Decision Making Model for the Architectural Integration of Photovoltaic (PV) Panels in buildings: The Case of Single Family Detached Housing Units in Northern Cyprus

John Emmanuel Ogbeba

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Architecture

Eastern Mediterranean University
July 2019
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Ali Hakan Ulusoy
Acting Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Doctor of Philosophy in Civil Engineering.

Prof. Dr. Resmiye Alpar Atun
Chair, Department of Architecture

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Doctor of Philosophy in Architecture.

Asst. Prof. Dr. Ercan Hoskara
Supervisor

Examining Committee

---

1. Prof. Dr. Serkan Abbasoğlu ____________________
2. Prof. Dr. Yavuz Kosaner ____________________
3. Prof. Dr. Gül Koçlar Oral ____________________
4. Asst. Prof. Dr. Ercan Hoskara ____________________
5. Asst. Prof. Dr. Nazife Özay ____________________

ABSTRACT

The rate at which fossil fuels are used for electricity generation is alarming. If this is not carefully checked, it will strain the resources and degrade the environment. In addition to that, the impact of climate change has become more obvious resulting from the burning of fossil fuels. Buildings are said to account for more than 40% of Europe's energy consumption. With all of these happenings, it has become evident that we need to seek more renewable means of energy generation. PV has been identified as one of the most important means of generation renewable energy especially when they are integrated into buildings. This research proposes a decision making model for the architectural integration of PV in single family detached housing units in Famagusta Northern Cyprus. The research focuses on BIPV as a decentralized means of generating cleaner and cheaper electricity. The findings of this thesis presents a decision making model for the integration of PV in single family detached housing units across the world. We used This model to evaluate a case study of a single family detached house in Famagusta Cyprus. The simulation result derived from the study presents 10 options on how PV panels can be architectural integrated on roof, facades, shading devices and canopies in single family buildings in Famagusta. In conclusion, the 7 stage decision making model presented in this study haven been tested in the case of Famagusta is a major contribution to the integration of PV in the residential sector.

Keywords: Building Integrated Photovoltaic, Building Model, Decision-Making, Northern Cyprus, Strategies for PV Integration

ÖZ

Bugün itibarıyla Dünya, elektrik üretiminde fosil yakıtlardan uzaklaşıp daha temiz enerjiye geçmeye çalışıyor. Bunun nedeni ise fosil yakıtlar gibi yenilenemeyen enerji kaynaklarının kullanımının çevreye vermiş olduğu zarardır. Ayrıca, fosil yakıt kullanımından kaynaklanan iklim değişikliği etkileri de daha görünür hale gelmektedir. Binalar ise iklim değişikliğine neden olan sera gazı emisyonlarının ana kaynaklarından biri olarak tanımlanmaktadır. Sözkonusu binalarda toplam enerji tüketiminin yaklaşık %78'i Elektrik kullanımından kaynaklanmakta ve bu durum sera gazı emisyonlarının artışına ciddi anlamda neden olmaktadır. Tüm bu nedenlerden dolayı, binalarda daha çok yenilenebilir enerji üretiminin sağlanabilmesi için araştırma yapma ihtiyacı belirgin hale gelmektedir.

Kuzey Kıbrıs elektrik üretiminin tamamına yakınını fosil yakıtlardan gerçekleştirmektedir (1.6 Milyar Kws/yılda). Bununla beraber, elektrik üretiminde çok miktarda fosil yakıt kullanımının Kuzey Kıbrıs'ta yarattığı çevresel etkiler üzerinde giderek artan endişeler oluşmaktadır. Yenilenebilir Enerji kullanımı ise oluşan endişeleri ortadan kaldırabilmek için hem ekonomik hem de çevresel açıdan en uygun yol olarak görülmektedir. Bu bağlamda, bir çok yenilenebilir enerji kaynağı arasından, photovoltaic panel kullanımı Kuzey Kıbrıs için en uygun yöntem olarak öne çıkmakta ve özellikle Fotovoltaik panellerin binalara başarılı bir şekilde entegrasyonu ciddi avantaj sağlamaktadır. Bu araştırma, Mağusa, Kuzey Kıbrıs örneği için, müstakil tek aile evlerinde Fotovoltaik Panellerin başarılı mimari entegrasyonu için bir karar verme modeli önermektedir. Bu araştırmanın bulguları, Fotovoltaik Panellerin müstakil tek aile evlerinde entegrasyonu için 7 pratik adım içeren bir karar verme modeli ortaya koymaktadır.

Anahtar Kelimeler: Binalarda Fotovoltaik Entegrasyonu, Fotovoltaik Entegrasyonu İçin Stratejiler, Karar Yerme Modeli.

I dedicate this dissertation to my Mother, brother and to those I have lost along our journey. Your love and life stands as a beacon of light in this dark world.

ACKNOWLEDGMENT

I would like to express my deepest appreciation to my supervisor, Assist. Prof. Dr. Ercan Hoskara, who patiently guided me from the initial phases of this study. His continues supervision, motivated me and put me back on track when I occasionally went astray, making this task an interesting learning experience. Without his encouragement and supports, it would not have been possible to successfully complete this thesis.

My thanks also go to Prof. Serkan Abbasoğlu and Assist. Prof. Dr. Nazife Özay who were on the monitoring team for this research work. Their guide and invaluable contributions are deeply appreciated. I will not forget to thank Assoc. Prof. Dr. Assoc. Prof. Dr. Türkan Uraz for her relentless support to me during the early stages of my Ph.D. studies. I also thank all the academic and administrative staff of the Architecture Department of the Eastern Mediterranean University for their friendship and for providing good environment and facilities to study.

My heartfelt gratitude and absolute respect goes to my parents, Rev. and Mrs. Emmanuel Ogbeba, my wife Ife Ogbeba for her invaluable support and my siblings; Jerry and Anita, Ehi and Fidel, Abraham and Esther for their support and understanding in all my educational endeavors., my friends in Cyprus, Ryan and Ness Keating, Jerry, Zach, Ugo, Tina, Hourasksh, Erika, Kanysh, and Innocent thank you for all your support.

Finally, I want to thank Christ Jesus my Lord from who I have obtained help for life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BIPV	Building Integrated Photo
CdTE	Cadmium Telluride
CIS	Copper Indium Selenide
CIGS	Copper Indium Gallium Selenide
DOE	Department of Energy
IEA	International Energy Agency
KIB-TEK	The Cyprus Turkish Electricity Authority
kWh	Kilowatt Hour
LLC	Life Cycle Cost
NP	Northern Cyprus
PC	Project Cost
PV	Photovoltaic
PVB	Polyvinyl Butyral
PVSD	Photovoltaic Shading Devices
RE	Renewable Energy
SWOT	Strengths Weaknesses, Opportunities and Threats
TiO^2	Titanium Dioxide
TRNC	Turkish Republic of Northern Cyprus
USD	United States Dollar

Chapter 1

INTRODUCTION

1.1 Introduction to Subject Area

The rate at which the world is consuming fossil fuels is disturbing, besides, these resources are being overly strained (Kanters, 2016). Buildings are said to take up more than 40% of energy consumption globally (Heinstein et al, 2013). This includes energy use in residential, commercial, and industrial buildings (Zogou & Stapountzis, 2011). Studies indicate that 30% of CO2 emissions in the European Union are from buildings. According to the European Parliament and Council (2002), heating living spaces in residential buildings account for 57% of the entire energy used (Filippini et al 2014). The growing awareness of these challenges has led to a global focus on clean energy and energy efficiency in buildings.

Today, one of the most widespread technologies of renewable energy generation is the use of photovoltaic (PV) systems which convert sunlight to usable electrical energy. The International Energy Agency (IEA) IEA Snapshot of Global PV Markets 2017 has stated that, *"the PV market grew in 2016 from around 50 GW to more than 75 GW, a growth unseen for years and mostly driven by China, the USA and India".* In spite of it being faced by numerous challenges, constant improvements in manufacturing, decrease in price and the increased awareness for sustainability, have made photovoltaics (PV) more popular worldwide, with the IEA reporting a steady annual increase in PV installations in the last few years, globally (Masson and Nowak 2015).

IAE (2018) has also noted that there has been a significant decrease in the price of PV systems (0.02 USD/kWh in extremely sunny locations), and that this price decrease is now becoming so visible that it is now influencing decisions in the energy sector. According to IEA report (2018), "With the cost of PV electricity going below 0.02 USD/kWh in extremely sunny locations, PV will become in the coming years the cheapest energy (and not only electricity) source of electricity for new plants*"*.

Furthermore, in the adoption of PV systems in the generation of electricity, there is also the question of whether to generate electricity centrally or by decentralized means. Using centralized or decentralized power systems has its advantages and disadvantages. The use of a central energy generating system to produce electricity is what is been referred to as centralized energy generation (Fig. 1.1), while decentralized energy is the energy produced closer to where it will be used, rather than at a large plant elsewhere and sent through the national grid.

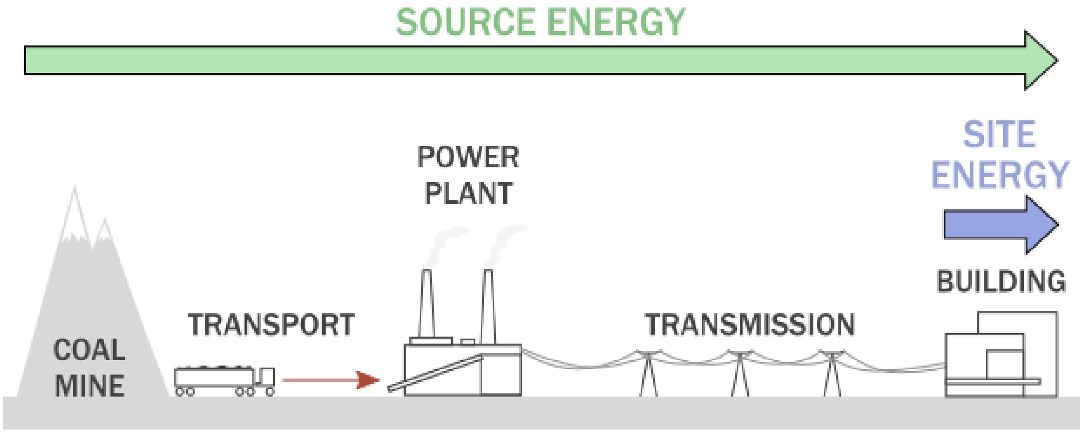


Figure 1.1. Centralized energy

A decentralized power system seems to be the most appropriate means of generating cheaper and cleaner energy. Other systems can hardly be used as decentralized systems because they produce disturbing sounds and some pollute the air. However, in the bid to generate energy in a decentralized way, there is a rising concern of the impact the solar PV element would have on the urban pattern of the environment. There is a major challenge on how to successfully mount the PV panels either as stand-alone energy generators or seamlessly integrating them into the outer surfaces of building without causing any damage to the architectural/ aesthetic characteristics of the building and the urban pattern. This means of power generation enhances the possibility of using PV elements architecturally (as a shading device, roof coverings, glazing, and façade cladding).

In the case of Northern Cyprus today, 70% of the electricity generated are consumed by buildings (KIB-TEK). Out of the 70%, 40% is consumed by residential buildings. Most of the electricity produced is for domestic use such as for heating and cooling spaces, powering electronic devices and lighting. Industry consumption is relatively low. In Northern Cyprus, a number of residential buildings are constructed without adherence to certain basic bio-climatic principles that result in over-dependence on appliances for cooling and heating of spaces. The lack of insulation in the buildings also increases thermal discomfort inside the buildings.

Petrakis et al. in 1998 rightly quoted that Cyprus has a daily average solar radiation of about 5.4 kWh/m2 on a horizontal façade (Figure 1.2). Cyprus also has about 300 days of sunshine annually. January is the coldest month with a minimum and maximum mean temperatures between 4℃ and 19℃ respectively (Ogbeba and Hoskara, 2019). August, the hottest month has minimum and maximum mean temperatures of about 23℃ and 38℃, respectively Petrakis et al. (1998).

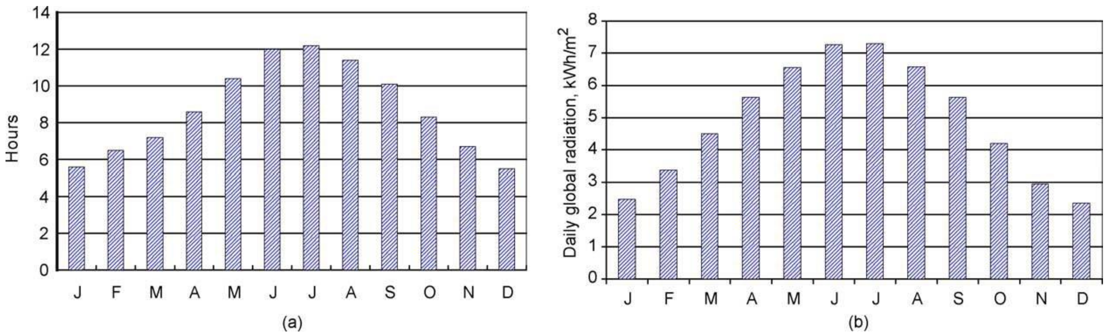


Figure 1.2. Sunny hours per day for each month and Daily Global radiation average (Elinwa et al. 2017).

There are no oil or gas reserves in North Cyprus, thus, there is a total reliance on imported energy in the form of oil and gasoline. Electricity is generated, sold, and distributed by Cyprus Turkish Electricity Authority (KIB-TEK), a state-run utility company, and (AKSA) a privately run company with a total of around 403.2 MW (KIB-TEK), (Elinwa et al., 2017).

It is clear that Northern Cyprus has all the necessary environmental conditions to produce its electricity through solar means. The housing sector consumes the largest chunk of the energy used in Northern Cyprus. This research is focused on finding possible ways of providing clean, cheaper and readily available energy to the buildings of Northern Cyprus by means of architectural integration of photovoltaic systems know as Building Integrated Photovoltaic (BIPV). This study is aimed at developing a decision making model that would enable the integration of PV panels to existing buildings without damaging the architectural characteristics of the building and also to ensure that there is little or no visual impact meted on the immediate environment/ urban pattern. Furthermore, the study will use Famagusta, Northern Cyprus as a case study for developing strategies for the seamless integration of PV in single family detached buildings of Northern Cyprus.

1.2 Research Problem

The world is today trying to move away from the use of fossil fuel for the generation of electricity to a cleaner means of energy. This is because of the damage that the use of non-renewables causes to the environment. Northern Cyprus uses too much of petrol and gasoline to produces its electricity. This is leading to serious environmental damage and has created a significant gap that needs to be filled. Renewable Energy (RE) seems to be the most appropriate means to fill up this gap environmentally and economically.

Besides, since about 70% of the electricity produced in Northern Cyprus is consumed by buildings, this study looks at the possibility of using the same building surfaces to generate the required energy that is needed instead of the conventional centralized system of power generation currently being used in Northern Cyprus today. In doing so the cost of transmission and distribution is eliminated as the energy is produced in situ. Building Integrated Photovoltaic (BIPV) is a viable option that this research proposes in order to fill this gap.

Over the most recent couple of years decentralized solar system has been perceived in numerous nations as the most encouraging sustainable power source for building application, and this has led to photovoltaic systems being increasingly introduced on the building envelope. Be that as it may, they most often do not integrate properly in the architectural sense, which often leads to visual damage to the environment (Schweizer, 2017). With an increased global installation of BIPV, the aesthetic aspect of energy generation, building energy performance and cost are all becoming a crucial element for deciding whether the BIPV can and should be installed. Heritage authorities have been major drivers of this move with claims that a large amount of PV will eventually disfigure the appearance of the city and buildings (Ogbeba and Hoskara, 2019; Schweizer 2017).

Furthermore, the common practice today in Northern Cyprus is a situation where the architect design the building, while a different set of professionals take on the task of integrating/attaching the PV systems to the building. This non-involvement of architects in the process of integration has often compromised the aesthetics of the building. PV installation experts most of the time are only concerned with the energy generation and performance of the PV system without a thorough consideration of the aesthetics and architectural features of the building. This neglect on the side of the PV installers contributes to the reason for the visual damage to the physical environment. It is a common sight today in Northern Cyprus to see residential buildings being defaced by PV panels, solar collectors and thermal water storage tanks mounted of the roof of the buildings. This research aims to provide a solution to this growing problem in the island of Northern Cyprus by developing a strategic decision making model for the architectural integration of PV in single family detached housing units globally as well as for Northern Cyprus.

1.3 Aims, Research Questions and Objectives

The main aim of this research is to propose a decision making model for the architectural integration of PV panels that will guarantee the successful architectural integration of PV panels for existing single detached family housing units. Consequently, the model would be applied to the Northern Cyprus city of Famagusta, which is the case study for this research. The research will focus on BIPV as a decentralized means of generating cleaner and cheaper electricity.

In line with the aim of this research, the following questions have been designed to guide the focus of this research:

- How can PV be integrated to single family detached housing units to serve the dual purpose of generating solar energy without damaging the architectural quality as well as enhancing the performance of the building by using PV panels as building elements?

The sub-research question is:

- How can the Building integrated photovoltaic decision making model be applied in detached single family housing units globally as well as in Northern Cyprus case?

In order to achieve the goals of this study, the objectives are:

- Literature reviews on photovoltaics and its integration in buildings.

- Analysing a number of BIPV models for residential buildings.

- Developing a decision making model for the integration of PV in single family detached housing units.

- Evaluating the architectural integration of PV in single family detached housing units in Famagusta, Northern Cyprus using the developed model.

1.4 Methodology

This study is a mixed-methods research employing both qualitative and quantitative methods as well as theoretical review (Figure 1.3). The first part of the study contains a theoretical review of studies in the area of building integrated photovoltaic. This is done with the intention of revealing the knowledge gap and then developing appropriate guidelines that fill in that gap. The architectural guidelines will be proposed with its integral parts being introduced and strategies that can be carefully followed to successfully integrate PV in detached family buildings without causing any physical damage to the architectural characters and urban form of the cities. The concepts composing the model is derived from a comparative analysis of existing models/ framework from existing literature after which a new model is developed from the analysis.

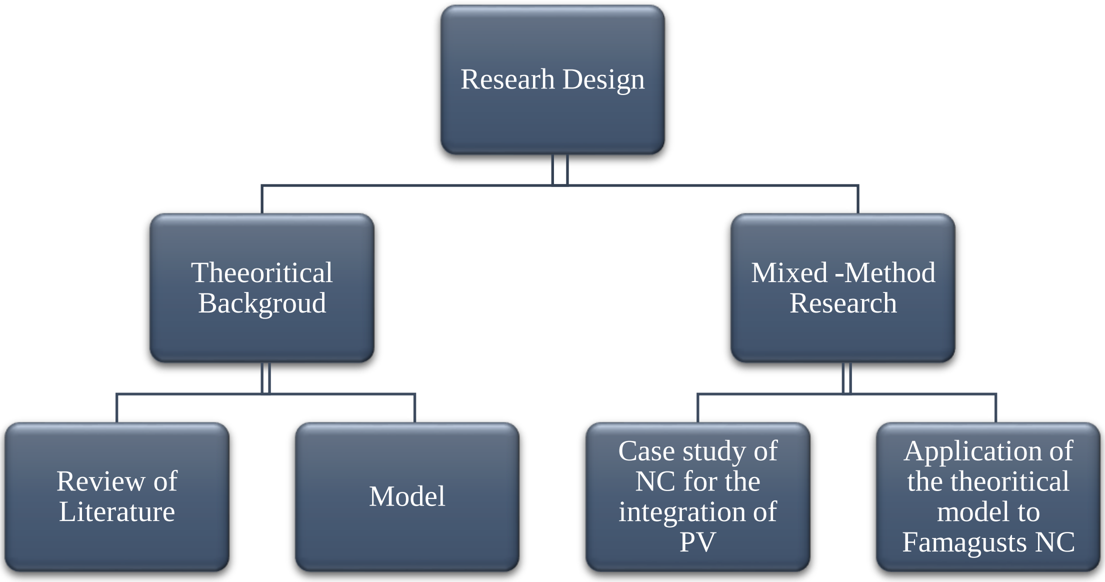


Figure 1.3. Study Design

The second part of the study relies on case study approach (Yin, 1994), it can be a proficient tool to present and analyses specific projects. The research evaluates the application of the developed model to Famagusta, Northern Cyprus which is the case study of this thesis. Therefore, an empirical study is carried out on a typical family detached residential building using design builder/ EnergyPlus software to identify the best strategy for the integration of PV on the residential building surface of Northern

Cyprus. Furthermore, Climate Consultant software was used to Analyse the selected building case model. The strategies derived from this empirical research will be extrapolated and used in Northern Cyprus, the Mediterranean regions and the world at large. The Analysis would include possibilities of Shading device integration, façade integration and roof integration.

1.5 Potential Users of the Result

The benefactors of this study will be the key players in the housing industry. This research aims to form guidance that will facilitate decision making in the application of PV panels in the housing industry. Therefore, the potential users will include but not limited to house designers (architects and engineers), constructors as well as policy makers all of which have the willingness and are currently considering the possibilities of integrating the PV technology in the housing sector of Northern Cyprus.

This research is novel in the sense that the results from this study will unravel the cumbersomeness of the process of PV integration into building and provide a step by step procedure that can be used by housing developers and policy makers. The model developed by this study will shed more light on the gray areas involved in the application of PVs, and serve as a guiding light that will help investors avoid pitfalls. It does so by pointing out the possibilities and the risk involved.

Finally, this study will serve as a basis for further research for those in academia into the areas of architectural integration of PV in residential building and other types of buildings as well.

1.6 Constrains and limitations of the Study

This research will focus on designing a decision making model for the architectural integration of PV panels in existing single family detached housing units. This study limits its case study to Famagusta, Northern Cyprus alone, and within Famagusta, the case will focus on existing single family detached housing units with flat roofs (flat roof single family detached housing typology was selected for this research because they are the most common type of detached housing types in the region). Besides, single family detached housing units have great potential for PV integration because it has more surface area that allows for PV integration compared to other types of building.

The inland of Cyprus is the third largest island in the Mediterranean Sea. This region is known to have solar radiation all year round. This strategic position needs to be taken advantage of by turning towards the sun for its supply of energy. Furthermore, the research will have a broad view of the state of PV and architectural integration globally but will focus its analysis to discover the best strategies for the architectural integration of PV in detached family housing surfaces in Northern Cyprus.

1.7 Thesis Structure

This thesis is structured into seven (7) chapter as can be seen in Figure 1.4. The first chapter introduces the main context of the study, which includes a definition of problem, aim and objectives of the study, research questions, research methodology. The second and third chapters set the stage for the current research as well as contains a literature review and definitions of major keywords in the areas of photovoltaics and its integration into buildings. The fourth chapter of this thesis contains selected cases of PV integration in buildings. In this section of the study, the cases were analysed to understand integration at three (3) different levels; energy integration, technology integration and aesthetic integration. The fifth and six (5 and 6) chapters deal with the development of a decision making model for the architectural integration of PV in single family detached housing units. The developed decision making model is then applied and used in the case of Northern Cyprus. The chapter seven presents the summary of the research work, conclusion and recommendation.

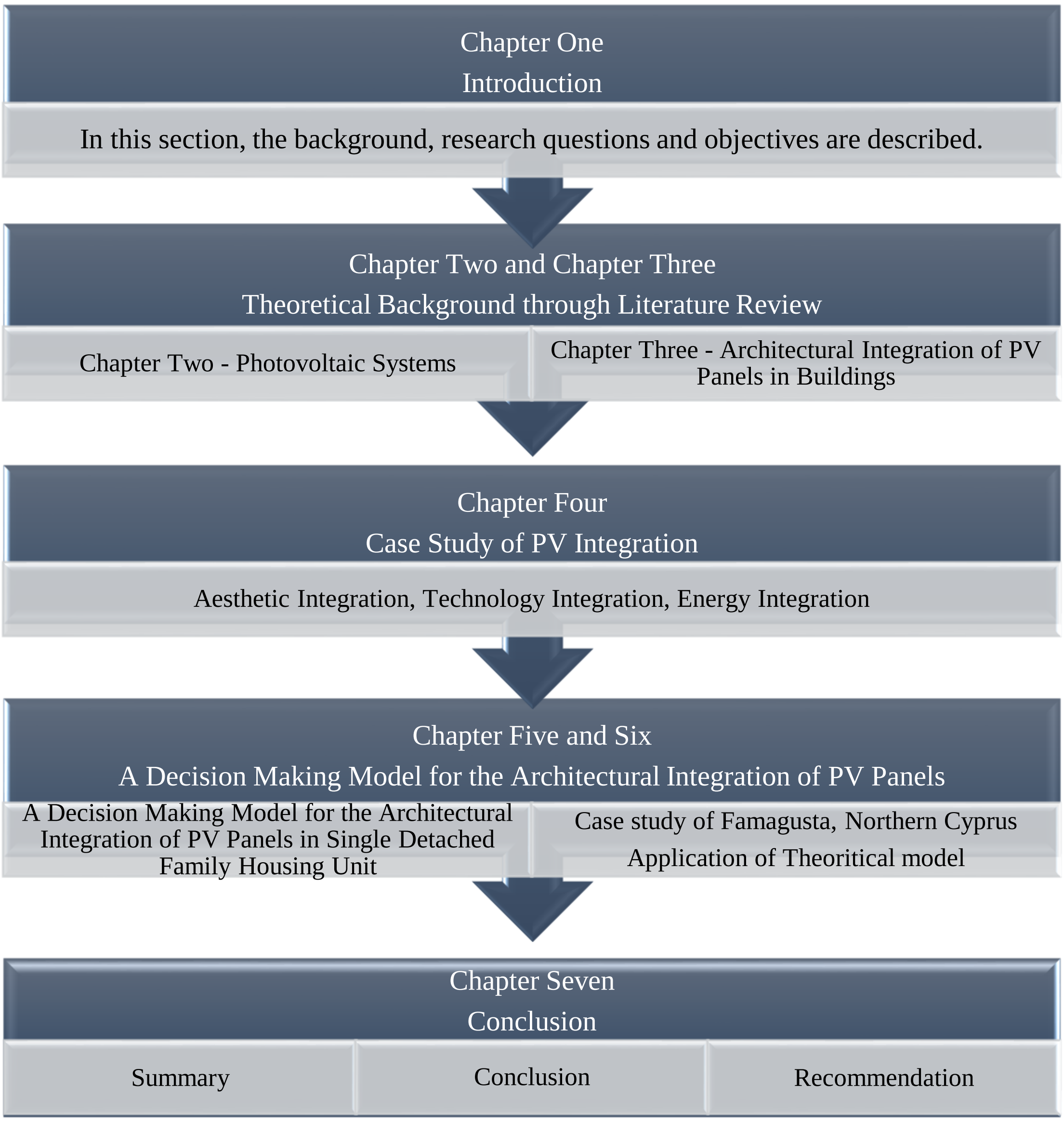


Figure 1.4. Structure of Thesis

Chapter 2

PHOTOVOLTAIC (PV) SYSTEMS

2.1 Introduction

This chapter includes a literature review on the concept of photovoltaic systems and its integration into the building envelope. The chapter gives a background as well as creates a theoretical framework for the study (Figure 2.1).

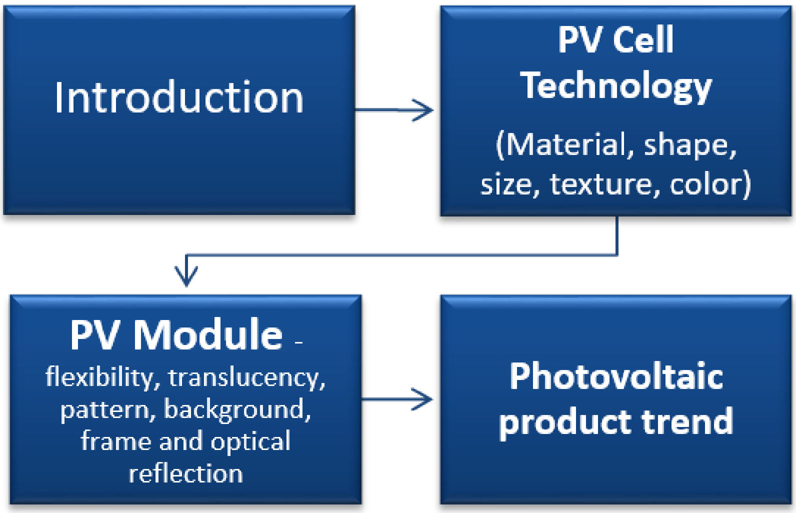


Figure 2.1. Structure of chapter two

The first part of the study focuses on providing definitions of the different types of photovoltaic cells and their characteristics. We evaluated and compared the characteristics of different technologies used for the production of the cells which are said to determine architectural integration possibilities. The evaluation and comparison were based on characteristics such as shape, size, texture, colour and modules (from an architectural perspective) such as pattern, texture, optical reflection, frame, background, transparency – opaque, transparent or translucent. In the third section, we discuss in detail the concept of ‘Building Integrated Photovoltaic (BIPV) systems. The origins of BIPV, elements, current and future technology applications and designs, are reviewed and considered in Chapters 2.

2.2 Photovoltaics (PV)

Photovoltaics (PV) is a method of generating electrical support and cabling structure, and an inverter system power by converting solar radiation into direct current to convert direct electricity to alternating current electricity using predominantly semiconductors or other electricity. materials that exhibit the PV effect (Sark, 2012). The fact that energy is generated silently and cleanly, seemingly out of nothing, combined with the wide range of potential applications, makes this a fascinating process. From individual solar cells with outputs in the mill watt range powering clocks or pocket calculators right up to large power plants covering several square kilometres and outputs measured in megawatts, the modular principle enables systems of any size for any electricity requirement. In all of this, the basic building block, the solar cell, is always the same (Wolfe, 2013; Weller et al., 2010).

2.2.1 History of Photovoltaics (PV)

A French physicist by the name Edmund Bequerel was the first person to discover the photoelectric effect. In his research, he discovered that certain materials can produce electricity when exposed to sunlight (Becquerel, 1839). Furthermore, Albert E (1905) made further discoveries on the possibility of generating electricity from the sun, he later won a noble prize for his ground breaking research findings on this issue (Einstein, 1905). Bell Laboratories was the first scientist to produce a photovoltaic module, he did so in the year 1954 (Knier, 2002). It was considered to be too expensive to replicate, so they developed as a solar battery. In the 1960s, the solar batteries became very popular and used most for space activities. It was billed as a solar battery and was mostly just a curiosity as it was too expensive to gain widespread use. In the 1960s, the space industry began to make the first serious use of the technology to provide power aboard spacecraft. The most important criteria are reliability, durability and low weight, coupled with high efficiency. The advantages of this location are the low ambient temperature in space and also the comparatively high level of radiation owing to the lack of an atmosphere (Knier, 2002).

2.2.2 Photovoltaic Cells

The devise that converts solar radiation into electricity is known as the solar cell (Sark, 2012). It is a form of photoelectric cell that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon. The solar cells available commercially differ in terms of their structure and the basic materials employed. Both of these aspects influence the efficiency of the energy conversion and also the appearance of the cells (Figure 2.2).

