OPTIMAL SOLAR DESIGN BASED ON 3D BIM MODEL ANALYSIS FOR ZERO ENERGY RESIDENTIAL BUILDING IN THE TROPICS

Dissertation Abstract

OPTIMAL SOLAR DESIGN BASED ON 3D BIM MODEL ANALYSIS FOR ZERO ENERGY RESIDENTIAL BUILDING IN THE TROPICS

Division: Environmental Design

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Abstract

This PhD research aims to analyse the optimal solar design in the tropical area by employing Building Information Modelling (BIM) to achieve zero energy residential building. This research contributes by presenting building parameters consideration for optimal solar design and providing a novel model of a second skin photovoltaic roof for optimal photovoltaic energy generation and building’s thermal performance that is suitable for the tropical area.

Daylighting and photovoltaic energy generation are chosen the study focus with the consideration of interior thermal condition. The appropriate daylighting design strategies for the tropical equatorial region was explored by measuring the daylighting condition in the existing vernacular houses. Meanwhile, the potential of photovoltaic application was assessed by the capacity of available surface area of residential building in providing an adequate amount of electricity for future energy demand. This work is executed by 3D insolation colour rendering analysis to visualise the optimal placement of photovoltaic installation and to predict the generated energy from available surface of the building envelope. The potential photovoltaic is the can be. The optimal roof design which served for energy generation, as well as a thermal barrier of the building, is resulted from optimization of photovoltaic roof energy and thermal performance by using Revit solar analysis tools and Autodesk CFD.

This study revealed that daylighting design is always incorporated with thermal design by avoiding direct sunlight penetrating to the interior of the buildings. The potential of photovoltaic application in the tropical area is very promising where the available envelope area can produce energy for self-consumption and supply to the national grid. The proposed roof design of “Second Skin Photovoltaic Roof” has been proven to be effective in maintaining the internal thermal condition to be at least the same as the residential building without photovoltaic installation.

Keywords: BIM model-based analysis; Daylighting strategies; Energy performance; Photovoltaic optimal placement; Photovoltaic potential; Renewable energy generation; Residential building; Second skin photovoltaic roof; Solar Design; Thermal performance; Tropical area; Zero energy residential building.

1. Introduction

The phenomena of electrical energy scarcity are widely found in many tropical developing countries. This condition is in contrast with the solar potential in the Tropics with its high and uniformly distributed global irradiation along the year. Responding to the electricity crisis, the concept of zero energy building can be implemented in a residential building because the residential sector is recorded as one of the highest energy consumers in the tropical developing countries. Zero energy building is a concept that highlights different aspects of energy efficiency and energy generation to reach zero energy building. This goal can be achieved through passive and active solar design integrated into building design. Passive solar design harness solar energy and converting it into usable heat or light without active mechanical systems. For fulfilling the required energy for electricity, the active mechanical system is needed for converting solar energy into electrical energy which is called active solar design.

This PhD research aims to provide a recommendation for optimal solar design in the tropical area by employing Building Information Model (BIM) to achieve zero energy residential building. The study results may deliver contribution which related to optimal solar design considering zero energy residential building in the Tropics. This research is expected to deliver the contribution to the body of knowledge by 1) providing the optimal daylighting design strategy for residential building in the Tropics; 2) presenting building parameters consideration for optimal photovoltaic installation in the equatorial region that accounts for both self-shading of the building geometry and shading from adjacent structures; 3) providing an optimal roof design which addresses photovoltaic as a second skin roof for energy and thermal performance of building. Furthermore, this research will give benefit for urban planner, building designer, and policymaker by 1) providing a recommendation for appropriate photovoltaic system which is suitable to be used in the tropical residential building; 2) presenting a design recommendation for residential building installed photovoltaic which is useful for revising the building codes for energy conservation and sustainable development; 3) The method proposed in this study is advantageous in evaluating the potential of photovoltaic installation not only on the design stage of new buildings but also for existing buildings as well.

