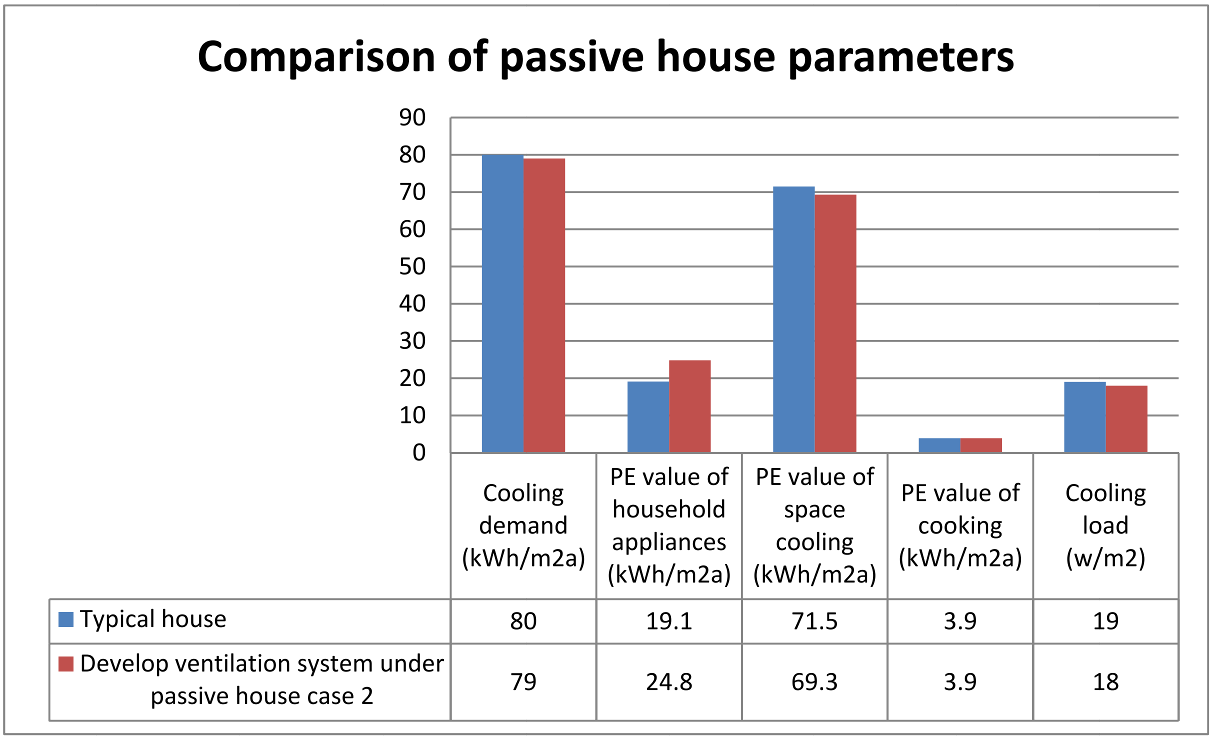
5.6.2.1 Natural ventilation

In the basic case model, there were both natural and cross ventilation systems. These were designed to generate a good internal air quality under the passive housing standards. The average air change rate of the simplified model was around 0.62 h^{-1}, determined by PHPP. This ventilation system was then developed under the Passive House Case Study 2 criteria: the cross ventilation was eliminated and the width of opening windows was reduced because this led to high ventilation heat gain, so the average air change rate became 0.22 h^{-1}. However, the cooling demand did not decrease because this factor slightly affected the ventilation heat gains and cooling demand.

5.6.2.2 Mechanical ventilation

In order to comply with the passive house standards, mechanical ventilation was required. The heat recovery was integrated to the passive house. The model and operation system of this ventilator was the same as in Passive House Case Study 2. Thus, the average air change rate of the mechanical ventilation increased to 0.38 h^{-1} to the ventilation system so it could affect the ventilation heat gain. All of these results were based on PHPP.