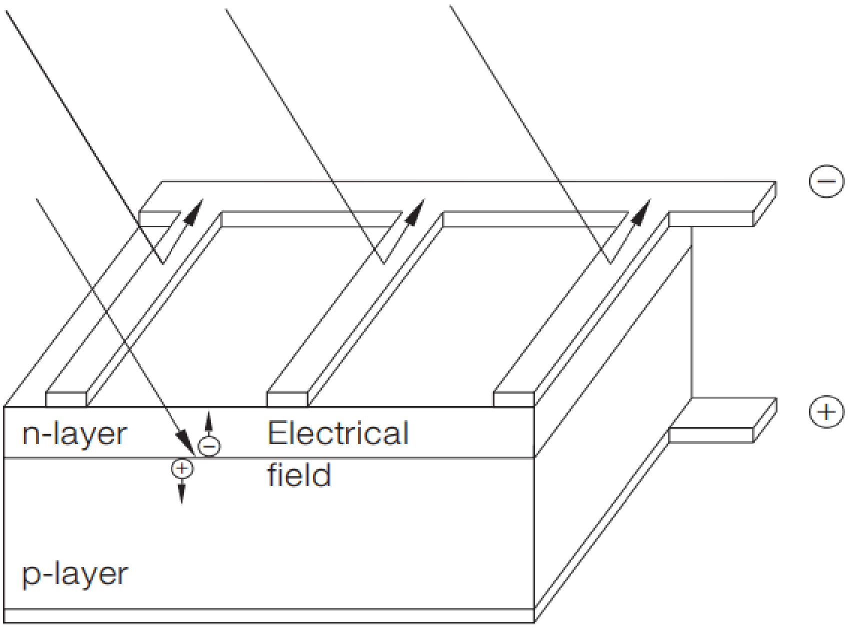
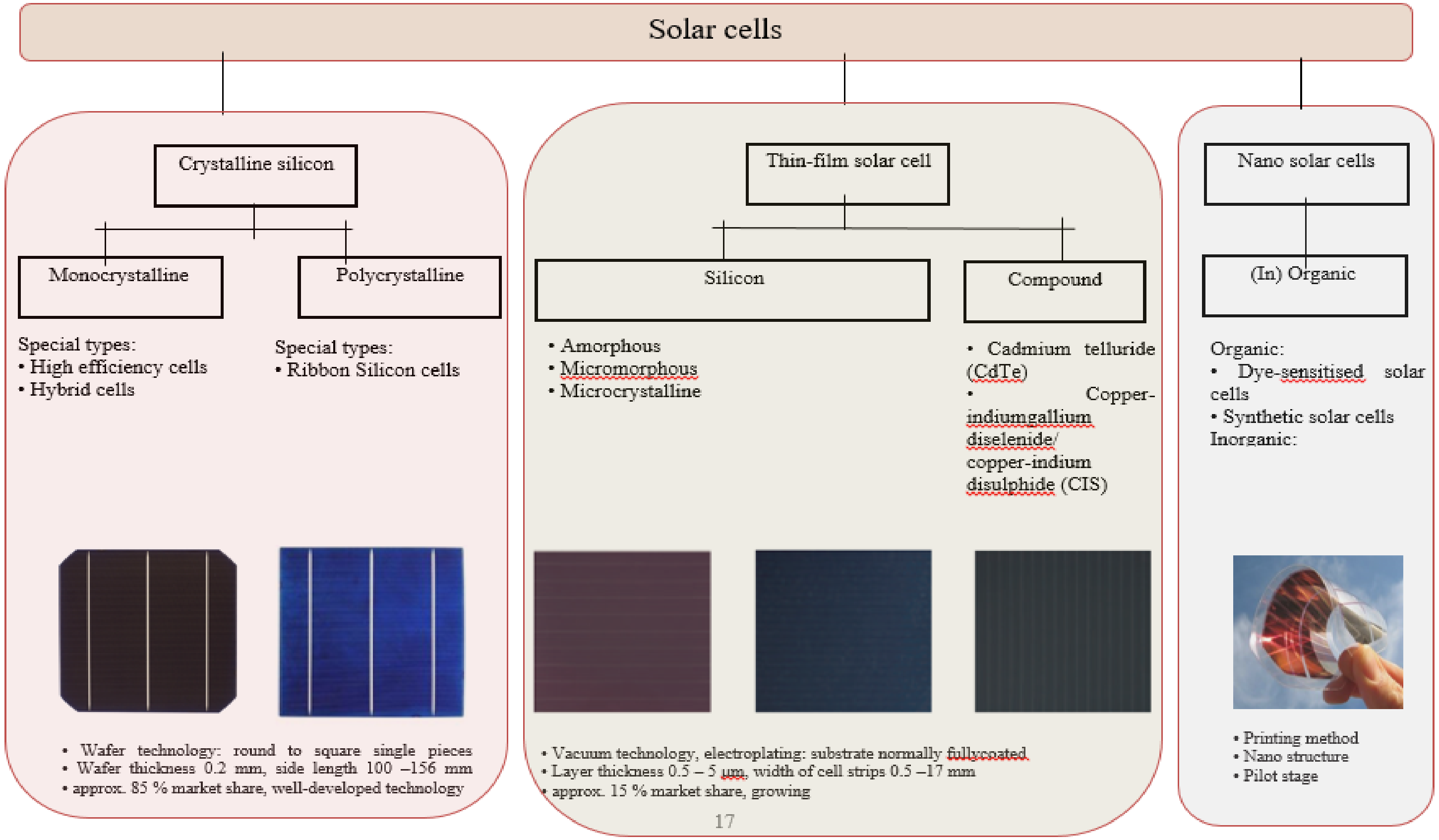


Figure 2.2. The structure and operational principle of a solar cell (Weller et al., 2010)

Cell types are divided into two principal groups: namely, the crystalline silicon thin-film cells produced from different semi-conductor materials. The first niche products employing the third generation of solar cells – based on nanotechnology are recently been seen in the PV market. The secret of the invisible and entirely quiet power conversions is to be found in the materials of the solar-cells, the semiconductors. At very low temperatures these behave like insulators and do not become electrically conductive until heat or light is applied. A solar cell is a combination of two layers with differently manipulated conductivity (Weller et al., 2010).

In crystalline silicon, for example, the layer on the sunlight side is negatively (n^-) doped with phosphorus, i.e. is deliberately contaminated, which gives it an excess of negative charge carriers. The layer beneath this is positively (p^-) doped with boron, which therefore has an excess of positive charge carriers (Figure 2.3). In thin-film cells, on the other hand, the p- and n-type layers sometimes consists of different raw materials. In both types of cell, the boundary between the layers is the p-n junction (Knier, 2002).



Special types:
- High efficiency cells
- Hybrid cells

Special types:
- Ribbon Silicon cells

- Amorphous
- Micromorphous
- Microcrystalline

- Cadmium telluride (CdTe)
- Copper-indiumgallium diselenide/ copper-indium disulphide (CIS)

Organic:
- Dye-sensitised solar cells
- Synthetic solar cells

Inorganic:

- Wafer technology: round to square single pieces
- Wafer thickness 0.2 mm, side length 100 –156 mm
- approx. 85 % market share, well-developed technology

- Vacuum technology, electroplating: substrate normally fullycoated
- Layer thickness 0.5 – 5 µm, width of cell strips 0.5 –17 mm
- approx. 15 % market share, growing

- Printing method
- Nano structure
- Pilot stage

Figure 2.3. Typology and features of customary solar cells: monocrystalline cells have characteristic rounded corners, polycrystalline cells a distinct crystal structure, and thin-film modules a stripy appearance (Weller et al., 2010).

2.3 Current BIPV Products

Silicon is a major raw material in the PV market. After oxygen, it is the second most common chemical element on Earth. It is a very hard, grey component that has a shiny appearance like a metal. Naturally, it can be found in its oxidized state as in gravel, or quartz. Due to its ability to conduct electricity, silicon has been widely used (Bonomo et al., 2015).

The two technologies mentioned above (crystalline cells and thin film cells) have significantly different characteristics that makes it imperative to explain the differences between them. Types, thin film technology, there is no limit on the size of the cells (Green, 2000). This it because it uses amorphous silicon to create a homogeneous thin layer. Thin-film silicon solar cells offset many of the disadvantages of the conventional silicon cells by using a fraction of the pure silicon required in manufacturing solar cells. They are also easier to manufacture and easy to use in a variety of applications (Shah, 2004) One major advantage of this technology is that smaller amounts of silicon are used for this process. Materials like CIS, CIGS, CdTE are used as well, although silicon dominates the market (Bonomo, et al., 2015; Green, 2000; Nelson, 2003).

The third generation photovoltaics are a range of novel alternatives to the aforementioned options. Through a process of artificial photosynthesis, dye-sensitized solar cells that use biomimics are currently used in building integration (Bonomo et al., 2015). It significantly cuts down the initial costs of solar cells and it is has promising prospects. In this case the semiconductor material is TiO^2.

2.3.1 Monocrystalline Cells

Monocrystalline silicon solar are known to be the oldest types of solar cell technology (Nelson, 2003). They consist of pure silicon crystals and has high efficiency of light conversion of between 22-24%. The diameters are 12.5 or 15 cm (Figure 2.4). The ingot is cut into thin slices which are processed to make PV cells. The circular shape is cut away for better packing into a module (Weller et al., 2010). This type of cell has a dark blue colour and have high durability that can span up to 25 years (Table 2.1).

Table 2.1. Advantages and disadvantages of Monocrystalline Silicon Cell

	Monocrystalline silicon cell
Advantages	Monocrystalline solar panels have the highest efficiency rate of 24.2% Has a long lifespan of at least 25 years Monocrystalline solar panels tend to be more efficient in warm weather They are space-efficient. Since these solar panels yield the highest power outputs, they also require the least amount of space compared to any other types
Disadvantages	They perform well in low light conditions compared to polycrystalline silicon They are the most expensive compared to the other technologies Tend to be more efficient in warm weather

Figure 2.4. Monocrystalline cells within the modules (https://www.sollatek.com)

2.3.2 Polycrystalline Cells

An alternative way of making silicon PV cells is from polycrystalline silicon (also known as multi crystalline silicon). The starting material is melted and cast in a cuboid form. As the silicon solidifies, large crystals are formed with grain sizes from a few millimetres to a few centimetres (Green, 2000). The grain boundaries reduce the efficiency slightly. Polycrystalline silicon is slightly less expensive than monocrystalline silicon but also slightly less efficient. There is a trend to larger cells of 21×21 cm (8 square inches) for lower costs and higher overall module efficiency (Roberts, 2009) (Table 2.2).

Table 2.2. Advantages and Disadvantages of Polycrystalline Silicon Cell

	Monocrystalline silicon cell
Advantages	Less expensive to make compared to monocrystalline silicon
Disadvantages	The efficiency of polycrystalline-based solar panels is typically 13-16% Lower space-efficiency Less aesthetically pleasing because of the speckled blue colour

2.3.3 Amorphous Silicon (Thin-Film)

The manufacturing process of thin film photovoltaic cells involves depositing silicon film onto substrate glass. This process uses less silicon when compared to mono- or polycrystalline cells (Kazmerski, 2012). However, this reduction has a negative impact on the conversion efficiency, with an efficiency of ~ 6% versus ~ 15% for single crystal Si cells. Cell efficiency can however be improved by creating a layered structure of several cells. The major advantage of thin-film PV technology is the ability to deposit amorphous silicon on various substrates, which can be made flexible, resulting in various shapes and can consequently be used in many applications. It is also less likely to overheat, thus resulting in an increase in solar cell performance. Amorphous silicon is most developed among the thin-film PV (Munzer, 1999).

2.3.4 Cadmium Telluride, CdTe (Thin-Film)

CdTe PV are another kind thin-film solar technology which gaining popularity due to its lower cost per kW-hour (Murr, 2012). The highest efficiency obtained with CdTe cells CdTe cells is around 16%. CdTe cells capture shorter wavelengths of light than silicon cells can do. The limited supply of tellurium and the toxic impact cadmium poses during CdTe panel disposal are some significant environment drawbacks. The development of recycling technologies may mitigate the risks in favour of this technology (Munzer, 1999).

2.3.5 Copper Indium Gallium Selenide (CIGS)

CIGS PV are another popular new material for solar cells. It has a higher efficiency level, under 20%, and it does not contain harmful Cd. It is currently the most efficient of all the thin-film PV technologies. Although, it has been confirmed to show high prospects of success, mass production remains a major problem. The CIGS cells are manufactured by thin film deposition on a substrate, which can also be flexible (unlike the silicon cells). It also not prone to heating like CdTe cells (Edoff, 2012).

2.3.6 Polymer and Organic PV

These are made from organic materials, can be made into various shapes and density and can be used for high-output manufacturing. They are lightweight when compared to silicon cells. Cost of fabrication is also relatively low since due to their weight and flexibility. One drawback with this technology is that they are less efficient and have a shorter service life (Murr, 2012).

2.4 Characteristics of the Photovoltaic Cells and Panels from an Architectural Perspective

The factors that determine the architectural characteristics of a PV solar cell/ panel include the colour, texture, shape, size, frame, flexibility, pattern, transparency, back ground of panel and optical reflection (Basnet, 2012) (Figure 2.5). The effect a BIPV application is going to make on a single family residential building is highly dependent its ability to meet considerable and sufficiently satisfy the afore mentioned architectural aspects (Farkas, 2009).

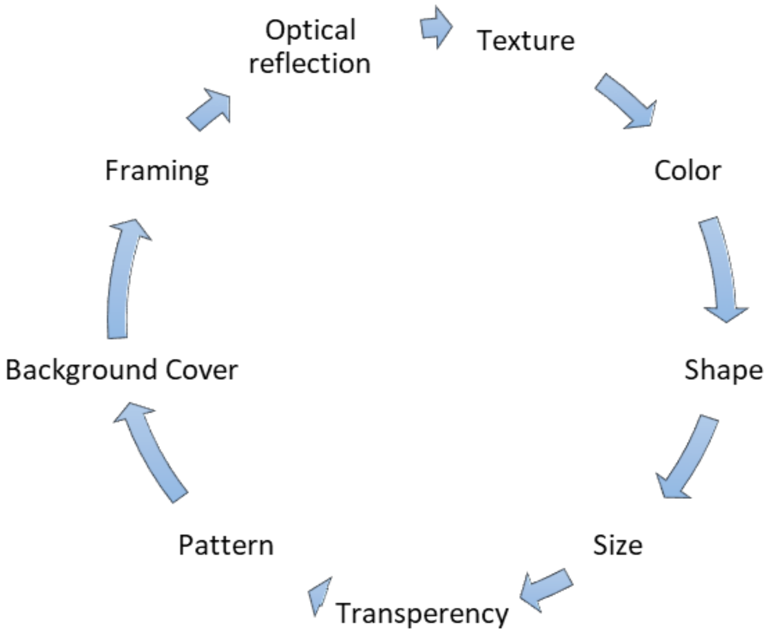


Figure 2.5. Factors That Influence the Architectural Aspects

2.4.1 Crystalline Cells

For the crystalline cells which are wafer based, the characteristics of the cells and the panels are clearly differentiated (Basnet, 2012). The panels serve as a firm protection for the cells as well as provide it with the necessary fittings for the several cells connected in series to produce electricity. Some of the features of the crystalline cells that can influence its architectural quality are; the shape, size, color, texture, and the pattern.

2.4.1.1 Size and Shape

The photovoltaic cells may have different shapes and sizes. The diameter of the monocrystalline cells is 12.5 cm or 15 cm. it has a wafer thickness 0.2 mm, side length 100 –156 mm. While for the polycrystalline cell, there is a trend to larger cells of 21×21cm (8 square inches). The shape of the crystalline cells can have different geometric structures like round, quadratic, semi-quadratic etc. Quadratic and semi-quadratic are however the most popular shapes available in the market because they cover the largest area possible (Marsh, 2008).

2.4.1.2 Texture and Colour

The texture, grain variation and crystallography of cells is the next most important feature after the shape and size of the cell. It contributes to how the architectural surface is perceived and it is a parameter in solar design. In crystalline cells, silicon crystals generate a perceptual effect based on its crystalline structure and they have the following characteristics:

Polycrystalline: irregular texture and grain size of crystal is between 0.001 mm to 1 mm. Monocrystalline: uniform texture, homogenous surface with grain size of crystal greater than 10 cm (Marsh, 2008).

Multicrystalline: a surface similar to marble is created by visibly anomalous blue and grey silicon crystals.

In both cases of polycrystalline and monocrystalline, the metal conductor strips which have basic colours like black and blue are visible from a close distance. Special anti-reflection layers can be applied to achieve various colours like grey, red, brown, yellow, green and magenta with varying efficiency from the original cell ranging between 73-98% (Shin and Choi, 2018).

2.4.2 Thin Film Cells

2.4.2.1 Size and Shape

Solar panels based on thin film technology have very different characteristics. They have no cell size limitation and have a “homogeneous” surface.

2.4.2.2 Texture and Colour

They are generally uniform in appearance and have their atoms arranged as in a liquid, a characteristics referred to as amorphous crystalline structure (Marsh, 2008).

2.4.3 Dye-Sensitized Solar Cells

These solar cells are homogenous, translucent cells that are incorporated into solar tile modules (Marsh, 2008). The tiles are mainly ochre in colour but can be grey, green or blue. They are also rectangular with six stripes of the cells creating a pattern on the homogenous surface structure. These tiles can be used to develop a solar wall panel when they are joined and compressed between two glass panes (Marsh, 2008). This creates a grid on the panel that is determined by the size of the tile. Glass coating is an important feature that also enhances the visual appearance and results in optical reflection.

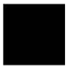
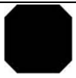
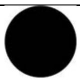
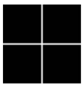
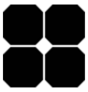
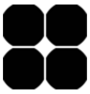
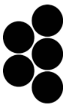
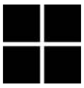
2.5 Characteristics and Visual Aspects of PV Panels

2.5.1 Crystalline Panels Visual Aspects

At the module or panel level, there are other features that determines the visual appearance. The main characteristics that determines the architectural quality of PV panels are; pattern, transparency, background, framing and optical reflection (Farkas et al., 2009).

The pattern of the wafer based technology panel is formed mostly by the arrangement of the cells which comes in various shapes and sizes. The standard cSi cells are typically 12.5×12.5 cm. Different variants of grids for electrical contacts may provide distinct appearances to the modules. Therefore, in order to redesign or create a desired pattern the cells have to be arranged in a certain way, either horizontally, vertically or any other pattern that the designer deems fit. Table 2.3 shows different cell forms and patterns produced form their assembly (Dim, 2017).

Table 2.3. Shows different cell forms and patterns produced form their assembly

	Square	Cut off angels	Rounded angels	Round
Cell form				
Pattern produced by cell assemblies				
Zoon on the space between the cells				

The translucency of the panel is generally derived from the spacing of the cells in the module (Figure 2.6). It should also be noted that from the point of view of energy efficiency, the spacing should be kept as smallest as possible, nevertheless, for aesthetics or building integration reasons, a greater separation can be chosen. Changing the distance between the cells can affect the level of clarity of the modules. Some performing cells may also improve transparency. Assembling the cells within the module can create semi-transparent crystalline silicon modules also to the scale of the solar cell (Dim, 2017). A semi-transparent effect can also be achieved when perforations are done with the laser to punctually remove the material. When the photovoltaic module is used to replace a glass, the result is semi-transparency, a crucial feature with regards to the light level and the thermal contribution. The semi-transparency of the cell, i.e. the level of clarity, varies between 0 and 30% with the standard being 20%, while there is a commensurate reduction in efficiency (http://www.bipv.ch/index.php/en).

Figure 2.6. Examples of Translucent Panels
(http://www.bipv.ch/index.php/en/visual-aspects/frame-color)

The background colour of the modules is often either white or black (Figure 2.7). However, changing the background colour is achievable in practice by varying the colour of the enclosed substance (Usually EVA or Polyvinyl Butyral - PVB).

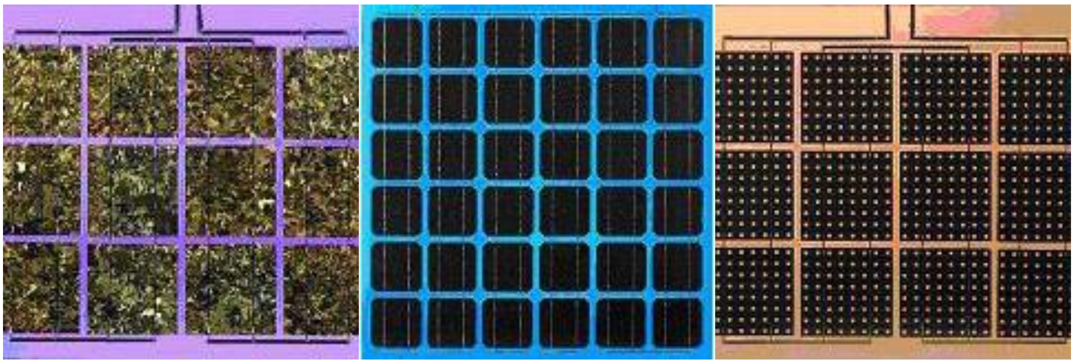


Figure 2.7. Examples of Background Design of Panels
(http://www.bipv.ch/index.php/en/visual-aspects/frame-color)

Using glass in the photovoltaic modules enables colour and feature variation, as well as the creation of engraved drawings. The background may also be transparent making it possible to use them in construction as semi-transparent materials (Dim, 2017).

Different architectural appearances can also be achieved using various types and colours of frames. Using a strong frame for example may accentuate form, whereas a lack of framing may accentuate cell texture. Modules are also protected and secured by the frames. Most of the frames have a natural or coloured anodized aluminium that improve the mechanical strength of the module and make fixing easier. Some modules can be fixed without frames through for instance, point or linear fastening (http://www.bipv.ch/index.php/en). The optical reflection also contributes to visual appearance. It varies based on the observer's distance as well as the angle of perception.

2.5.2 Thin Film Technology Panel Characteristics

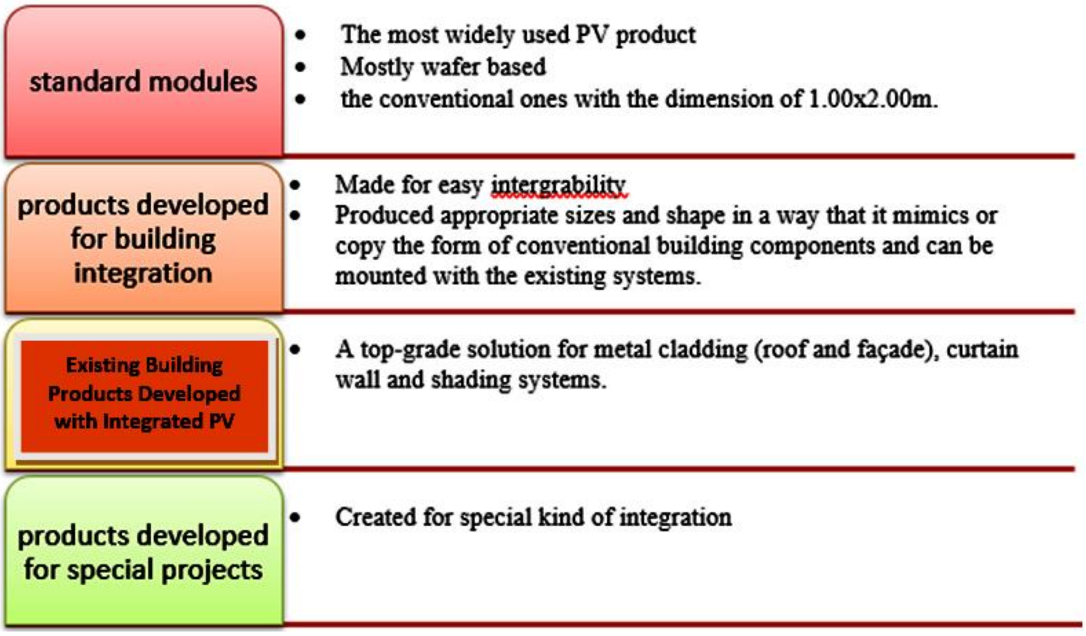
It is possible to have flexible modules that improve their building integration possibilities, for example curved or corrugated metal sheets used as substrates. Another good feature is the prospect for translucent modules, with various patterns and colours incorporated into glazing. The patterns can be seen only from short or middle distances, while maintaining the homogeneous appearance from large distance. Optical reflection also varies based on the substrate material (http://www.bipv.ch/index.php/en). Apart from the traditional modules, there are in the market also other types of modules that can be integrated into the flexible or curved parts of a building (Table 2.4).

Table 2.4. Characteristics of the Cells

	Crystalline technology		**Thin film technology**		**Nano tech**
	Monocrystalline	Multicrystalline	Thin film opaque	Thin film translucent	Dye solar cell
Characteristics of the cell					
Size and shape	The diameter of the monocrystalline cells is 12.5 or 15cm. wafer thickness 0.2 mm, side length 100 – 156 mm. The shape of the crystalline cells can varies between quadratic, semi-quadratic, round, half-round etc.	Layer thickness 0.5 – 5 µm, width of cell strips 0.5 –17 mm the polycrystalline cell, there is a trend to larger cells of 21× 21cm (8 inch square) The shape of the crystalline cells varies between quadratic, semi-quadratic, round, half-round, etc.	homogeneous surface, with no cell size limitation		Translucent
Texture and color	Blue, grey, brown, yellow and magenta	Blue, grey, red, brown, yellow and green anomalous blue and grey silicon crystals are visible and produce a surface like marble.	“homogeneous” surface The cells in thin film, characterized by an amorphous crystalline structure (atoms arranged as in a liquid), have instead a generally uniform appearance.		Homogeneity Colors
Characteristics of panels					
Pattern	Determined by the arrangement of the cells	Determined by the arrangement of the cells	Flexibility various substrates of the building skin	translucency pattern of cell	Stripe pattern
Translucency	Determined by the arrangement of the cells	Determined by the arrangement of the cells	Flexibility varying substrates of the building skin	translucency pattern of cell	Translucent cell itself
Background	Has different colors and pattern	Has different colors and pattern			Grid size of tile
Framing	Color and type	Color and type			
Optical reflection	Glass coating	Glass coating	Optical reflection	Optical reflection	Optical reflection

2.6 PV Product Development Trend

This section of the study will focus more on four major trends of PV products available today. Farkas et al. (2009) grouped PV products into four categories. The four main BIPV products that are available today include: standard modules, products developed for building integration, products developed for building integration and products developed for special projects.



standard modules	• The most widely used PV product • Mostly wafer based • the conventional ones with the dimension of 1.00x2.00m.
products developed for building integration	• Made for easy intergrability • Produced appropriate sizes and shape in a way that it mimics or copy the form of conventional building components and can be mounted with the existing systems.
Existing Building Products Developed with Integrated PV	• A top-grade solution for metal cladding (roof and façade), curtain wall and shading systems.
products developed for special projects	• Created for special kind of integration

Figure 2.8. PV product development (Farkas et al., 2009)

2.6.1 Standard Modules

The vast majority of the photovoltaic modules normally available are square or rectangular elements with various standardized dimensions and ratings. The aim of such standard modules is to achieve cost-effective production, maximum system yields and rational assembly (Bhatia, 2014). The most widely used PV modules today are still the wafer based technology. the first use of panels applied in building were the conventional ones with the dimension of 1.00×2.00 m (Gul et al., 2016). Standard crystalline modules are usually fitted into an aluminium frame and have a cover of toughened low-iron clear safety glass 3.2 or 4 mm thick, which is also known as “solar glass”. Panels this size can still be found both for the crystalline technology and the thin film technology. In the process of developing and manufacturing this type of module, the efficiency is usually the focus of the developers without consideration for their architectural quality. This is the reason why they are difficult to integrate into buildings. These type of modules are still the most common on the market today and because of their size, dimension and make, they are difficult to integrate them into buildings in an architectural way. In recent times, structural integration is becoming very common, and different mounting technics are being developed to have been integrated into both roofing systems and façades of buildings. A common case of the module on building roof can be seen in the Figure 2.9, where a rack system was designed to hold the panels in place (Bhatia, 2014).

Figure 2.9. A general module attached to the roof of a building using a rack system (https://www.yellowlite.com)

2.6.2 Products Developed for Building Integration

Realizing the limitations of the wafer based technology in terms of building integrability, effort of been made by producers to create producing that easily be integrated into buildings; in this regards, two major trends in the developments of products have begun. A major stream is made of panel designed strictly for building integration, mainly for roof integration and glazing purposes. The main aim is to seek for good structural integration, by producing them in the appropriate sizes and shape in a way that it mimics or copy the form of conventional building components and can be mounted with the existing systems (Ogbeba and Hoskara, 2019).

Products design for roofing: developing products for roof integration differs from one place to another, depending on the individual building traditions and dominant building elements applied as roof covering; e.g. Roof tiles, shingles, modules, galvanized or metal sheets. To maintain continuity, the new products develop by copying and mimicking the existing form of the mounting system. Even with the pv product being integrated structurally, they still lack aesthetical integration as this is not often taken into account. The major areas of concern are the fact that the visual aspects such as the colour, pattern, surface texture of the building component they are copying does not exactly match. This can obviously be seen in the junctions or connections like gable endings, ridges, valleys and or skylights. Most of the time, these new photovoltaic products do not blend harmoniously with the existing as can be seen in Figure 2.10. the situation is completely different if the entire surface of the structure is covered with the new PV products. Usually, a simply roofing design would be appropriate for that and a homogeneous surface required that is void of other elements like chimneys and skylights. Nevertheless, the ridges, valleys and other junction will still require structural solutions if the entire architectural quality of the building is to be improved (Gul, 2016).

Figure 2.10. Roof and translucent glazing integration examples (Jelle, 2012)

Glazing products: secondly, another major possibility in the architectural integration is the based on integrating transparent of translucent PV into glazing materials (Tang et al., 2014). When integrating PV cells for the purpose of translucency, it is done differently with the two major technologies. To achieve translucency with the wafer based technology, the spaces between the cells are increased to allow for light to pass through. A space of about 3cm is ideal for this purpose. The silicon cells have been used for this purpose originally. However, because of the unattractive nature of their back surfaces they are often been used for canopies and skylights. Some manufacturers now seal the back side of the cell using screen printing. By doing so, manufacturers are able to apply various colours, patterns, texture, etc. That further improves the architectural quality (Tang et al, 2014).

In the case of the thin film technology, there is a wider range of possibilities in making the cell translucent. The density of the various materials used for the thin film technology can be varied to achieved different levels of transparency on one homogenous surface. Different manufacturers present a variety of pattern, texture and design with the use of silicon and CIS. Daylighting is a crucial factor in these scenarios that needs to be appraised in the design phase. The major hindrance to the ubiquitous use of this innovative solution is the low efficiency despite the high cost of the materials, especially because the translucent elements further reduce the already low efficiency of thin film products (Jelle, 2012).