The main body of this dissertation is organised into four parts (*Figure 1.1*). The first discussion addresses for the evaluation of suitable daylighting design strategies for residential building envelope application in the tropical area. The second session is analysing the photovoltaic potential for the tropical residential building based on available surface area and projected future energy demand. After that, the discussion is moving forward to energy generation prediction based on optimal photovoltaic location on building envelope and the actual electricity consumption. Lastly, we proposed a new roof design that regarded photovoltaic as the second skin roof by optimizing photovoltaic roof energy performance and building thermal performance. The proposed model is addressed for the residential building located in the tropical warm and humid climate which is subjected to overheating in its indoor environment.

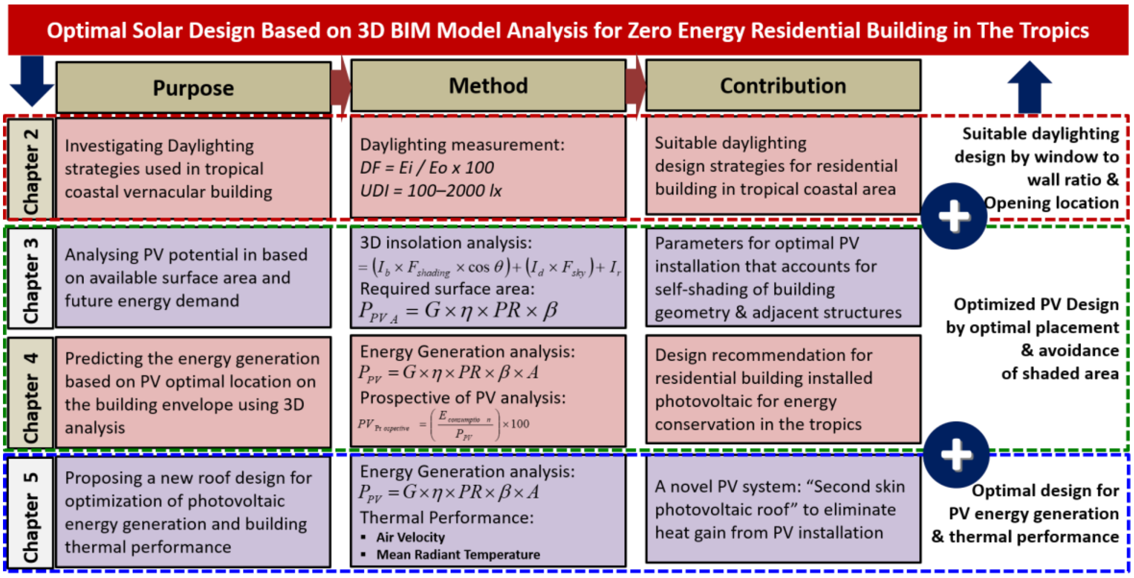

Figure 1.1. The Framework of Dissertation Research

2. Daylighting Strategies for Residential Building in Tropical Coastal Area

Chapter 2 is delivered to present the evaluation of daylighting design strategies that are appropriate for residential building in the tropical area. The daylighting condition was measured in three existing vernacular building in the tropical coastal area. The evaluation is made by considering several daylighting design parameters such as opening ratio, opening position, interior reflectance, and external and internal shading devices.

This study indicates that the target of better daylighting performance in the tropical coastal house is the guest room, where social activities held. Thereby, the openings were installed in two perpendicular or parallel walls in all sample houses (*Figure 2.1*). It leads to an excellent daylighting performance on all guest rooms. In contrast, bedroom received the least priority of daylight, because daytime activities are not held in the bedroom. This might be the reason for most of OWR and OFR in the bedroom are small. The opening to floor ratio (OFR) and opening to wall ratio (OWR) was the most influential design parameters in a daylit room. The study recommends that the ratio of 20% - 40% for both OFR and OWR to achieve the illuminance level 100 – 2000 lux and daylight factor more than 0.5 (*Figure 2.2*). The curtain and ray-band glass might be used to reduce the effect of glare on the side-lit room. The level of illuminance in the interior of the house can be enhanced if the use of curtain is not to be paired with a dark glass (i.e. ray-band glass) or curtain might be used at the clear glass window.