An important parameter that was required according to passive house standards was the pressurisation test of average air change rate at 50 Pa pressure difference. The rate needed to be less than 0.6 h^{-1}, thus this value was changed because the simplified model had 13 h^{-1} (the usual value of a house). Pursuant to the standards of passive house, the average air change rate at 50 Pa was reduced to 0.6 h^{-1} but it did not affect the cooling demand. This influenced the infiltration rate of the building. This rate decreased from 1.14 h^{-1} to 0.05 h^{-1} for annual demand; all of these figures were based on PHPP calculations. However, after the HRV was installed, the cooling demand reduced slightly while primary energy increased due to the addition of mechanical ventilation. The heat recovery efficiency was 88%, as mentioned in the previous ventilation modification section. If the heat recovery efficiency varied, there was not a big difference in the cooling demand, the primary energy value varied depending on the electrical efficiency of the HRV. The following graph shows the comparison between passive house parameters in the Typical House and the Passive House Case Study 2 following the ventilation system modification.



	Cooling demand (kWh/m2a)	PE value of household appliances (kWh/m2a)	PE value of space cooling (kWh/m2a)	PE value of cooking (kWh/m2a)	Cooling load (w/m2)
Typical house	80	19.1	71.5	3.9	19
Develop ventilation system under passive house case 2	79	24.8	69.3	3.9	18

Figure 37: Passive House Parameters Comparison Following Ventilation Strategy of Passive House Case Study 2

Figure 37 shows the comparison of passive house parameters between the ventilation system of the simplified model and the Passive House Case Study 2, by PHPP calculations. The cooling demand of the Passive House Case Study 2 was reduced by less than 1% after the integration of mechanical ventilation and the modification of the natural ventilation system. However, the primary energy value for the household appliances increased by 20% because of the heat recovery ventilation deployment, while the primary energy value for the space cooling decreased a little due to cooling demand reduction.

It can be concluded that the modified ventilation system does not significantly affect the cooling demand when compared with other factors, such as integrated insulation and a window and shading strategy. The important parameters of developed ventilation system influencing the cooling demand were the annual cooling degree hours and the effective air change rate, both related to the ventilation heat gains. In this instance, the annual cooling degree hours were the same in both case studies of construction development.

5.6.3 Conclusion

The aim of this study was to identify the most effective factor of passive housing modification; the insulation strategy has been ascertained to be highly effective, followed by the window and shading strategy and then the ventilation system. However, the passive house modification could not insert too many insulation layers within the exterior building surfaces. Therefore, the insulation could be deployed moderately and kept to a U-value under the passive housing standards. The list below details the percentage of effectiveness for each strategy, depending upon the cooling demand reduction:

- 36% for insulation strategy
- 30% for window and shading strategy
- 1% for ventilation system

Another important parameter influenced by the modification was the primary value, which was reduced under the insulation condition and the window and shading strategies. The primary energy value under the ventilation system condition increased due to the addition of mechanical ventilation, as discussed before. The total carbon emissions also varied under the primary energy value so if the primary energy value had a high rate, the carbon emissions would be high as well.

Chapter 6: Conclusion and recommendations

This chapter summarised all the performances of typical low-energy house model and both passive house models under different comfort temperature conditions. The first passive house case study had 25°C of comfort temperature following passive housing standards and 28°C of Thai comfort temperature in the second case study.

6.1 Conclusion of typical house model in Thailand

The simplified model was created by the common low-energy house in Thailand so the construction details such as materials and types of window of this model usually used in Thailand. The ventilation system operated in this case study was cross ventilation and natural ventilation during the daytime, and the air conditioner was used at the night time. The set point temperature of the basic case model was 28°C as comfortable temperature for Thais. All of these criteria specified in the PHPP software. The electrical household appliances and cooling units were calculated by PHPP to determine the primary energy value. After creating this model, the performance of this house could be shown as the list below.