2.6.3 Existing Building Products Developed with Integrated PV

Some companies that manufacture certain building materials understand that there is the need to undergo further development using integrated photovoltaics. These materials are already a representation of high-quality metal cladding, curtain walls and shading systems. Integrating photovoltaics into these already well-known building products will improve the value of the product by the addition of a new function – generating clean electricity (Nelson, 2003). Integrating photovoltaics thus serves as an enhancement to the product's value. This is immensely beneficial because the structural integration of the already existing product system is available for the product without PV (Jelle, 2012).

Integrating aesthetics in these cases if often questionable even when the main goal of structural integration is already fulfilled. The economic issue is again an important factor, with these products representing high-quality and high-prize solutions, that increases by PV integration (Bonomo, 2015).

2.6.4 Products Developed for Special Projects

Experimenting with materials may be permitted on certain projects, even though financial barriers may often hinder such experiments in the building integration of photovoltaics. Innovative solutions however become crucial in special scenarios where focusing on some characteristics of the modules or the cells is essential (Bonomo, 2015). These can serve as a means of maintaining continuity in the built environment, to match the overall design and context, as well as to present the characteristics of the material. For instance, the colour can be selected to suit other materials used on the building skin (Figure 2.11).

Figure 2.11. Products developed for special projects (Farkas et al., 2009)

In other scenarios, emphasis is placed on the quadratic form and framing of the module used as a new façade cladding. The texture of the multi-crystalline cells may be used in place of marble on the façade.

2.7 Building Integrated Photovoltaics (BIPV)

In order to get a fully understand the subject of BIPV within the context of this research work. This section of the thesis presents a review of BIPV beginning with descriptive definitions of the subject. The reviews presented here will form the theoretical framework of the study. Since BIPV is currently positioned primarily as a niche-product, definitions of what is and what is not included in BIPV differ from one region of the world to another. According to Donker and Jong (2015), PV integration can be definitively categorized into aesthetics, functional and building envelop as can be seen in Table 2.5.

According to Agentschap (2011), “BIPV is part of the building envelope; it has a ‘structural’ building function, e.g. water proofing. Building Integrated PV system means that PV is integrated in the (Energetic) building design and thus is a structural part of the construction of a building. It replaces regular building components”.

Another researcher described BIPV modules as building elements providing at least one additional functionality to the building envelope beside electricity generation. (Weather proofing, Aesthetical integration, shadowing sun protection, thermal insulation, noise protection, Safety) (Folkerts, 2013).

Table 2.5. Architectural integration of PV (Donker and Jong, 2015)

Description of integrability	
Aesthetical integration	Does it look good? Does it match the environment?
Functional integration	Is it water- and wind proof? Is it resistant to low and high temperatures? Is it soundproof? Does it include solar heating solutions?
Integration in the building envelope	Does it replace regular building components? Can it be delivered as a prefabricated module?

Ferrara et al. (2012) describes BIPV as a multifunctional building component: Electricity generation, Shading systems, Weather protection, Noise protection, Heat insulation and Sunlight modification." (Ferrara et al., 2012). According to The Department of Energy & Climate Change of the United Kingdom (2013), "Building Integrated PV (BIPV) refers to photovoltaic systems that generate electricity and function as part of the building. Products such as windows, walls, façades and roofs can be designed as BIPV (e.g. solar shingles/tiles) and architects can use these products to provide both function and style".

From the above definitions it is clear that there is no consensus about which requirements a system should at least meet to be regarded as BIPV. Not every researcher includes the contribution to the aesthetics of the building in its definition, neither the requirement to be weather proofing. But one thing remains obvious and that is the fact that each of the researchers mentioned one of the three (3) requirements mentioned above.

2.8 Review on BIPV's Application in Buildings

It is noteworthy to mention that a good number of scholars have conducted literature studies on building integrated photovoltaic (BIPV). The outcome of these studies is of value to any research on this subject as it will serve as foundation on which other studies are built upon. Some of the key contributors to BIPV research are as follows; Tripathy et al. (2015) carried out "A critical review on building integrated photovoltaic products and their applications" and Heinstein et al. (2013) gave a comprehensive review on "Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths. From the several reviews carried out, findings from three of them which were conducted specifically on BIPV application to the building skin are presented below. The findings from these review works are very critical to this thesis. The first study considered was carried out by Biyik et al. (2017), the second by Zhanget al. (2018) and the third was by Patrick Heinstein et al. (2013). The first review paper studied was written by Biyik et al. (2017). The results from their study are very informative and applicable to all BIPV research. For this reason, a number of findings from their study which are very relevant to this thesis are presented here. The paper provided a comprehensive review of the current state of the art in the BIPV technology. It started with a brief description of BIPV systems, and then reviewed the current literature in details. The review article also summarized the previously conducted studies in a tabulated form. Emrah et al. (2017) referenced the work of Bloem et al. (2012) where the different parameters that need to be considered for the integration of PVs into the building envelope were presented as shown in Figure 2.12.

.

Figure 2.12. Parameters for PV (Bloem et al., 2012)

2.9 Placement of This Study

According to what has been said above, some areas have been more research on compared to others in terms of BIPV. This signifies an urge to deal with the less studied issues more in this thesis. This study, as a continuation of the developing trend in BIPV research aims at examining the less observed issues both theoretically and in application. This work is of an interdisciplinary stance, combining design, architecture and urban planning viewpoints with photovoltaic integration in buildings. Also, the focus is on the architectural integration of PV on the building skin such that it does not diminish the architectural characteristics of the building as well as the urban pattern.

In sum, this work combines photovoltaic systems, the architectural design aspect and the general impact of both into the urban pattern of the Northern Cyprus setting.

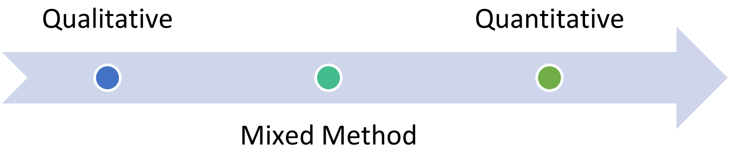
Regarding the conceptual foundation, this thesis works on the integration of PV in buildings, and specifically on achieving a seamless integration of PV into the buildings without affecting the architectural characteristics of the of the building and the urban pattern. As found by Biyik et al. (2017), this field, i.e. architectural integration of PV, appeared to a lesser extent than concern for the energy output of the PV systems in the literature. Moreover, like a number of other works of research, this study focuses on model development and application; but the difference is that contrary to those studies, it is not solely built upon traditional BIPV models developed for integration into buildings and infrastructure. Furthermore, with regard to the theoretical structure, this blended study focuses Energy, Architecture and Construction (integration).

On the design, as mentioned by Heinstein et al. (2013) in his review article, “that the goal of energy change linked to greater use of renewables can be successfully achieved only when all aspects are taken into account and when visual appeal (architecture) and energy efficiency (Energy) thus no longer appear to be an oxymoron but unified (through the process of a seamless integration in building through construction)”.

To fill in this gap, this study maintains to be a mixed-methods one, incorporating qualitative as well as quantitative design. Finally, in regards with sample units applied in studies, it was mentioned that most studies used simulations and documentations. This study, also makes uses simulations as well as other multiple sample units such as documentation, professionals, citizens, etc. for developing the theoretical foundations.

All in all, as a recapitulation of the above-mentioned, the placement of this study is shown in Table 2.6.

Table 2.6. Placement of study

Feature	This research work is placed with the confines of renewable energy and building integrated photovoltaic literature
Research Area	BIPV, housing and urban form, BIPV strategies
Conceptual Core	Development of a design strategies for the integration of PV in single family detached housing
Theoretical Framework	Photovoltaic technology, building integrated photovoltaic, architectural aspects of PV, building simulation
Design	
Sample Unit	Documents, SWOT analysis, Professionals, Citizens

2.10 Conclusion

This chapter has provided definitions and literature to the keywords of this study photovoltaics (cell, modules, and panels) and building integrated photovoltaics (BIPV). Furthermore, this chapter has systematically defined the mode of operation of the PV system and its connection to the building envelope. The architectural aspects (colour, shape, size, texture, framing, transparency, optical reflection, etc.) PV material and how it can be successfully integrated into buildings was clearly defined too.

Having carried out a general study on a good number of the research done so far on the subject of BIPV, it is discovered that most of the studies carried out were more concerned on the efficiency of the PV panels integrated, net-zero energy buildings, etc., thus the aesthetic aspect of it has not been given the needed attention. The integration of PV in buildings has a strong connection to the environment. This makes its consideration for the urban environment very pertinent. In order to successfully install PV systems in a building, it is crucial for designers to put into consideration the visibility of the PV installation and its level of dominance on the appearance of the building, hence the need for integrating PV in a way that the architectural characteristics of the building and the urban form of the city is not compromised. The next chapter will further discuss the strategies for the architectural integration of PV.

Chapter 3

ARCHITECTURAL INTEGRATION OF PV IN BUILDING ENVELOPE

3.1 Introduction

The following chapter aims to explain the basic thoughts about PV from an architectural and design point of view. PV modules can be integrated into different parts of the building envelope, to create specific architectural systems. In this chapter we explore the four (4) different categories of BIPV systems, including i) photovoltaic roofs, ii) Photovoltaic façades, iii) Photovoltaic windows and overhead and iv) photovoltaic shading devices. These categories require different techniques of using PV in the envelope, which in turn leads to different choices of the PV components and materials.

As earlier mentioned, the term Building Integrated Photovoltaics (BIPVs) refers to the integration of photovoltaic panels into the building skin (Aristizabal et al., 2018), with the dual roles of replacing building components and of simultaneously serving as electricity generators (Assoa et al., 2017; Shukla et al., 2017). The growing pattern where buildings are now being transformed from being only energy users to energy generators is not a recent development. Seeking structural, architectural and aesthetic means of integrating PV into buildings have been on since the first appearance of PVs in the market. Heinstein et al. (2013) in his words stated that:

"After the Swiss engineer, Real (1986) took the very first initiative ('Megawatt') of calling for 333 Zurich house owners to install PV panels on their roofs, the idea of using PV for decentralized energy harvesting through the 'smart grid' was born".

The use of BIPV systems have been identified by several researchers as one of the tenable technologies that could be adopted in buildings to improve their power performance as well as cut down on their environmental effects. Several researchers have presented different approaches to the integration of PV into the construction of buildings, some of these options and descriptions are discuses on the following sections.

3.1 The Principal Installation Options for Photovoltaics

Typical applications have evolved within the domain of building photovoltaics. The descriptive terms now commonly used were derived from the essential constructional features. When planning a PV installation on the roof, there are fundamental differences between flat roofs and pitched roofs to be observed. PV installations mounted above an existing roof are known as stand-off systems (Figure 3.1). But if the PV modules replace the roof covering and provide a rainproof layer, we speak of an integral system. On the facade, the systems currently in use are distinguished according to the thermal properties, i.e. cold and warm facades (single- and double-leaf respectively). A warm facade implies full integration; the PV elements are incorporated into insulating glass units and can then fulfil all facade functions. In cold facades the PV installation is either additional to or a substitute for the weatherproofing (Weller et al., 2012). Sun shading elements represent another suitable area of application for photovoltaics. In the form of fixed sunshades, they protect the building and users against overheating and at the same time generate electricity.

Movable sunshades adapt to the solar altitude angle and thus also optimize their energy yield (Weller et al., 2012).

When designing with photovoltaics it is also necessary to ensure that the choice of constructional integration is directly tied to the architecture. On a facade in particular, PV installations are much more obvious. The facade to the sports hall in Burgweinting is a very good example of how constructional solution supports the architectural concept of the facade and achieves a clear design language. The design of the glazing bars for fixing the PV modules has led to a horizontal segmentation of the facade. Building integration has been successful here, in terms of both construction and architecture (Weller et al., 2012).

Furthermore, in principle it is possible to use photovoltaics (PV) in any area of the building envelope that is exposed to direct sunlight. In literature, there are three architectural possibilities of integrating BIPV products (Figure 3.2). They are; i) photovoltaic roofs, ii) Photovoltaic façades, iii) photovoltaic shading devices. (Dehra, 2017; Luo et al., 2017; Ali et al., 2018; Martin, 2011; Hagemann, 1998, Tablada et al., 2018). PV modules can be added or integrated into existing buildings but integrating them at the design stage gives a better architectural finish. The three architectural possibilities of integrating BIPV products mention in Figure 3.2 will be extensively discussed in the preceding headings.

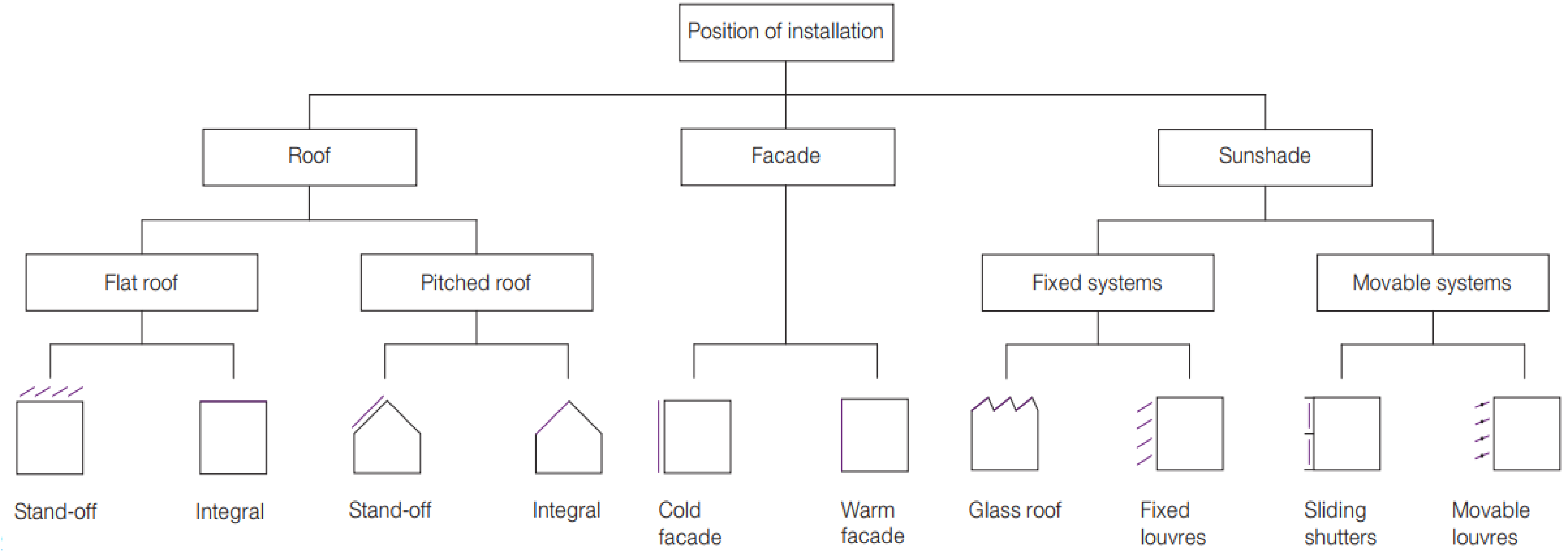


Figure 3.1. The principal installation options for photovoltaics: roofs, facades and sunshades (Weller et al., 2012)

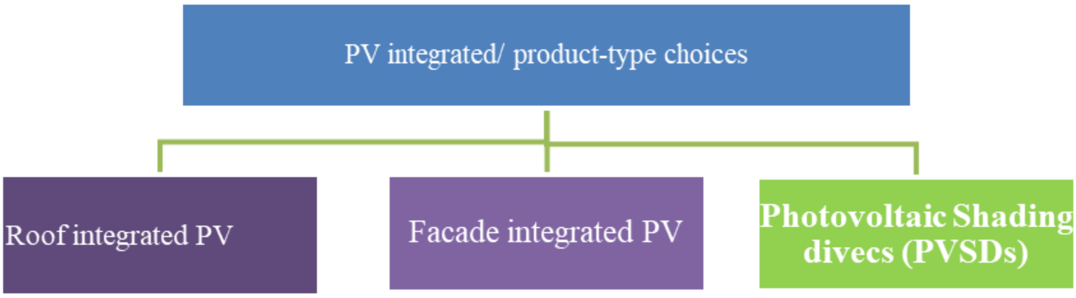


Figure 3.2. Three types of BIPV product choices (Pester and Crick, 2013)

3.2 Roof Integration of Photovoltaics

Roof areas are preferred locations for PV systems. A PV system can be integrated into the roof in several ways. In Central Europe a south-facing module surface mounted at an angle of 30° achieves the maximum energy yield when considered over a 12-month period. Small deviations from this orientation result in only very minor losses and changing the angle does not have a very significant effect on the yields attainable either. Even a horizontal rooftop installation leads to only a 10 % drop in the yield compared to the ideal orientation and angle. Preferred rooftop installations for PV applications are (Figure 3.3).

Roofs are generally categorized according to the pitch of their surfaces (Figure 3.4). Flat roofs are generally built with a pitch of 5–10°. Three basic forms of flat roof are possible: cold roof (with air space below roof covering), warm roof (no air space) and inverted (or upside-down) roof (thermal insulation above waterproofing). At angles less than 10° we generally speak of a shallow pitched roof and at angles greater than 22° a steep pitched roof. In the following, roofs between 10° and 80° are grouped under the heading of pitched roofs. The subdivision at 22° is based on the minimum pitch of the very common small-format roof covering materials (clay or concrete tiles, slates) and represents the minimum for ensuring a rainproof design (Weller et al., 2012).

Opaque metal roof coverings or transparent glass elements tend to be used for shallow pitched roofs. Glazing or glass PV modules inclined at an angle greater than 10° to the vertical are classed as overhead glazing. Constructions between 80° and 90° to the horizontal are classed as facades. PV modules in this range fall into the vertical glazing category. This division into vertical and overhead glazing is based on the different loads and risks associated with the angle of the installation (Weller et al., 2012).

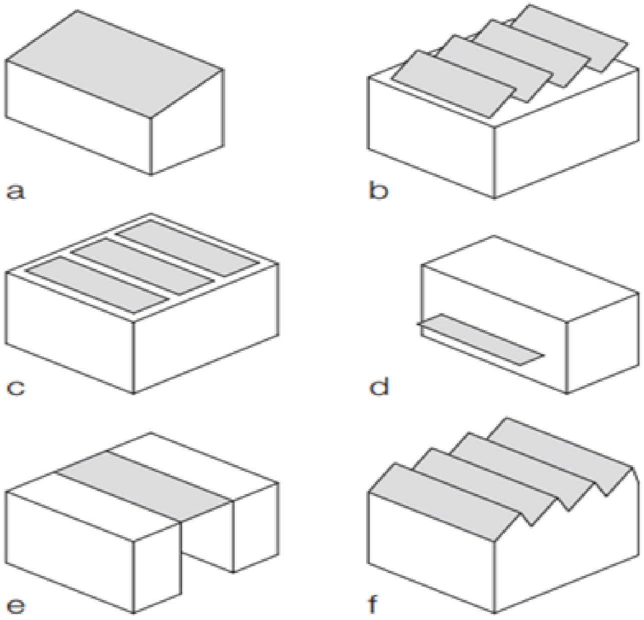


Figure 3.3. Preferred roof areas for PV applications a) Pitched roof, b) Flat roof, stand-off mounting, c) Flat roof, as roof waterproofing, d) Canopy, e) Atrium roof, f) Sawtooth roof (Weller et al., 2012)

Rooftop PV installations are broken down into stand-off and integral systems depending on the nature of the constructional integration. In a stand-off system the PV modules are supported clear of the roof on separate loadbearing supports. Contrasting with this, in an integral system PV elements replace the conventional roof covering. Complying with stability requirements is critical; the individual parts of PV installations as well as the installation as a whole must be stable. With existing roofs in particular, the roof structure must be able to carry the additional loads and transfer them to other parts of the structure (Gul, 2016).

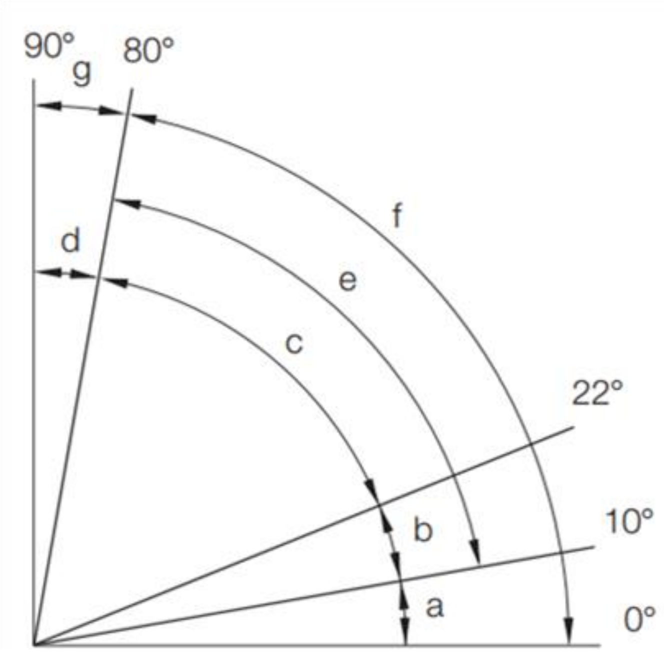


Figure 3.4. Classification of roof areas and allocation according to building legislation, a) Flat roof, b) Shallow pitched roof, c) Steep pitched roof, d) Façade, e) Pitched roof, f) Overhead glazing, g) Vertical glazing (Weller et al., 2012)

3.3.1 Flat Roof

Flat roofs potentially offer ample space and have a number of advantages in terms of planning. As a rule, there is a certain freedom of choice regarding the exact inclination and orientation of the essentially south-facing PV modules Reijenga and Kaan, (2011). The roof waterproofing is generally at the water run-off level and in the form of bituminous or synthetic sheeting. However, such forms of waterproofing are vulnerable to damage and great care must be taken because even minor damage can lead to leaks and moisture problems. A PV installation mounted on a flat roof does curtail accessibility for roof maintenance and repairs. For this reason, prior to installing a PV system it should be ensured that the roof will remain functional over the service life of the installation. The free-standing system is worthwhile when the roof structure has enough loadbearing reserves or the PV installation has already been taken into account in the structural analysis. In this approach the construction supporting the PV installation is held in place by additional ballast in the form of concrete paving slabs, concrete sleepers or loose gravel fill, an arrangement that avoids having to penetrate the waterproofing materials. If there is already gravel on the roof to protect the waterproofing, this can be used as ballast (Weller et al., 2012).

Gravel-filled trapezoidal profile sheeting or trough systems can serve as a counterweight to prevent wind uplift (Figure 3.5). Where the roof construction has a higher loadbearing capacity along certain axes, concrete plinths represent a better solution. On flat roofs where point loads can be better accommodated, concrete paving slabs are to be preferred. Whatever the form of support, protective sheeting must be laid underneath to protect the waterproofing materials against damage by the framework supporting the PV installation.

If the free-standing method is unsuitable for structural reasons, a fixed anchorage system is the best choice. In such systems each row of modules is generally supported on a grid of members (often a type of grillage) erected in situ. These in turn rest on a row of individual supports which penetrate the roof covering and are permanently connected to the structure below (Figure 3.6).

The PV modules are arranged in rows for both the free-standing and anchorage methods. Sufficient clearance between the rows is essential in order to avoid one row of modules casting a shadow on another row. The spacing of the rows depends on the width of the modules, the mounting angle and the lowest elevation of the sun at which shadows are undesirable.

Figure 3.5. Free standing PV on roof (http://www.greenbuildingenergysavings.com)

Figure 3.6. PV on roof with tubular section (http://www.greenbuildingenergysavings.com)

For planning purposes, the angle of the sun at 12 noon on 21 December has proved useful as the so-called shading angle; this angle varies between 12° and 19° in Germany depending on latitude, but an average value of 15° can be assumed for simplicity. So with an ideal mounting angle of 30° the rule of thumb is a module spacing of three times the module width (Figure 3.7), which means that the area of the roof must be greater than the total area of the modules that are to be installed (Weller et al., 2012).

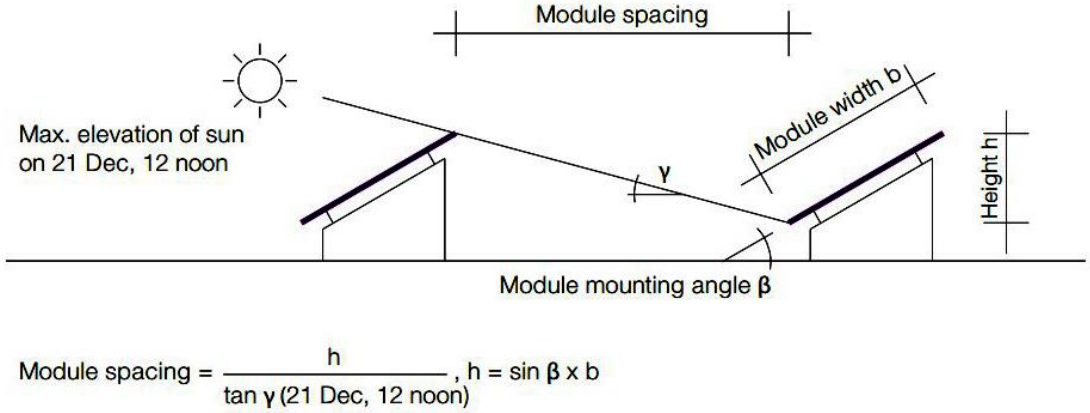


Figure 3.7. Calculating the module spacing for rows of PV modules on a flat roof (Weller et al., 2012)

3.3.1.1 Opaque Flat Roof

Weller et al. (2012) opines the possibility to use crystalline modules with plastic substrates allowing a seamless integration on the roof with an adhesive backing (Table 3.1). Thin-film technologies have an array of different flexible laminates, with plastic or stainless steel substrates, that can be easily mounted on flat roofs. Water proof membrane is also commonly used as a support on which flexible thin-film laminates are glued. This can serve as a simple and economic integration possibility. It is however important to use module substrates that are in compliance with the fire-fighters requirements.

Table 3.1. Opaque flat roof systems (http://www.greenbuildingenergysavings.com)

Product	Special rack system for flexible laminate on stainless steel substrate	Powerply monocrystalline module with plastic substrate	flexible laminate on metal substrate
Image			
Producers	Unisolar. Centre	Lumeta Solar	Kalzip

3.3.2 Pitched Roof

Building-added PV systems are often used on shallow and steeped pitched roofs especially in case of retrofit systems. When using this solution, there is often the need for an additional mounting system in most cases of the reinforcement of the roof structure because of the additional loads. In contrast to a flat roof, the angle and orientation of PV modules on a pitched roof are determined by the roof surface itself. The south-facing surfaces of pitched roofs represent those surfaces of the building envelope with the highest energy yields for PV systems. This fact has led to the appearance of a multitude of different fixing systems for new and existing buildings. Roof surfaces facing south-east or southwest, although not optimal, are still suitable. Dormer windows or structures that penetrate and rise above the roof covering diminish the yield if they cast shadows on the PV installation. Traditional roof structures generally have enough loadbearing reserves to enable the addition of a PV installation to an existing roof. A structural engineer should be consulted in cases of doubt and where roofs are possibly on the limit of their loadbearing capacity. As with flat roofs, PV installations can be erected on pitched roofs according to two principles: the stand-off system and the integral system. Sometimes, the aesthetics of the building-added PV systems on the roof is highly criticized . As a result, the market is compelled to provide building-integrated products that replace all types of traditional roof claddings, especially for special contexts, such as historic centres.

3.3.2.1 Opaque Pitched Roof

Pitched roof products for architectural integration are either opaque or semi-transparent. Several opaque roof products have been manufactured with crystalline and thin-film technologies for roof tiles, shingles and slates that are aesthetically similar to common roof products. Table 3.2 shows available products in the market today.

Table 3.2. Commonly used opaque pitched roof products (http://www.greenbuildingenergysavings.com)

Product	semi-transparent modules (crystalline cells)	semi-transparent module with a stripe pattern of crystalline cells	semi-transparent thin-film modules
Image			
Producers	Ertex Solar	Atlantis Energy Systems	Onyx Solar

3.3.3 Stand-Off Systems

The stand-off installation requires a metal supporting construction above the existing roof covering. In this case a fully functioning, separate roof covering is necessary. Systems consisting of aluminium or stainless steel rails enable quick erection and render the PV installation independent of the grid of the roof structure. The minimal erection work involved with stand-off systems makes them the least expensive variant for a retrofitted PV system on an existing roof. Ventilation below the PV modules is generally good, which boosts their conversion efficiency. The actual mounting system for a stand-off construction consists of three main components: the roof fixings, the mounting rails and the module fixings.

3.4 Façade Integration of Photovoltaics

In the past, facade constructions were essentially passive components from the energy viewpoint. Maximum thermal insulation was intended to minimize the energy flows between interior and exterior. Maximizing the solar gains in winter through transparent components also represented a passive use of solar energy. But thanks to photovoltaics we are now able to shift from a passive to an active approach and exploit the substantial energy potential of facade surfaces. Although vertical surfaces are not ideal in terms of their orientation and are associated with lower yields, when PV elements also provide other facade functions, these deficits can be offset. The following forms of construction can be used for an extensive use of PV elements on part of the facade and open up numerous applications:

- Cladding plus ventilation cavity

- Post-and-rail facades

- Double-leaf facades

- Prefabricated facades

According to the review performed by experts of IEA Task 41, the general way by which PV is used on facades in buildings are; opaque facades, and semi-transparent facades (IEA, 2012). In what follows, the opaque facades are grouped into two categories: 'cold' (those for which a back-ventilated layer supplies necessary weather protection) and 'warm' facades (those for which a non-back-ventilated layer supplies necessary weather protection).

3.4.1 Opaque Cold Facades

In opaque cold facades, the PV panel is usually used as a cladding element. The cladding (PV) is hanged on a substructure anchored to the load-bearing wall. In these scenarios, the PV performance can deploy its back-ventilation, to reduce the operating temperature of the PV. They are often based on solar cells (e.g. Si-PERC) which are highly efficient, covered with a special layer (e.g. printed on the glass). South-facing cold facades, i.e. with a ventilation cavity, are preferred for PV applications. In these designs the PV modules replace the exterior cladding and provide the weather protection. The remaining elements such as thermal insulation, loadbearing structure and anchorages are the same as for a conventional design (Figure 3.8 and 3.9).

