POTENTIAL ELECTRICITY SAVINGS ANALYSIS FROM IMPLEMENTING BUILDING INTEGRATED PHOTOVOLTAICS AT AN INDUSTRIAL PLANT

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FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2021

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RESEARCH PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MECHANICAL ENGINEERING

**FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR**

2021

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Matric No: KQK170037

Name of Degree: Master of Mechanical Engineering

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Field of Study: Renewable Energy

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POTENTIAL ELECTRICITY SAVINGS ANALYSIS FROM IMPLEMENTING BUILDING INTEGRATED PHOTOVOLTAICS AT AN INDUSTRIAL PLANT

ABSTRACT

Malaysia is striving towards meeting its climate goals as part of the Paris Agreement, of which Malaysia is one of the signatories. Two of our current main sources of greenhouse gas emissions in Malaysia is the energy industries and manufacturing industries. To develop more energy diversity in our country, solar photovoltaic technology will be key to further reduce our greenhouse gas emissions, given its suitability for our climate and the advancements in the technology that has lowered its cost and increased its electricity generation capacity. Therefore, this study was done to spur the adoption of BIPV technology in the industrial sector by showcasing the electricity savings potential at industrial sites by using an existing site to simulate the estimated savings from implementing a BIPV system. This study utilised a method for estimating the BIPV system by considering the current available Solar PV technologies that can be implemented, and considering the physical, geographic, technical and economic potential for a selected site. This study used a widely used simulation software PVSyst to input the localised meteorological data and utilising its wide database of PV modules. The chosen site has an effective roof area of 7,000m^2 was selected for the study and PV modules were selected based on their availability in the Malaysian market. The electricity tariff used was based on the local electric utilities provider's classification for medium voltage industries. System losses were also considered in the simulation model to provide better relations to real world conditions. By applying the proposed methods, a total of six models were developed, with each utilising different PV technologies to generate the technical and economic potential, which led to an analysis on the electricity savings for each type of proposed system. Overall, the estimated annual electrical savings was from a range of 1,503MWh/year to 1,801MWh/year, with an LCOE range of between

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0.182 MYR/kWh to 0.351 MYR/kWh. The thin film cell simulation model was also found to have the best payback period among all generated models. While this study has shown that, different types of technology will provide varying results in terms of potential electric savings for a company, further studies can be conducted to expand the technical and economic aspect to provide more accurate simulations in future reports, with focus provided on any potential funding aids e.g. private or government and more research on degradation over time of PV modules.

Keywords: Solar energy, Building Integrated Photovoltaic, Payback period, LCOE

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POTENTIAL ELECTRICITY SAVINGS ANALYSIS FROM IMPLEMENTING BUILDING INTEGRATED PHOTOVOLTAICS AT AN INDUSTRIAL PLANT

ABSTRAK

Malaysia sedang berusaha untuk mencapai matlamat iklim yang telah dimeterai dalam Perjanjian Iklim Paris, di mana Malaysia merupakan salah sebuah pihak yang telah menandatanginya. Dua daripada sumber utama gas rumah hijau di Malaysia adalah daripada sektor tenaga dan sektor pembuatan. Bagi mengembangkan lagi jenis sumber tenaga di negara kita, teknologi fotovoltaik solar merupakan kunci utama untuk mengurangkan emisi gas rumah hijau kita. Hal ini kerana teknologi ini amat sesuai dengan iklim kita dan teknologi ini telah berjaya mengurangkan kos pembuatannya sementara meningkatkan kapasiti penjanaan elektriknya. Oleh itu, kajian ini dilakukan untuk memacu penggunaan teknologi BIPV di sektor perindustrian dengan mempamerkan potensi penjimatan elektrik di kawasan perindustrian dengan menggunakan tapak sediada untuk mensimulasikan anggaran penjimatan daripada melaksanakan sistem BIPV. Kajian ini memakai kaedah untuk menganggarkan sistem BIPV dengan mempertimbangkan teknologi fotovoltaik solar teerkini yang dapat digunakan serta mempertimbangkan potensi fizikal, geografi, teknikal dan ekonomi untuk tapak yang dipilih. Kajian ini menggunakan perisian simulasi PVSyst untuk memasukkan data meteorologi setempat dan menggunakan pangkalan data modul PV yang dibina masuk dalam perisian ini. Tapak yang mempunyai keluasan atap 7,000m^2 telah dipilih untuk kajian dan modul PV dipilih berdasarkan ketersediaannya di pasaran Malaysia. Tarif elektrik yang digunakan adalah berdasarkan klasifikasi penyedia utiliti elektrik tempatan untuk industri voltan sederhana. Kerugian sistem juga dipertimbangkan dalam model simulasi untuk memberikan kaitan yang lebih tepat dengan keadaan dunia nyata. Dengan menerapkan kaedah yang diusulkan, sejumlah enam model PV telah dihasilkan, masing-masing menggunakan teknologi yang berlainan untuk menghasilkan

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potensi teknikal dan ekonomik dan membawa kepada analisis penjimatan elektrik untuk setiap jenis sistem yang dicadangkan. Secara keseluruhan, anggaran penjimatan elektrik tahunan adalah dari julat 1,503MWh / tahun hingga 1,801MWh / tahun, dengan julat LCOE antara 0.182 MYR / kWh hingga 0.351 MYR / kWh. Model simulasi sel filem nipis didapati mempunyai tempoh pembayaran balik terpendek di kalangan semua model yang dijanakan. Kajian lanjut boleh dilakukan untuk memperluas aspek teknikal dan ekonomik untuk menghasilkan simulasi yang lebih tepat bagi kajian seterusnya.

Keywords: Tenaga solar, Building Integrated Photovoltaic, Payback period, LCOE

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ACKNOWLEDGEMENTS

This research project has been a fruit of labour that has stretched longer than what I would have wanted it to be. It could not have been completed without the technical and moral support of a few key individuals.

Firstly, to my supervisor Dr Nashrul for his encouragement and support throughout the journey of completing this report. Your passion for the work you do is something that I strive to embody in my educational and professional work.

Secondly, to my colleagues Ir. Karthegasen Nakulan and Ir. Punitha Raman. It has been a very difficult period at work given the challenges we have faced in this pandemic. Thank you for being understanding on my need to take some time off to focus on this research project as well as providing your technical experience in utilising the software and interpreting the generated results.

Lastly, to Mr. Murali from Bolt Industries Sdn. Bhd. Thank you for sharing your experience in considerations for a solar PV system design and insight into appropriate site selections. Your invaluable experience has whetted my appetite into learning more about this technology.

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LIST OF SYMBOLS AND ABBREVIATIONS

INDC	:	Intended Nationally Determined Contribution
GHG	:	Greenhouse gas
GDP	:	Gross Domestic Product
CO_2	:	Carbon dioxide
PV	:	Photovoltaic
BIPV	:	Building Integrated Photovoltaic
PERC	:	Passivated emitter and rear cell
CdTe	:	Cadmium telluride
CIGS	:	Copper-indium-gallium-diselenide
ROI	:	Return of Investment
PP	:	Payback Period
NEM	:	Net Energy Metering
NOVA	:	Net Offset Virtual Aggregations
SMP	:	System Marginal Price
FiT	:	Feed-in Tariff
GIS	:	Geographic information system
c-Si	:	Crystalline silicone
sc-Si	:	Single crystalline silicone
mc-SI	:	Multicrystalline silicone
Wp	:	Watt peak
Pnom	:	Nominal power
NPV	:	Net Present Value
LCOE	:	Levelised Cost of Energy

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CHAPTER 1: INTRODUCTION

Climate change is a real and present threat to our world today, both socially and economically. Rising sea levels, prolonged droughts, more extreme typhoons and intense forest fires have all been linked to climate change and human activities have played a large part in exacerbating this issue.

Malaysia is one of the signatory parties to the Paris Agreement and have set an intended nationally determined contribution (INDC) goal of reducing its greenhouse gas (GHG) emissions intensity of GDP by 45% by 2030 relative to the emissions intensity of 2005's GDP (UNFCCC, 2015). This formed the framework for the government's policy planning in various sectors such as agriculture, industries, energy etc. to work towards achieving this INDC target.

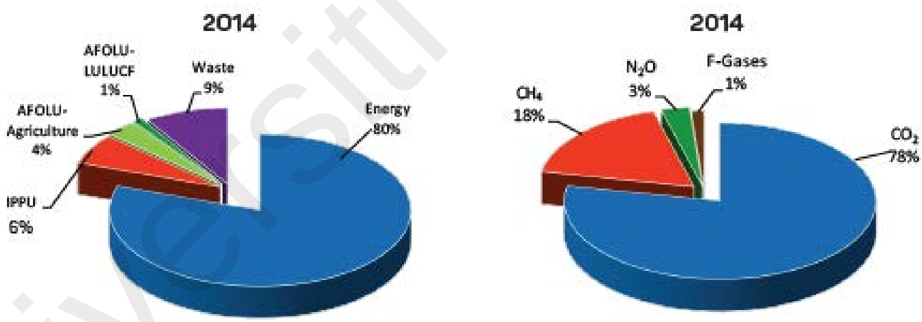

Figure 1.1: Percentage of Greenhouse Gas Emissions by Sector in 2014 (Ministry of Natural Resources & Environment, 2018)

It is important to highlight what are the major sources of GHG emissions in Malaysia, by sector and by type of gas. The most recent data from 2014 shows that a whopping 80% of GHG emission comes from the energy sector and CO_2 gas makes up the largest GHG emission gas at 78%. Translating that to a number, emissions from the energy industries i.e. fuels used by the power and auto producers for producing electricity, petroleum refining and natural gas transformation equated to 133,097 Gg CO_2 (Ministry of Natural Resources & Environment, 2018)