- 80 kWh/ m^2a of cooling demand
- 95 kWh/ m^2a for primary energy consumption
- 19 W/ m^2 for cooling load
- 13 h^{-1} for pressurization test result at 50 Pa
- 23.7 kWh/ m^2a of carbon emission

As can be seen, the cooling demand of the low energy house model was far away from the passive house standard of 15 kWh/m^2a. The causes of high cooling demand were the high rate of heat gains by conduction and solar heat gains. The significant parameters leading to the change of transmission heat gains were cooling degree days, U-values of building fabric and surface areas whereas solar heat gains depended upon the solar radiation, reduction factor, glazing area and G-value. All of these parameters were related to insulation, window and shading design.

Other parameters could meet standard of requirements. A value of pressurization test result was higher than the requirement, but this value was the average value of a typical house. PHPP determined the primary energy value of this case study that was based on household electrical appliances consumption, space cooling consumption and cooking. The variation of cooling demand also influenced to the primary energy value because the energy of space cooling consumption was related to cooling demand.

As a result of the monthly method calculation of PHPP software, the highest cooling demand was in April (summer) and its lowest was in winter. It could be concluded that a low-energy house in Thailand could not meet passive house standard requirements under Thais comfort temperature condition. However, this case study could be improved to meet the passive house criteria by integrated insulation, shading suitable windows and proper ventilation system.

6.2 Conclusion of passive house model in Thailand

In order to examine the potential of passive house in the tropical climate, this passive house case study was developed from the simplified model. The building construction and systems in the house were improved following passive housing standards. In addition, PHPP could determine all the results to evaluate the efficiency of passive house in the hot and humid climate.

The standard strategy of passive housing development consisted of integrated insulation, shading, suitable window and ventilation system. In this case study, most strategies were utilised. In this research, there were 2 case studies of passive house model; namely Passive House Case Study 1 and Passive House Case Study 2. The difference of both case studies was the interior set point temperature. Passive House Case Study1 had 25°C for cooling set point temperature that was based on passive house standards. While the Passive House Case Study 2 set interior temperature at 28°C that was Thai comfort temperature. The design of both passive houses still had the same criteria to assess their efficiency in the tropical climate condition.

To insulate the insulation in the building fabrics, U-value and thickness of building elements were considered. The U-value of each construction depended on thermal conductivity and thickness of material in each layer. However, there was a limitation of U-value under standards of passive house; the U-values needed to be in a range between 0.1-0.15 W/m^{2}K. The effect after insulation was the reduction of transmission heat gains of each exterior construction. The important parameter that influenced the transmission heat gain variation was the cooling degree hours related to the cooling set point temperature. As a result, heat gains by conduction played an important role in the Passive House Case Study 1 as there was a high rate of this factor whereas there was a little effect in the Passive House Case Study 2. Although both passive house case studies were designed in the same criteria, rates of transmission heat gains were different due to set point temperature.

The window and shading strategy, adopted could also reduce solar heat gains of passive house. Types of window glazing were altered to be low-e glazing and the Straz softline Iv 92 window frame used. This decreased the transmission heat gains of window as average U-values reduced. Meanwhile, window heat gains by conduction of both passive house case studies had different rate due to the different set point temperatures. Consequently, the Passive House Case Study 2 had lower transmission heat gain of windows than the Passive House Case Study1. In addition, the addition of shading and change of window types also reduced solar heat gains because the reduction factor and g-values of frames declined as well. In these passive house case studies, more trees have been included to reduce solar gains, as one shading strategy. However, both passive house case studies had the same rates of solar heat gains since this did not depend on set point temperature.