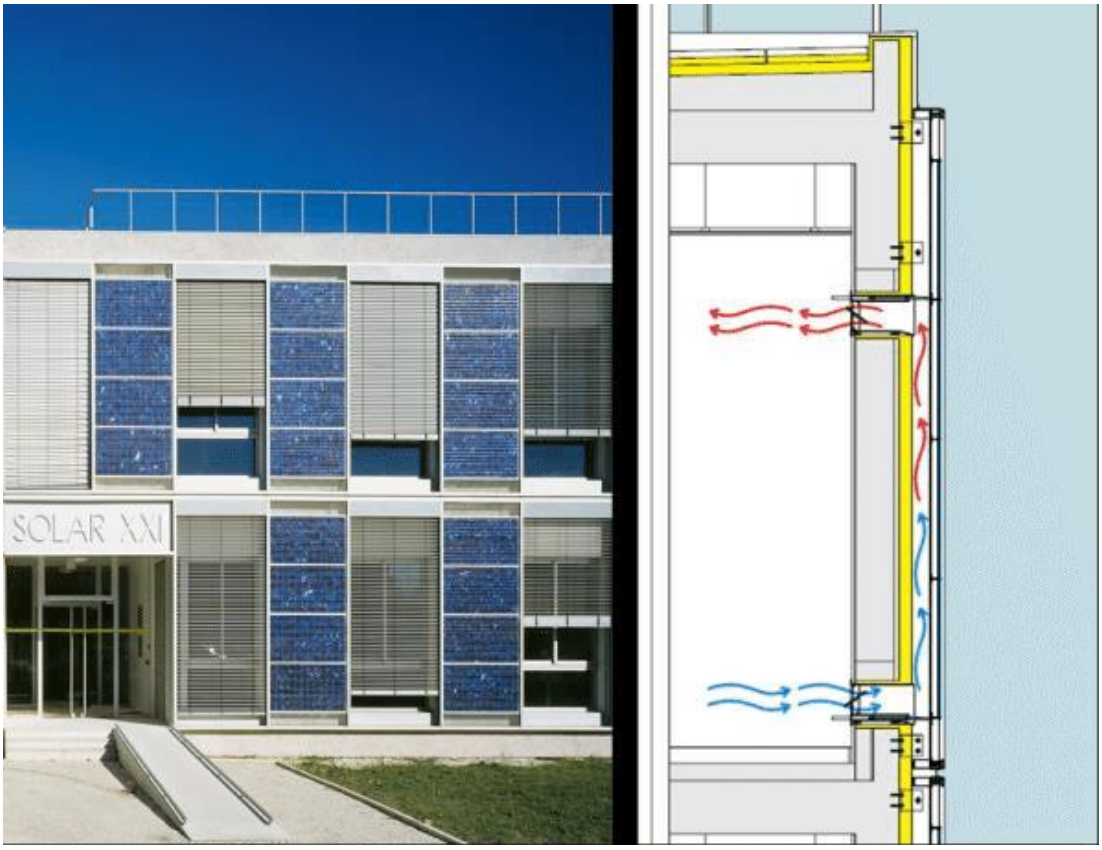


Figure 3.8. Example of a PV facade with framed thin-film modules
(Aelenei et al, 2013)

Figure 3.9. 41 Active energy façade (Kulka, 2007)

3.4.2 Opaque Warm Facades

These are faaced that provide the dual function of weather/ acoustic protection as well as thermal insulation (Sonnenenergie, 2007). Curtain wall systems fall into this category (Table 3.3) and can be used for PV integration. In this scenario, the PV can either be integrated on the semi-transparent PV or on the spandrel (the opaque part). If the sprandel is used, depending on the PV technology adopted, it might be important to foresee a PV back-ventilation.

3.4.3 Semi-transparent Façade

This type of PV panels can be integrated into parts of the building that are semi trasnarent, most often on the façade fo the building. (Table 3.4 and Figure 3.10).

Table 3.3. Opaque warm facades (http://www.greenbuildingenergysavings.com)

Project/ Location	Zara Fashion Store of Cologne, Germany	GDR Headquarter, Spain	Zwolle multi-storey parking, the Netherlands
Description	Opaque monocrystalline cells combined with transparent glazing in post-beam curtain wall structure	thin-film modules	thin-film modules
Image			
Producers	Solon. Centre	Onyx Solar	Schott Solar

Table 3.4. Semi-Transparent Façade (http://www.greenbuildingenergysavings.com)

Description	crystalline glass modules	crystalline glass modules	semi-transparent thin-film modules
Image			
Producers	Issol. Centre	EnergyGlass	Sanyo

One crystalline cell, which is one with grooved holes in the cell, can also be semi-transparent. Thin-film modules can be used to create transparency by adding a grooved pattern to the strip of the cell, to create a fine patterned surface that is unique to the thin film panel (IEA, 2012). However, this is rarely used because of its costs.

3.5 Photovoltaic Sun Shading Devices

Photovoltaics can be integrated on the building skin as shading devices, louvres or canopies, movable shutters, parapets, balconies and in general as architectonical elements added to the building (Figure 3.11 to 3.13). Shading systems are the most commonly used. Semi-transparent glass–glass components with semi-transparent crystalline or thin-film are very often used. Glass semi-transparent modules that are made of security glass are often used on balconies. Opaque systems are also widely used.

Figure 3.10. Example of a structural sealant glazing facade with PV modules in the form of insulating glass units (Pierre, 2003)

Figure 3.11. Typical examples of sun shading devices (Pierre, 2003)

.
Figure 3.12. Louvre-type sunshades fitted with PV cells (Pierre, 2003)

Figure 3.13. Combination of coloured louvres and PV elements (Pierre, 2003)

Photovoltaics and sunshading elements are ideal partners. At the same time, this means an optimum orientation for PV elements and hence improved shading in conjunction with maximum energy yields. The good ventilation below the modules also helps to maximize the amount of solar electricity generated.

3.6 Key Factors in PVSDs in Residential Buildings

Over the years, several strategies have been proposed that promote the use of PV systems within the residential housing stock. According to James et al. (2011), "declining module cost, growing consumer interest in solar energy and policy schemes" are some of the key factors to put into consideration. Other major factors that influence the generation and consumption of energy include the location and climate data of the building, the orientation of the building, installed materials, building design and the selection of the technical systems. In this section, some of the important factors are discussed.

3.6.1 Cost

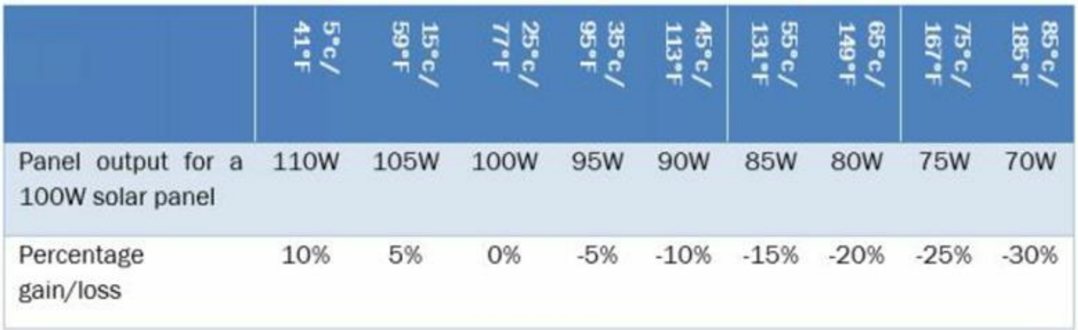
According to Boxwell (2017), solar modules are now 24% more efficient than when they were first introduced to the market, and their prices have dropped significantly. It also now has a longer life expectancy than previous years. 1 kWp capacity PV modules will cost £400 ($530) if redesigned and produced with more efficient solar cells (ignoring twenty years of inflation). In fact, the prices of solar panels have dropped to less than one-sixth its price almost one decade ago (Boxwell, 2017). Boxwell (2017), also pointed out the need for consumers to imbibe a sustainable lifestyle which includes avoiding wasteful use of electricity and encouraging the use of appliances that consume less energy. Though solar electricity might not generate enough electricity to power the average family home it can at least serve as alternative energy for the house. From the finding, consumers seem to prefer a price lower than €4500 for a 3 kWp integration of solar power equipment to their apartments in Famagusta.

3.6.2 Orientation

Orientation and the positioning of solar panels in a building is another very critical factor to consider in BIPV. For buildings located in the northern hemisphere, solar panels should face the south to get the best output. While in the southern hemisphere, the panels should be integrated towards the north for best performance, although it is not often possible to position solar panels such that they align perfectly towards the sun because of the varying nature of the building form. For example, if solar panels were to be integrated into the roof of an east/ west facing building, the efficiency of the panels will be low. While the efficiency of panels varies from region to region and from one producer to another as well as from one season to another, the average efficiency reduction for solar panels positioned away from the south façade in the northern hemisphere or due north in the southern hemisphere is about 1.1% for every 5 degrees. Boxwell (2017) noticed a 20% drop in efficiency for panels position away from the south and towards the east and west direction, and a 40% loss for panels facing the north direction.

3.6.4 The Effects of Temperature on Solar Panels

Excessively high temperature does affect the efficiency of PV panels. Boxwell (2017), opines that solar panels are less efficient in areas where the temperatures are extensively high compared to those of moderate temperature. To ensure that the temperature of solar modules is properly moderated, the panels should be well ventilated by allowing a free flow of air both below and above the panels. Usually, a space of about 7 to 10cm below roof-mounted PV panels is sufficient enough to allow for a free flow of air. To determine the wattage of the solar module, it is usually tested at 25°C (77°F) against a 1000 w/m^2 source of light (Figure 3.15).



	5°c/ 41°F	15°c/ 59°F	25°c/ 77°F	35°c/ 95°F	45°c/ 113°F	55°c/ 131°F	65°c/ 149°F	75°c/ 167°F	85°c/ 185°F
Panel output for a 100W solar panel	110W	105W	100W	95W	90W	85W	80W	75W	70W
Percentage gain/loss	10%	5%	0%	-5%	-10%	-15%	-20%	-25%	-30%

Figure 3.15. Temperature of solar panels (Boxwell, 2017)

3.6.5 Dimensions and Efficiency

1 m^2 of amorphous solar panel generates about 60 W of electricity, while 1 m^2 of crystalline module generates about 160 W Therefore, to generate 320 W electricity, between 5.0 m^2 and 7.6 m^2 will be required for amorphous and 2–3 m^2 area for monocrystalline.

3.6.6 Angle of Inclination

Some angles provide better performance during the summer months; others provide better performance in the winter months, whilst others are able to provide a good compromise all-year-round solution (Boxwell, 2017) (Figure 3.16). in order to deeply understand the different possibilities for the architectural integration of PV in single family detached housing units, a study of different approaches is presented in Table 3.5.

Table 3.5. Different types and methods of PV integration to the building envelop

Position on building/ Method (references)		Image	Description of method
FLAT ROOF INTEGRATION METHODS	Flat roof parallel installation (Josef and Heinz, 2012)		The PV is mounted on a welded or bonded to a frame directly connected to the roofing membrane. This method makes the PV less visible to onlookers and exerts less impact on the urban pattern. Advantages are: high covering rate, superior wind performance, natural ventilation and "out of water solution"
	Opaque Flat Roof free standing roof (Josef and Heinz, 2012)		freestanding Concrete plinths method of integrating standard pv module on a flat roof the advantage of using this method is the fact that the modules can be arrayed to the orientation of the building conveniently

Continuing Table 3.7.

FLAT ROOF INTEGRATION METHODS	Opaque Flat Roof free standing roof (Josef and Heinz, 2012)		PV integrated on flat roof using racking system to mount the modules
	Opaque Flat Roof free standing roof (Josef and Heinz, 2012)		An array of PV modules installed on a large raking system inclined towards the south. This installation lack proper architectural properties

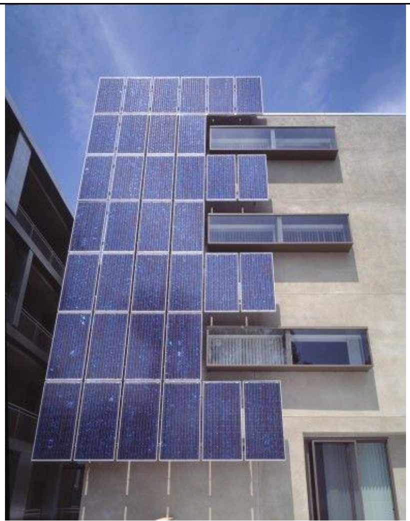
Continuing Table 3.7.

FLAT ROOF INTEGRATION METHODS	Translucent Flat Roof		semi-transparent module with a stripe pattern of crystalline cells. This method uses steel frames as support for the PV.
	Membrane integrated PV (Josef and Heinz, 2012)		This method of combines the functions of energy generation and water proofing

Continuing Table 3.7.

PITCHED ROOF INTEGRATION	Skylight/ roof window and PV on pitched roof		PV modules integrated to a pitched roof using a horizontal rail and roof anchor to hold it in place. A window on the roof was architecturally integrated
	Opaque Pitched Roof (http://www.solarprofessional.com)		PV modules integrated to a pitched roof using a horizontal rail and roof anchor to hold it in place. The carefully design rail and anchors make the integration seamless

Continuing Table 3.7.

PHOTOVOLTAIC FACADES	Opaque cold facades		PV panels integrated on the south facing façade of this residential building using a frame structure to attach standard PV modules. The method of integration is not excellent but quite commendable.
PHOTOVOLTAIC SHADING DEVICES	Solar PV canopy		Transparent PV Module used o wooded noggin to cover porch area of a residential building. The PV solar cells were spaced to allow for penetration of solar radiation.

Continuing Table 3.7.

PHOTOVOLTAIC SHADING DEVICES	Photovoltaic roof and Shading device system(http://www.nydailynews.com)		Robert Scarano's Bright 'n Green project in Brighton is a good example of how PV modules can be integrated as shading device in a residential building. this was done using steel frame to form the frame along the sides of the walls to receive the PV panels.
	Semi-transparent Skylight integration		Light roofs in the form of glass domes, arcades, pyramids and round arches can be realized with solar PV panels. This sky light was constructed on a well design metal frame.

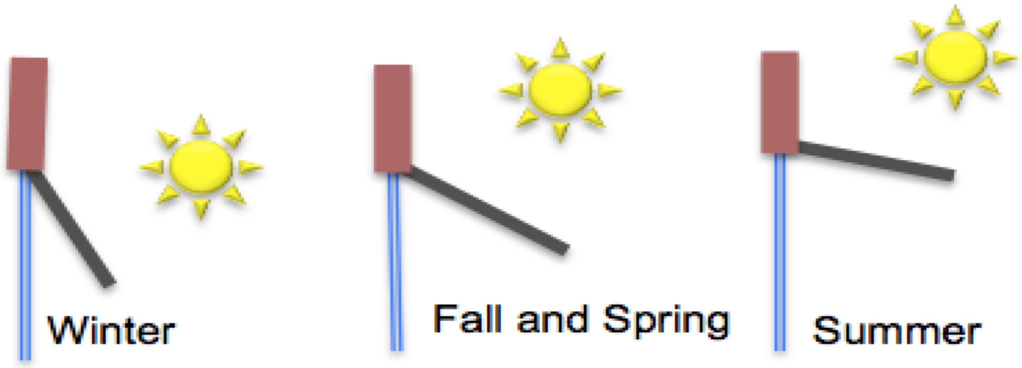


Figure 3.16. Different Inclination of PVSDs

3.7 Conclusion

This chapter of the thesis discussed the different integration possibilities on the building skin and how to integrate and install PV into each surface without damaging the architectural quality of the building. the main suitable surfaces of the building envelope namely; roof, façade and sun shading devices, and nature of materials that best fit these surfaces were discussed and categorized.

Chapter 4

CASE STUDIES OF ARCHITECTURAL INTEGRATION OF PV IN SINGLE FAMILY BUILDINGS

4.1 Introduction

This chapter shows a collection of ‘ordinary BIPV high-quality examples’ of single family homes realized in different regions of the world. The case studies and were selected so that their strategies of integration can be identified so that they can be easily replicated in other regions. In doing this case study, the EN standard 50583:2016 of categorization as well as the Reijenga Classification was used to evaluate the architectural aspects of the cases. They include several kinds of architectural aspects of PV integration on buildings. A detailed description of each case study is provided in order to evaluate the BIPV projects from different points of view. In conclusion, a table containing the entire study was formulated by the author.

4.1.1 Aesthetics and Integration Aspects

The IEA-PVPS Task have been able to compile a list of essential criterial that should be considered in order to achieves an acceptable level of aesthetic integration of PV in buildings (Maturi and Adami, 2018), and they are summarized (Figure 4.1):

- Naturally integrated:

the PV system constitutes a natural part of the building. It completes the building such that removing the PV would result in the building lacking something.

- Architecturally pleasing: based on a good design, the PV system enhances the architectural features.

- Good composition: there is a good blend of the colour and texture of the PV with other materials.

- Grid, harmony and composition: the building sizing and grid is equal to that of the PV system.

- Contextuality: the BIPV concept and complete view of the building is in harmony.

- Well engineered. The elegance of design details are well conceived; the amount of materials is minimized.

- Innovative new design.

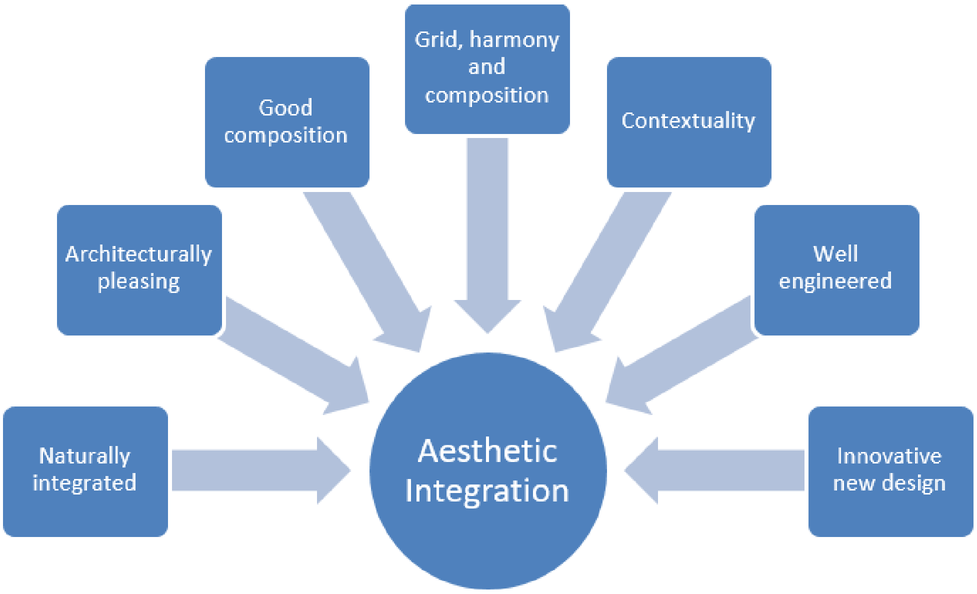


Figure 4.1. Aesthetic integration of photovoltaics (Maturi and Adami, 2018)

In order to get the best out of the case studies, we evaluated the individual cases along the following aspects:

Overall impression global approach, considering:

- The approach adopted when integrating the PV into the whole concept of the building and its contribution to preserving architectural quality.

- The concept of the entire building.

- Texture of the surface, the makeup of the seen material, colours correlations, details which focus on design, joint, fixings which are new.

Lessons learnt, considering:

- How interesting the PV integration experiment was beyond the results achieved.

- Lessons to learn from the PV integration Innovative architectural concepts, solutions, and applications that were adopted.

The case studies were analysed based on the EN standard (Maturi and Adami, 2018) (Figure 4.2 and Table 4.1).

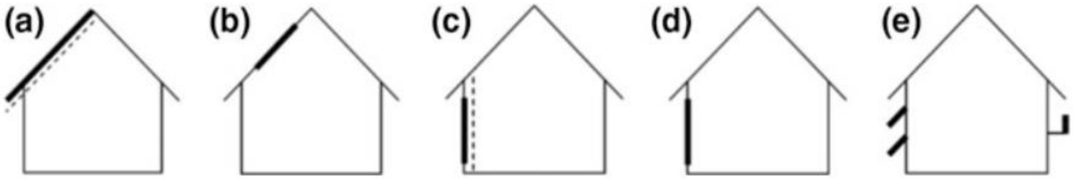
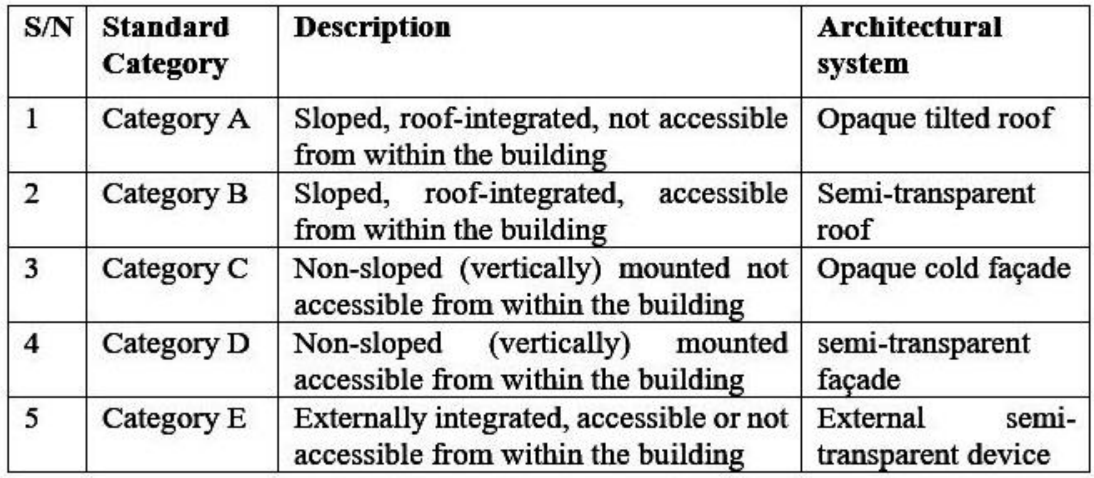


Figure 4.2. EN Standard for PV Integration (Maturi and Adami, 2018)

Table 4.1. PVs in building categories, description and architectural system (Maturi and Adami, 2018)



S/N	Standard Category	Description	Architectural system
1	Category A	Sloped, roof-integrated, not accessible from within the building	Opaque tilted roof
2	Category B	Sloped, roof-integrated, accessible from within the building	Semi-transparent roof
3	Category C	Non-sloped (vertically) mounted not accessible from within the building	Opaque cold façade
4	Category D	Non-sloped (vertically) mounted accessible from within the building	semi-transparent façade
5	Category E	Externally integrated, accessible or not accessible from within the building	External semi-transparent device

4.2 Building Integrated Photovoltaic Idea, Criteria and Definition

At the international level, the recent standard EN 50583-1:2016 ‘Photovoltaics in buildings’ CENELEC (2016), recommends that photovoltaic modules can be termed well integrated when the PV panels acts as a construction material (Maturi and Adami, 2018).

4.3 Case Studies

4.3.1 Single Family detached home in Mittlere Schurwald, Germany

This single family house was constructed in Mittlere Schurwald nature conservation area in Germany (Figure 4.3 and Table 4.2). The standard roofing slope required by the local development plan was 20° to 35° slope, the building needed to have a slope of 18° to achieve maximum efficiency. The local council approved the 18° slope. A total of 66 PV modules were used to generate the whole energy requirement for the building. The architectural integration of the pv panels was well done. Serious consideration was given to the architectural aspects of the building. this can be seen in the color and texture blend of the roof; the shape of the panels was done to match the existing roof covering (Maturi and Adami, 2018).

Figure 4.3. The Private house in Hegenlohe with PV integration
(Maturi and Adami, 2018)

Table 4.2. Showing the technical details of the case study (Weller et al., 2010)

Project	Private house in Hegenlohe
Location	Germany
Size of installation	120 m^2
(Rated) power output	12 kWp
Orientation, angle	south-west, 18°
Yield	approx. 11 000 kWh /a
CO_2 saving	approx. 6400 kg/a
Architectural integration system	Opaque tilted roof (category A)
Modules	bespoke production
Number	66
Dimensions	1700 ≈ 1000 mm and 1750 ≈ 1000 mm
Configuration	frameless glass/plastic laminate
Manufacturer	Sunset Energietechnik, Adelsdorf
Cells	polycrystalline, dark blue
Manufacturer	unknown
Special	features German Solar Prize 2005

4.3.2 The Eco Terra house, Quebec, Canada

The Eco Terra house is a two storey single family detached house located in Eastman, Canada (Figure 4.4 and Table 4.3). The home was built on a 1.1 ha rural lot of a new mass housing development in Eastman, Quebec. The house was designed with the intention to combine energy-efficient construction techniques and renewable energy systems to achieve Canada's energy efficient guide.

Figure 4.4. The Eco Terra house in Eastman, Canada (Noguchi et al., 2008)

Table 4.3. The table contains the technical information of the Eco Terra house (Noguchi et al., 2008)

Project	Private house in Hegenlohe
Location	Eastman Canada
Size of installation	55 m^2
(Rated) power output	3 kWp
Orientation, angle	south, 30.3°
Yield	approx. 3,420 kWh /a
CO2 saving1	-
Architectural integration system	Opaque tilted roof (category A)
Modules	-
Number	22
Dimensions	-
Configuration	Unisolar amorphous silicon Sunset
Manufacturer	-
Cells	polycrystalline, dark blue
Manufacturer	unknown
Special	-

Several active and passive design strategies were use in the building to achieve a building that wholly generates the amount of energy it needs. The building was design with the architectural aspects in mind from the beginning. The colour and texture of the roof match well with the building, the shape and form of the module are also very appropriate (Noguchi et al., 2008).

4.3.3 The La Pedevilla Chalet, Marebbe, Italy

In this building which is located in Strada Pliscia 13, Marebbe, the pv was integrated into the wooden roof of the building roof of the residential building (Figure 4.5 and Table 4.4). the pv module is black in color, replacing the conventional roof board perfectly blending manner. The texture and shape of the building was considered in the integration process making the PV element to blend well with the building (Maturi and Adami, 2018).

Figure 4.5. La Pedevilla Chalet BIPV roofing system (Maturi and Adami, 2018)

Table 4.4. Technical detail of the building

Project	Private wooden stand-alone house
Location	Strada Pliscia 13, Marebbe (BZ)
Size of installation	43.3 m2
(Rated) power output	6 kWp
Orientation, angle	south,east 30.°
Yield	6,592 kWh
Architectural integration system	Opaque tilted roof (category A)
Number	25
Dimensions of module	1,016 X 1,704 mm
	-
Cells	Monocrystalline silicon, black
Manufacturer	Aleo Solar GmbH

4.3.4 Nest Home: 2015 Solar Decathlon

The Nest home is a creative design concept that was design to be environmentally friendly (Figure 4.6 and Table 4.5). The family buildings were made out of three containers connected together to form the building space. The designers were able to integrate about 24 PV arrays for energy generation. Building pays attention to the architectural aspects of the design. The colors, texture, shapes, and other architectural considerations were followed.

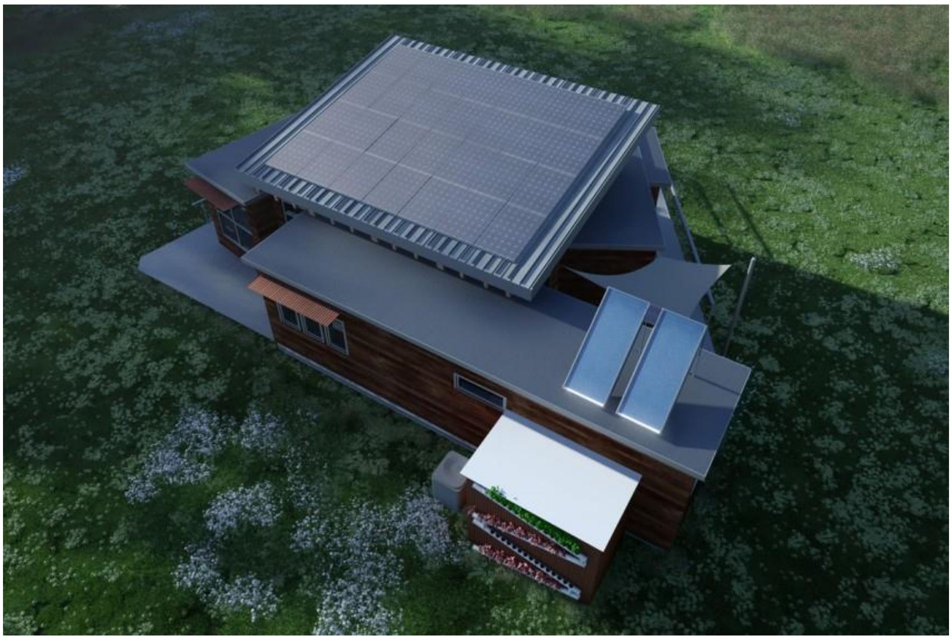


Figure 4.6. Nest Home Solar Decathlon (https://www.solardecathlon.gov)

Table 4.5. Technical Detail of the Building (https://www.solardecathlon.gov)

Project	Nest home, MISSOURI
Location	United states of America
Size of installation	-
(Rated) power output	7.14 kW
Orientation, angle	south
Module	24
Architectural integration system	Opaque tilted roof (category A)
Cells	Monocrystalline silicon, black
Manufacturer	LG
Special	Swiss Solar Prize 2011
Frame	Framed module

4.3.5 Single-Family House, Lasa

The PV system is integrated into a 2-storey residential building located in Val Venosta, Spain. The BIPV system comprises of a combination of the energy production functionality and an aesthetic aspect due to the refined design.

Figure 4.7. Single-Family House, Lasa (Maturi and Adami, 2018)

Table 4.6. Technical detail of the building (Maturi and Adami, 2018)

Project	Single family residential building, Lasa
Location	Spain
Size of installation	13 m^2
(Rated) power output	1.3 kWp
Orientation, angle	South 90°
Architectural integration system	External semi-transparent device (category E)
Modules Number Dimensions of module Configuration Manufacturer	- 24 1.120×1.905 mm, 1.120×2.005 mm - EnergyGlass Srl
Cells Manufacturer	Monocrystalline silicon, black EnergyGlass Srl
Special	Swiss Solar Prize 2011
Frame	Framed module

Table 4.7. The evaluation of the single family detached houses in terms of their architectural integration

	Case study	BIPV				Architectural Aspects																									**Score**
		Application				application						Building physics						Integration		Construction				Category		Reijenga Classification					
		Modules	Solar cell glazing	Foil	Tiles	Replacement of building component	On façade	On roof	On building component	Flexibility	Ease on application	Transparency	Thermal insulation	Noise reduction	Shading	Weather proofing	Structural integrity	Visible collector profile	Surface color texture	Prefabricated unit	Curtain wall	Customized design	Double envelope structure	New building	Renovation	1. applied invisibly	2. added to the design	3. Adding to the architectural image	4. determining architectural image	5. leading to new architectural concepts	
1	Private house in Hegenlohe	✓			✓			✓	✓		✓					✓	✓	✓	✓	✓		✓			✓		**5**	**5**			**good**
2	The Eco Terra house, Canada	✓						✓	✓				✓		✓	✓	✓	✓	✓	✓		✓		✓		**5**	**5**	**5**		**5**	**Very good**
3	Standalone villa, Strada Pliscia 13, Marebbe (BZ), Italy	✓						✓	✓							✓	✓	✓	✓						✓	**5**	**5**	**5**			**good**
4	Nest Home : 2015 Solar Decathlon	✓						✓	✓				✓			✓	✓	✓	✓	✓		✓		✓		**5**	**5**	**5**	**5**	**5**	**Very good**
5	Single family residential building, Lasa		✓			✓	✓				✓						✓	✓	✓	✓					✓		**5**	**5**		**5**	**good**

4.4 Reijenga Classification

From the case studies conducted above, it will be worthwhile to refer the classification system of Tjerk H. Reijenga with regards to the architectural integration of the PV in the cases studied above. In his study, he classified the level of architectural integration into 5 different levels, namely, 1. applied invisibly; 2. added to the design; 3. Adding to the architectural image; 4. determining architectural image; and 5. leading to new architectural concepts.