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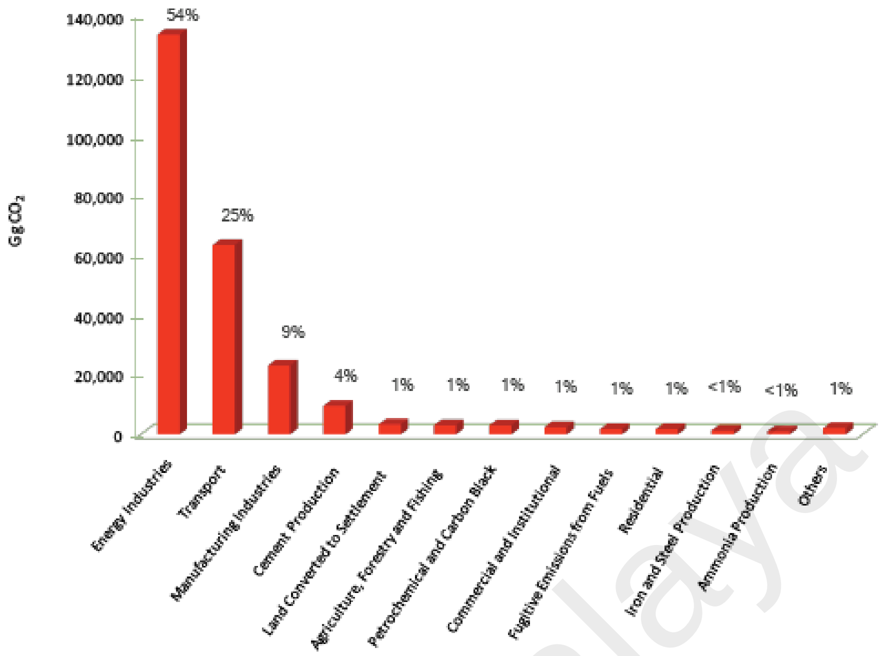

Figure 1.2: Major Sources of Carbon Dioxide Emissions in 2014 (Ministry of Natural Resources & Environment, 2018)

In September 2018, as part of the push to reduce CO_2 emissions from the energy sector, the government has set an ambitious target of 20% of the country's electricity to be generated by renewable sources by 2030, from the existing 2% (Eusoff, 2018). Bear in mind that this 20% is not inclusive of large-scale hydroelectric power as it has an initial net negative impact on the environment. Hence, considering the main contributors of CO_2 emissions in our country, geographical location, weather patterns and resource availability, the two driving renewable energy sources to achieving this target will be biogas/biomass technology and solar photovoltaic cells (PV). PV has the distinct advantage of being able to be implemented nearly everywhere that the sun is available.

PV has come a long way in terms of cost and efficiency and becoming a widely accepted technology adopted in Malaysia. Field studies in Malaysia for four types of PV modules (monocrystalline silicon, polycrystalline silicon, amorphous silicon and copper-indium-diselenide (CIS or thin film)) have shown measured average output efficiency

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(ratio of measured average power output over rated maximum power) of between 30.1% to 35.31% (N. Amin, 2009).

Attractive tax incentives, feed-in tariffs, net energy monitoring and continuous reduction of manufacturing, maintenance & installation costs will inevitably lead to wider adoption of this technology in Malaysia. Not only can it be connected to the electricity grid from an LSS plant, a system can be easily installed on the roofs or facades of commercial and residential buildings and directly supply electricity to the facility (this system is also known as Building Integrated PV or BIPV). Excess electricity generated can also be sent back through the grid.

The third biggest source of carbon dioxide emissions in our country is the manufacturing industries and construction sector with 22,906Gg CO_2 (Ministry of Natural Resources & Environment, 2018). The manufacturing industry is a prime target for implementation of BIPVs as in the long run, it will reduce their operational expenditure and carbon footprint, making both economic and environmental sense. Also, most industrial facilities are in industrial parks that have relatively flat terrain, low building heights and have no geographical impedance that can cause sustained shading of panels. The installation of BIPV is picking up in this sector, but more can be done to spur widespread adoption.

Hence, this research project will focus on the potential electrical savings that can be achieved from implementation at an industrial factory. A suitable industrial site will be identified and consider the available installation area and slope, building orientation, historical weather patterns and potential partial shadow from surrounding obstacles at a feasible location.

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The main objectives of this research project are as follows:-

1. To design and simulate the expected electrical output of theoretical solar PV designs that can consider all technical, geographic and physical potential using available software in the market;
2. To calculate the estimated electricity savings potential for each option by factoring in electricity generated and PV cell degradation over time.

It is hoped that through this study, we can provide the spur for large scale implementation of BIPVs, which can reduce a facility's carbon footprint and contribute to achieving our country's climate goals.

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Fossil fuels dominate the current energy source for electricity production in Malaysia. As of 2017, 38.0% of Malaysia's electricity production coming from natural gas, 44.2% from coal and 0.6% from oil. Renewable energies, mostly consisting of large hydroelectric dams, contribute only 17.2% to the mix (Latif, et al., 2021). This energy mix is in-line with our regional neighbours, who also rely heavily on fossil fuels.

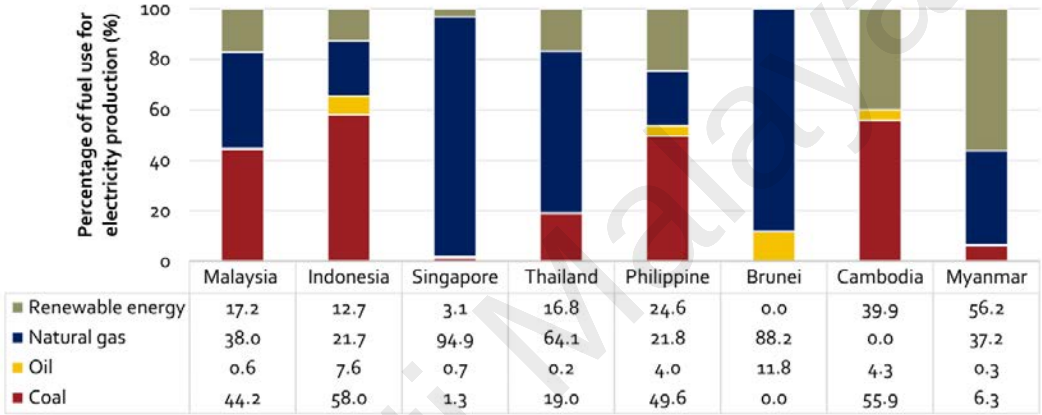

Figure 2.1: Percentage of Energy Inputs Use for Electricity Production (%) in ASEAN Countries in 2017 (Latif, et al., 2021)

Electricity generation is also the largest source of greenhouse gases (GHGs) in Malaysia, specifically CO_2. The latest available data from 2017 shows that the amount of CO_2 produced by fossil fuels was estimated at more than 100,000 Gg.

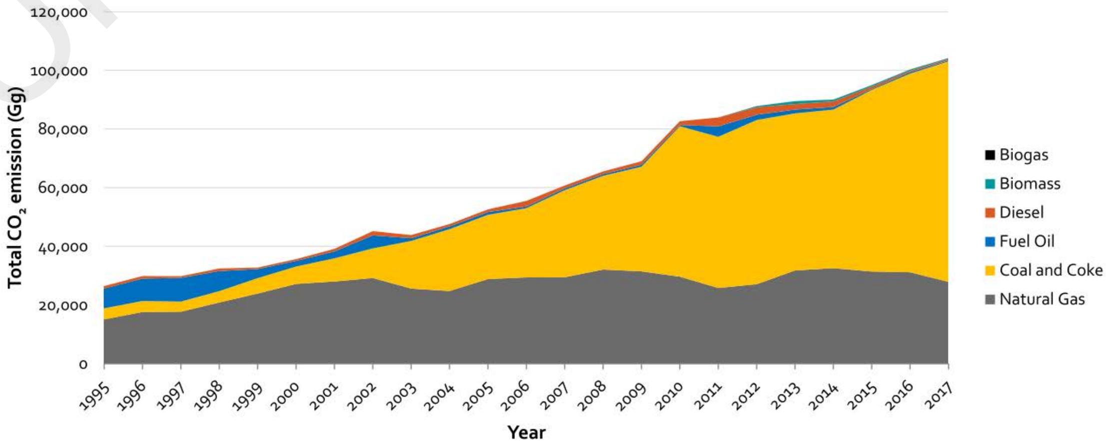

Figure 2.2: Total Annual CO2 Emissions from Malaysian Electricity Generation (Latif, et al., 2021)

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If Malaysia is serious about meeting their climate goals, a shift towards renewable energy must be intensified. Our country is blessed with a lot of natural resources, including renewable energies like sun and wind. In an urban environment where a lot of energy is consumed, there are many potential areas where renewable energy can be implemented, including Building Integrated Photovoltaics (BIPV). PV cells require large installation areas and no obstructions to be able to generate sufficient electricity at a scale that can be deemed economical. For that, factories are prime study cases as they have large roof areas and have clear surroundings i.e. no natural or man-made obstructions. This is aided by generally favourable solar radiation in Malaysia that ranges from 1470 kWh/m2 to 1900 kWh/m2 based on measurements at major cities of Malaysia (Mekhilef, 2012) as shown in the table below.

Table 2.1: Tabulation of Annual Mean Solar Radiation in Malaysia (Mekhilef, 2012)

Irradiance Location	Yearly average value (kWh/m^2)
Kuching	1470
Bandar Baru Bangi	1487
Kuala Lumpur	1571
Petaling Jaya	1571
Seremban	1572
Kuantan	1601
Johor Bahru	1625
Senai	1629
Kota Baru	1705
Kuala Terengganu	1714
Ipoh	1739
Taiping	1768
George Town	1785
Bayan Lepas	1809
Kota Kinabalu	1900

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Thus, our focus of this literature review will be on the technical aspect of BIPV, specific applications related to BIPVs, current technological performance, simulation methods used, and limitations of previous studies done to identify gaps for improvement.

2.1 Building Integrated Photovoltaics (BIPV)

Quite simply put, a BIPV is the integrations of photovoltaic (PV) cells into a building's external structure. BIPVs could either be stand-alone that stores generated electricity in a battery storage bank (otherwise known as off-grid), supply power back into the power grid (on-grid) or a hybrid model of both on-grid and off-grid. It can serve a dual function of replacing conventional building materials to be the "skin" of the building and power generation. For existing buildings, it can also be securely mounted on existing structures, such as walls and roofs (Strong, 2016).