Figure 2.1 The Level of Illuminance and Daylight Factor in the Sample Houses

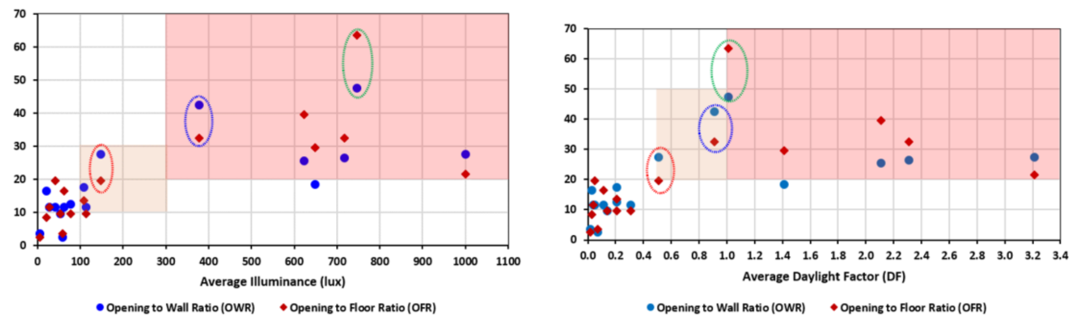

Figure 2.2 Opening Size vs Average Illuminance and Average DF

3. Photovoltaic Potential for Tropical Residential Building Based on Available Surface Area and Projected Future Energy Demand

Chapter 3 is addressed for discussion of photovoltaic potential analysis for its implementation on the envelope of the tropical residential building. The analysis performed based on the available surface area and future energy demand. This analysis demonstrated by utilising 3D BIM Revit colour rendering for presenting the incident solar radiation superimposing to the building envelope. Hence, the potential surface area for photovoltaic placement can be easily detected by the colour coded presentation.