4.5 Conclusion

The results above indicate that building integration is possible in existing buildings. The case study also reveals the most popular integration is the BIPV technology of Modules and solar cell glazing. One of the important finding from the selected cases is that a number of the pv modules can be visibly added on existing roof without compromising the architectural quality, this is possible when the color, texture, shape and dimension of the module match the existing roof cover. Meanwhile, solar panels indicate the relative ease of integration, as well as weather proofing, noise reduction and shading possibilities very significantly. It is also remarkable that no technology offers high system panel transparency. Besides, the studies also reveals that the use of foil is still very rare even though it very easy to apply compared to the other technologies. It is also quite important to note that none of the technology makes significant contributions to the building's structure. Furthermore, it is quite obvious that the technology mostly used BIPV in single family detached housing units is the PV panel, tiles and the solar cell glazing. From the cases considered it is significant to note that there are free application of PV as shading device in single family detached houses in spite of its capacity to being used as both passive and active strategy. According to Florides et al. (2002), the cooling load of Cyprus is six times more than its heating load, it is therefore quite important to consider the use of active shading device which is a passive and active measure towards energy conservation for buildings.

Chapter 5

A DECISSION MAKING MODEL FOR THE INTEGRATION OF PV IN SINGLE FAMILY DETACHED HOUSING UNITS

5.1 Introduction

The chapter contains a proposed procedure for the integration of PV in single family detached houses. the model serves as a conceptual framework that cities in different parts of the world can follow to integrate PV in single family detached housing units in an architectural way. The model is developed based on a comparative analysis on existing models and a compressive literature review carried out on BIPV. BIPV is a multidisciplinary area of research that includes knowledge from various fields such as physics, electrical and mechanical engineering, planning and environmental management, architecture and urban design. Though not all of the afore mentioned factors are covered in this thesis, the essential elements and components that affect the aesthetics, energy generation, energy performance and technological aspects of BIPV were mainly considered.

5.1.1 Decision Making Model

Decisiom making model can be decribed as the process of choosing the best option out of several alternatioves. Decision making is a process we engage in in our day to day life. Making dicisions, be it at a personal level of at a cooperate level is a very important act that usually has long lasting consequences. Therefore, individuals, cooperate bodies and the government often do their due deligience when it comes to decision making, in other to avoid having to suffer from choosing the wrong approch that might result in problematic consequences. Accoeding to Hanh (2019). some of the commonly used decision making models include:

- Rational decision mking model

- Intuitive decition making model

- Creative decision making model

- Recognnition primed decisionmking model

5.1.2 Rational Decision Making Model

This study employs the rational decision making model. This model is a classic one consisting of eight (8) key steps (Hanh, 2019) (Figure 5.1).

In this model in order to develop the best decision option, a list of criteria which is used for the evaluation is developed. Hanh (2019) further stated that: “By adopting this model, the decision-makers have the opportunities to contemplate on what are the things that matter the most in their situation and select the choices that best reflect their standards. However, the problem of this model is the fact that people do not always know what they want or have enough information about the available alternatives, and usually, people end up just making a "good enough" or a safe-bet decision”.

Figure 5.1. Rational decision making model (Hanh, 2019)

5.1.3 A Decision Making Model for the Architectural integration of PV in Single Family Detached Family Housing Units

Though this area is an emerging field of research, there are a number of researchers from different fields who have written extensively on the subject and have been able to develop and propose various framework and models for the successful integration of PV in residential buildings. In developing the model for this study, the models/ theoretical frameworks referred to in this study include those proposed by Kosorić et al. (2018), Elinwa et al. (2017), Radmerhr et al. (2014), Abel et al. (2018), Kosoric et al. (2011), Ogbeba and Hokara (2019). The model design by Kosorić et al. (2011) presents the different levels involved for the integration of pv high-rise residential buildings in Singapore as shown in Figure 5.2.

Furthermore, a study carried out by Elinwa et al. (2017) evaluated the integration of PV in apartment buildings of Northern Cyprus. The study presents a framework that begins from a conceptual stage to an implementation stage, it also evaluated the willingness of people to pay for the integration of PV in their homes. An earlier study by the same authors had been carried out in 2014 (Radmehr et al., 2014) on the integration of PV in standalone villas of Northern Cyprus, the framework for these studies is shown in Figure 5.3.

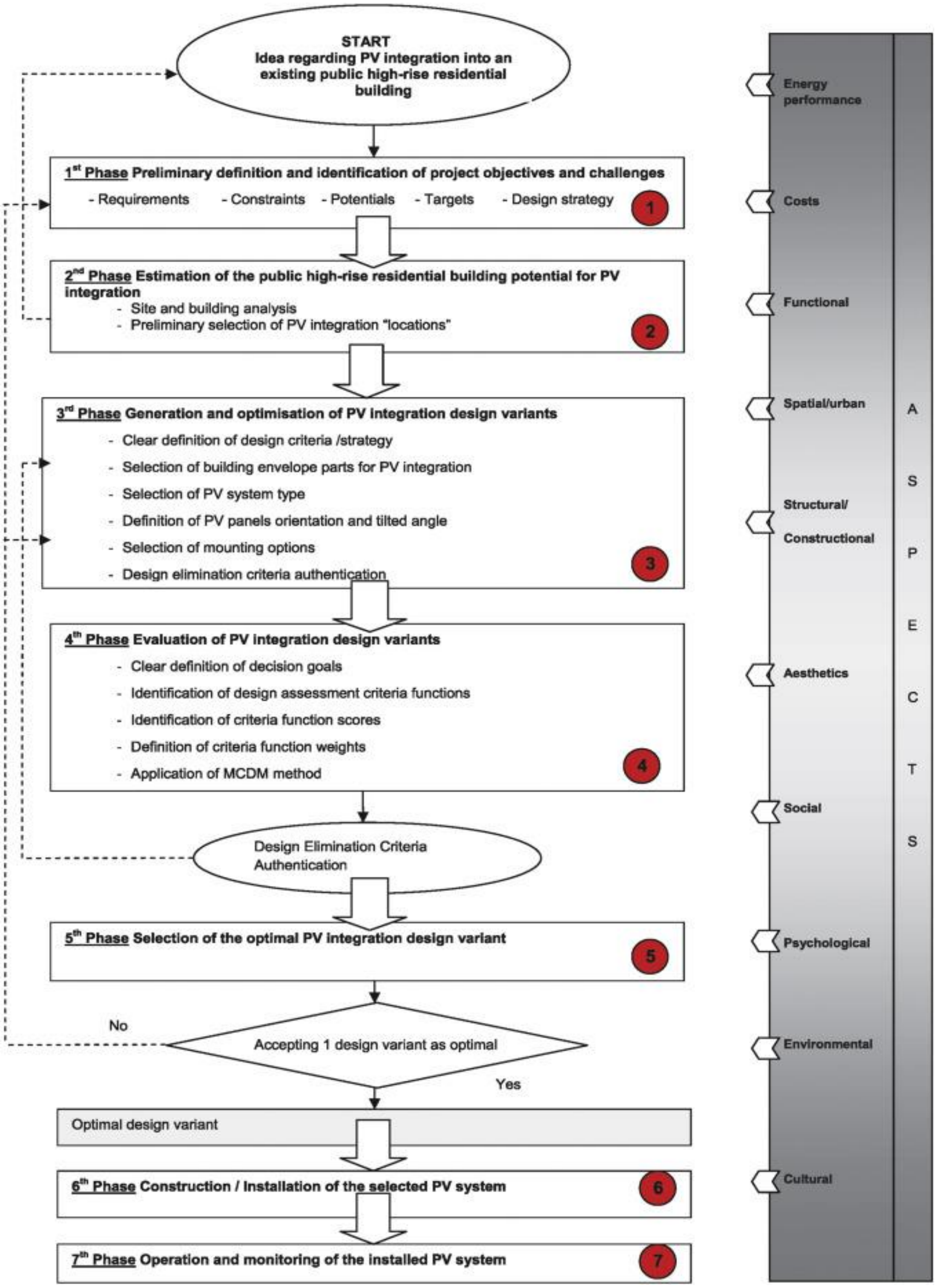


Figure 5.2. Model for the integration of PV into High-rise residential building in Singapore (Kosorić et al., 2018)

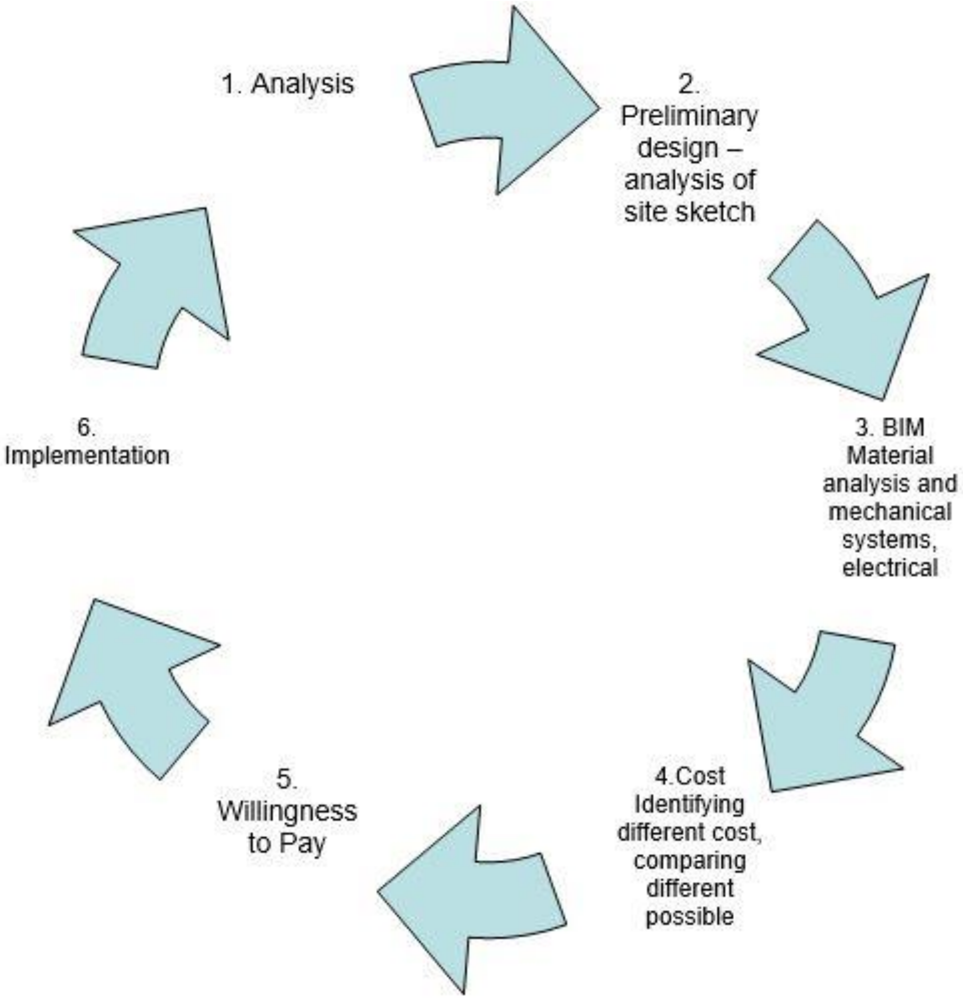


Figure 5.3. Proposed Model for Apartment building in North Cyprus (Elinwa et al., 2017)

The next model that analysed by this study is a model with three major stages, design for PV integration in buildings in Singapore. The model can be seen in Figure 5.4. It presents a design method for BIPV integration using a PV demonstration site in Singapore. It began with a concept for the integration of PV and ended with the development of a design which was considered to the best option for the successful integration of PV. The methodology used includes three major steps.

To form the new model as earlier mentioned, a process of comparing and contrasting a number of PV integration models was done and tabulated. Table 5.1 presents a summary of the factors that determine the architectural integration of PV in residential buildings from the perspectives of the different BIPV models proposed on literature. In the different models presented, the authors combine several essential components to make up the entire model. These different components come together to form the building blocks of the PV integration models and as such are very critical in carrying out a successful PV integration in detached family residential buildings. What is evident from the models studied is that firstly, there are a number of components that are very critical and should be included in any model that will be developed on how PV are to be integrated into residential buildings. Furthermore, the components that seem to be reoccurring are carefully integrated into the new model. The criterion used in developing the model includes selection if the components that are common in the model studied. Some other elements that were frequently mentioned in the literature review carried out by this study are included as well. From the combination of the key components in the studied model, the following seven stages of the models were developed for the new model.

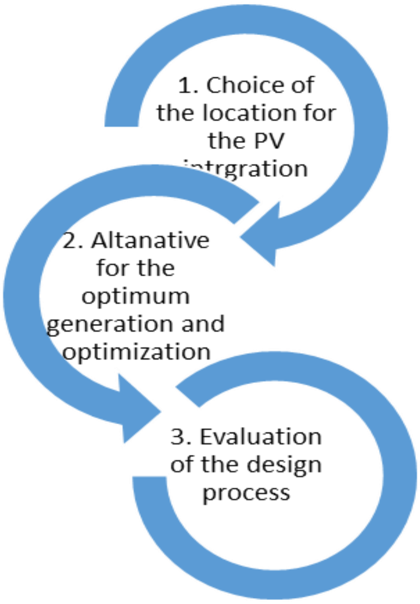
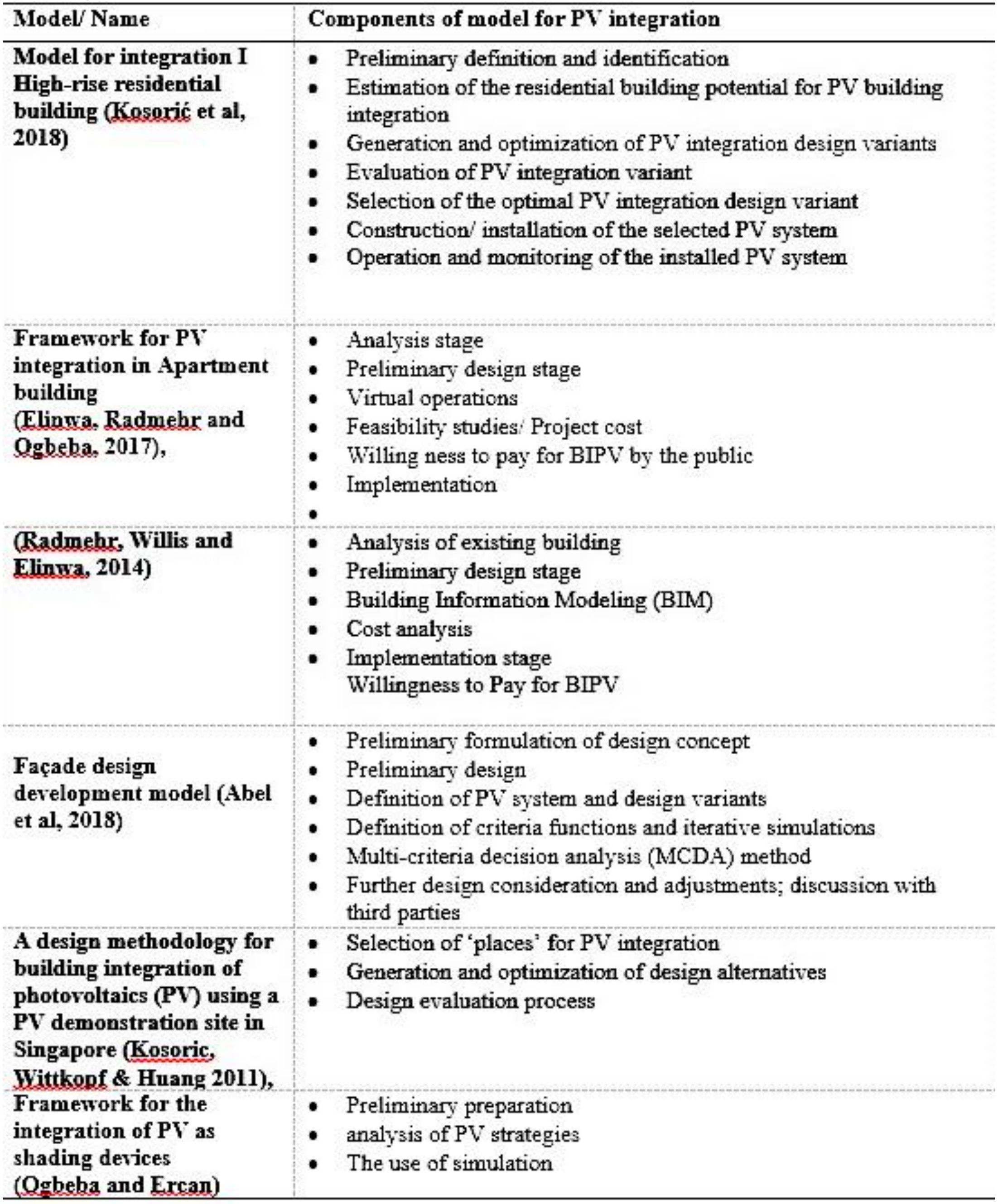


Figure 5.4. Model for BIPV in Singapore (Kosorić et al., 2011)

Table 5.1 BIPV models and their components referred to in the study for new and existing models



Model/ Name	**Components of model for PV integration**
Model for integration I High-rise residential building (Kosorić et al, 2018)	• Preliminary definition and identification • Estimation of the residential building potential for PV building integration • Generation and optimization of PV integration design variants • Evaluation of PV integration variant • Selection of the optimal PV integration design variant • Construction/ installation of the selected PV system • Operation and monitoring of the installed PV system
Framework for PV integration in Apartment building (Elinwa, Radmehr and Ogbeba, 2017),	• Analysis stage • Preliminary design stage • Virtual operations • Feasibility studies/ Project cost • Willing ness to pay for BIPV by the public • Implementation •
(Radmehr, Willis and Elinwa, 2014)	• Analysis of existing building • Preliminary design stage • Building Information Modeling (BIM) • Cost analysis • Implementation stage Willingness to Pay for BIPV
Façade design development model (Abel et al, 2018)	• Preliminary formulation of design concept • Preliminary design • Definition of PV system and design variants • Definition of criteria functions and iterative simulations • Multi-criteria decision analysis (MCDA) method • Further design consideration and adjustments; discussion with third parties
A design methodology for building integration of photovoltaics (PV) using a PV demonstration site in Singapore (Kosoric, Wittkopf & Huang 2011),	• Selection of 'places' for PV integration • Generation and optimization of design alternatives • Design evaluation process
Framework for the integration of PV as shading devices (Ogbeba and Ercan)	• Preliminary preparation • analysis of PV strategies • The use of simulation

The new model presents seven major stages for a successful integration of PV panels in single family detached housing units (Figure 5.5). This model contains all the necessary details that needs to be put into consideration from the preliminary stage of a project to the construction, putting into consideration the architectural aspects of a single family detached housing unit project. The seven stages for the successful integration of PV in detached family housing units will be discussed in the next sub headings.

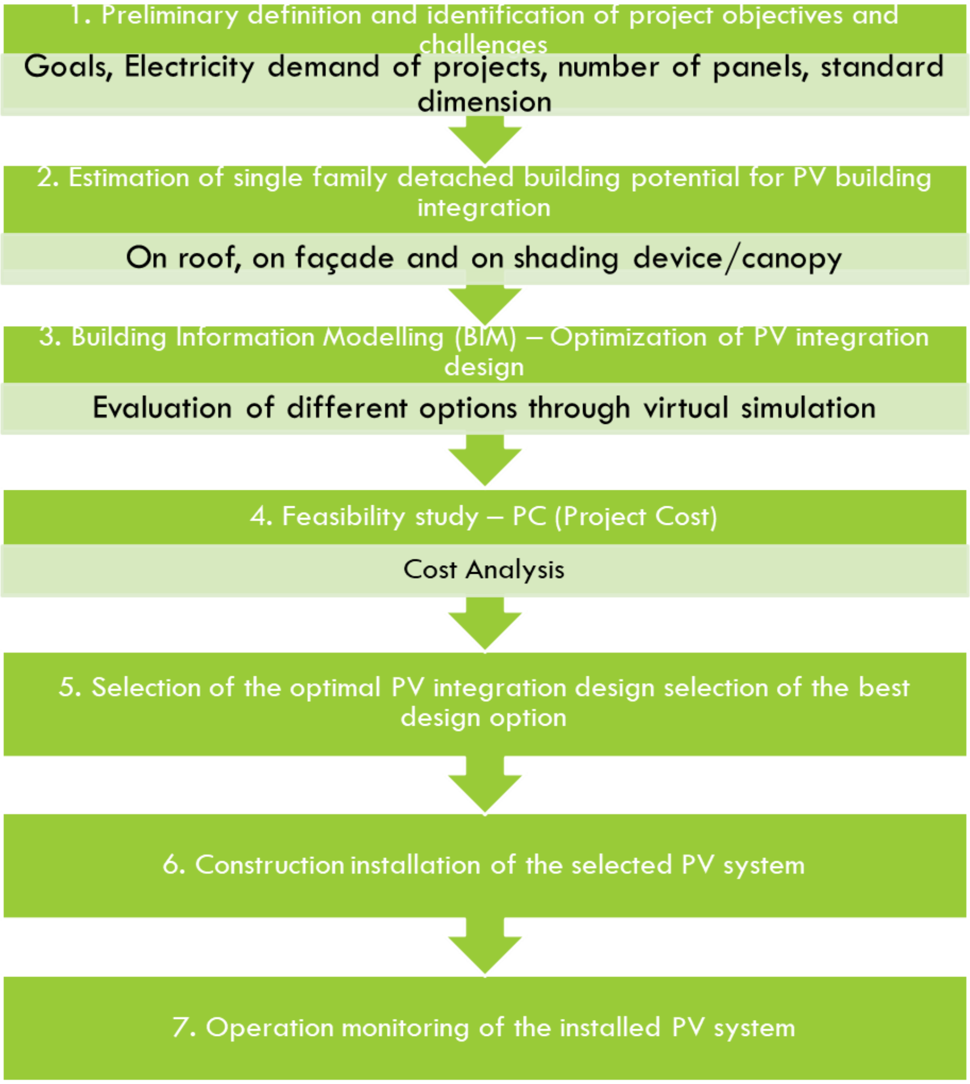


Figure 5.5. Essential components of the detached housing model as derived from studied existing model

5.1.4 Stage 1: Preliminary Definition and Identification of Project Objectives and Challenges

It is very important to define the goals, aim and objectives of the project at the beginning stage of the model (Figure 5.6). This helps to guide the expectations from the out of the project as the success of the project is dependent the clarity of its defined objectives. Here, a rough estimate of the entire project is evaluated, including other factors such as; requirements, constraints, potentials, target, and design strategies. The SWOT (Strengths, weaknesses, opportunities, and threats) analysis is introduced at this stage. The SWOT analysis methodology is used for this preliminary phase of the model to study the strength, weakness, opportunities ad threats to the installation of PV in the detached houses in N. Cyprus.

SWOT analysis (or SWOT matrix) is a strategic planning technique that aids a person or organization identify strengths, weaknesses, opportunities, and threats related to business competition or project planning (www.mindtools.com 2009). It enables users to specify critically evaluate the objectives, as well as the internal and external factors of the business venture or project that are aid or hinder the achievement of those objectives. Users of a SWOT analysis often need to ask and answer questions that aid the generation of meaningful information for each category. SWOT has been described as a very reliable tool for strategic analysis (Gregory, 2018). Strengths and weakness often relate to internal factors, while opportunities and threats commonly relate to the external factors. The name is an acronym for the four parameters the technique examines:

- Strengths: the advantages that the characteristics of the business has over others.

- Weaknesses: the disadvantages that the characteristics of the business has when compared to others.

- Opportunities: features of the environment that the business or project could take advantage of.

- Threats: features of the environment that can adversely affect the business or project.

The next important aspect of this first stage is the climatic and site analysis. Here the surrounding environment is carefully analysed to ensure that the shading from neighbouring buildings, trees and vegetation will not affect the building. the architectural and urban patterns of the neighbourhood is also very carefully studied so as to preserve the cultural and historic values of the community.

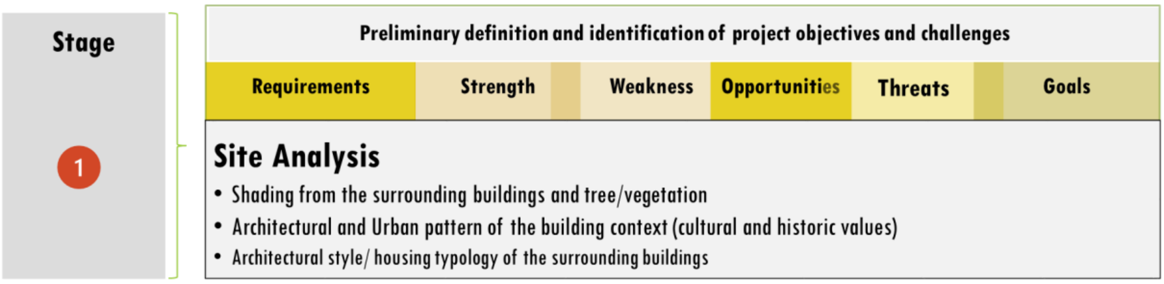


Figure 5.6. Stage 1: Preliminary definition and identification of project objectives and challenges

5.1.5 Stage 2: Estimation and Analysis of the Detached Family Building Potential for PV Building Integration

In this stage, the estimation and analysis of the detached family building potential for PV building integration is done under the following headings (Figure 5.7):

- Housing needs

- Energy saving measures

- Site context

For a design to be successful, the architect must pay attention and adhere to providing the spatial needs of the client in a healthy arrangement that projects good functionality. After the briefing and debriefing processes have been carried out, several options could then be considered as possible solutions for the spatial arrangement of the building. At this level consideration is given to using materials that have a strong ability to enhance energy conservation. Energy potentials can be maximized if the site context is studied adequately before proposing or choosing a best fit design for the project. The possibility of doing this without distorting the general aesthetics and architectural characteristics of the building is the main objective for the analysis in this stage. It further analyses the importance of introducing BIPV in single family detached housing units.

In this second stage of the process, the building location is analyzed alongside with the characteristics of the building. The analysis of the preliminary project objectives, addresses:

- Criteria for climate and urban planning e.g favorably oriented facades, shading effects on roof and facades,

- The capacity of residential building in terms of building size, consumption of electricity and architectural criteria relevant to BIPV - applicability on roof and facades, ease of mounting, spatial and architectural organization. Load bearing requirements are necessary for PV integration. Fig. 5.6 describes the task carried out in stage 2 of the model.

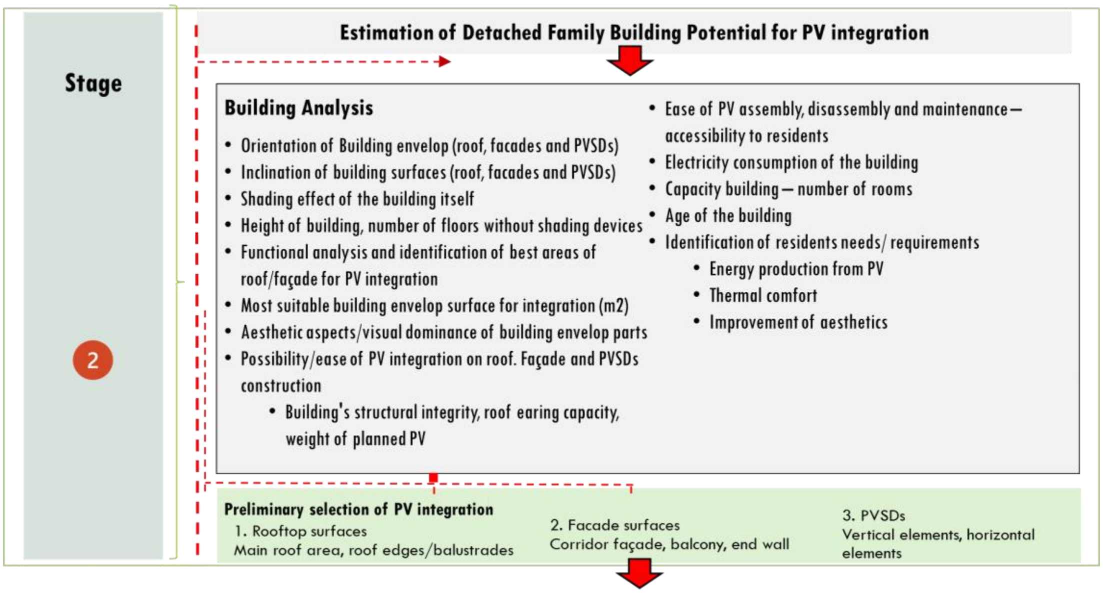


Figure 5.7. Estimation of the single family detached bulding potential for PV integration

5.1.6 Stage 3: Building Information Modeling (BIM) - Generation and optimization of PV integration design options

Virtual Operations:

- Simulation

- Testing of options

This procedure facilitates the adoption of the best environmentally friendly solution for BIPV integration. With this, several building options and materials can be tested using an element/component based integration approach (i.e. wall facades, roofs, shading devices) modelled on a virtual platform (BIM). If PV systems are carefully integrated into the building at the design stage using BIM, this will eliminate certain challenges such as additional cost, time and labour. Besides, the use of simulation will help designers develop passive design strategies that will lead to a reduction in the heating and cooling load of the building.

The design options development often commences with the selection of PV technology, the criteria for this choice is depends on the type of project, the objectives and some characteristics of the building envelope. The selection also depends design solutions, and the techno-economic and aesthetic characteristics of PV technology types available in the local market.

5.1.7 Stage 4 Evaluation of design alternatives and selection of the optimal design options

This stage begins with a general concept on how to integrate PV into the detached family building., thereafter, it concentrates of the individual components that makes up the building. Furthermore, the type of PV technology, the shape and dimensions, colours, transparency, texture, frame of the panel, angle of inclination etc, are all put into consideration as well. Often several options are explored and the results are analysed in order to optimize the design solution. The design phase consists of a sketch of different design options and the verification of the energy output, performed using energy simulation software. Final solutions represent a compromise shared between energy performance, costs and aesthetics.

5.1.8 Stage 5 Feasibility Study - PC (Project Cost)

After the best design solution have been selected, a feasibility study is done to analyze the total cost of the project, (i.e. from the design stage to the commissioning). Life cylle cost analysis (LCCA) is used for this process. This gives the contractor an idea of the viability of the project in order not to incur unprecedented losses resulting from the project. After carrying out a full assessment of the project, the potential users are also aware of the cost implications for choosing a particular solution and so they know what they stand to gain or lose.

5.1.9 Stage 6 and 7 Construction, Installation, Operation and Maintenance

Realization of the Project:

From the design stage, attention is paid to the building skin in order not to destroy the aesthetics of the façade. The goal of the designer is to make sure that the component based integration of the PV collectors leaves a clean and appealing finishing.