A full system consists of the following components: -

a) the chosen PV modules;
b) a charge controller, to regulate power directed into our out from a battery storage bank (for stand-alone systems);
c) a power storage system which can either be built-in capacitor banks or the main utility grid;
d) inverters for converting the PV modules' direct current output into alternating current for consumption;
e) alternative power supplies or connection to the main grid to compensate for shortage of power produce; and
f) appropriate support and mounting hardware, wiring, and safety disconnects

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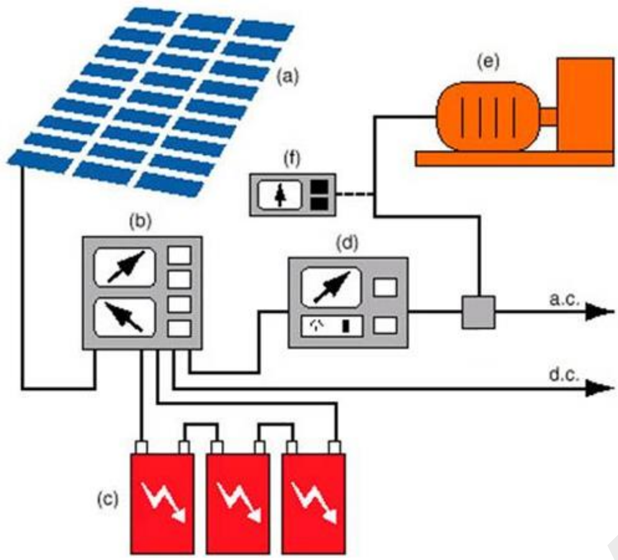

Figure 2.3: Typical BIPV System Diagram (Strong, 2016)

2.2 Solar PV Technologies Available for BIPV Designs

In recent years, there has been a concerted push for higher efficiency in the solar PV industry, where technology has grown from the conventional silicon and thin films panels into newer passivated emitter and rear cell (PERC) technology (IRENA, Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper), 2019), with varying levels of market maturity and efficiency (conversion of solar power to electrical power).

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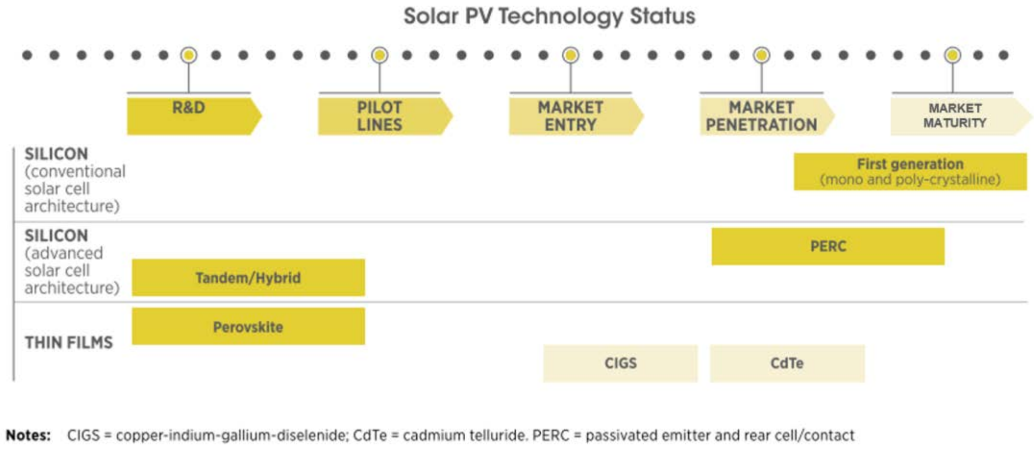

Figure 2.4: Solar PV Technology Status (IRENA, Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper), 2019)

First generation crystalline silicon (abbreviated as c-Si) panels currently hold a 95% share of worldwide PV production. This market dominance is mainly due to economics of scale of its main material, which is silicon. They consist of either monocrystalline or multicrystalline cells and deliver an average module efficiency of 18% or 17% as of 2019, with this efficiency expected to trend higher through to 2030. Its manufacturing cost has continuously dropped over the year, making it harder for other PV technologies to penetrate the market.

Another form of silicon-based technology is PERC, which is similar to monocrystalline PV cells, but with the key improvement of integrating a back-surface passivation layer. This layer increases efficiency in three main ways, which are reducing electron recombination, increase absorption of light and enable higher internal reflectivity. By applying this PERC architecture, efficiency gains for monocrystalline cells are in the range of 0.8% to 1.0%, while for multicrystalline cells it results in an efficiency gain of 0.4% to 0.8%. PERC is steadily becoming the industry standard for monocrystalline cells (mainly due to its higher efficiency gain compared to multicrystalline cells), facilitated by increased reliability in production tooling and investment in PERC production by a number of solar cell manufacturers.

Tandem or hybrid cells are individual cells basically stacked on top of one another. Each layer is able to selectively convert specific bands of light into electrical energy, maximizing all bandwidth of lights. This technology has resulted in the fabrication of the world's most efficient solar cells, which has an efficiency of 46%. However, the material and fabrication process is still very expensive, leading it to not being feasible for widespread market adoption.

Thin-film products typically incorporate very thin layers of photovoltaically active material placed on a glass superstrate or a metal substrate using vacuum-deposition manufacturing techniques similar to those employed in the coating of architectural glass. It can either be silicon-based (amorphous silicon 9a-Si) and micromorph silicon) or non-silicon-based (perovskites, cadmium telluride (CdTe) and copper-indium-gallium-diselenide (CIGS). Presently, commercial thin-film materials have a 5% global market share. Thin-film technologies have lower costs of production due to much lower requirements for active materials and energy in their production when compared to c-Si products but have much lower efficiency.

Thin-film technologies do have potential of reaching comparable efficiencies to c-Si, as perovskites (24.2%) and CIGS (22.9%) technologies being held back by durability and raw material availability issues. CdTe technology has been shown to be able to achieve an efficiency of 21% and has the largest market share of all thin-film technologies.

There are a few other advanced module technologies being developed to complement existing technologies, with bifacial solar cells, half-cut cells, multi-busbars and solar shingles being the latest innovation in the market. A summary of the technologies maturity and prospects by the International Technology Roadmap for Photovoltaic (ITRPV) are as shown in Table 2.2.

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Table 2.2: Level of Maturity and Prospects for Advanced Module Technologies (IRENA, Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper), 2019)

Technology	Level of Maturity and Prospects
Half-cut	Substantial increase expected from >3% market share in 2017 to 10% by 2020
Shingles	Very few firms have prototypes (such as Tesla)., The technology is not yet mature enough, with manufacturing machinery not completely optimised being a major hurdle
Bifacial	Insignificant presence in 2017 but tipped to have close to 10% market share in 2018, 15% in 2020 and 40% by 2030
Multi-busbars	Current three-busbar layout to be taken over progressively with layouts consisting of 4, 5, 6 or more busbars

For the basis of BIPVs, based on our review of currently available technologies, the most applicable technologies are either c-Si panels (either monocrystalline or multi-crystalline), CdTe thin-film modules or solar shingles (where panels are designed to mimic conventional roofing materials). However, solar shingles are very new in the market, with very limited adoption or availability. It would also constitute the need to change existing roofing materials. Therefore, this study shall focus on the current most widely adopted technologies, which are c-Si and CdTe panels.

2.3 Considerations for Studying of BIPV Systems

Rooftop solar PV potential can be placed into five different categories, in order of chronological steps to be taken (T. Hong, 2017):

(i) Physical potential – roof or wall area for potential installation, accessibility for installation and maintenance, etc.

(ii) Geographic potential – natural obstacles, weather patterns and typical temperature readings, etc.

(iii) Technical potential – PV module type selection and design

(iv) Economic potential – life cycle cost

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(v) Market potential – Amount of electricity production forecasted when market adoption of PV systems is saturated

This study will focus on the first four aspects with the fifth is beyond the focus of our study which is only using one case study on the potential electricity savings instead of mass market adoption. There is a research framework that will be adopted for our study, which will consider data collection, system selection, simulation and analysis (Minhyun Lee, 2018).

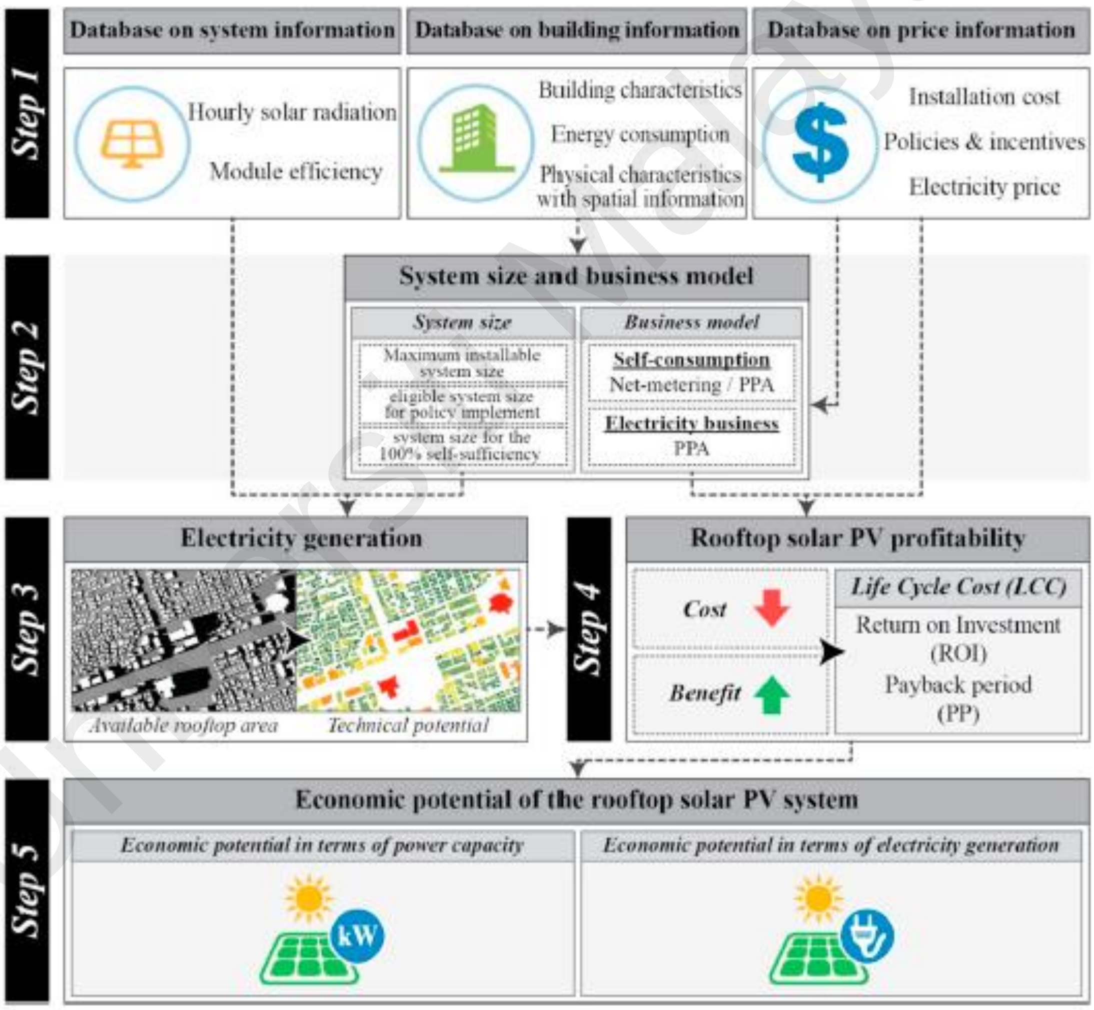

Figure 2.5: Research Framework for Estimating the Economic Potential of BIPV Systems (Minhyun Lee, 2018)

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As the market conditions of the solar PV industry, including the installation cost, policies and support schemes, and electricity price, vary significantly by year, the rooftop solar PV economic viability and profitability can be considerably different each year.