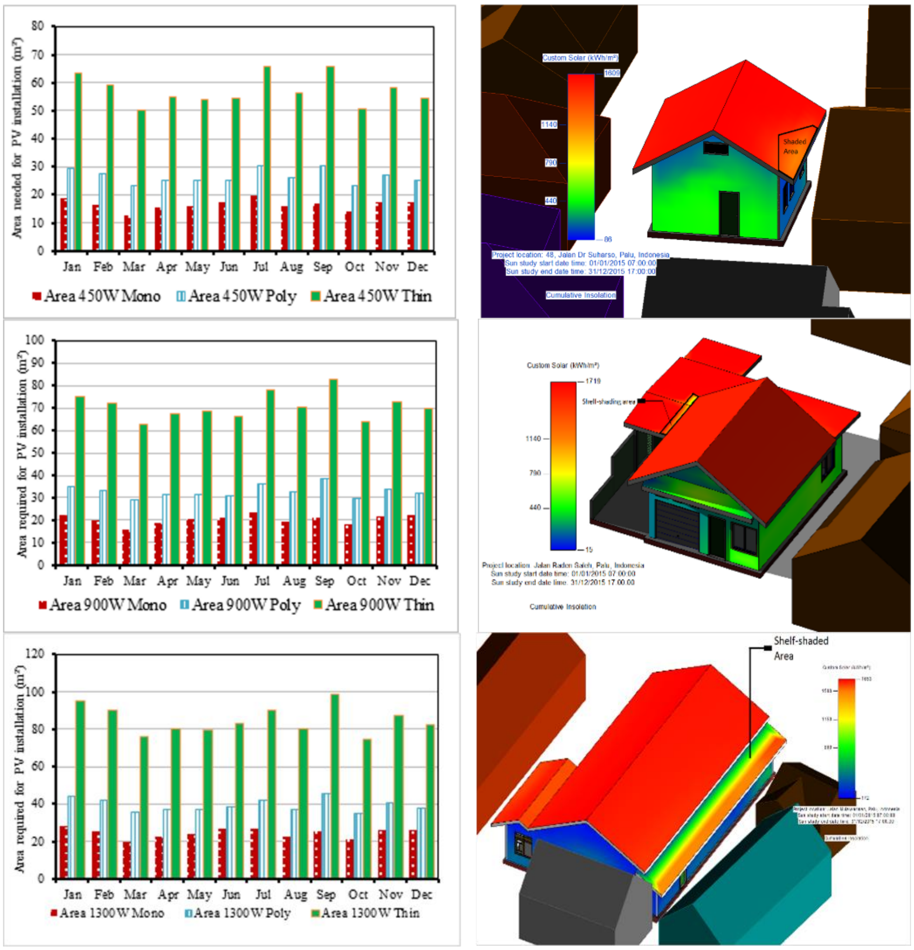

Figure 3.1 Required Area for Photovoltaic Installation on 450W, 900W, and 1300W Model (left) and Annual Insolation Mapped on Building Envelope (right)

The average electrical energy consumption from 836 households in Palu city Indonesia, within the period of one year was used in the evaluation of photovoltaic potential. The actual energy consumption from residential sectors was divided into five types represent installed electrical power capacity namely: 450W, 900W, 1300W, 2200W and 3500-6600W and will be associated with existing residential building in the study location that modelled in the BIM Revit. After that, we calculated the future energy demand based on the 10 years residential sectors energy consumption and predicted the required building envelope area to suffice the residential building energy demand for future energy security.

The result indicates that for optimal energy generated, the shaded area by adjacent building can be avoided for the photovoltaic placement (*Figure 3.1*). Therefore, the net area used for photovoltaic installation will be reduced. With the remain net surfaces area, this model still surpasses the required area to serve the average energy demand. The roof surfaces alone is more than enough to suffice their own future energy demand. Therefore, photovoltaic mounting on residential building envelope is generally very potential to supply future energy demand.

4. Energy Generation Prediction Based on Photovoltaic Optimal Location on Building Envelope and Actual Electricity Consumption

Chapter 4 designed for predicting energy generation that can be harvested by residential building envelope in the tropical area based on the optimal placement of photovoltaic installation to supply the actual energy consumption and future energy demand. The optimal location of photovoltaic panels and potentially shaded areas are identified by superimposing the estimated solar energy on the building envelope and visualising the result in 3D BIM Revit models.

These models were constructed based on the existing residential building in the study location. The built-in Revit solar analysis tool was used to visualise incident solar radiation (insolation) that falls onto the building envelope. The amount of insolation is then used to compute the generated energy that can be produced by each model. This insolation data was then plotted into the Cartesians diagram to analyse the building orientation for optimal photovoltaic energy generation. The generated energy is then used to evaluate the prospective photovoltaic implementation by comparing the result with the actual energy consumption.

The study results showed that implementation of photovoltaic on the residential building has a huge potential in tropical areas. The roof of the residential building can be covered by PV for the high and relatively constant amount of solar radiation falling in this area throughout the year. The walls of the building oriented to the East and West also had the potential to harvest electrical energy (*Figure 4.1*). An additional requirement for wall installed PV is the surrounding obstructions like buildings and trees and provision of space for solar radiation access to the walls would need to be considered. For designing a new building for optimal PV energy generation, a simple roof design is highly recommended and a building form that avoids potential self-shading. The larger wall areas could be oriented to the East and West as an additional area for PV Installation; however thermal loading to the dwelling would need to be considered.