5.2 Conclusion

This chapter presents a decision making model for the architectural integration of PV in single family detached family units. The components of the model were introduced, then by putting the components together in stages the new model was sustained. Following this process, PV can be integrated into single family detahced family housing units in Northern Cyprus and in other parts of the world. This would make up the basis for the empirical investigations which are going to be reported in the next chapter (Figure 5.8).

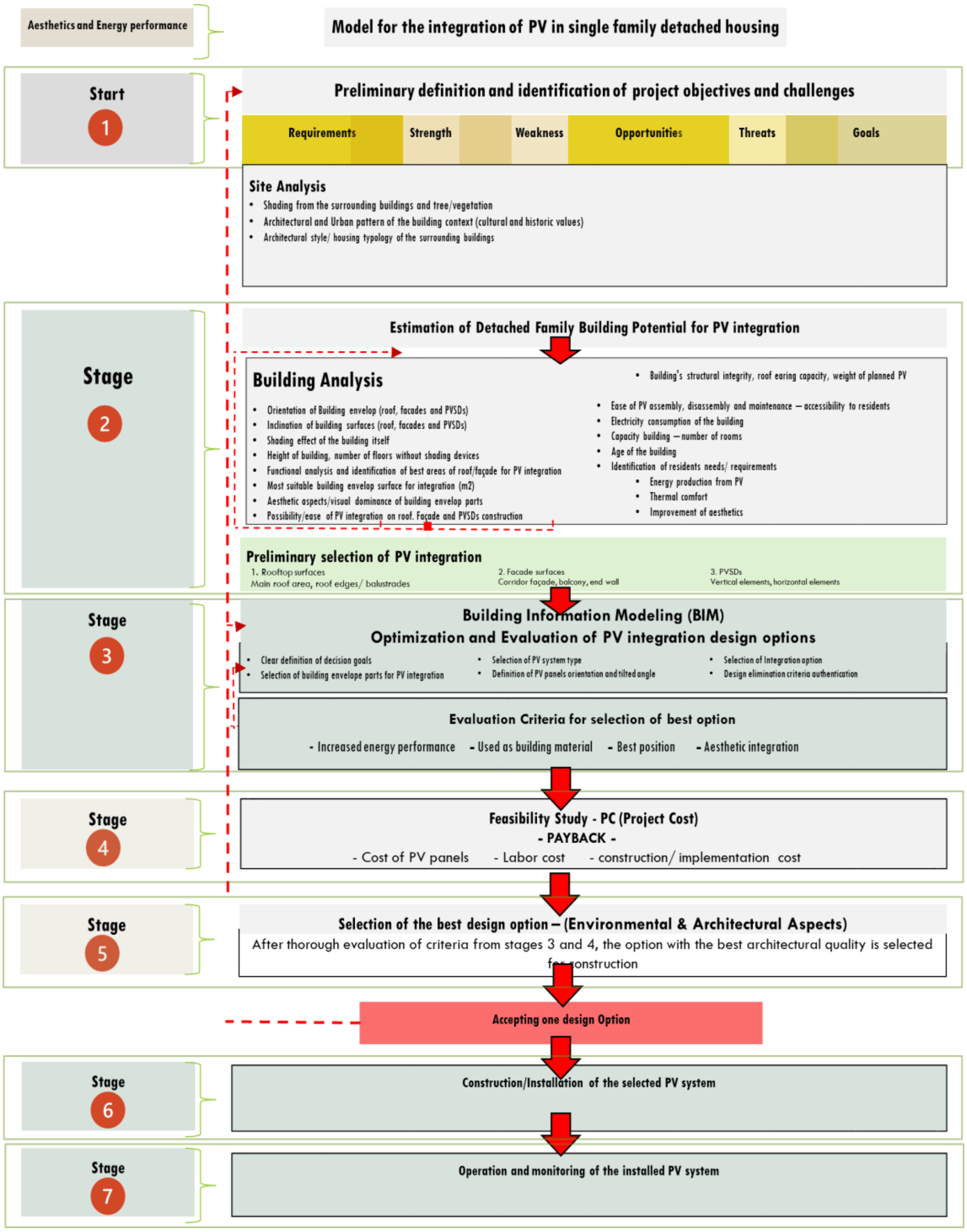


Figure 5.8. A decision making model for the architectural integration of PV panels in existing single detached family housing units

Chapter 6

THE EVALUATION OF SINGLE FAMILY DETACHED HOUSING UNITS IN NORTHERN CYPRUS

6.1 Introduction

In this chapter of the study, the model developed in the previous chapter was used to evaluate a single family detached family unit in Famagusta. From the results of this evaluation, guidelines for the architectural integration of PV in single family detached housing units in Northern Cyprus was developed. The Chapter begins with a SWOT analysis of the potential and possibilities of the BIPV systems in and then presents a model that reveals a step by step procedure to achieving the proper integration of PV.

6.1.1 The Decision Making Model for the Architectural Integration of PV in Single Family Detached Unit of Northern Cyprus

The new global model developed in Chapter 5, (as shown in Figure 5.8) of this study is locally applied to the case of Famagusta in Northern Cyprus.

6.1.2 Preliminary Definition and Identification of the Objectives and Challenges of the Detached Family House in Famagusta

Under this preliminary stage, the building is analysed under the following headings:

- Strength

- Weakness

- opportunities

- threats

- goals

- Requirements

6.1.3 SWOT Analysis of Famagusta

A SWOT analysis was carried out to identify the strength, weakness, opportunities and threats to the successful integration of PV in single family detached family housing units in Famagusta. The SWOT analysis carried out in this study was to analyze the potential for solar technology in Northern Cyprus, identify the potential threats to this possibility as well as opportunities and weakness that the product might encounter. In doing so the results from this SWOT evaluation was presented in Table 6.1.

6.1.4 Site Analysis

The single-family detached housing type case study is located in Famagusta, Northern Cyprus. Cyprus is the third largest island in the Mediterranean Sea. The city of Famagusta is a coastal town and is on the east side of the island, with a seven meters elevation above sea level (Ozay, 2005). The population of Famagusta is 42,526 according to the 2006 census (TRNC. 2006).

6.1.5 Climate Condition

The climate in Famagusta is a transitional one, it lies between a composite and a hot, humid climate, however, because of its close proximity to the Mediterranean Sea, it has a hot and humid climate (Özdeniz et al., 2005; Hancer, 2005). According to the Cyprus meteorological station report about Famagusta, the temperature of Famagusta rises to more than 30°C in the summer months and drops to a low of 3°C in the winter months (Figure 6.1). The relative humidity for the city of Famagusta is between 33 to 72% in the different months of the year. January records the highest and October the lowest humidity in the year. Famagusta has an average of 9 hours of sunlight each day (Weather and climate, 2016) and an average of 3328 of sunlight in a year. The city also experiences an average of 403.5 mm of rainfall each year and an average of 33.6 mm each month (Hancer, 2005).

Table 6.1. SWOT Analysis for Solar PV-Technology in Northern Cyprus

Strength	Weakness
Availability of solar radiation for more than 300 days annually The use of PV in residential buildings will help generate clean energy in situ Availability of sufficient surface area for the integration of PV compare to other types of residential buildings Improved architectural aspects leading to appealing visual view	Lack of proper installation techniques Lack of proper guidelines for the integration of PV Lack decision making model for PV integration
Opportunities	**Threats**
Increase in the current cost of electricity Opportunity to achieve the net zero building goals Growing PV market Government support for up 70 MW energy produce from solar radiation	Lack of guidelines for the integration of PV in residential buildings

The most comfortable months of the year are the months of April, May, October and November, while the months of December, January, February and March require heating. The summer months of June, July, August and September require cooling and ventilation (Lapithis, 2005). According to Climatemps.com (2018), Famagusta has high solar energy during the winter (5.26 KWh/m^2 /day), which rises to 7.12 KWh/m^2

/day during the summer season (Figure 6.2). In addition, the total solar radiation in Famagusta usually rises from 6 MJ/m2 in December to a high of about 24 MJ/m^2 in June and July. Besides, the energy generation rises from 70 W/m^2 in December to 280 W/m^2 in June and July (Pourvahidi, 2010; Atalar, 2001).

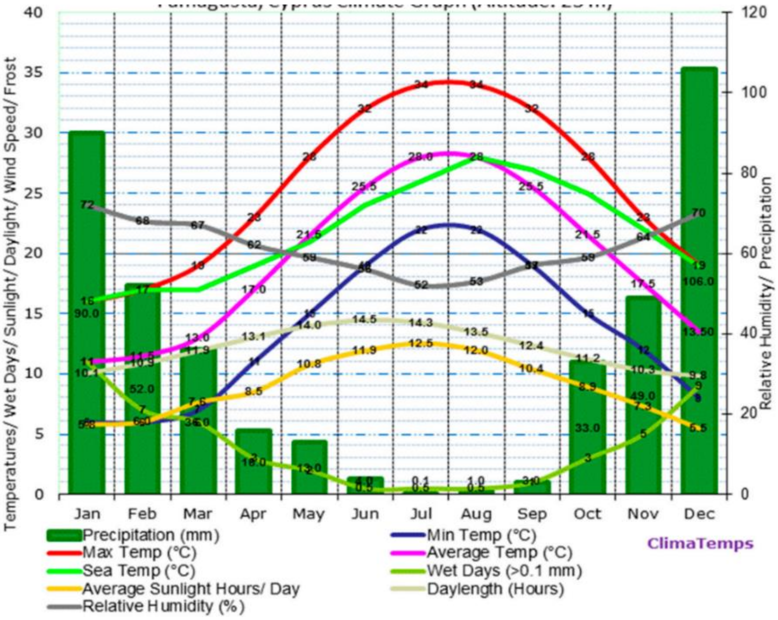


Figure 6.1. Annual climate graph of Famagusta (Weather and climate, 2016)

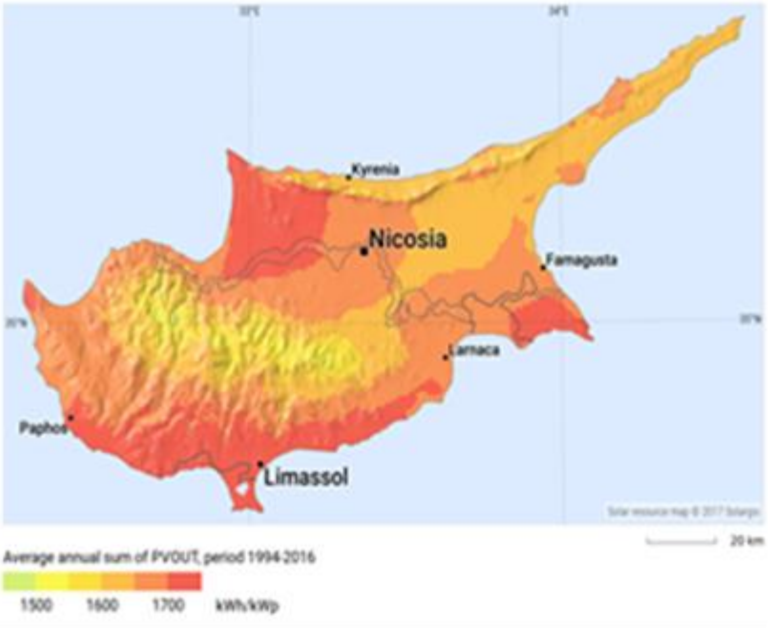


Figure 6.2. Photovoltaic power potential in North Cyprus (Weather and climate, 2016)

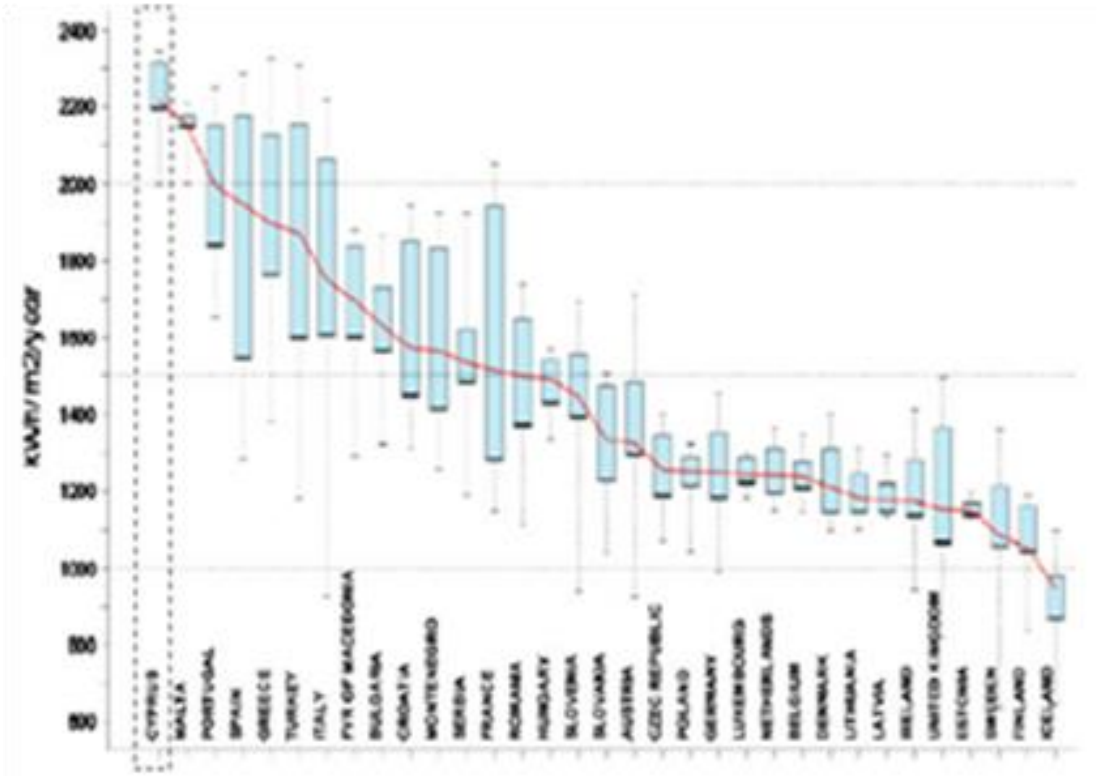


Figure 6.3. Photovoltaic power potential in North Cyprus (Zachariadis et al., 2016)

Figure 6.2 and 6.3 illustrates that the countrywide solar potential of Cyprus is the highest in Europe. Moreover, studies have shown that a polycrystalline or monocrystalline solar PV system with nominal power of 1 kW installed in the coastal region of Cyprus, with a 27° still angle of the panels and south direction, produces on average more than 1500 1900 kWh per year throughout the first 20 years of its operation (Zachariadis et al., 2016). This is a clear indication of why the government should invest in solar energy as an alternative source of energy.

6.2 Estimation of Single Family Detached Building Potential for PV Building Integration

6.2.1 Building Analysis

This section of the study covers the details of the building. it includes orientation, inclination, shading effects, the details of the building, identification of the resident’s needs, etc., as shown in Figure 6.4. For the model setup, a common single family detached dwelling with a living room, a garage, a kitchen, two bathrooms and five bedrooms was evaluated using Design Builder software. The house has a south orientation, a flat roof and a total floor area of 149m2. The details about the building model are shown in Figure 6.4 and Table 6.2.

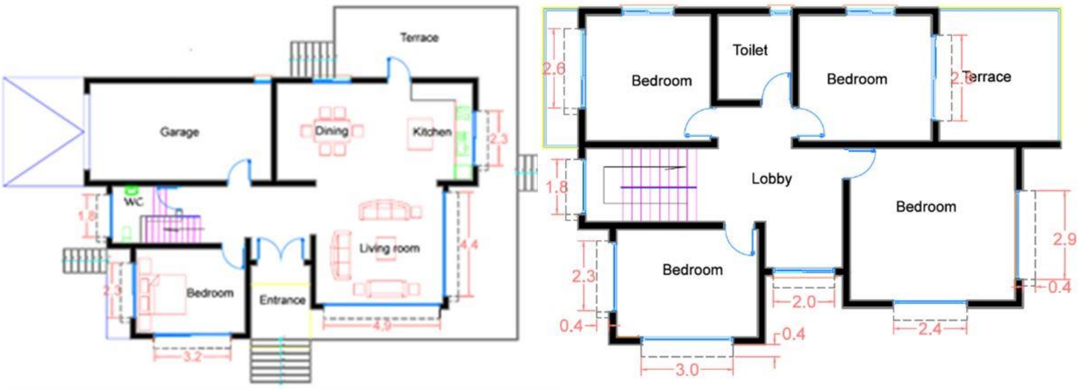


Figure 6.4. Ground first floor of the building model building

EnergyPlus operational and occupancy schedules default values for residential buildings were used for the simulation. The building's energy demand includes; lighting, domestic hot water DWH, air-condition system and other household appliances. Design Builder software default residential operational schedule was used to determine the building's electricity requirements. The input parameters and boundary conditions for Energy-Plus simulation used to determine the light, DHW, and other appliances are given in Table 6.3. The heat transfer coefficients of the construction elements of the building were gotten from Mesda (2012) for the heating and cooling load calculations and tabulated in Table 6.4.

Table 6.2. Information about the single family building model

s/n	Building information	Description
1	Project	Residential building
2	Type	Single family detached house
3	Area of building	149m^2
4	Climatic region	Mediterranean climate
5	Orientation:	South
6	Number of floors	Two floors
7	Windows material	PVC
8	Windows configuration	Double glazing
9	Windows type	3 mm clear glass + 6 mm air gap + 3 mm clear glass
10	Level above ground	1m
11	Orientation of the openings	South, east, west and north
12	Outside shading device	louver and cantilever
13	Door material	Wood
14	Wall type	Bearing and partition
15	HVAC system	Slit unit

Table 6.3. Heat transfer coefficient (U) for construction components (Mesda, 2012)

City	U – Value (W/m^{2}k)			
	Wall	Roof Ceiling	Floor	Windows
Famagusta North Cyprus	0.56	0.67	0.44	0.8

Table 6.4. Parameters for residential electricity demand

Lighting	Illuminance (lux)	150
DHW	Consumption rate (l/m^2-day)	0.72
	Delivery temperature (^{o}C)	65
Equipment	Unit consumption (W/m^2)	3

6.3 Building Information Modeling (BIM) - Optimization and Evaluation of PV Integration Design Options

6.3.1 Materials and Methodology

To achieve the objectives of this research, both qualitative and quantitative methodology were employed (Figure 6.5). A building simulation model was generated to reproduce the interior and outside of the house, as well as the materials used for the construction of the building. The computer program, design builder was used. This software uses EnergyPlus™, a simulation software developed by the US Department of Energy (DOE) to simulate heat transfer processes, climate conditions and other factors relating to energy consumption in buildings. EnergyPlus™ is a whole building energy simulation program that researchers and professionals in the building industry use to model both energy consumptions for: heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings (Energyplus, 2018; Reta, 2017). Furthermore, Consultant Program and the weather file of Famagusta (epw) was used to develop the best strategies for both passive and active design that would create a unique list of Design Guidelines for the building. The building was simulated with and without solar panel integration, and finally with the PV integration for five options. The ASHRAE Standard 55 was also used as the comfort model in the Climate Consultant simulation. Milne (2009) describes Climate Consultant as a graphic-based computer program that helps users create more energy efficient, buildings, each of which is uniquely suited to its particular location in the world (Milne, 2009).

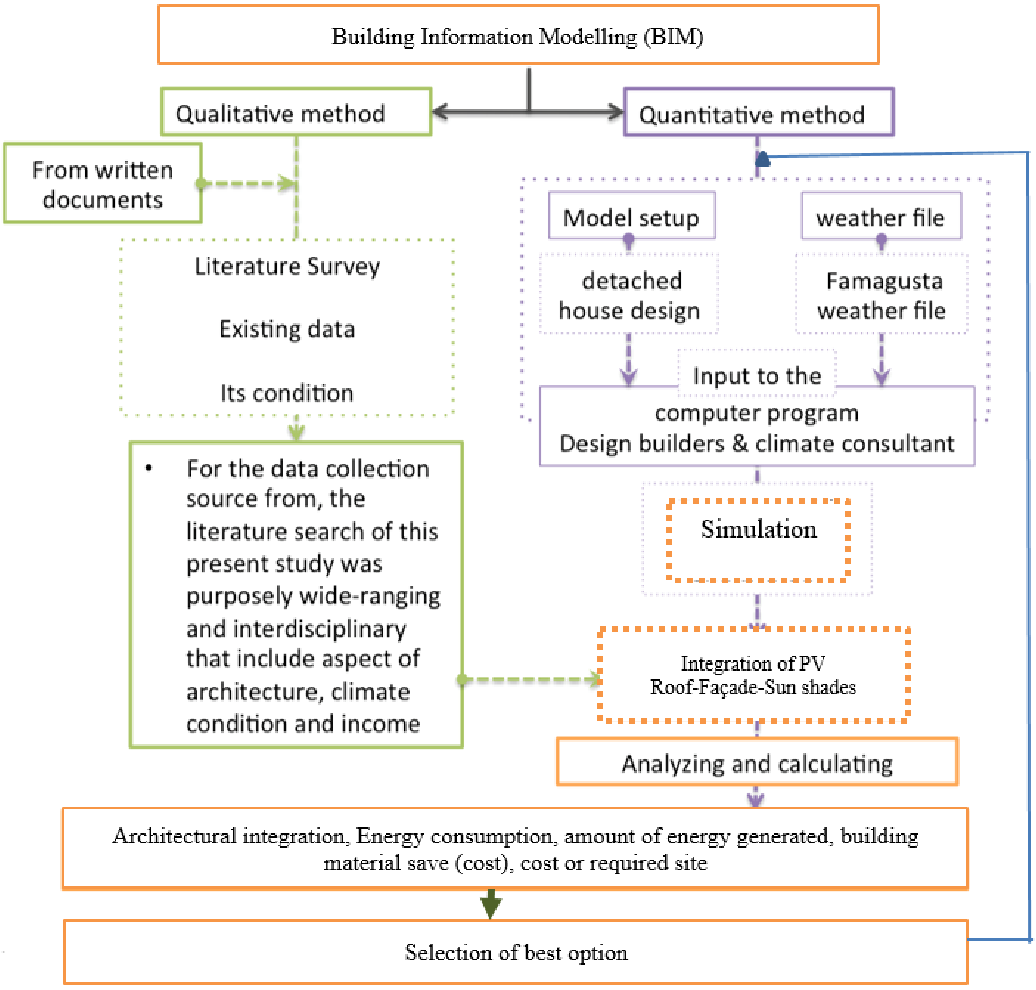


Figure 6.5. Illustration diagram of Building Information Modelling

6.3.2 Sun Shading Chat

From the Climate consultant program, the number of hours that shading is required for the simulated building is derived. The result of the simulation presented in Figure 6.6 and 6.7 show the annual number of hot, cold and comfortable hours in the simulated building. Between the winter and spring months (December 21 to June 21), shade would be needed for 174hours, the sun will be needed for 1590 hours and 748 hours are the comfortable hours within this period of the year. While for the summer months as shown in Fig. 13 (June 21to December 21), shading will be required for 1203 hours, direct solar radiation for heating is required in the building for 499 hours and the remaining 896 hours are the comfortable hours of the year. Furthermore, from the Figure 6.6 and 6.7, we can deduce that the two-floor single family house which is classified as low rise residential building needs shading devices for a total of 1218 hours in a year.

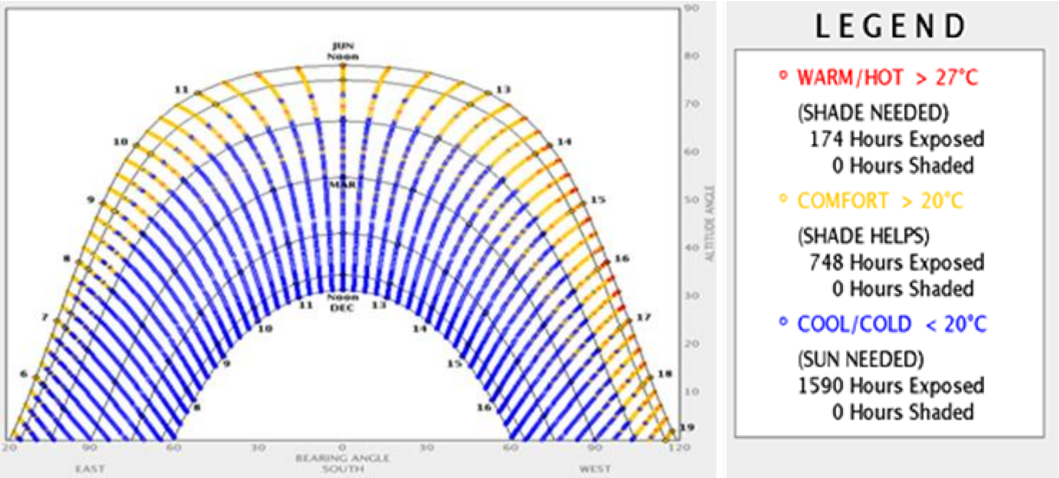


Figure 6.6. sun shading chart in winter spring December 21 to June 21

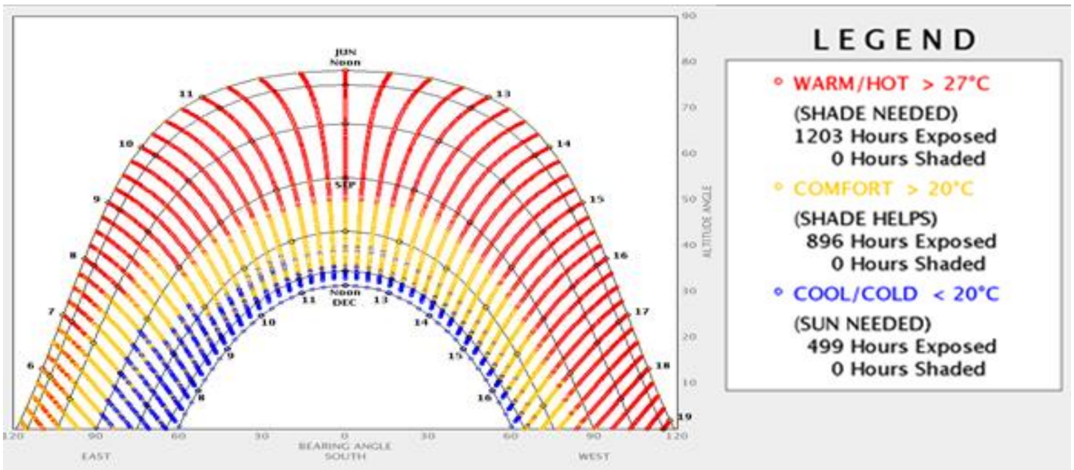


Figure 6.7. Sun shading chart in Summer Fail June 21 to December

6.3.3 Psychrometric Chart Results

An important output of the climate consultant software is the psychrometric chart. Beyond just representing the climatic data, the psychometric chart helps to organize the information in a way that is plain and easy for people to understand the influence of climate on the immediate environment. Comfort zone: Figure 6.8, is the psychrometric chart for the simulated house. It can be clearly seen that the area of the comfort zone for the building is quite small (16.8%), implying that a large amount of energy would be needed for heating and cooling. Therefore, very good passive and active design strategies need to be developed to solve the heating problem.

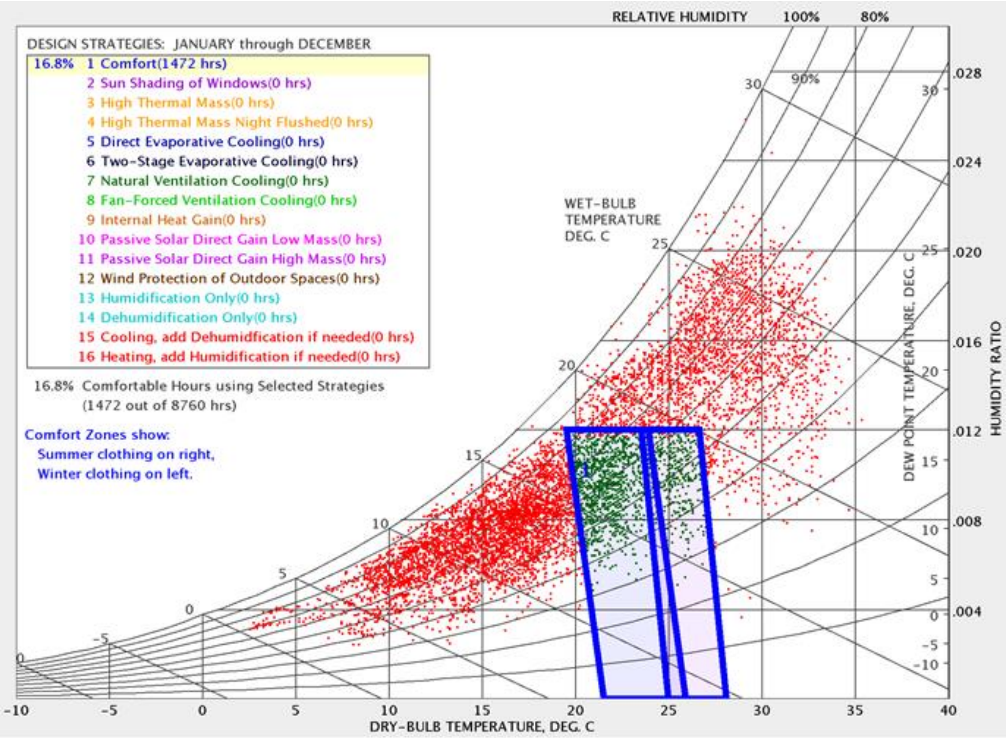


Figure 6.8. Psychrometric chart for Famagusta: Comfort Zone

Figure 6.9 presents the best design strategies for buildings envelopes in Famagusta. The strategies are able to modify or filter extreme external climate conditions to create comfortable indoor environments in Famagusta.

The design strategies for the simulated building are explained as follows:

- Sun shading of windows: as presented in figure 6.11, shading on the chart takes up to 15.2% that is about 1328 hours of the year. Through the use of shading devices, 1328 uncomfortable hours are converted to comfortable hours.

- Two stage evaporative cooling: the in the two stage evaporative cooling strategy, first a thermal converter is used to reduce the temperature, then the comfort condition is applied by direct evapourative cooling. This process makes up 1.7% (146 hours annually).

- Natural ventilation cooling: Natural ventilation is required for cooling for about 102 hours of the year (1.2%)

- Internal heat gain: 36.4% of thermal comfort can be achieved by internal heat gained from with the building from artificial lighting, electrical equipment, and indoor activities by occupants. This is about 3188 hours of the year.

- Passive solar direct gain high mass: the is the number of hours in the year where thermal comfort is achieved through passive solar gain. This includes a total of about 1713 hours (19.6%).

- Wind protection of outdoor spaces: In this segment of the chart building wind protection by some outdoor elements such as plants is required to achieve the comfort conditions. This includes 0.5 % making up a total of 43 hours of the year.

- Dehumidification only: Dehumidification is required to achieve thermal comfort in the building for a total of about 984 hours of the year, Making up 11.2%.