The study will be conducted in five steps, as outlined in the framework in Figure 2.4:

(i) Step 1: Set up the information for the chosen building and geography, which covers the physical and geographic potential;

(ii) Step 2: design the system size and proposed business model, which covers the technical potential;

(iii) Step 3: simulating the solar PV system capacity;

(iv) Step 4: analysing the system's profitability;

(v) Step 5: determining the economic potential of the system

In terms of policy and schemes, there are a few in place for industrial sectors that are ongoing to spur market adoption in the commercial and industrial sectors (Velautham, Wei-nee, & Weng Han, 2019), namely: -

1. Net Energy Metering (NEM) 3.0: Net Offset Virtual Aggregations (NOVA): The latest scheme was introduced in 31st March 2021 and applies only for non-domestic usage. This scheme allows prosumers to sell excess electricity back to the utility provider i.e. Tenaga Nasional Berhad (TNB) at the same electricity retail tariff that they are currently being charged at, which will be reflected in their following month's utility bills. But unlike the domestic scheme, the credit to the prosumer shall be based on the Average System Marginal Price (SMP) (Commission, 2021). SMP is defined as the monthly price of the most expensive marginal generator scheduled / dispatched to meet demand in a half hour period.

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Average SMP is the monthly average SMP for the daily period between 7.00 a.m. to 7.00 p.m. in the preceding calendar month

2. Self-consumption (SELCO): This was first carried out in 2017 to compliment NEM. Electricity produced by owners under this arrangement cannot be sold back to TNB, with any system size above 72kW requires a specific license as to be an independent producer. Organisations that choose to do this will also need to invest in a battery bank for storage of excess electricity as it is fully for the premises' consumption.
3. Feed-in Tariff (FiT): A scheme that works in conjunction with NEM. This scheme obliges energy utilities to buy renewable energy from produces at a mandated price for a specific duration. It is applicable for systems up to 30MW in size. Asides from solar PV systems, it also covers biogas, biomass and small hydro systems.

The new NEM 3.0: NOVA scheme is more complicated than the benefit under NEM 2.0 which allows all types of prosumers to sell electricity back to the grid at the same rate they are paying. The average SMP fluctuates month-by-month and is governed by data from Single Buyer, an authorised entity under the Ministry of Energy and Natural Resources, which provides this particular data on a monthly basis (Single Buyer, 2021).

2.4 Methods of Modelling

Estimating solar rooftop potential is a very broad topic, with researchers always analysing appropriate ways and methods to develop an accurate framework to help planners estimate the potentials for implementation of these technologies

For solar radiation, two main sources of data is either by using accurate measurements collected on the ground by weather stations or via maps generated by devices installed on satellites (Buffat, Grassi, & Raubal, 2018). Ground weather stations are sparse and

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measure solar irradiation at ground level at a particular location with different time intervals while satellites use images of the earth at different wavelength to estimate the cloud cover and corresponding solar irradiation at ground level to estimate the rooftop solar PV potential. This is the important first step as this data will determine the expected generation capacity for a BIPV system

Geographic information system (GIS) are often used as well to complement data from ground station measurements by providing a spatial distribution of solar radiation in areas such as South Korea, Fujian Province in China and Auckland, New Zealand. This can prove to be a challenge in localities that do not have suitable weather station infrastructure installed. Satellite data and maps have the distinct benefit of being able to cover large space and time marks.

A great way to provide more accurate data would be to utilize Light Detection And Ranging (LiDAR) data to significantly improve identification of rooftop dimensions (area and roof pitch) to estimate roof PV electricity generation more accurately (Seme, Lukac, & Zlaus, 2013).

LiDAR is a remote sensing technology used to collect topographic data of the earth's natural and man-made surface features. It can be collected either by using aircraft or a ground radar system with the added benefit of being used in areas where there are no infrastructures to use a ground-based system. LiDAR sensors will be mounted onboard an aircraft and the sensors will send laser light pulses in visible and near infrared wave lengths to the earth's surface. Upon hitting solid objects on the earth's surface, the beams are reflected back to the LiDAR sensors, with the time difference between the emission of the laser beam and the return of the reflected laser signal recorded. LiDAR only collects elevation data and requires an accurate GPS antenna to tie in the data points with fixed coordinates. The final product will provide accurate, geographically registered longitude, latitude, and elevation positions for every data point.

Equally as important as estimating the solar radiation figures is to have an accurate and wide range amount of PV modules and ancillary equipment to conduct the modelling works. To this end, we shall be utilizing a modelling software called PVSyst, a Swiss-developed modelling software being used widely in the industry as they have a very extensive library of PV modules and inverters, which are kept updated in line with industry progress. The software also has default data for solar radiation and meteorological data for multiple sites around the world.

2.5 Theory for Calculations

Whilst we are dependant on the chosen software to generate out our results, there must be a basic understanding behind the general theory for calculation of physical potential, geographic potential, technical potential and economic potential.

2.5.1 Physical Potential

The physical potential refers to the total solar radiation on a chosen location. It can be derived into the equation below, by multiplying the nett usable area with the solar radiation of the chosen area (T. Hong, 2017).

$$Physical_T = TRA \times \sum_{i=1}^{12}\left(\sum_{j=6}^{18}\left(\sum_{k=1}^{n} SR_{ijk}\right)\right)$$

$Physical_T$ stands for the total physical potential of the rooftop solar PV system for a year (MWh), TRA represents the total rooftop area of the target region while SR_{ijk} stands for the solar radiation on a specific day in MWh/m^2. i represents the month, j represents time in 24-h format, k stands for the day of a month, and n stands for the total number of days in a specified month.

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2.5.2 Geographic Potential

For geographic potential, it can be calculated using the equation below by taking into account only the nett usable area.

$$Geographic_{ijk} = TRA - SRA_{ijk} - UIA_{ijk},$$

$Geographic_{ijk}$ represents the geographic potential of the rooftop solar PV system on any given time of the month in m^2, while TRA stands for the total area of the target region, SRA_{ijk} represents the shaded area of a specific time of month with UIA_{ijk} covers unsuitable installation area on day k of month i at time j to j + 1 (m^2).

2.5.3 Technical Potential

Technical potential has the most variables to consider given the wide array of technology available. It can be represented by the equation below

$$Technical_T = e_{PV} \times \sum_{i=1}^{12}\left(\sum_{j=6}^{18}\left(ARA_{ij} \times \sum_{k=1}^{n} SR_{ijk}\right)\right).$$

$Technical_T$ stands for the total technical potential of the solar PV system in a year (MWh), ePV stands for the solar PV module efficiency in percentage, ARA_{ij} stands for the available area, SR_{ijk} stands for the solar radiation on a specific day. Each day in a month is then summed up before being multiplied. This process can be repeated for basically any frame of time to get the technical potential either in term of hourly, monthly or yearly. This process is accelerated with PV system simulation software that will even be able to include meteorological weather data to account for weather patterns that varies the available solar irradiation to come out with the level of detail required for the technical potential.

2.5.4 Economic Potential

Some of the most widely used method to justify the profitability of a solar PV system is through calculation of return on investment (ROI) and payback period (PP) (Lee, Hong, Koo, & Kim, 2018). Net Present Value (NPV) is also a useful tool.

ROI is the ratio of the discounted cash inflows and outflows. When ROI exceeds the value of 1, it can be inferred that the economic viability of the rooftop solar PV system has been achieved i.e. it has hit the break-even point. Meanwhile, PP represents the length of time, usually in terms of years, required for recovering the investment cost and reaching a break-even point, without considering depreciation or currency inflation, giving a simple indicator for decision making.

NPV considers fluctuations in currency and inflation. It is the sum of the present value of all cash inflow (e.g. from electricity savings/sold to the grid) and outflow (e.g. maintenance and repair costs) which is discounted back based on a discount rate to determine the economic feasibility of implement a project.

ROI is a straightforward comparison between the amount of money spent against money generated over the lifecycle of the system. For NPV, it is a more realistic approach that factors in the time value of money.

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CHAPTER 3: METHODOLOGY

As previously detailed in Section 2.3 of this Research Paper, we need to determine our site selection and gather the existing data for solar irradiation to determine the physical potential of a chosen location. This will then form the basis for working out the technical potential and economic potential. The methodology is further detailed in the following sub-chapters.

3.1 Establishing the Database

3.1.1 Site Selection

Each state in Malaysia has industrial zones set up to centralise these economic activities. The site chosen for this study is located in Shah Alam and belongs to the multinational company, Nestle which is engaged in the Food & Beverage Industry. There are currently no installed BIPVs in any of their facilities there.

Figure 3.1: Birds Eye View of the Factory Complex

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There are four separate complexes located within this complex, with three being food manufacturing site and one functioning as a warehouse and logistics centre. The site plan of these buildings with their orientation are shown in Figure 3.2. The four buildings are demarcated as follows: -

(i) Building A – Nestle Shah Alam Complex

(ii) Building B – Nestle Batu Tiga Factory

(iii)Building C – Nestle Sri Muda Factory

(iv)Building D – Nestle Central Factory Warehouse

Figure 3.2: Satellite Image of the Factory Complex

A site survey was conducted to determine the suitability of installing BIPVs at each building in terms of the structural support system, safety, shading potential, practicality, orientation and available roof space. In terms of orientation and shading, all sites were suitable as there are no man-made or geological obstructions in the area. However, some of these roofs do not have the necessary accessibility for installation and maintenance, as well as safety hazards i.e. no safety line or roof structure design unable to cater to the additional load of solar panels in addition to roofing and any other ancillary equipment within the building.

Accessibility is also considered for the purpose of installation and periodic preventive maintenance. While a new access can be built, for this study, we will only consider availability of existing amenities in our site selection.

The buildings were ranked in terms of feasibility for installation as shown in Table 3.1 below.