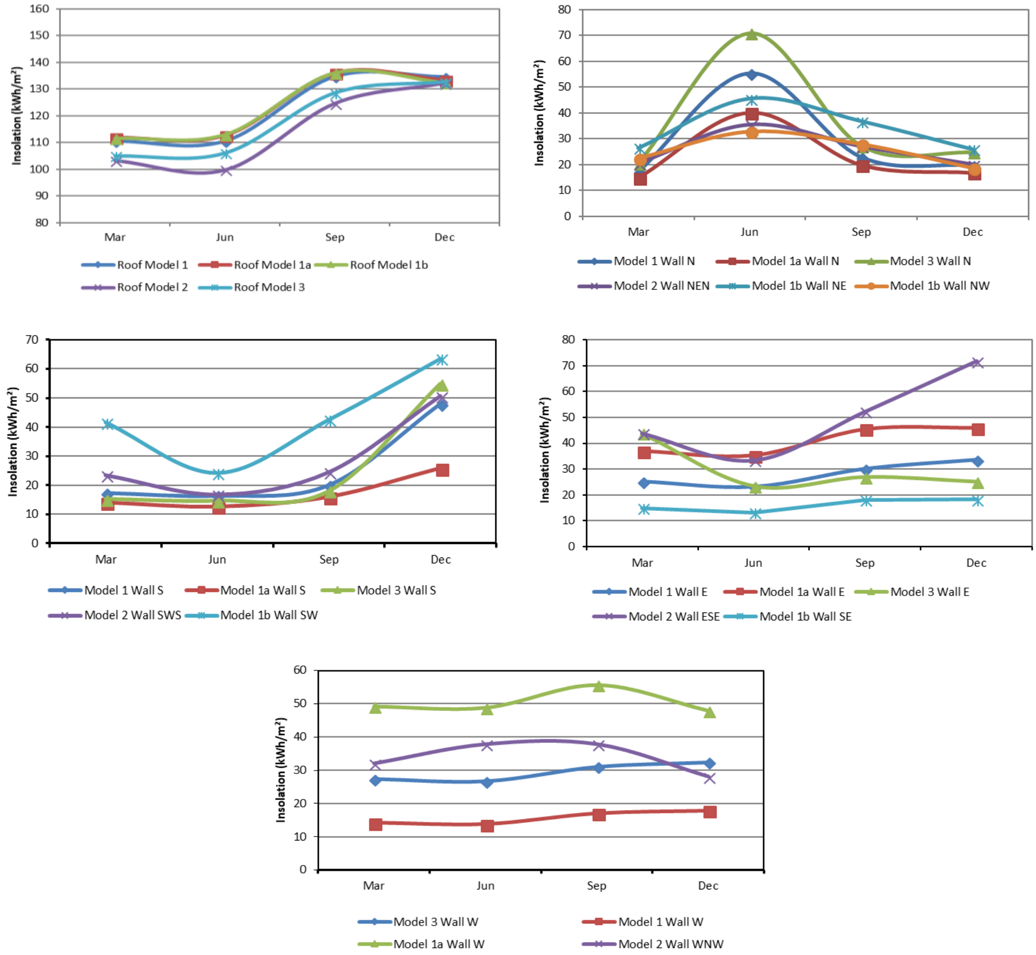

Figure 4.1 Insolation Gain by Building Envelope

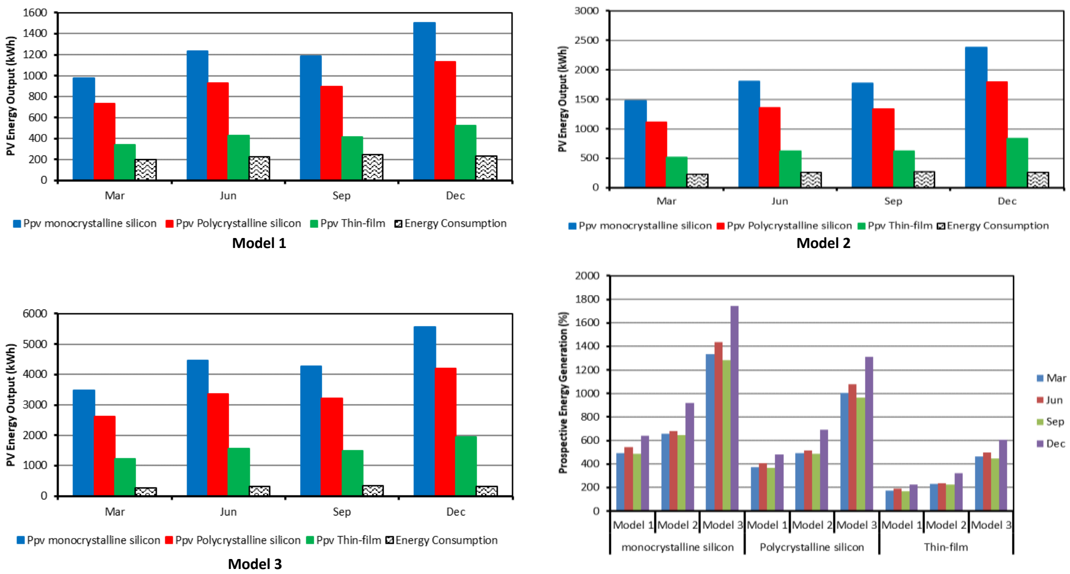

Figure 4.2 Photovoltaic Electrical Energy Generation by the three Models and their Prospective of photovoltaic Installation

PV energy generation offset compared to current energy consumption exhibited a promising availability of electrical energy even when considering future demand growth. Energy generation offset given by three types of PV technology ranged from 172% - 1,744% against recent actual energy consumption (*Figure 5.2*). These conditions might vary due to photovoltaic temperature effects and weather dynamics especially under a cloudy sky and rainy days. The recent development of photovoltaic technology with an efficiency of up to 40% offers potential greater promise of electrical energy security in the future.

5. Optimal Roof Design for Photovoltaic Energy Generation and Building Thermal Performance

Chapter 5 is delivered to present the evaluation of appropriate photovoltaic technology that is suitable to be implemented on the residential building's envelope in the tropical area. Furthermore, this chapter is focused on the development of optimal roof design in the tropical area which considering photovoltaic as the second skin roof. The optimization was demonstrated by accounted energy generation of photovoltaic installation as well as decreasing the heat gain effect from photovoltaic placement to the indoor environment. The models were constructed in BIM Revit and optimised by considering energy and thermal performance. Revit Solar analysis tool was utilised for energy performance analysis including total annual insolation, energy generation, payback period, and energy savings.