- Cooling, add humidification if needed: to achieve comfort, this strategy requires both cooling and humidification at the same time. This includes a total of 1806 hours of the year (20.6%)

- Heating, add humidification if needed: to achieve comfort, this strategy requires both humidification and increasing air temperature by mechanical heating. This includes a total of 772 hours of the year (8.8%)

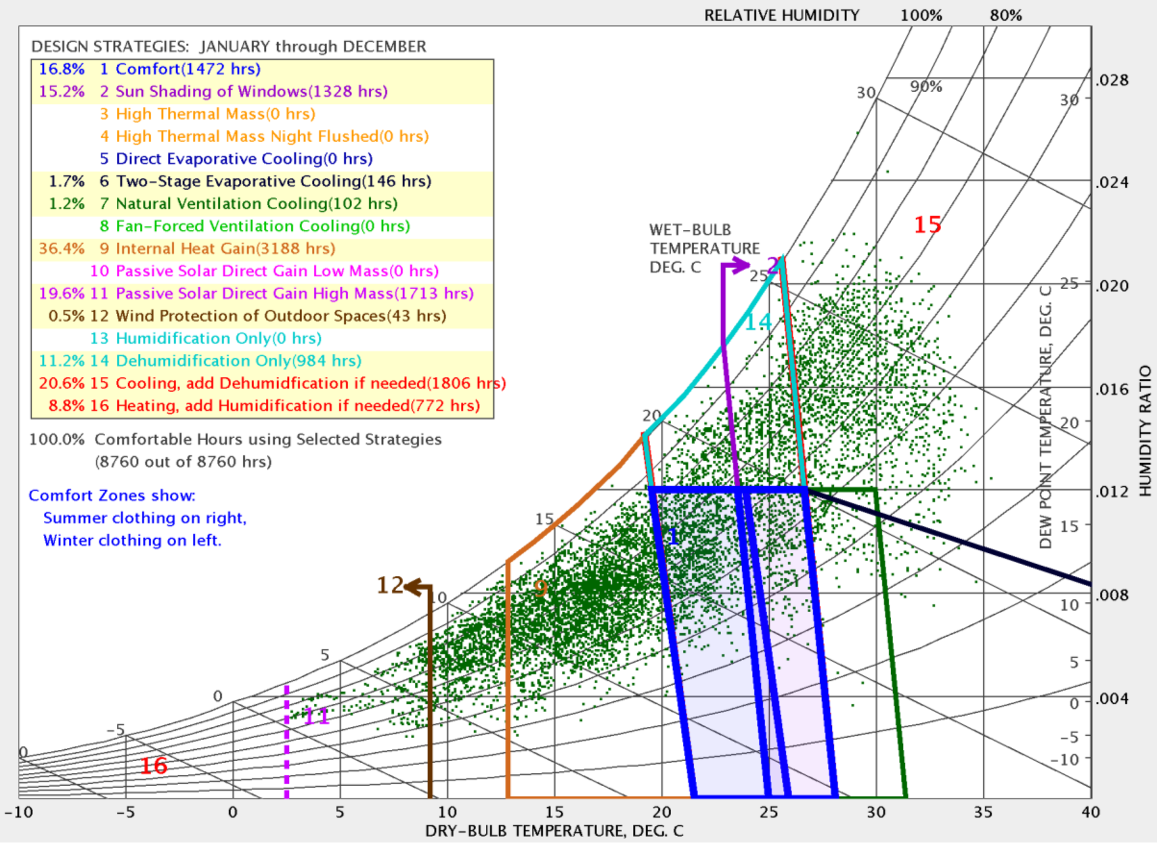


Figure 6.9. Psychrometric chart for Famagusta

6.3.4 Solar shading performance result

Solar shading performance was as also assessed using climate consultant. Shading elements work differently based on their orientation. Shading device strategies are usually tailored towards the orientation of each window. Whilst some orientations are easy to shade, others are much more difficult as the sun can be almost direct-on at certain times of the day. The number of hours exposed to the sun that needs to be shielded is also different based on the direction the façade is facing (north, south, east, and west). From the simulation, the types of shading elements that should be used are also different as illustrated in figure 6.10 and 6.11. The results from the simulation are that.

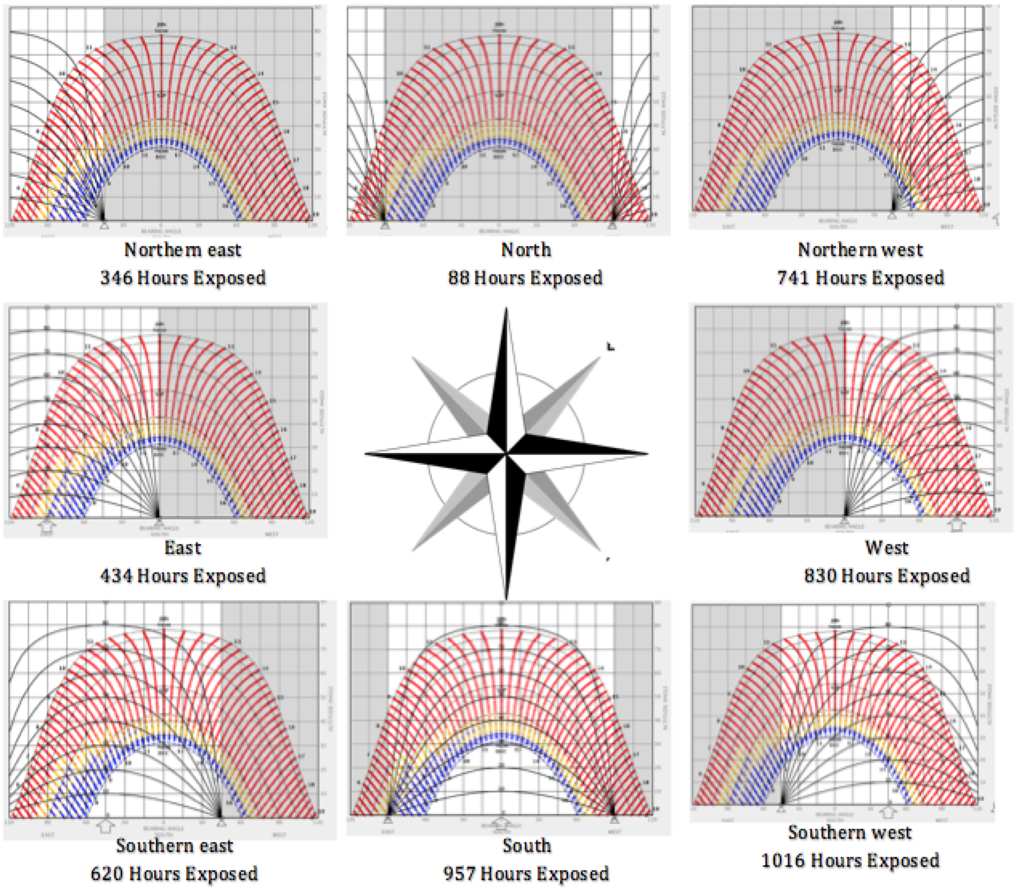

Northern east
346 Hours Exposed
North
88 Hours Exposed
Northern west
741 Hours Exposed
East
434 Hours Exposed
West
830 Hours Exposed
Southern east
620 Hours Exposed
South
957 Hours Exposed
Southern west
1016 Hours Exposed

Figure 6.10. The Shading Calculator Overlay, in eight different orientation cases by focusing on Sun exposure during June 21 to December 21

Windows directly facing the south would need more shading from the sun, and the horizontal overhangs work better for southern facades. The east and west would require both vertical fins and horizontal overhanging used in the passive design strategies, while on the northern façade, shading is completely avoided as exposure to the sun is needed for the interior space of the building. By having shading devices with PV integrated retrofits, shading can be provided and electricity generated simultaneously which is what this research seeks to achieve.

Having identified shading as one of the best strategies, the next step would be to identify what shading system best fits the orientation of the building. Through the use of climate consultant, this study has been able to identify the best shading strategy that best fits the single family building location (Figure 6.11).

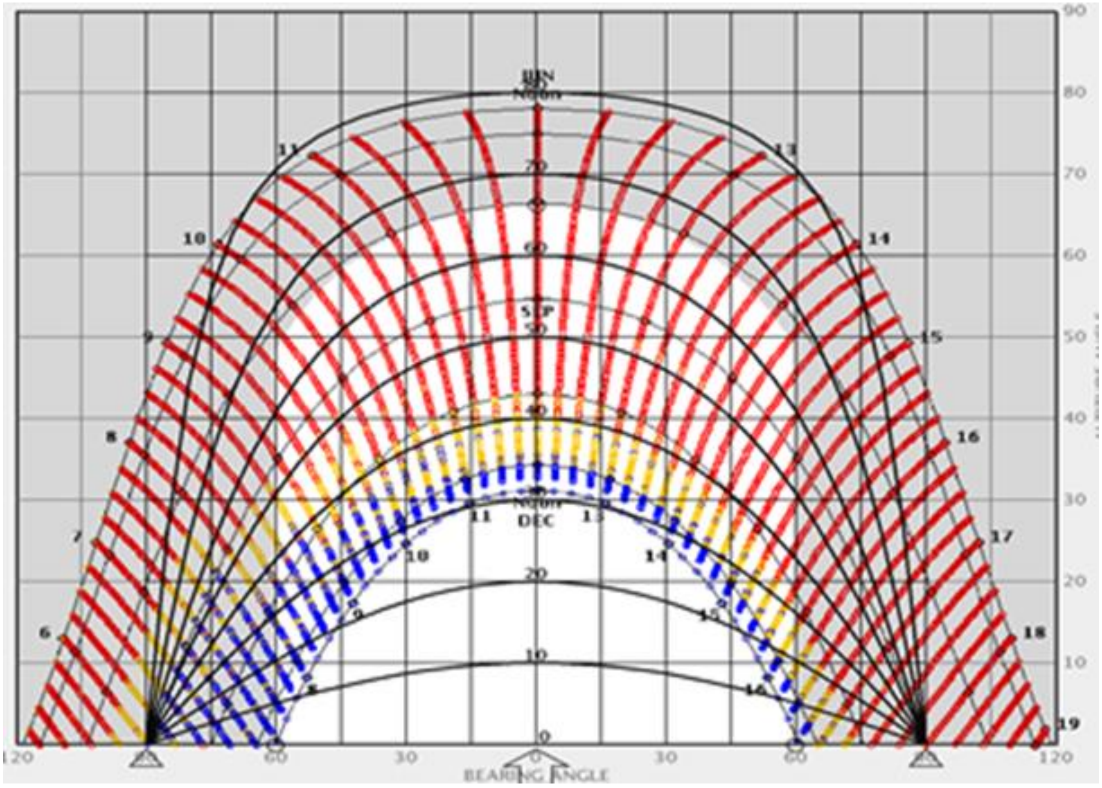


Figure 6.11. Overhang angle and Vertical fin angle

6.3.5 Cooling Design Strategy

The cooling design is aimed at solving the overheating problem of the building, especially in the summer months. Figure 6.12 and 6.13 show the cooling design calculation, the size of the cooling plan required in design during summer condition, and the impact of changing aspects of shading to help find a design solution.

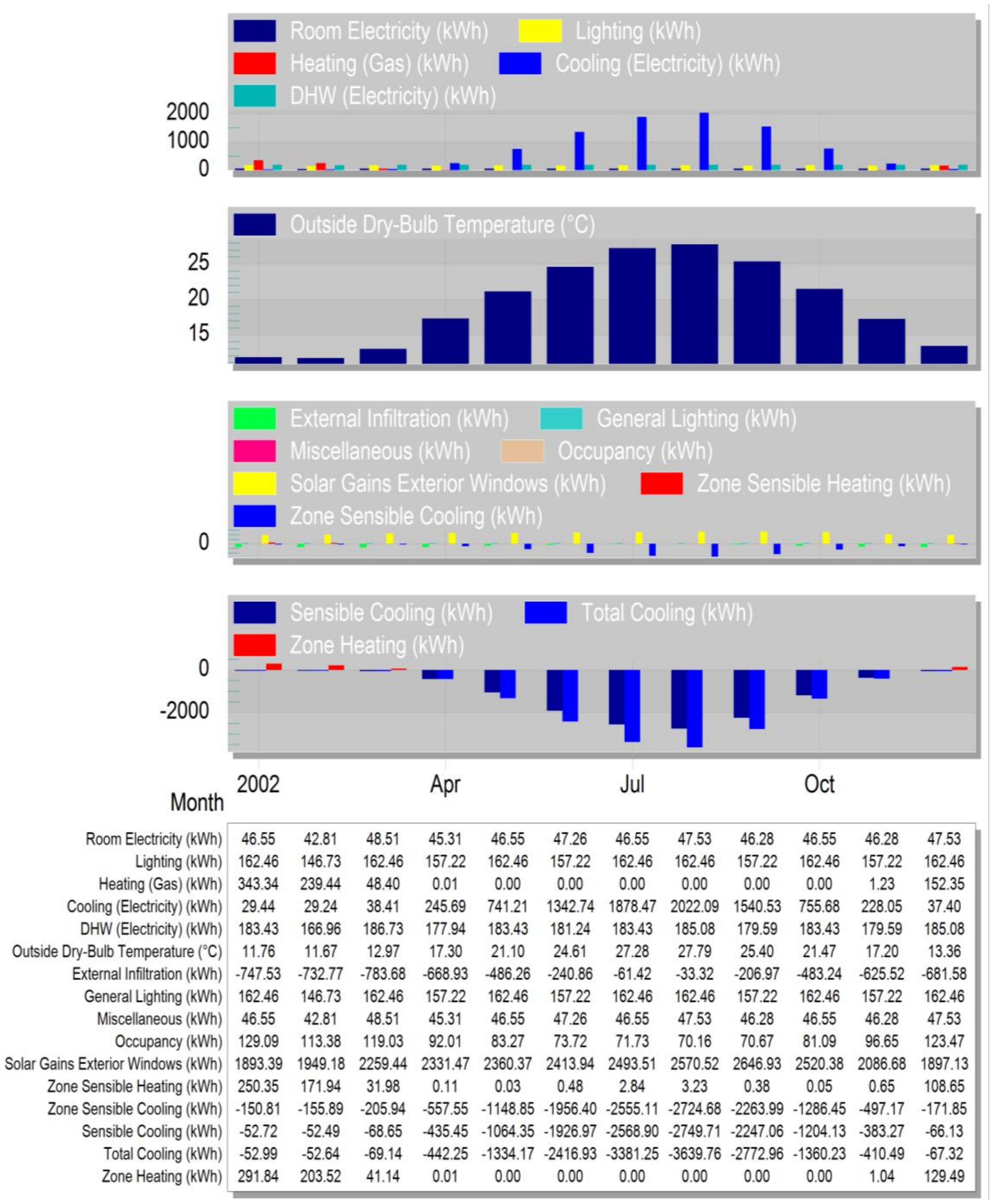
Figure 6.12 shows that the amount of energy needed for cooling the sample building is very high, especially in the summer months of June, July, August, and September. Implementing the shading device strategies derived from the Solar shading performance result of this research would lead to a more than 400 kWh reduction especially in some of the summer months and the entire annual cooling load reduced by almost half (total cooling load - Figure 6.12). From the simulation, the total energy consumption that will be reduced in the summer months of June, July, August, and September is 716.02 kWh. On the other hand, the heating load increases in winter but not in a significant measure. The increase in the heating load for winter months of December, January, February, and March amounts to 115.70 kWh. In this tradeoff, the reduction in energy consumption in the summer months still out weights the increase in the winter months.

6.4 Generation and Performance Prediction of the Various Options (BIM)

A number of design options were explored and evaluated, ten (10) design options were devised. The technology used for all of the option is the monocrystalline cell (Table 6.5).

Design Option 1, PV used as Canopy:

The integration of PV as roofing material for building canopy. A total of about 18 PV panels were integrated and used as canopy providing shade for the family from the sun as well as being used as energy generators. In this option the PVs were inclined at 25° and generating an optimum power of 3.9 KW.

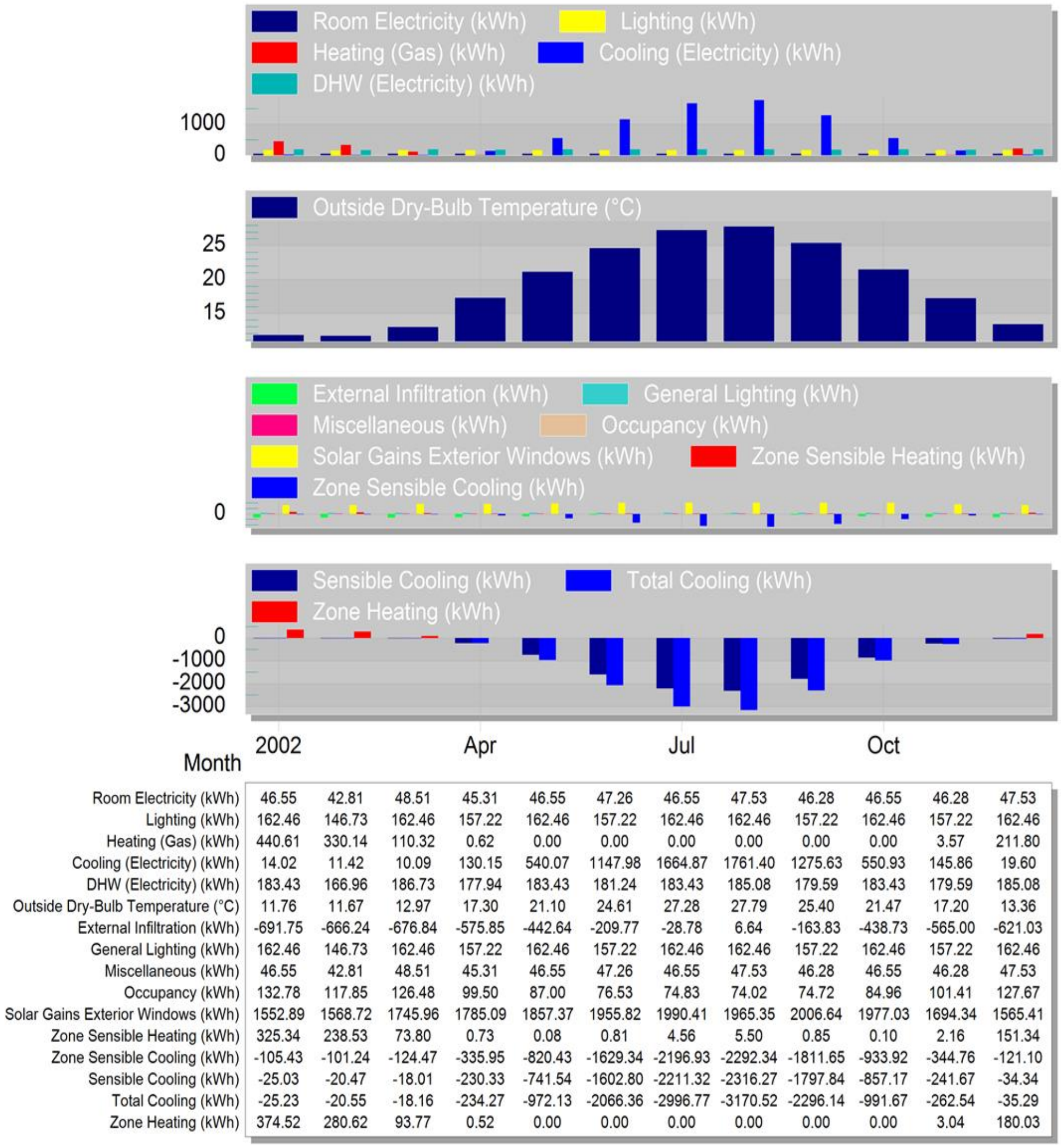


Month	2002			Apr			Jul			Oct		
Room Electricity (kWh)	46.55	42.81	48.51	45.31	46.55	47.26	46.55	47.53	46.28	46.55	46.28	47.53
Lighting (kWh)	162.46	146.73	162.46	157.22	162.46	157.22	162.46	162.46	157.22	162.46	157.22	162.46
Heating (Gas) (kWh)	343.34	239.44	48.40	0.01	0.00	0.00	0.00	0.00	0.00	0.00	1.23	152.35
Cooling (Electricity) (kWh)	29.44	29.24	38.41	245.69	741.21	1342.74	1878.47	2022.09	1540.53	755.68	228.05	37.40
DHW (Electricity) (kWh)	183.43	166.96	186.73	177.94	183.43	181.24	183.43	185.08	179.59	183.43	179.59	185.08
Outside Dry-Bulb Temperature (°C)	11.76	11.67	12.97	17.30	21.10	24.61	27.28	27.79	25.40	21.47	17.20	13.36
External Infiltration (kWh)	-747.53	-732.77	-783.68	-668.93	-486.26	-240.86	-61.42	-33.32	-206.97	-483.24	-625.52	-681.58
General Lighting (kWh)	162.46	146.73	162.46	157.22	162.46	157.22	162.46	162.46	157.22	162.46	157.22	162.46
Miscellaneous (kWh)	46.55	42.81	48.51	45.31	46.55	47.26	46.55	47.53	46.28	46.55	46.28	47.53
Occupancy (kWh)	129.09	113.38	119.03	92.01	83.27	73.72	71.73	70.16	70.67	81.09	96.65	123.47
Solar Gains Exterior Windows (kWh)	1893.39	1949.18	2259.44	2331.47	2360.37	2413.94	2493.51	2570.52	2646.93	2520.38	2086.68	1897.13
Zone Sensible Heating (kWh)	250.35	171.94	31.98	0.11	0.03	0.48	2.84	3.23	0.38	0.05	0.65	108.65
Zone Sensible Cooling (kWh)	-150.81	-155.89	-205.94	-557.55	-1148.85	-1956.40	-2555.11	-2724.68	-2263.99	-1286.45	-497.17	-171.85
Sensible Cooling (kWh)	-52.72	-52.49	-68.65	-435.45	-1064.35	-1926.97	-2568.90	-2749.71	-2247.06	-1204.13	-383.27	-66.13
Total Cooling (kWh)	-52.99	-52.64	-69.14	-442.25	-1334.17	-2416.93	-3381.25	-3639.76	-2772.96	-1360.23	-410.49	-67.32
Zone Heating (kWh)	291.84	203.52	41.14	0.01	0.00	0.00	0.00	0.00	0.00	0.00	1.04	129.49

Figure 6.12. Simulation results monthly Temperature, Heat Gains and Energy Consumption – 1, Building 1 EnergyPlus 1 Output 31 Dec (Zone conditions reported for occupied periods, defined by schedule) Monthly Evaluation

Design Option 2, PV used as Canopy:

The integration of PV as roofing material for building canopy. A total of about 18 PV panels were integrated and used as canopy providing shade for the building from the sun as well as being used as energy generators.



Month	2002			Apr			Jul			Oct		
Room Electricity (kWh)	46.55	42.81	48.51	45.31	46.55	47.26	46.55	47.53	46.28	46.55	46.28	47.53
Lighting (kWh)	162.46	146.73	162.46	157.22	162.46	157.22	162.46	162.46	157.22	162.46	157.22	162.46
Heating (Gas) (kWh)	440.61	330.14	110.32	0.62	0.00	0.00	0.00	0.00	0.00	0.00	3.57	211.80
Cooling (Electricity) (kWh)	14.02	11.42	10.09	130.15	540.07	1147.98	1664.87	1761.40	1275.63	550.93	145.86	19.60
DHW (Electricity) (kWh)	183.43	166.96	186.73	177.94	183.43	181.24	183.43	185.08	179.59	183.43	179.59	185.08
Outside Dry-Bulb Temperature (°C)	11.76	11.67	12.97	17.30	21.10	24.61	27.28	27.79	25.40	21.47	17.20	13.36
External Infiltration (kWh)	-691.75	-666.24	-676.84	-575.85	-442.64	-209.77	-28.78	6.64	-163.83	-438.73	-565.00	-621.03
General Lighting (kWh)	162.46	146.73	162.46	157.22	162.46	157.22	162.46	162.46	157.22	162.46	157.22	162.46
Miscellaneous (kWh)	46.55	42.81	48.51	45.31	46.55	47.26	46.55	47.53	46.28	46.55	46.28	47.53
Occupancy (kWh)	132.78	117.85	126.48	99.50	87.00	76.53	74.83	74.02	74.72	84.96	101.41	127.67
Solar Gains Exterior Windows (kWh)	1552.89	1568.72	1745.96	1785.09	1857.37	1955.82	1990.41	1965.35	2006.64	1977.03	1694.34	1565.41
Zone Sensible Heating (kWh)	325.34	238.53	73.80	0.73	0.08	0.81	4.56	5.50	0.85	0.10	2.16	151.34
Zone Sensible Cooling (kWh)	-105.43	-101.24	-124.47	-335.95	-820.43	-1629.34	-2196.93	-2292.34	-1811.65	-933.92	-344.76	-121.10
Sensible Cooling (kWh)	-25.03	-20.47	-18.01	-230.33	-741.54	-1602.80	-2211.32	-2316.27	-1797.84	-857.17	-241.67	-34.34
Total Cooling (kWh)	-25.23	-20.55	-18.16	-234.27	-972.13	-2066.36	-2996.77	-3170.52	-2296.14	-991.67	-262.54	-35.29
Zone Heating (kWh)	374.52	280.62	93.77	0.52	0.00	0.00	0.00	0.00	0.00	0.00	3.04	180.03

Figure 6.13. simulation results with shading devices monthly

In this option the PVs were inclined at 15° and generating an optimum power of 4.3 KW. The angle of inclination used for this option seem to produce more energy than option 1.

Design Option 3 and 4, PVSDS:

In this option PV was integrated as shading devices on the south facade. The main goal of this option is architectural integration and energy production. A total of 15 panels used to serves as both energy generators and as a shading device covering an area of 22.4m^2. By serving as a shading device, the PV integration satisfies both passive and active strategies of building design. Besides becomes part of the building component. The advantage of this option is the fact that the PVSDs serves dual purpose; as a building component and as an active façade component. Two varied tilt angles were used; 25^o and 15^o.

Design Option 5, on flat roof:

The integration of PV on flat roof Total energy generated by the PV panels were integrated on flat roof at 0^o . The PVs were laid flat on the roof and simulated. A total of about 2.9KW of electricity was generated. The advantage of this option is the fact that it is invincibly integrated. Its position directly on the roof also reduces the heat on the roof covering.

Design Option 6 and 7, Stand alone on flat roof:

25 PV panels mounted on the roof of the single family detached family home and oriented towards the south. The panels are place at an angle of 15^o and 25^o tilt to achieve optimum yield. The position of the se panels prevent them to be easily seen

by onlookers. The main disadvantage of this option is the fact that the primary role of roof mounted stand-alone PVs would merely be energy production and does not serve as an architectural component on the building.

Design Option 8, Cladding on façade:

This option aims to integrate PV on the south façade of the building. The main goal of option 8 is to achieve architectural integration and energy generation. A total of about 27 monocrystalline were systematically integrated on the south façade of the building. As part of the façade, it serves as energy generator, an insulation material, and an aesthetic contributor to the building.

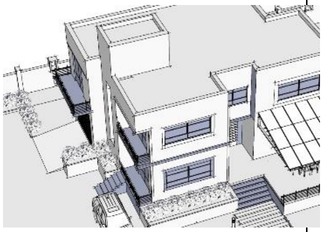
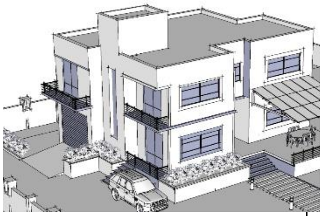
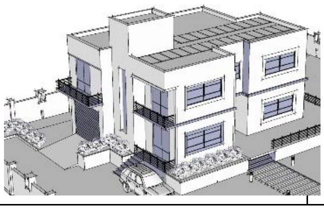
Design Option 9, Cladding on façade and standalone roof flat roof:

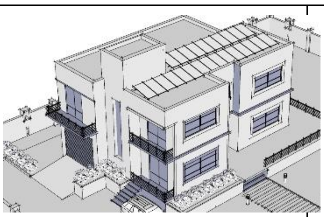
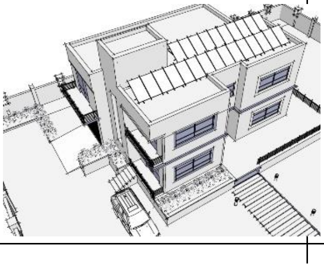
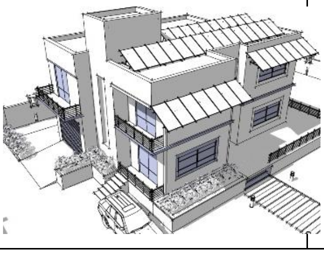
This option combines both PV cladding and façade integration. The main aim of this option is to achieve architectural integration and the best possible energy yield from the building. The façade integration meets the need for architectural integration, while the roof is mainly used to generate electricity. This option is seen to generate the highest possible energy yield.

Design Option 10, Stand alone on flat roof and PVSDs:

The integration of PV on flat roof and on shading devices. Total energy generated by the PV roof and PVSDs and Cell Type. The type of solar cell used for the simulation is the monocrystalline cell. 39 standard PV panels were integrated as shading devices and on the roof, occupying a total area of 62.4 m^2. Each of the solar panel is estimated to produce 250 W of electricity. Since there are 39 panels generated a total installed capacity of about 9.75 KW.

Table 6.5. Options from BIM modeling

	Image	Area (m^2)	No. of Panels	Tilt angle	Total Installed capacity power	Aesthetics (Tjerk H. Reijenga Classification)
Option 1 canopy		28.8	18	25^{o}	3.9 kW	**5**
Option 2 canopy		28.8	18	15^{o}	4.3 kW	**5**
Option 3 PVSDs		22.4	14	15^{o}	3.5 kW	**5**
Option 4 PVSDs		19.4	14	25^{o}	2.9 kW	**5**
Option 5 Flat		40	25	0^{o}	8 kW	**5**

Option 6 13.5DEree		40	25	15º	8.4 kW	**4**
Option 7 roof		40	25	25º	6.25 kW	**3**
Option 8 facade		43.2	27	90º	6.75 kW	**4**
Option 9 Roof and facade		-	52	25º /90º	13 kW	**5**
Option 10 Roof and PVSDs		62.4	39	25º	9.75 kW	**4**

6.5 Evaluation Criteria for arcitectutal integration

Based on the energy performance, best position and Aesthetic integration the option 3/4 has been selected as the best option that meets the architectural and energy demand. In deciding the quality of aesthetics in arechitecture, basic architectural design principles are considered. This include: pattern, contrast, empasis, balance, ryhythm, scale, harmony, unity, variety. besides conasidering these basics, Tjerk H. Reijenga who has done significant research in the area of architectural integration of PV has been able to develop a criteria to measure the level of integration of PV in buildings. This study adopted his evaluation critaria (Figure 6.14).

From the case studies conducted above, it will be worthwhile to refer the classification system of Tjerk H. Reijenga with regards to the architectural integration of the ten options presented. In his study, he classified the level of architectural integration into 5 different levels, namely, 1. applied invisibly; 2. added to the design; 3. Adding to the architectural image; 4. determining architectural image; and 5. leading to new architectural concepts.