Table 3.1: Feasibility of Installing BIPVs at Each Location

Rank	Building	Approximate Available Roof Area (m^2)	Accessibility	Safety	Practicality
1	Sri Muda Factory (Building C)	7,000	Staircase access available	Safety line at the middle of roof provided	No equipment on roof; Minimal shading
2	Batu Tiga Factory (Building B)	2,500	Staircase access available	Flat roof	Multiple equipment and chimney on roof
3	Shah Alam Complex (Building A)	500	Staircase access available	Flat roof	Multiple equipment on roof
4	Central Factory Warehouse (Building D)	3,500	No access available	No safety line available; Unable to support additional loads	Multiple shading due to different roof heights; Multiple equipment on roof

The most feasible site was Building C as it has the largest available roof space, has a direct access from external staircase and via the reinforced concrete roof available, with multiple safety lines on the roof. The only source of shading is from the protruded RC roof (circled in red in Figure 3.3).

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Building B, A and C all have their own issues which prevents them from being considered in this study. Thus, we shall model BIPV system for only Building C.

Figure 3.3: Closer Look at the Sri Muda Factory

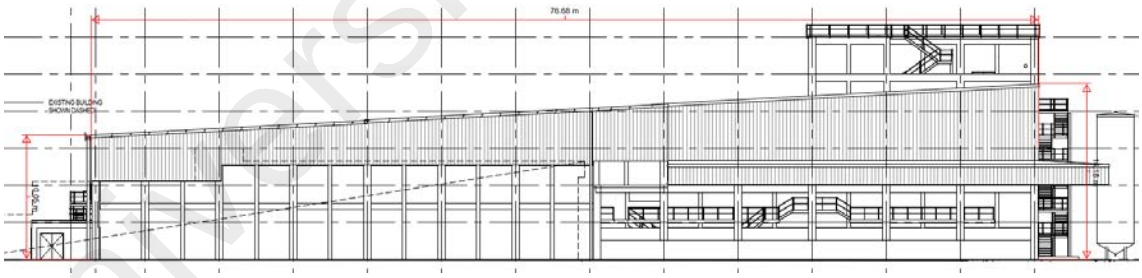

Figure 3.4: East Elevation of the Sri Muda Factory

Building C has a roof that has relatively few obstructions, save for seventeen numbers of mechanical ventilation fans and a section of the building that protrudes out from the highest point of the metal deck roof by about 3.0 metres (the circled area in Figure 3.3). The total usable metal deck roof area is about 7,000 m^2 and consists of corrugated metal sheets functioning as structural roof decks supported by steel beams and purlins, which has high strength-to-weight ratio that reduces erection and material handling cost. This area takes into account spacing for maintenance walkways and avoiding obstructions.

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The roof has a 3° incline angle from the direction of South to North, with multiple safety lines and access used for roof and fan equipment maintenance. There are no natural or man-made obstructions that can cause substantive shading throughout the day. Hence, Building C will be the most suitable to conduct our study due to its minimal need for additional infrastructure, minimum all-day shading and suitable building orientation for PV modules to harvest solar irradiation.

3.1.2 Database for the BIPV System

Our chosen software PVSyst has its own built-in meteorological data source and it allows weather data from other sources to be imported in to give more accurate simulations. The data for the solar radiation were collected to calculate the electricity generation of the BIPV system in the study area. We checked the data for the solar radiation for this particular area with Solargis, which maintains up-to-date solar resource maps of Malaysia in their database (Solargis, 2020).

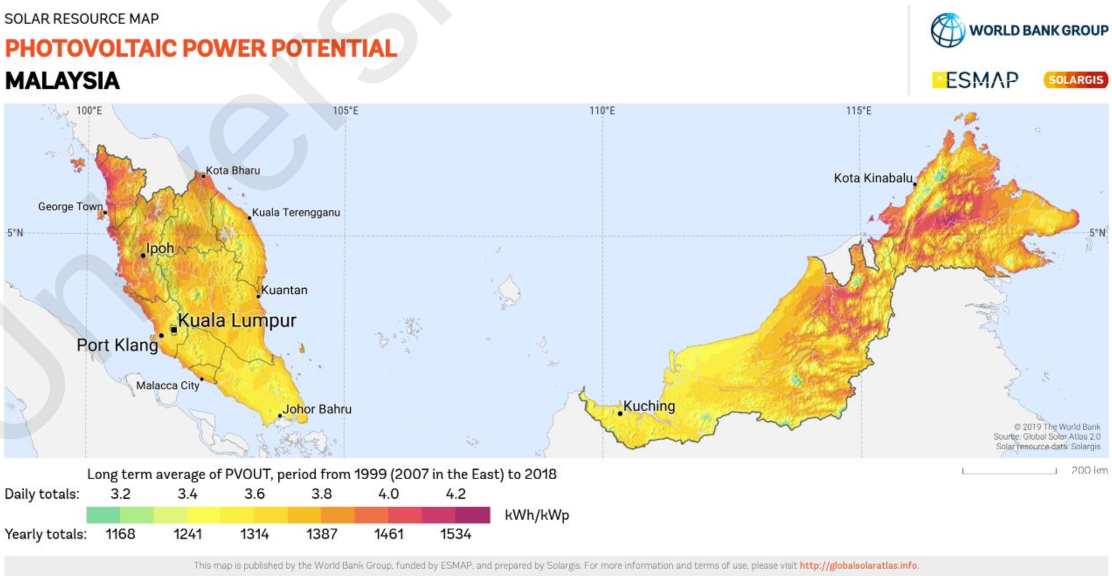

Figure 3.5: Solargis' Data for Photovoltaic Power Potential in Malaysia (Solargis, 2020)

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The database for PV modules and inverters is obtained from PVSyst 7.2, which is the latest version released as of July 2021. Hence, this study utilises the module efficiencies of the most widely used commercially available PV modules in the market right now, which typically ranges between 15% to 20% (Aggarwal, 2021).

For the latest available market conditions in Malaysia, data was obtained via the National Survey Report of PV Power Applications in Malaysia 2019 (Velautham, Wei-nee, & Weng Han, 2019). This comprehensive report gives the best available record of the existing market trends in Malaysia, the average installation costs for different usages (residential, commercial, industrial), electricity tariffs, as well as the latest policies and support schemes provided by the government.

This data is quintessential in helping us quantify the results for the economic potential for the various types of system we plan to model. The figure below shows the average installation costs from 2015 to 2019 in Malaysia which has shown a consistent downtrend in terms of price, showing that PV is becoming more cost-effective over time.

Table 3.2: National Trends in System Prices for Different Applications (Velautham, Wei-nee, & Weng Han, 2019)

Year	Residential PV (Grid-connected, roof-mounted, distributed PV system 5 -10kW)	Small Commercial PV (Grid-connected, roof-mounted, distributed PV system 10 - 100kW)	Large Commercial PV (Grid-connected, roof-mounted, distributed PV system 100 - 250kW)	Small Centralised PV (Grid-connected, ground-mounted, centralised PV system 10 - 20MW)
2015	RM 8.70/W	RM 8.11/W		
2016	RM 7.83/W	RM 7.61/W	N/A	N/A
2017	RM 7.98/W	RM 6.40/W		
2018	RM 6.00/W	RM 5.50/W	RM 4.00/W	RM 2.95/W
2019	RM 5.58/Wp	RM 4.43/Wp	RM 3.83/Wp	RM 2.91/Wp

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3.2 Designing the System

A flowchart was developed to guide the process of utilising the PVSyst software in coming out with the desired simulation models. It ties back to our steps that we established in Section 2.3 regarding the various potentials to account for.

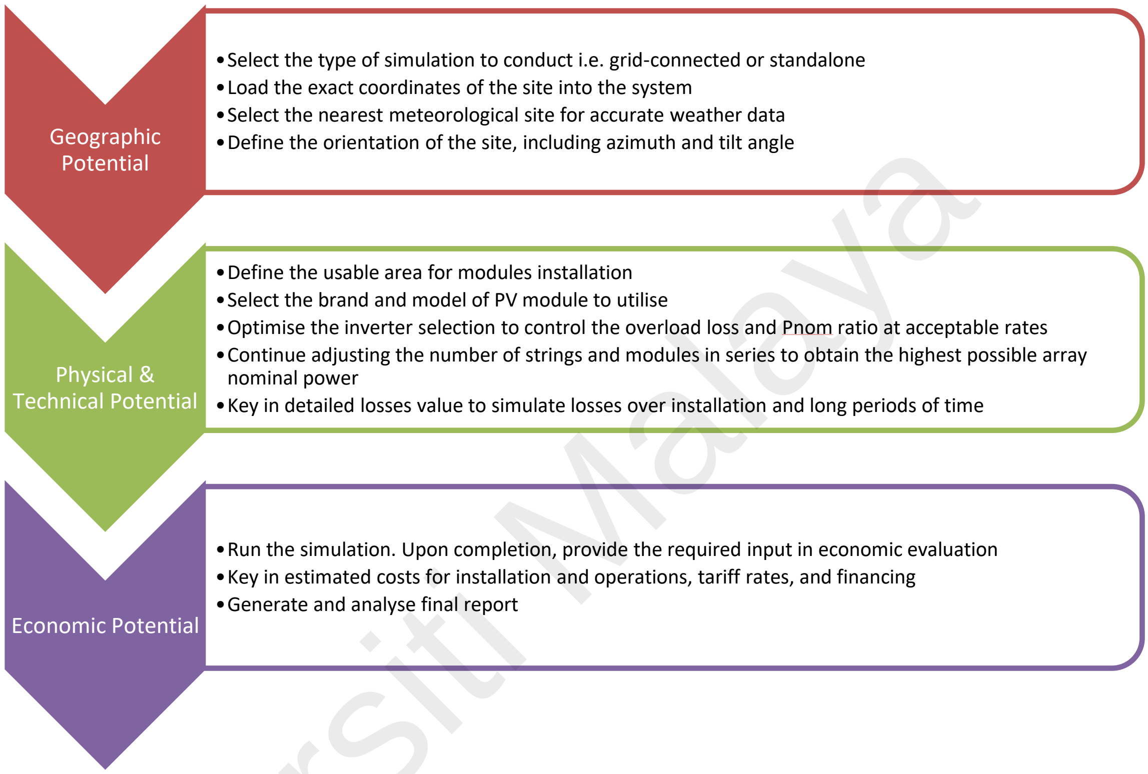

Figure 3.6: Flowchart for Creating Simulation Models with PVSyst

At the project setup, we established the geographic potential by keying in the coordinates of the site and meteorological data. Upon that, the setting of the orientation is done, where we need to set the tilt angle of our panels along with the azimuth. There has been research done on determining the optimum tilt angle in many different countries, with Malaysia having an optimum tilt angle of 1° since our country is close to the equator. However, we know that the roof slope of the building is 3°. Hence, a modified support will need to be installed to tilt the PV angle to 1°. As for the azimuth, solar panels are more productive when the sun's rays are perpendicular to the surface. But we are limited to the building's existing orientation. Based on our As-Built Drawing, the building is orientated at -17.5°. This data is then inputted into the system. Since Malaysia does not have four seasons, the optimisation was set for yearly irradiation.