For the ventilation system in both case studies, the mechanical ventilation needed to be deployed. The Passive House Case Studies integrated HRV to improve some air quality and to run all day. The natural ventilation was optimized in this building during daytime; at the night time, the air conditioner was turned on. The model and specifications of the air conditioner was the same as the basic case model. HRV specifications were given by PHPP as previously discussed. The modification of the ventilation system led to a reduction in ventilation heat losses when compared with the simplified model due to the reduction of average air change rate and cooling degree hours. However, both case studies had different ventilation heat gains rates because the set point temperatures were dissimilar. This also influenced cooling demand variation and change of primary energy. The following table was all of the results of both case studies in evaluating the efficiency of passive house in the tropical climate.

Verifications	Passive House Case Study1	Passive House Case Study 2
Annual cooling demand	46 kWh/ m^2	23 kWh/ m^2
Annual primary energy consumption	77 kWh/ m^2	63 kWh/ m^2

Maximum cooling load	8.5 W/ m^2	6 W/ m^2
Pressurization test result	0.6 h^{-1}	0.6 h^{-1}
Annual carbon emission	19.3 kWh/ m^2	16 kWh/ m^2

Table 21: The Result of Both Passive House Case Studies

The performance of both passive house case studies gave a conclusion that the passive housing standard requirements could not be met for the reason that each exceeded the standards of cooling demand of 15 kWh/ m^2a. The main important parameter of the Passive House Case Study 1 to vary cooling demand was the transmission of heat gain of building elements whereas internal heat gain played a key role in the Passive House Case Study 2. The primary energy value was altered under cooling demand variation. However, primary energy value of both case studies could meet passive housing standards with 120 kWh/ m^2a; both cooling loads also met the requirement that was below 10 W/ m^2.

In assessing the qualifications of passive housing design in the tropical climate, the design of passive house could not reach the passive housing standard especially Case Study 1 in which the set point temperature was based on maximum interior temperature of passive housing standards. While cooling demand of passive house case study 2 could not meet the requirements as well, its rate was not too far away from the standards as shown in the Table 21. Therefore, it could be said that the passive house was not fully achievable in Thailand but its performance was so satisfactory when compared with the basic case study as it could significantly reduce cooling demand.

In examining the most efficient feature of passive housing design, additional insulation was the most useful. It was possible to reduce cooling demand by 40% because the most important need for cooling was to offset the transmission of heat gains. The insulation could reduce heat gains by conduction effectively; higher specification windows and shading also reduced the solar gains through windows. Increased insulation had a greater impact than change to the ventilation system. However, most of these strategies improved the passive housing performance. The following graph showed some prices of energy consumption and carbon emission comparison between 3 case studies and general houses in Thailand as a result of PHPP calculation.