To analyse thermal performance of the roof design, Autodesk CFD Revit add-ins was used for visualizing the air velocity and mean radiant temperature in the building interior (*Figure 5.2*). The optimization resulted from the two analyses will deliver the optimal model in energy and thermal performance of roof design which is suitable for tropical warm and humid climate. The parameters included in the analysis are the roof geometry (flat roof, shed roof, hip roof and gable roof), roof inclination angle (0º, 5º, 10º, 15º, 20º, 25º, and 30º), roof area, and the height between the roof skin construction.

The optimal roof design resulted by this study is then proposed as a new novel photovoltaic system which integrates the advantage of building attached photovoltaic (BAPV) system and building integrated photovoltaic (BIPV) system and further called as "Second Skin Photovoltaic Roof" which regarding photovoltaic as the second skin of the roof system.

The Result of the study reveals that monocrystalline silicon produced the highest energy yield (*Figure 5.1*). However, it is very affected to the rise of photovoltaic operative temperature which impacted to a drop in its efficiency (Chow, Hand, and Strachan 2003; Ye et al. 2013). Polycrystalline silicon can be considered as the best choice. It provided higher energy generation compared to amorphous silicon and less affected by the rise in temperature (*Figure*

5.2). This result is confirmed by Saber et al. (2014) where the polycrystalline silicon performed better than monocrystalline silicon in the tropical area.