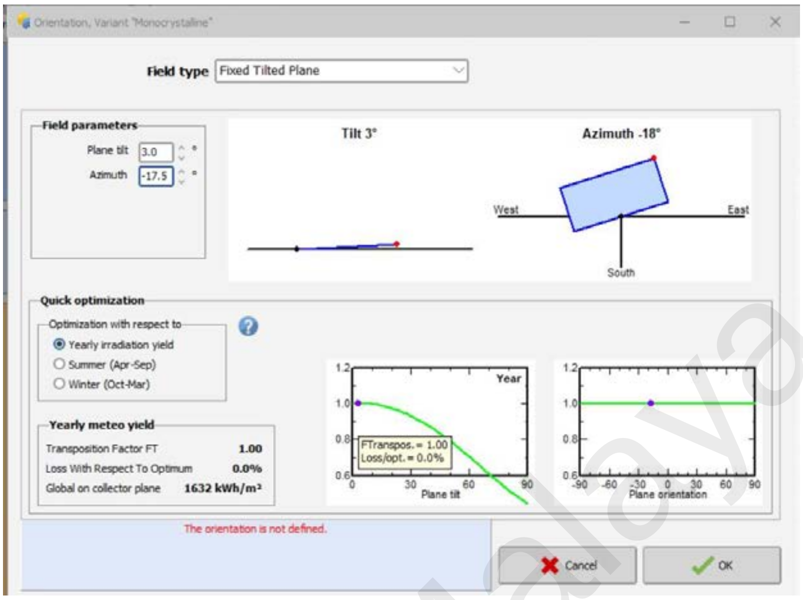

Figure 3.7: Inputting the plane tilt and azimuth data in PVSyst

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The next step is to define the physical and technical potential of the system. In Section 3.1.1, we have established that the available area for PV module installation is approximately 7,000m^2 with consideration for shading and maintenance space. As discussed in Section 3.2, the study shall focus on the current most widely adopted technologies, which are c-Si (consisting of single crystalline or multi crystalline) and CdTe panels (thin film).

As for defining the technical potential via the types of PV modules and other equipment to use, given the massive number of manufacturers in the world, we are focussing on just simulating for manufacturers that have a presence in Malaysia. These global companies manufacture monocrystalline silicone cells (also called single crystalline or sc-Si), multicrystalline silicone cells (mc-Si) and thin film cells (CdTe). The local manufacturers are summarised in the table below (Velautham, Wei-nee, & Weng Han, 2019).

Table 3.2: List of PV Module Manufacturers in Malaysia (Velautham, Wei-nee, & Weng Han, 2019)

Manufacturer	Technology
Hanwha Q CELLS	mc-Si
LONGi (Kuching) Sdn. Bhd.	sc-Si
LONGi Technology (Kuching) Sdn. Bhd.	sc-Si
Jinko Solar Technology Sdn. Bhd.	mc-Si
Sun Everywhere Sdn. Bhd. (manufactures Panasonic PV modules)	sc-Si
SunPower Malaysia Manufacturing Sdn. Bhd.	sc-Si
First Solar	CdTe

All manufacturers are available in the PVSyst software. Given the many different variations that are available within each company and the large roof areas, we will be selecting the PV module with the largest generation capacity (Wp) to maximise the technical potential of the site. Each manufacturer shall also only be simulated based on the products they manufacture in Malaysia. Thus, we will be modelling a total of six different systems, with constant variables of the site, orientation and inverters. PV modules shall be based on the best in-class for each individual company.

Inverter selection shall be based on controlling the overload loss at between 0.1% to 3.0% and a Pnom ratio of 1.25 to 1.30, which are the recommended settings to prolong system stability. Pnom ratio is the ratio of the installed PV power (Pnom) against the Pnom (ac) of the inverters, which convert the DC produced by PV panels to AC.

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Designers strive to achieve a Pnom ratio of between 1.25 to 1.30 to minimise conversion losses i.e. the loss from converting DC-generated electricity to AC.

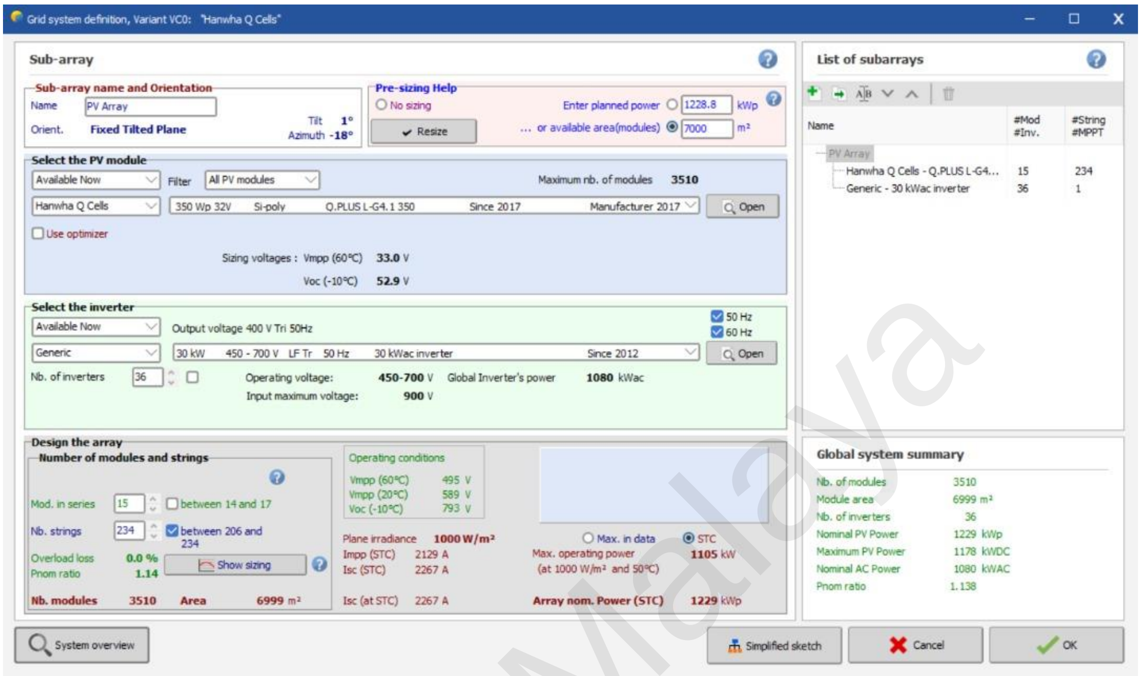

Figure 3.8: Setting Up the Technical Potential

In terms of system losses that will affect the performance of the system over time, PVSyst allows users to define certain parameters: -

1. Field thermal losses: We considered the installation to be "free" mounted modules with air circulation, which gives a thermal loss factor of 29 $W/m^2.K$
2. Ohmic losses: Accounts for the ohmic resistance of wiring circuit induced losses. We utilised a factor of 1.5%
3. Module losses: We utilised the default settings to standardise between different manufacturers. This covers any quality issues upon installation
4. Aging losses: We consider degradation over time. PVSyst is able to adjust this value based on the type of module used as different technologies have diverse degradation rates.

Upon setting up all of these details, the simulations can be ran.

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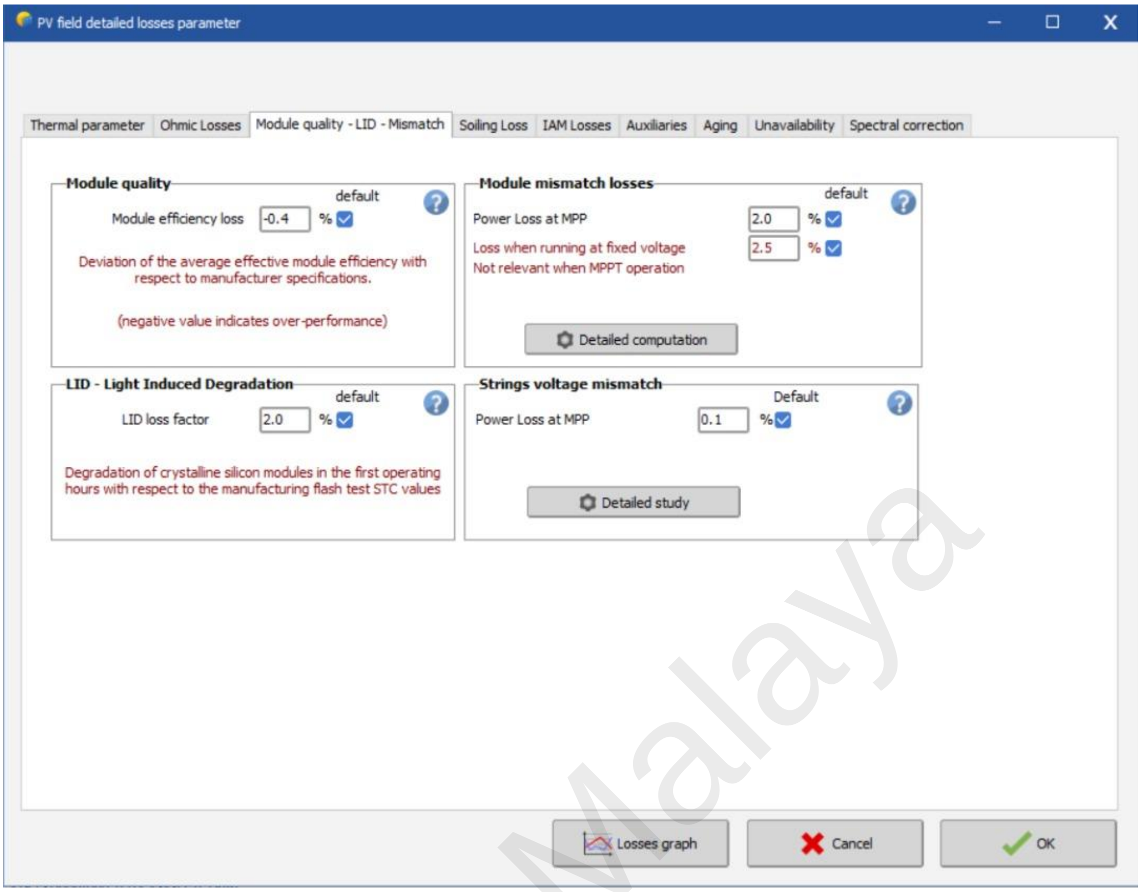

Figure 3.9: Defining the Detailed Losses in the System

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All systems shall be designed to be grid-connected systems to maximise their economic potential. However, we shall only assume that all electricity generated is fully utilised by the factory. Under the current NEM 3.0: NOVA scheme, the Average SMP rate fluctuates on a monthly basis, which will complicate our ROI analysis. If we assume that the consumption is fully utilised by the plant, we can control it based on the fixed tariff that the plant is currently using.