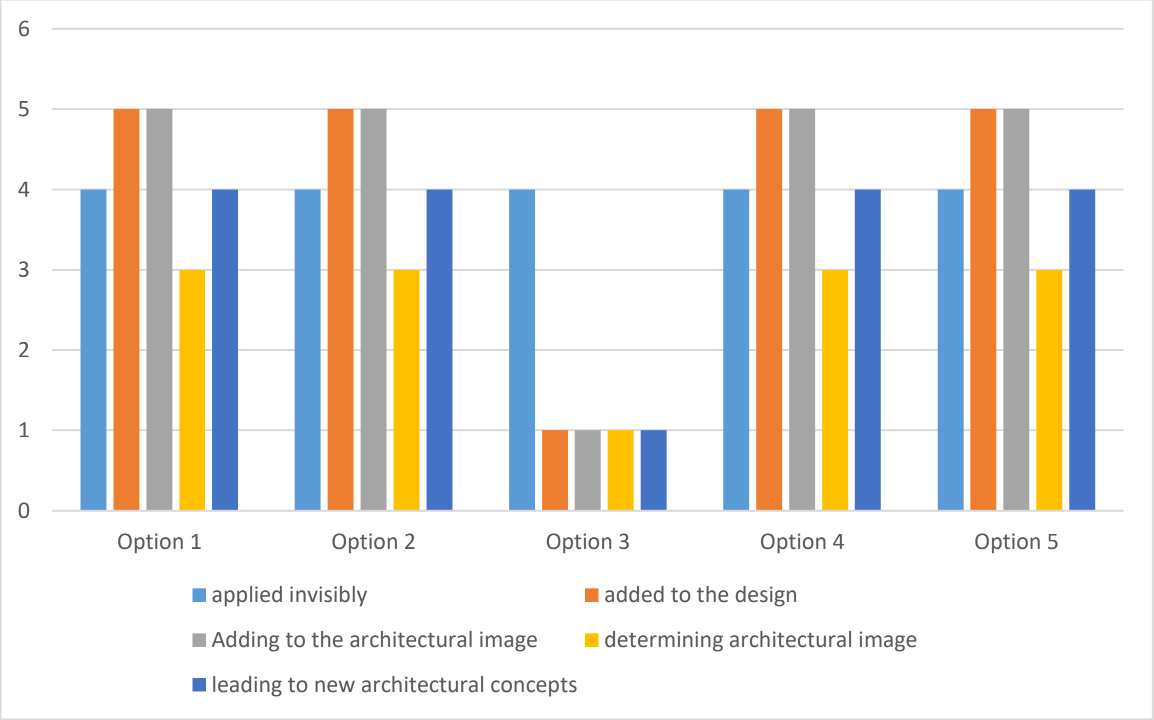


Figure 6.14. Tjerk H. Reijenga Classification

The ten options presented above are different achitectural integration alternative derived from integrating PV panels on the roof, facades and as shading devices.

6.5.1 Design Option 1 The Integration of PVSDs and Roof Standalone Integration

The type of solar cell used for the simulation is the monocrystalline cell. 1 m^2 of monocrystalline cell produces 250 W as earlier mentioned. Since there is 20.4 m^2 available surface for integration, the PV shading device will generate a total of about 3,264 W of electricity and from due south with every 5°, the average deficiency drop is about 1.1% and the number of windows oriented to both east and west.

$E = A * r * H * PR$

Where E = Energy (kWh),

A = Total solar panel Area (20.4 m^2),

r = solar panel yield (estimated to12%),

H = Annual average irradiation on tilted panels (1800 W), and PR = Performance ratio, coefficient for losses (0.75). the energy become more then 3300 kWh.

6.6 Conclusion

Openings and proper orientation for buildings within the Mediterranean region have always played a critical role in enhancing the comfort level of users. Nevertheless, it comes with a price; it often leads to overheating of the interior space in summer or inadequate penetration of sunlight in winter especially when the building lacks proper orientation. The result is high energy consumption for heating and cooling. Therefore, developing good strategies that will conserve energy as well as generate clean energy for the building in Cyprus and other countries facing the Mediterranean Sea is critical.

Today, there are several strategies as well as new technology/products that have been designed to enhance the architectural integration of PV in buildings. Openings on the south façade are often considered most appropriate for integration. This research provides strategies for increasing the comfort level in buildings through the integration of PV into roofs, facades and shading elements in the residential building.

Having conducted an empirical study on the use of PV as integration through a simulation on a typical single-family house, this study proposes the use of photovoltaic integrated shading instead of reinforced concrete which is the commonly used building material for shading device on the south façade and as standalone integration on the roof of the building all oriented towards the south façade as this was the selected option form the ten (10) options derived from the simulation.

The major benefit derived from the several options generated from the simulation is the diverse spectrum of opportunities and possibilities of PV panel integration in buildings it presents. Individuals will be able to select from the given options what they best prefer. Some may want to select an option that is inclined more towards energy generation output as oppose to aesthetic integration, while others may be more interest is an option that is more aesthetically pleasing but does not produce as much energy. This spectrum of options is essential to the and important in order to achieve an architectural integration of PV panels in single family detached residential buildings.

Chapter 7

CONCLUSION AND RECOMMENDATION

7.1 Introduction

This research work sets out to investigate the architectural integration of PV panels in single family detached housing units. And it does so with the aim of providing a practical model that will aid decision making for the architectural integration of PV in single family detached housing units. The potential users will include but not limited to house designers, construction industry as well as policymakers, all of which have the willingness and are currently considering the possibilities of integrating the PV technology in the housing sector in Northern Cyprus local conditions. This study through literature reviews and simulation of an existing single-family detached housing unit in the city of Famagusta Cyprus presents a decision-making model for the architectural integration of PV panels in single-family detached housing units in Northern Cyprus. The model was then qualitatively and quantitatively applied to the case of Famagusta, Northern Cyprus local conditions. For the main purpose of this study, these objectives were determined:

- Literature reviews on photovoltaics and its integration in buildings

- Analyzing a number of BIPV models for residential buildings

- Developing a decision making model for the integration of PV in detached family buildings

Evaluating the architectural integration of PV in detached family housing units of Northern Cyprus using the developed model Table 7.1 contains a detailed summary of this thesis.

Table 7.1. Summary of chapters

	Description/ Summary of Chapters
Chapter 1 - Introduction	Statement of problem and identification of the missing Gap in literature Strategies for the Architectural Integration of Photovoltaic (PV) in detached family buildings Research question How can the best option for PV integration be decided? And how it can be integrated to single family detached housing units to serve the dual purpose of generating solar energy and enhancing architectural quality? How can the Building integrated photovoltaic model be applied in detached family homes globally as well as in Northern Cyprus? Objectives Literature reviews on photovoltaics and its integration in buildings Analysing a number of BIPV models for residential buildings Developing a model for the integration of PV in detached family buildings Evaluating the architectural integration of PV in detached family housing units of Northern Cyprus using the developed model Methodology Theoretical study Literature review Conceptual model Mixed method research (qualitative and quantitative study) Building evaluation and analysis – case of Famagusta Application of the model to the case Famagusta

Chapter 2 Photovoltaic (PV) Systems	Photovoltaics (Cell – Modules) PV Product Development Trend Building Integrated Photovoltaics (BIPV) Placement of This Study Haven carried out a general study via literature review on a good number of the research done so far on the subject of BIPV, it is discovered that most of the studies carried out were more concerned with the efficiency of the PV panels integrated, net-zero energy buildings, etc., thus the aesthetic aspect of it has not been given the needed attention. The integration of PV in buildings has a strong connection to the environment. This makes its consideration for the urban environment very pertinent. In order to successfully install PV systems in a building, it is crucial for designers to put into consideration the visibility of the PV installation and its level of dominance on the appearance of the building, hence the need for integrating PV in a way that the architectural characteristics of the building and the urban form of the city is not compromised.
Chapter 3 Architectural Integration of PV in building Envelope Integration	Roof integration Façade integration Sun shading devices methods of PV integration to the building envelop This chapter of the thesis discussed the different integration possibilities on the building skin and how to integrate and install PV into each surface without damaging the architectural quality of the building. the main suitable surfaces of the building envelope namely; roof, façade and sun shading devices, and nature of materials that best fit these surfaces were discussed and categorized.

Chapter 4 Case studies	BIPV: Aesthetic Integration BIPV Concepts, Definition and Criteria Case Studies of PV integration in detached family homes The case study also reveals the most popular integration is the BIPV technology of Modules and solar cell glazing. One of the important findings from the selected cases is that a number of the PV modules can be visibly added on an existing roof without compromising the architectural quality, this is possible when the color, texture, shape and dimension of the module match the existing roof cover. Meanwhile, solar panels indicate the relative ease of integration, as well as weather proofing, noise reduction and shading possibilities very significantly. It is also remarkable that no technology offers high system panel transparency.
Chapter 5 A Model for the Integration of PV in Detached Family Houses	Comparing various existing model/ framework for the integration of PV to detached family housing units A model for the architectural integration of PV to detached family homes 7 components 1. Preliminary definition and identification of project objectives and challenges 2. Estimation of detached family building potential for PV building integration 3. Building Information Modeling (BIM) - Optimization of PV integration design options 4. Feasibility Study - PC (Project Cost) – Payback - 5. Selection of the optimal PV integration design Selection of the best design option 6. Construction/ installation of the selected PV system 7 Operation and monitoring of the installed PV system

Chapter 6 The case of Famagusta	Application of the model to the city of Famagusta in Northern Cyprus 1. Preliminary definition and identification single family detached family house unit SWOT analysis of Famagusta city Building context study Climatic analysis of Famagusta Site analysis of the single family building used for the evaluation building 2. Estimation of detached family building potential for PV building integration Building Analysis of the single family detached housing unit studied 3. Building Information Modeling (BIM) Building simulation of the building case in Famagusta Five (5) different options a possibilities of PV integration were generated from the simulation 4. Feasibility Study - PC (Project Cost) Feasibility Study on the project 5. Selection of the optimal PV integration design Selection of the best design option Selection of the best option out of the 5 generated options based on best architectural integration, cost and optimum energy generation capacity The option 1 was selected because it scored higher than the rest in terms architectural integration, energy efficiency, and passive and active design strategies. 6/7. Construction, operation, and monitoring
Chapter 7 conclusion	Findings o Conceptual Findings Based on the Literature o Findings Based on the Proposed PV integration into detached family housing model Research Questions Revisited Recommendations for Further Research

7.2 Conclusion

In conclusion, the major findings of the research is the decision making model for the architectural integration of PV panels in single family detached housing units. However, there are other finding that this thesis presents, these findings are presented in the section below. For easy presentation the conclusion section is subdivided into two; finding based on literature/ studies of existing cases carried out by this research and findings derived from the application of the model to the city of Famagusta.

7.2.1 Conclusion Based on Literature

From the study of the different existing BIPV models comparatively studied in this research, there are certain critical components that must be included in the development of any BIPV model that aims to achieve a considerably satisfactory level of architectural integration and energy efficiency. The common items that were seen throughout out all the BIPV models studied include, a clear definition of goals and objectives, building information modeling (BIM), orientation, inclination, and a good understanding of the PV technology to use.

Through the use of BIPV, clean and cheaper energy can be generated, and if PV is properly integrated as sun shading devices in detached family housing it can serve the dual purpose of energy generation and passive design strategy as well.

The integration of PV in residential buildings is a good way archiving centralized energy generation as the energy needed for the building is generated in situ, cutting down of cost and carbon emission.

7.2.2 Conclusion from the PV Integration Model

This research presents a decision making model that contains strategies for successful architectural integration of PV in existing single family detached housing units.

The decision making model developed by this study has seven stages (7) that if carefully followed would lead to a successful integration of PV in single family detached housing units. The model was then applied qualitatively and quantitatively to the case of Famagusta in Northern Cyprus. after taking this single family detached housing unit studied through the stages of the model, certain strategies, guidelines and recommendations that can be easily followed were developed for the case of Northern Cyprus.

The study postulates that the successful integration of PV in detached family housing lies between a balance between the following; i) aesthetics integration, ii) cost, iii) energy generation and iv) possible energy performance.

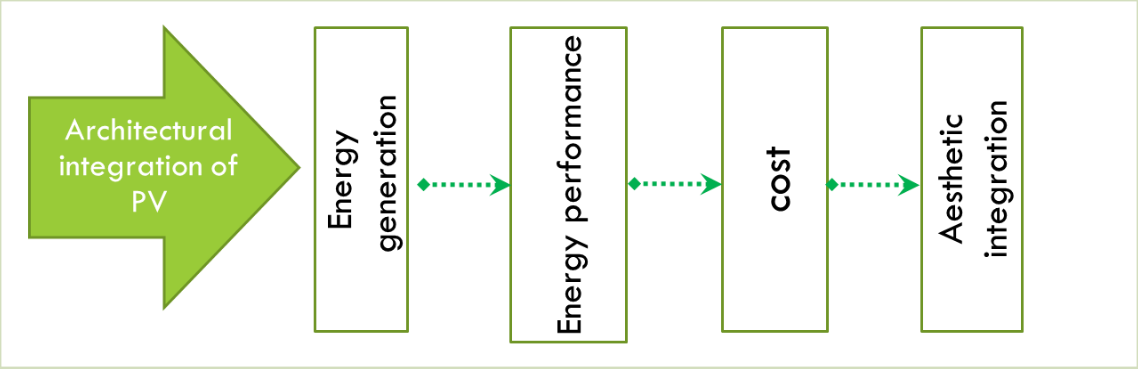


Figure 7.1. Criteria for The Architectural Integration of PV

The model developed in this study has been successfully applied to the city of Famagusta and has been tested through empirical study which concluded that PV can be integrated architecturally into detached family housing of Famagusta. The success of this model further implies that the model can prove useful in other regions of the world.

When integrated PV in detached buildings in Northern Cyprus, the south façade produces the best yield. When the PV panels are integrated to the east or west façade the efficiency drops by over 20%. Thus this study recommends the integration of PV on the south façade of single family detached housing units. Therefore, if the potential user intends to integrate PV panels on a different orientation order than the south, the integration possibilities should be re-evaluated and solved through proper architectural design solutions.

Through the application of the model, 10 options which covers façade integration, roof integration and sun shading integration were generated and the best option was selected based on a pre-determined criterion.

For integration on the roof, the findings of this study suggest a sloped roof the south façade. This will ensure maximum yield, more reliable energy generation all through the year.

From the simulations carried to on the south oriented building, the authors recommend the use of horizontal overhang on the south façade and a combination of fins and overhangs for the east and west facades for optimal energy generation, and performance.

PV panels should be integrated as cladding on the south façade. It is not recommended on the north, east and west façade.

When integrating PV panels, a shading device on the south façade, it should be inclined at 12% to get the optimum energy generation.

From options 3 and 4 generated the following findings were made:

The simulation result derived from the single-family detached house in Famagusta indicates that the strategic use of PV on roofs, facades and PVSDs (option 3/4) for openings oriented towards south can reduce its energy consumption by almost 50% in three peak months of the year.

The integration of PVSDs cut down up to 400kWh of energy consumption through the year and raises the comfort level of the building by about 20%.

PVSDs used as a shading device, inclined at 12° will provide nearly 3500watt that can provide up to 60% of the electricity demand of the single family detached housing units.

The cost of the substituted materials and green field that would otherwise have been used to mount the panels will be saved.

7.3 Recommendations for Future Studies

In this thesis the Life Cycle Cost (LCC) analysis of the options was not comparatively considered. The author recognizes that base on the LCC, different results can be obtained. Therefore, future studies can be done in this regards. Another recommendation for future studies, the energy analysis and options can be calculated and compared using BIM studio programs. Although the decision making model for the architectural integration of PV panels developed in this study can be applied to existing buildings globally, based on the limitations of this studies, the result should be used as applied in the given conditions stipulated in the study case of this thesis.

The decision making model for the architectural integration of PV in single family detached family housing units presented in this study is limited to existing buildings, future studies can be done to modify the model for application in new buildings.

REFERENCES

Aksugur, E. (1996). Potential of passive cooling strategies in Cyprus. In Housing Research Conference, *European Network in Housing Research*; ENHR: Helsingor, Denmark (Vol. 174).

Ali, M. M., & Armstrong, P. J. (2008, March). Overview of sustainable design factors in high-rise buildings. In Proc. of *the CTBUH 8th World Congress* (pp. 3-5).

Altin, M. Binaların Enerji Ihtiyacinin PV Bilesenli Cepheler ile Azaltilmasi. 3. Ulusal Cati ve Cephe Kaplamalarinda Cagdas Malzeme ve Teknolojileri Sempozyumu. 17-18 Ekim 2006, ITU Mimarlık Fakultesi, Taskisla. Retrieved from *World Wide Web* on June 1, 2011: http://www.catider.org.tr/pdf/sempozyum/Bil7.pdf

Assoa, Y. B., Mongibello, L., Carr, A., Kubicek, B., Machado, M., Merten, J., ... & Zamini, S. (2017). Thermal analysis of a BIPV system by various modelling approaches. *Solar Energy*, 155, 1289-1299.

Atalar, E. (2001). *Evaluation of Solar Insolation in Northern Cyprus* (Doctoral dissertation, Eastern Mediterranean University).

Bahr, W. (2014). A comprehensive assessment methodology of the building integrated photovoltaic blind system. *Energy and Buildings,* 82, 703-708.

Bauer, M., Mösle, P., & Schwarz, M. (2009). Green building: guidebook for sustainable architecture. *Springer Science & Business Media*.

Becquerel, M. E. (1839). Mémoire sur les effets électriques produits sous l'influence des rayons solaires. *Comptes rendus hebdomadaires des séances de l'Académie des sciences,* 9, 561-567.

Bonomo, P., Chatzipanagi, A., & Frontini, F. (2015). Overview and analysis of current BIPV products: new criteria for supporting the technological transfer in the building sector. *VITRUVIO-International Journal of Architectural Technology and Sustainability, (1),* 67-85.

Boxwell, M. (2017). The Solar Electricity Handbook-2017 Edition: A simple, practical guide to solar energy–designing and installing solar photovoltaic systems. *Greenstream Publishing*.

Cardona, A. J. A., Chica, C. A. P., & Barragán, D. H. O. (2018*). Building-Integrated Photovoltaic Systems (BIPVS): Performance and Modeling Under Outdoor Conditions.* Springer.

Climatemps.com. Available online: http://www.famagusta.climatemps.com/ (accessed on 14 august2018).

Costanzo, V., Evola, G., Marletta, L., & Pistone Nascone, F. (2018). Application of climate based daylight modelling to the refurbishment of a school building in Sicily. *Sustainability, 10*(8), 2653.

Council, A. B. (2007). Building Energy Efficiency: Why green buildings are key to Asia’s future. *Asia Business Council Publication,* Hong Kong.

Das, S. K., Verma, D., Nema, S., & Nema, R. K. (2017). Shading mitigation techniques: State-of-the-art in photovoltaic applications. *Renewable and Sustainable Energy Reviews,* 78, 369-390.

Dehra, H. (2017). An investigation on energy performance assessment of a photovoltaic solar wall under buoyancy-induced and fan-assisted ventilation system. *Applied Energy*, 191, 55-74.

Dim, D. (2017). *Overview and discussion on recent applications of building integrated daylighting systems and photovoltaics* (Master's thesis, İzmir Institute of Technology).

Dunn, J. R., & Hayes, M. V. (2000). Social inequality, population health, and housing: a study of two Vancouver neighborhoods. *Social Science & Medicine, 51*(4), 563-587.

Edoff, M. (2012). Thin film solar cells: research in an industrial perspective. *Ambio, 41*(2), 112-118.

Elinwa, U., Radmehr, M., & Ogbeba, J. (2017). Alternative energy solutions using BIPV in apartment buildings of developing countries: A case study of North Cyprus. *Sustainability, 9*(8), 1414.

Energyplus (2018), EnergyPlus ,. https://energyplus.net/; [Acessed: 4 Deember, 2018].

Farkas, K., Andresen, I., & Hestnes, A. G. (2009, June). Architectural integration of photovoltaic cells—Overview of materials and products from an architectural point of view. In Proceedings of *the 3rd CIB International Conference on Smart and Sustainable Built Environments (SASBE), Delft, The Netherlands* (pp. 15-19).

Filippini, M., Hunt, L. C., & Zorić, J. (2014). Impact of energy policy instruments on the estimated level of underlying energy efficiency in the EU residential sector. *Energy Policy*, 69, 73-81.

Garde, F., Bastide, A., Wurtz, E., Achard, G., Dobre, O., Thellier, F., ... & Bornarel, A. (2007). ENERPOS: *A National French Research Program for developing new methods for the Design of Zero Energy Buildings*.

HAGEMANN, I. (2014). Shading systems with PV A new market for prefabricated building elements. Environmentally Friendly Cities: Proceedings of *Plea 1998, Passive and Low Energy Architecture*, 1998, Lisbon, Portugal, June 1998, 373.

Halpern, D. (2014). Mental health and the built environment: more than bricks and mortar. Routledge.

Hancer, P. (2005). *Thermal insulations of roofs for warm climates* (Doctoral dissertation, Eastern Mediterranean University).

Hanh Vu (2019). An Overview of Decision-Making Models. (https://toughnickel.com/business/An-overview-of-decision-making-models#).

Heinstein, P., Ballif, C., & Perret-Aebi, L. E. (2013). Building integrated photovoltaics (BIPV): review, potentials, barriers and myths. *Green*, *3*(2), 125-156.

IEA report (2018), http://iea-pvps.org/index.php?id=267 [Accessed 5 November 2018]

Imal, M., Yılmaz, K., & Pınarbaşı, A. (2015). Energy efficiency evaluation and economic feasibility analysis of a geothermal heating and cooling system with a vapor-compression chiller system. *Sustainability, 7*(9), 12926-12946.

iSHAN JAIN (2017) How to Design a Shading Device? Online, available at (http://talkarchitecture.in/how-to-design-a-shading-device/) [Accessed on 7.08.2018].

James, T., Goodrich, A., Woodhouse, M., Margolis, R., & Ong, S. (2011). Building-Integrated Photovoltaics (BIPV) in the residential sector: an analysis of installed rooftop system prices (No. NREL/TP-6A20-53103). *National Renewable Energy Lab*.(NREL), Golden, CO (United States).

Jelle, B. P., Breivik, C., & Røkenes, H. D. (2012). Building integrated photovoltaic products: A state-of-the-art review and future research opportunities. *Solar Energy Materials and Solar Cells*, 100, 69-96.

Kahoorzadeh, A. (2013). *Improvement of thermal comfort in residential buildings by passive solar strategies using direct gain techniques* (Doctoral dissertation, Eastern Mediterranean University (EMU)-Doğu Akdeniz Üniversitesi (DAÜ)).

Kang, S., Hwang, T., & Kim, J. T. (2012). Theoretical analysis of the blinds integrated photovoltaic modules. *Energy and Buildings,* 46, 86-91.

Kanters, J., & Wall, M. (2016). A planning process map for solar buildings in urban environments. *Renewable and Sustainable Energy Reviews,* 57, 173-185.

KIB-TEK (2018), https://www.kibtek.com/ [Accessed 5 December, 2018]

Kirimtat, A., Koyunbaba, B. K., Chatzikonstantinou, I., & Sariyildiz, S. (2016). Review of simulation modeling for shading devices in buildings. *Renewable and Sustainable Energy Reviews*, 53, 23-49.

Kuhn, T. E., Bühler, C., & Platzer, W. J. (2001). Evaluation of overheating protection with sun-shading systems. *Solar Energy,* 69, 59-74.

Lapithis, P. A. (2005). Passive solar architecture in Cyprus. *Lapithis Architectural Firm*: Lefkosa, Cyprus.

Leskovar, V. Ž., & Premrov, M. (2011). An approach in architectural design of energy-efficient timber buildings with a focus on the optimal glazing size in the south-oriented façade. *Energy and Buildings, 43*(12), 3410-3418.

Li, X., & Strezov, V. (2015). Energy and greenhouse gas emission assessment of conventional and solar assisted air conditioning systems. *Sustainability, 7*(11), 14710-14728.

Liu, Z., Osmani, M., Demian, P., & Baldwin, A. N. (2011). The potential use of BIM to aid construction waste minimalisation.

Luo, Y., Zhang, L., Liu, Z., Wu, J., Zhang, Y., Wu, Z., & He, X. (2017). Performance analysis of a self-adaptive building integrated photovoltaic thermoelectric wall system in hot summer and cold winter zone of China. *Energy,* 140, 584-600.

Mappery, Solar Radiation Map of Cyprus, http://www.mappery.com/Solar-RadiationMap-of-Cyprus, Accessed in 2017.

Martin II, J. (2011) BIPV: Building-integrated Photovoltaics, the future of PV [online]. Available at: http://www.solarchoice.net.au/blog/bipv-building-integrated-photovoltaics-the-future-of-pv/ [Accessed 12 October 2016].

Mesda, Y. (2012). Heat Transfer Coefficient Analysis of the Chamber of Cyprus Turkish Architects Office Building on the Zahra Street in the Walled City of Nicosia. *Architecture Research, 2*(4), 47-54.

Milne, M., Liggett, R., Benson, A., & Bhattacharya, Y. (2009, December). Climate Consultant 4.0 develops design guidelines for each unique climate. In *American Solar Energy Society Meeting*.

Munzer, K. A., Holdermann, K. T., Schlosser, R. E., & Sterk, S. (1999). Thin monocrystalline silicon solar cells. *IEEE transactions on electron devices, 46*(10), 2055-2061.

Nagy, Z., Svetozarevic, B., Jayathissa, P., Begle, M., Hofer, J., Lydon, G., ... & Schlueter, A. (2016). The adaptive solar facade: From concept to prototypes. *Frontiers of Architectural Research, 5*(2), 143-156.

Nocera, F., Lo Faro, A., Costanzo, V., & Raciti, C. (2018). Daylight Performance of Classrooms in a Mediterranean School Heritage Building. *Sustainability, 10*(10), 3705.

Oktay, D. (2002). Design with the climate in housing environments: an analysis in Northern Cyprus. *Building and Environment, 37*(10), 1003-1012.

Optimum Tilt of Solar Panels. https://www.solarpaneltilt.com/ ; [Acessed: 28 Deember, 2018]

Ozay, N. (2005). A comparative study of climatically responsive house design at various periods of Northern Cyprus architecture. *Building and Environment, 40*(6), 841-852.

Özbalta, T. G. (2001). *Fotovoltaik teknolojisi ile bina kabuğunun değişen işlevleri ve yüzeyleri*.

Özdeniz, M. B., & Hançer, P. (2005). Suitable roof constructions for warm climates—Gazimağusa case. *Energy and Buildings, 37*(6), 643-649.

Pérez-Alonso, J., Pérez-García, M., Pasamontes-Romera, M., & Callejón-Ferre, A. J. (2012). Performance analysis and neural modelling of a greenhouse integrated photovoltaic system. *Renewable and Sustainable Energy Reviews, 16*(7), 4675-4685.

Pester, S., & Crick, F. (2013). *Performance of photovoltaic systems on non-domestic buildings. IHS BRE Press.*

Pourvahidi, P. (2010). *Bioclimatic Analysis of Vernacular Iranian Architecture* (Doctoral dissertation, Eastern Mediterranean University (EMU)).

Reta, T. (2017). *Leveraging a Building Information Model to Carry Out Building Energy Performance Analysis*.

Roberts, S., & Guariento, N. (2009). *Building integrated photovoltaics: a handbook. Walter de Gruyter.*

Rungta, S., & Singh, V. (2011). Design Guide: Horizontal shading devices and light shelves. *Vipul Singh, Assignment,* 3.

Sadalla, E. K., & Sheets, V. L. (1993). Symbolism in building materials: Self-presentational and cognitive components. *Environment and Behavior, 25*(2), 155-180.

Shah, A. V., Schade, H., Vanecek, M., Meier, J., Vallat-Sauvain, E., Wyrsch, N., ... & Bailat, J. (2004). Thin film silicon solar cell technology. Progress in *photo-voltaics research and applications.*

Shukla, A. K., Sudhakar, K., Baredar, P., & Mamat, R. (2018). Solar PV and BIPV system: Barrier, challenges and policy recommendation in India. *Renewable and Sustainable Energy Reviews*, 82, 3314-3322.

Dudley, B. (2015). BP statistical review of world energy 2016. London, UK.

Šúri, M., Huld, T. A., Dunlop, E. D., & Ossenbrink, H. A. (2007). Potential of solar electricity generation in the European Union member states and candidate countries. *Solar energy, 81*(10), 1295-1305.

Tablada, A., Kosorić, V., Huang, H., Chaplin, I., Lau, S. K., Yuan, C., & Lau, S. (2018). Design Optimization of Productive Façades: Integrating Photovoltaic and Farming Systems at the Tropical Technologies Laboratory. *Sustainability, 10*(10), 3762.

Taveres-Cachat, E., Bøe, K., Lobaccaro, G., Goia, F., & Grynning, S. (2017). Balancing competing parameters in search of optimal configurations for a fix louvre blade system with integrated PV. *Energy Procedia*, 122, 607-612.

TRNC (2006) TRNC general population and housing unit census. Webpage: http://nufussayimi.devplan.org/Census%202006.pdf. [Accessed 5 December, 2018]

Valladares-Rendón, L. G., Schmid, G., & Lo, S. L. (2017). Review on energy savings by solar control techniques and optimal building orientation for the strategic placement of façade shading systems. *Energy and Buildings*, 140, 458-479.

Van Sark, W. G. J. H. M., Louwen, A., de Waal, A. C., Elsinga, B., & Schropp, R. E. (2012, September). UPOT: The Utrecht photovoltaic outdoor test facility. In *27th European Photovoltaic Solar Energy Conference and Exhibition* (pp. 3247-3249). Munich, Germany: WIP.

Vesna, K., Wittkopf, S., & Huang, Y. (2011). Testing a design methodology for building integration of photovoltaics (PV) using a PV demonstration site in Singapore. *Architectural Science Review, 54*(3), 192-205.

Weather and climate (2016), *Average Monthly Hours of Sunshine over the Year in Famagusta*

Weller, B., Hemmerle, C., Jakubetz, S., & Unnewehr, S. (2012). Detail Practice: Photovoltaics: Technology, Architecture, Installation. *Walter de Gruyter*.

Yoo, S. H., & Lee, E. T. (2002). Efficiency characteristic of building integrated photovoltaics as a shading device. *Building and Environment, 37*(6), 615-623.

Zachariadis, T., & Hadjikyriakou, C. (2016). State of the Art of Power Generation in Cyprus. In Social Costs and Benefits of Renewable Electricity Generation in Cyprus (pp. 7-16). *Springer, Cham*.

Zhai, X. Q., Wang, R. Z., Dai, Y. J., Wu, J. Y., Xu, Y. X., & Ma, Q. (2007). Solar integrated energy system for a green building. *Energy and buildings, 39*(8), 985-993.

Zhang, W., Lu, L., & Peng, J. (2017). Evaluation of potential benefits of solar photovoltaic shadings in Hong Kong. *Energy*, 137, 1152-1158.

Z Zhang, X., Lau, S. K., Lau, S. S. Y., & Zhao, Y. (2018). Photovoltaic integrated shading devices (PVSDs): A review. *Solar Energy*, 170, 947-968.

Zogou, O., & Stapountzis, H. (2011). Energy analysis of an improved concept of integrated PV panels in an office building in central Greece. *Applied Energy, 88*(3), 853-866.