For the energy performance, the flat roof with 5º inclination angle is considered as the best choice. However, when the thermal performance comes as the first consideration, the gable roof with 30º inclination is highly recommended (*Figure 5.3*). In the warm and humid tropical regions, the operating temperature of photovoltaic modules is high. Furthermore, the amount of solar radiation that converted to heat will heat the building interior. The use of photovoltaic as a second skin roof will provide convection heat transfer thus reducing the radiative heat transfer released by photovoltaic by air movement within the gap. The optimal height for the gap distance between the first roof and the main roof is 50 cm (*Figure 5.4*). This height of air gap will modify the indoor thermal environment at least the same with the building without photovoltaic installation. Additionally, this research indicates that the photovoltaic placement right the roof element without any air gap such as BIPV will create a high indoor temperature thus creating overheating in the interior of the building.

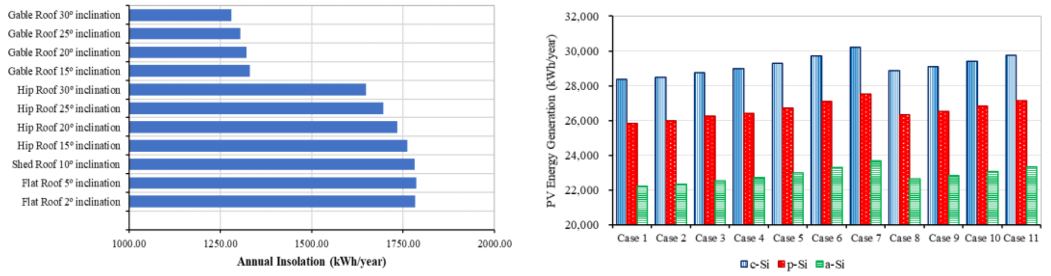

Figure 5.1 Total Annual Insolation Received by the Roof element (left) and Photovoltaic Energy Generated of Simulated Models

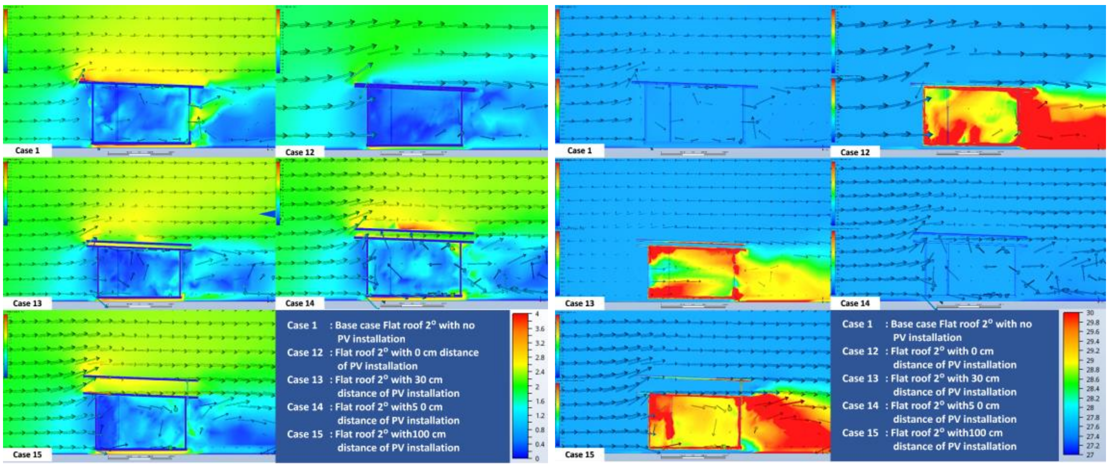

Figure 5.2 Air Velocity in m/s (left) Mean Radiant Temperature in ºC (right)
Inside and Around the Tested Models

6. Conclusion

This PhD research introduced Building Information Model (BIM) based analysis in evaluating an optimal solar design by daylighting design and photovoltaic installation on the building envelope. The research result indicates that daylighting design for the residential building is very favourable in the tropical area. However, care should be taken to reduce glare and heat energy penetrate building interior. Therefore, the use of internal shading device or ray-band glass might be utilised to reduce the effect of glare from the side-lit room. This study also revealed that daylighting design is always incorporated with thermal design by avoiding direct sunlight penetrating to the interior of the buildings using the external shading device.