To calculate the expected ROI, we utilised data that shows that the typical price of a standard module crystalline silicon in Malaysia in 2019 was at 0.21 USD/Wp to 0.25 USD/Wp (approximately 0.87 MYR/Wp to 1.04 MYR/Wp based on approximate exchange rate in August 2021) (Velautham, Wei-nee, & Weng Han, 2019).

Therefore, to standardise our analysis based on purely the maximum economic potential, we shall utilise the following parameters, with module pricing coming from a combination of studies done by Velautham, et al and a recent study from 2019 by IRENA (IRENA, Renewable Power Generation Costs in 2019, 2020): -

1. Single crystalline (sc-Si) PV module price: MYR 1.04/Wp installed
2. Multicrystalline (mc-Si) PV module price: MYR 0.87/Wp
3. Thin film (CdTe) PV module price: MYR 0.60/Wp
4. Inverter price: MYR 0.33/Wp
5. Balance of system MYR 0.72/Wp
6. Installation work: MYR 2.91/Wp

For operating costs, we are estimating that it will be at MYR 0.04/Wp based on recent market trends that were reported (Yun, 2020).

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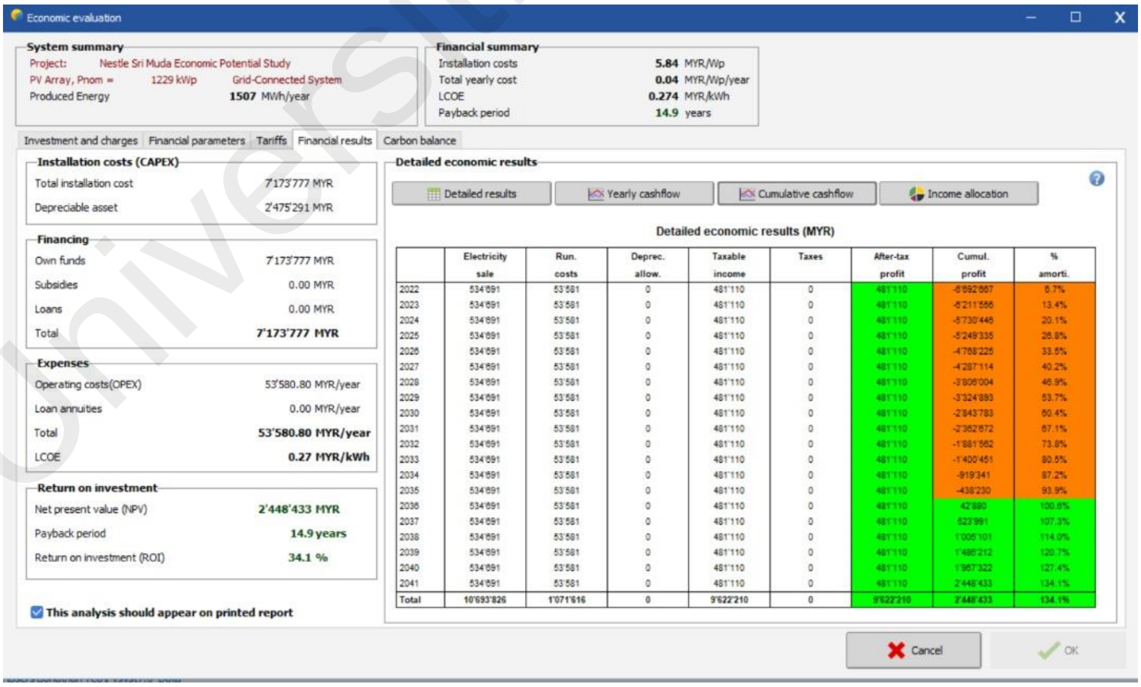

Figure 3.10: Sample Detailed Economic Results Generated by PVSyst

For financial parameters, although there are leasing schemes under the NEM, our consideration will be on outright purchase of system to establish a basis for ROI without consideration of fluctuations in government policies.

Tariffs shall be utilising Tariff E2 as based on this facility's location and their application, they qualify as medium voltage. Off-peak period is from 10.00 p.m. to 8.00 a.m. (Tariff Book, 2006). As a comparison, for the month of July 2021, the Average SMP is only 17.47sen/kWh, 18.03sen/kWh lower than the peak period rate, which is when electricity will be generated our simulated system.

Table 3.3: Tariff E2 - Medium Voltage Peak/Off-Peak Industrial Tariff (TNB, 2021)

For each kilowatt of maximum demand per month	37.00 RM/kW
For all kWh during the peak period	35.50 sen/kWh
For all kWh during the off-peak period	21.90 sen/kWh

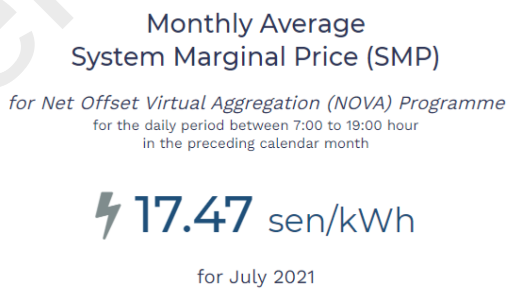

Figure 3.11: Snippet of the Average SMP for the month of July 2021 taken from Single Buyer's website (Single Buyer, 2021)

The study period was set over a 20-year period. Although modules can last longer, we consider a 20-year period to be a sufficient period to evaluate the economic performance of all simulated models, including the ROI and PP.

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CHAPTER 4: RESULTS

The BIPV profitability was analysed by looking at the capacity of each installed system and based on self-consumption without any subsidies. Consideration for contributions back to the grid was not included as mentioned in Section 3.2 as contribution back to the grid is lower than offsetting the facility's usage. Furthermore, as an industrial plant that operates full-time, it can fully utilised electric generated, except for long scheduled shutdowns.

4.1 Technical Performance Results

Table 4.1 summarises the designed systems' technical performance. For ease of reference, we shall label each system from Model A to F. The table includes the installed power, PV module type, average energy production capacity/year, Pnom ratio and Performance Ratio (PR). PR is the ratio of nett produced electricity over maximum electricity produced if the system was continuously working at its nominal STC efficiency. It is an important metric used to evaluate the system's efficiency. The higher the PR, the more electricity the system can generate. We also included the total installed modules and unit nominal power of each system given that each chosen module has different sizes and specified efficiencies.

The PV module from LONGi had the highest nominal power for a monocrystalline cell. Panasonic, though a monocrystalline, only had a highest output of 240 Wp module available in their product catalogue while Jinko Solar's unit has a nominal of 350 Wp. For polycrystalline modules, Hanwha and Sun Power has a nominal power rating of 350Wp and 470Wp respectively, which is commendably close or better than some other monocrystalline ratings. First Solar, the only thin film cell manufacturer, has an even more impressive 480 Wp nominal power. There are differences in terms of the available dimensions of all modules, which led to different total of installed modules able to be fit

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on to the available roof area. A graph was also produced to visualise the difference between each model's projected electricity generation capacity and its performance ratio as shown in Figure 4.1. The estimated annual electrical savings was from a range of 1,503MWh/year to 1,801MWh/year

Table 4.1: Summary of System Technical Performance for Building C

Simulation Model	A	B	C	D	E	F
PV Module Brand	Hanwha	LONGi	Jinko Solar	Panasonic	Sun Power	First Solar
PV Module Type	mc-Si	sc-Si	sc-Si	sc-Si	mc-Si	CdTe
Unit Nominal Power (Wp)	350	550	350	240	470	480
Total Installed Modules	3,510	2,736	3,585	5,551	2,870	2,775
Pnom Total (DC) (kWp)	1,229	1,254	1,255	1,332	1,349	1,332
Pnom Total (AC) (kWac)	1080 kWac	1200 kWac	990 kWac	1050 kWac	1050 kWac	1032 kWac
Pnom Ratio	1.138	1.254	1.267	1.269	1.285	1.291
Produced Energy (MWh/year)	1,503	1,866	1,539	1,606	1,693	1,801
Performance Ratio	75.12%	76.14%	75.31%	74.00%	77.06%	82.99%

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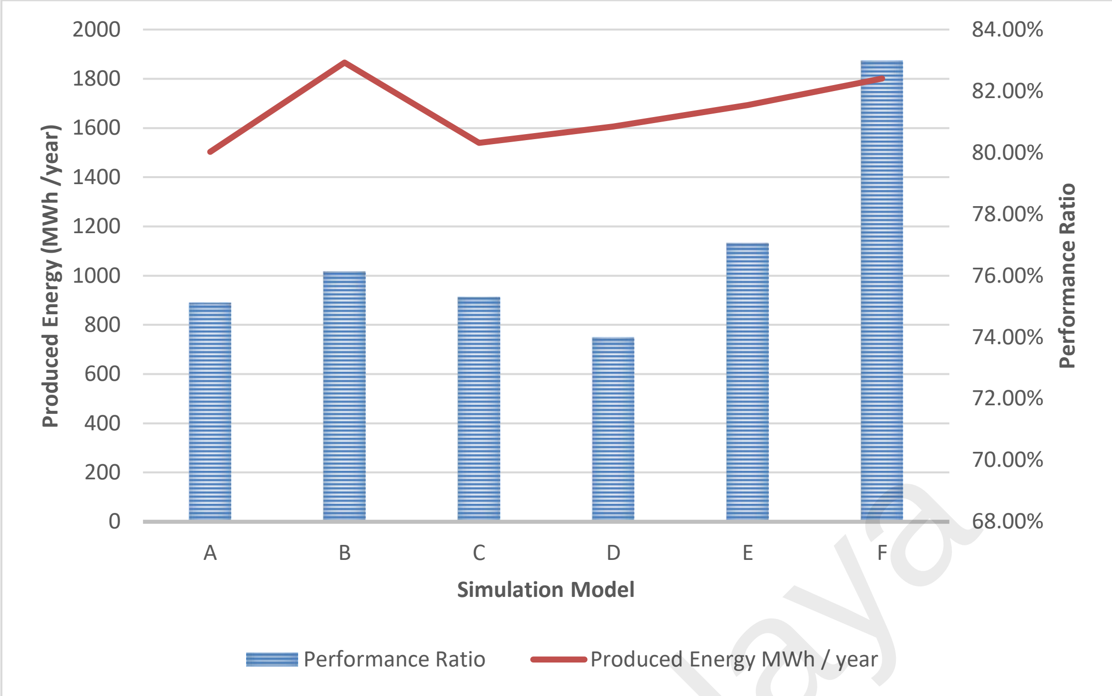

Figure 4.1: Graph Depicting Difference Between Produced Energy and Performance Ratio for All Models

The highest performance ratio among all simulated system was Model F, which used thin films. It managed to reach a performance ratio of 82.99%. The best performing monocrystalline system is Model B that achieved a performance ratio of 76.14% while for polycrystalline system it is Model D, which achieved a performance ratio of 77.06%.