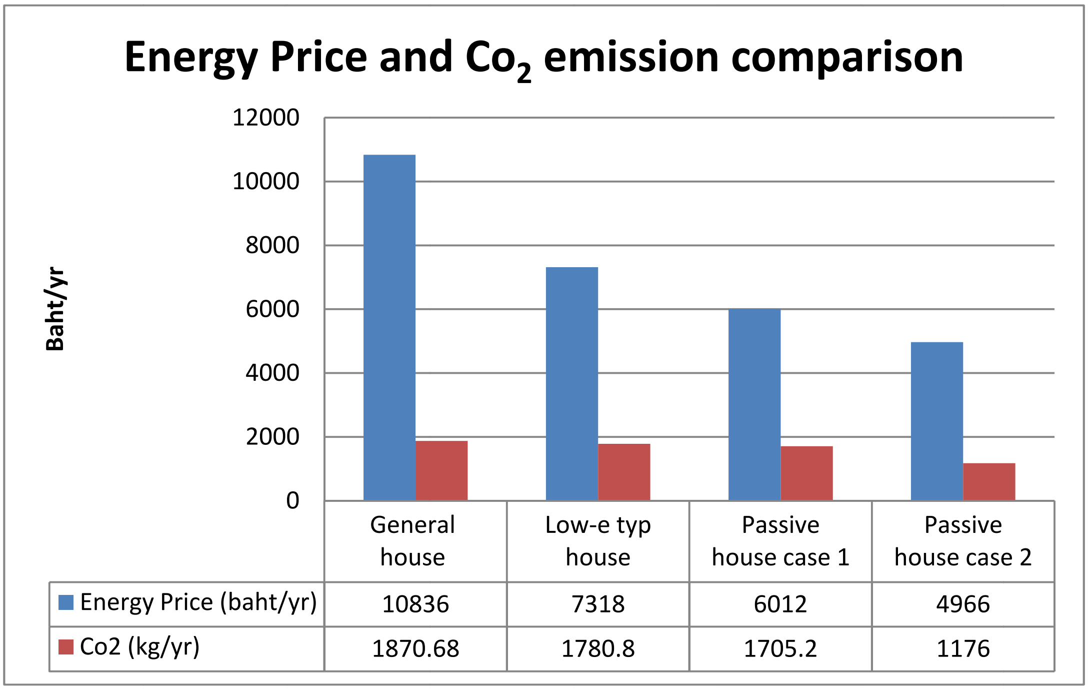


Figure 38: Comparison of Annual Energy Consumption Price and Carbon Emission between four Case Studies.

It can be seen that in the recent years, general houses in Thailand usually consumed some energy around ฿10,000 per year (£175/year) reported by Thailand National Statistical Office (National Statistical Office of Thailand 2004). The low energy houses could save money around ฿3000/year (£50/year) while Passive House Case Study1 and Case Study 2 can save more money by 50% and 54% respectively when compared with general houses. Moreover, the percentage of saving energy price was around 20% of passive house case study 1 and 32% of passive house case study 2 compared with low-e typical housing model. Moreover, the Passive House Case Study 2 could save more carbon emission around 37% while 8% of the Passive House Case Study1 when compared with general houses in Thailand.

Therefore, it could be said that the implementation of the passive house was not fully successful in the tropical climate, but it gave satisfactory results when compared with typical house model. The cooling demand decreased to nearly meet the standard of passive house requirements while cooling load and primary energy value could meet the established conditions. This building could also have significant energy cost saving. However, the increase of high shading caused an unacceptable of luminance levels.

6.3 Limitation of PHPP software

The PHPP software was created by Passive House Institute in German and this software is a tool to design the passive house worldwide. However, this software is quite complex and without clear explanation of cooling demand calculation and other section involving cooling areas.

In addition, there were no good details in some worksheets of PHPP. The PHPP manual gave only some simple definitions in the cooling section such as cooling unit worksheet, ventilation worksheet and cooling load worksheet. It seems that this PHPP is suitable to design the passive house in Europe where the climate is cold and warm and not fit for the tropical climate. Some details were required in PHPP software and the system was not visibly defined.

Thus, it can be concluded that there are many limitations of PHPP software used as a tool to design the passive house in the hot and humid climate. The information in PHPP manual is not precise enough, especially in cooling part, and some explanations in this software are in German.

6.4 Recommendation and Future work

The thesis forms a good starting point of passive housing design in the tropical climate and it can be applied to other types of building such as the 2-storey detached house or high rise building.

In the future, the modelling of ventilation system and cooling units should be improved this system. The investigation on the ventilation system could be further improved. Additionally, new strategies could be adopted to cool any building; for example, using traditional roof to get a good air flows in the building to cool the house. Further investigation in renewable energy is recommended, for example installing solar cells or biomass energy applies to a passive house in the tropical climate that can reduce the primary energy value, and can prevent more carbon emission. Moreover, the financial and environment evaluation can be analyzed more.

From this research, it is recommended that the characteristic of materials, cooling units and mechanical ventilator deployed in the passive housing design should be defined in PHPP manual. Moreover, the details of electrical household appliances and some parameters should be explained more. It needs to take more time to be familiar and understand PHPP acutely.

Finally, the implementation of passive house design in the tropical climate gave a satisfactory result in this research although it could not fully meet the passive house standards. The performance of passive house can be improved more in the future by applying new approaches.

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