In the other side, the implementation of photovoltaic in residential building envelope has enormous potential in the equatorial region. The roof surfaces of a residential building can be attached by photovoltaic because the optimal location for photovoltaic implementation is on the roof. The available roof area alone can self-support the residential buildings future-energy demand. Additional placement which has great potential for photovoltaic installation is on the East and West walls. However, walls mounting photovoltaic should consider about the surrounded obstruction like buildings and trees.

This study revealed that for the energy performance, the flat roof with 5º inclination angle is considered as the best choice. However, when the thermal performance comes as the first consideration, the gable roof with 30º inclination is highly recommended. The proposed roof design of "Second Skin Photovoltaic Roof" has been proven to be effective in maintaining the internal thermal condition to be at least the same as the residential building without photovoltaic installation.

7. Future Work

The limitation of daylighting study conducted is the length of measurement which should be improved for annual daylighting performance analysis. Additionally, field measurement cannot isolate or modify the design parameters of daylighting thus the influence of design parameters such us different window materials and curtain cannot be clearly shown. The future research study may be focused on simulating the influence of different window materials and curtain under the tropical coastal climate.

The photovoltaic prediction only focused on energy generation from photovoltaic, and the available area from building envelope surfaces for photovoltaic mounting, thus giving rise to several interesting points for future research. First, our models only consider total incident solar radiation gained by the photovoltaic panel for energy output calculation, the temperature effect behaviour of the photovoltaic panel is a factor that should be considered in future research especially in tropical climates. Second, the economic aspect should be considered in building installed prospective photovoltaic assessment. Finally, extending the study scope from single buildings to neighbourhoods and entire areas will become a future point of the study.

For the proposed novel photovoltaic system which is “Second Skin Photovoltaic Roof” leaves the unfinished work for testing its form using the wind load which is very important for our future work. Furthermore, the detailed construction also still needs to be design and tested by construction simulation.

平成30年8月3日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Optimal Solar Design Based on 3D BIM Model Analysis for Zero Energy Residential Building in the Tropics

（和）熱帯地域における３次元BIMを用いたゼロエネルギー住宅のためのソーラーデザインの最適化に関する研究

2．論文提出者　(1) 所　　属　環境デザイン学　専攻

(2) 氏　　名　PUTERI　FITRIATY
（ふりがな：ぷてり　ふぃとりあてぃ）

3．審査結果の要旨（600～650字）

プテリ氏の学位請求論文は「熱帯地域における３次元BIMを用いたゼロエネルギー住宅のためのソーラーデザインの最適化に関する研究」である。研究の目的は、建築計画の初期段階において、ソーラーエネルギーを活用するため、太陽光発電のポテンシャル、エネルギー消費の効率を考慮したソーラーデザインの最適化に関する研究である。

ソーラーデザインに関する研究は、太陽光発電システムの材料と発電効率を対象にした既存研究が多くみられるが、プテリ氏の研究は、熱帯地域においてゼロエネルギー住宅を実現するために、計画デザインの視点からシミュレーション手法を活用した都市計画と建築計画分野の新しい試みである。具体的には、隣地建物の太陽光反射による影響も考慮し、最も大きな太陽光の放射量を受けられる屋根や立面の場所を解明した。また、ソーラーエネルギーの利用を前提に、住宅の窓や外壁などの開口部デザインをパラメーター化することを通して、BIMを用いて室内照明の照度をシミュレーションし、エネルギー消費の効率化を図る室内照明のデザインを検証した。そして、屋根を対象に、ソーラーパネルとの構造一体化を図り、室内の熱環境とエネルギーの利用効率の視点からソーラーデザインの最適化を検証した。

プテリ氏は、本学在学中に、査読論文６編、国際会議１編を公表した。そのうち、４編を学位論文の参考論文としている。本審査委員会は、プテリ氏が優れた研究成果を挙げており、博士（工学）に値すると判定した。

4．審査結果　(1) 判　　定（いずれかに○印）　合　格　・　不合格

(2) 授与学位　博　士（工学）