In terms of outright electricity produced, Model B managed to generate on average 1866MWh/year. However, Model C and D, which are also monocrystalline cells underperformed compared to the polycrystalline cells' simulations of Model A and E. As we have kept the inverters as a generic constant for all system, the intrinsic difference is between different company's module performance and efficiency.

Another interesting result is that Model F generates 1801MWh/year, which seems to point towards the module's good performance for this particular application. Overall, in terms of performance alone, Model F gave the outright best performance among all the simulated models in terms of the produced energy and performance ratio relative to the installed capacity.

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4.2 Economic Performance Results

In terms of economic performance, we tabulated the data for the estimated installation costs, operating costs, payback period, Net Present Value (NPV), Return of Investment (ROI) and the levelized cost of energy (LCOE) over a 20-year period. Operating costs were kept a constant and we utilised the average maintenance costs that was documented by Virautham, et al.

LCOE basically measures the lifetime cost over the energy production of the system. It is a useful comparison against different technologies of unequal life spans, capital cost, risk, and capacities. The lower the LCOE, the more competitive the system is. The variance in the installed power capacity shown in Section 4.1 plays a large part in the overall economic performance of the modules, as shown in the following table.

Table 4.2: Summary of System Economic Performance for Building C

Simulation Model	A	B	C	D	E	F
PV Module Brand	Hanwha	Longi	Jinko Solar	Panasonic	Sun Power	First Solar
PV Module Type	mc-Si	sc-Si	sc-Si	sc-Si	mc-Si	CdTe
Installation Cost (MYR)	7,173, 777.00	6,683, 013.33	7,260, 172.70	10,210, 315.27	6,638, 855.07	5,478, 269.40
Operating Costs/ Year (MYR)	53,580.80	53,580.80	53,580.80	53,580.80	53,580.80	53,580.80
Payback Period (years)	14.9	11.0	14.7	19.8	12.1	9.4
NPV (MYR)	2,424, 674.06	5,491, 025.43	2,592, 230.70	117,030.47	4,306, 720.03	6,228, 214.39
ROI over 20-year period	33.80%	82.20%	35.70%	1.10%	64.90%	113.70%
LCOE (MYR/kWh)	0.274	0.208	0.271	0.351	0.228	0.182

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From the table above, Model D has the highest installation cost by virtue of it having the largest installed capacity and having a higher cost due to available data on monocrystalline PV cells. This leads to it having the longest payback period of 19.8 years, which is close to the end of our 20-year simulation study.

For Models B and C (monocrystalline PV cells) it has a payback period of 11.0 years and 14.7 years respectively. For Models A and E (polycrystalline PV cells), the payback period was 14.9 years and 12.1 years. The only thin film cell model, which is Model F, has the shortest payback period of 9.4 years.

The LCOE value for Model F was the lowest at 0.182 MYR/kWh, which gives it a large advantage over the other five models which used c-Si technology. It has to be noted that the installation cost for Model F is also the lowest by virtue of it having the lowest installation cost per module as well.

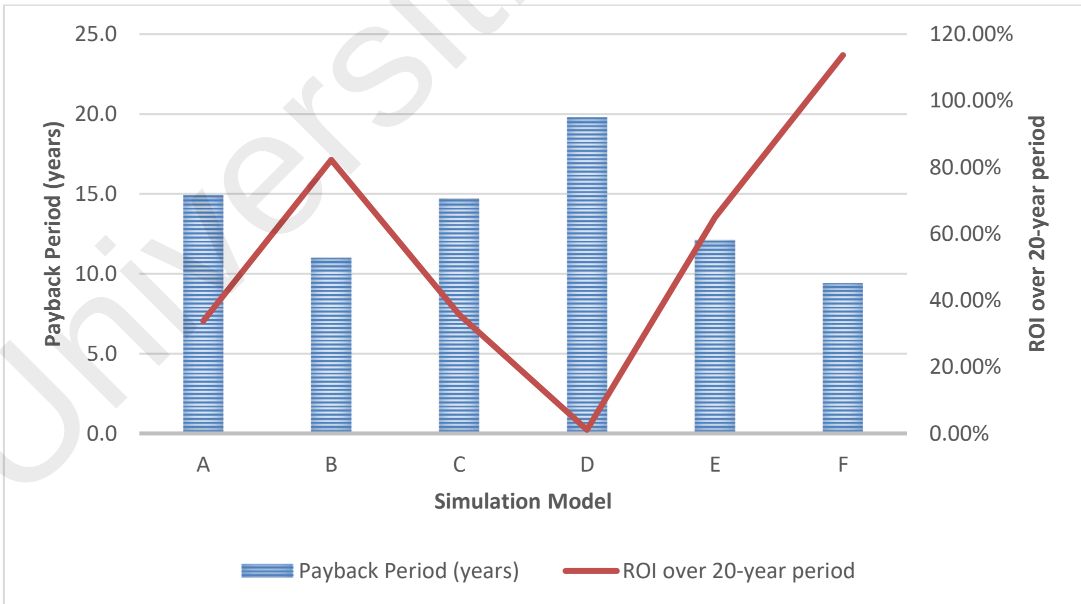

Figure 4.2: Graph of Payback Period and ROI for Each Simulation Model

Further analysis shows the inverse relation between the payback period and ROI, as shown in Figure 4.2. As we have considered the maintenance cost to be a constant among all systems, the main differentiating factor was the cost of installation and projected

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electricity generation capacity. Model D shows the worst economic potential as the payback period is at 19.8 years and ROI is only 1.10%. The best payback period and ROI of 9.4 years and 113.70% goes to Model F again.

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CHAPTER 5: DISCUSSION

From the results that we obtained, it can be seen that thin film cells were the best overall performance in terms of technical and economic potential, having an LCOE value of only 0.182 MYR/kWh. This could be due more towards thin film cells better performance given the inputted meteorological data. Thin film cells generally have better temperature coefficient, which leads to less difference in electricity production at different temperatures (IRENA, Renewable Energy Technologies: Cost Analysis Series, 2012). Given that our temperate climate causes fluctuation between cloud cover and direct sunlight to be ever present in our daily weather, this could be a reason why thin film is suitable for this particular site.

Thin film cells have also been improving significantly over time that manufacturers have managed to reach efficiency rates as good or better than c-Si technology, with the added benefit of it being lightweight and easily installed and maintained. However, one of the main concerns with this technology is that studies have shown that thin films degrade much faster than c-Si (Society, 2021). This is compensated by the payback period and ROI, but this study worked on the assumption that degradation rates for all types of modules are similar. Any follow-up study must look closely into each manufacturer's internal data on degradation which is not available in the simulation software.

Models A to E, which utilised different types of crystalline silicone have an LCOE ranging from 0.208 MYR/kWh to 0.351 MYR/kWh. We compared our simulated installation LCOE against benchmarks applicable for Malaysia. However, the closest we could find is a study done by the ASEAN Centre of Energy that collates data from the ASEAN region and prices are shown in USD/kWh (Energy, 2016).

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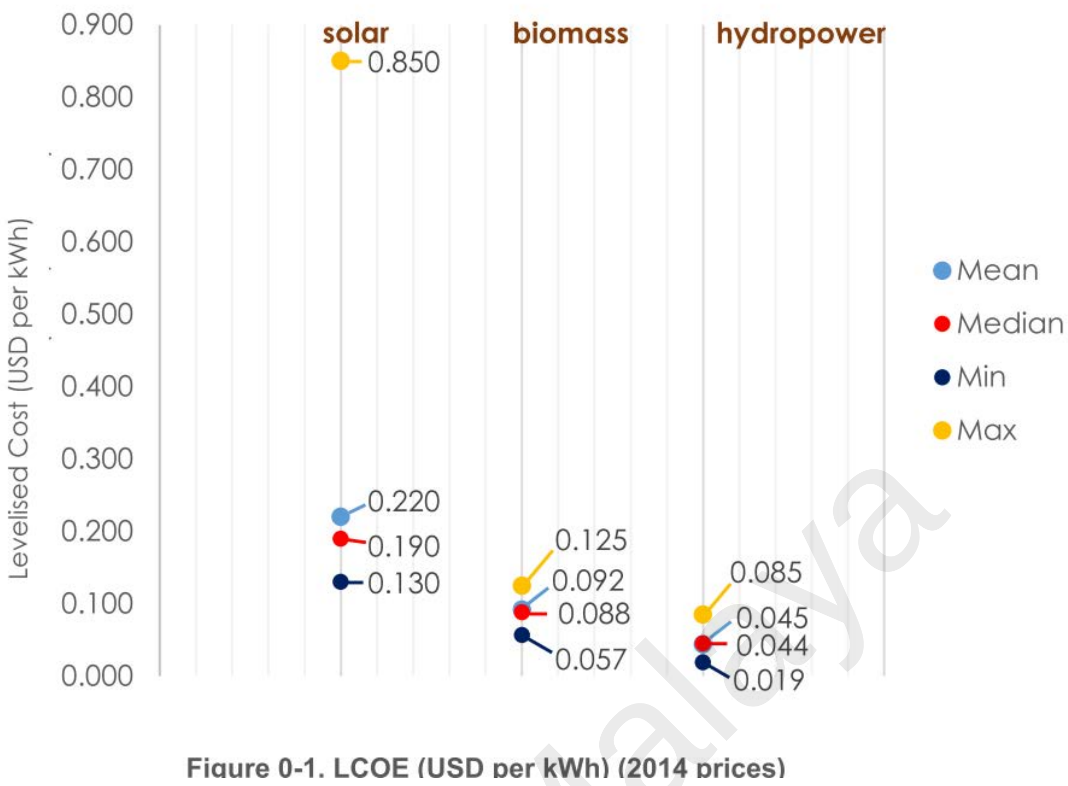

Figure 5.1: Levelised Costs of Electricity (USD per kWh) (2014 prices) (Energy, 2016)

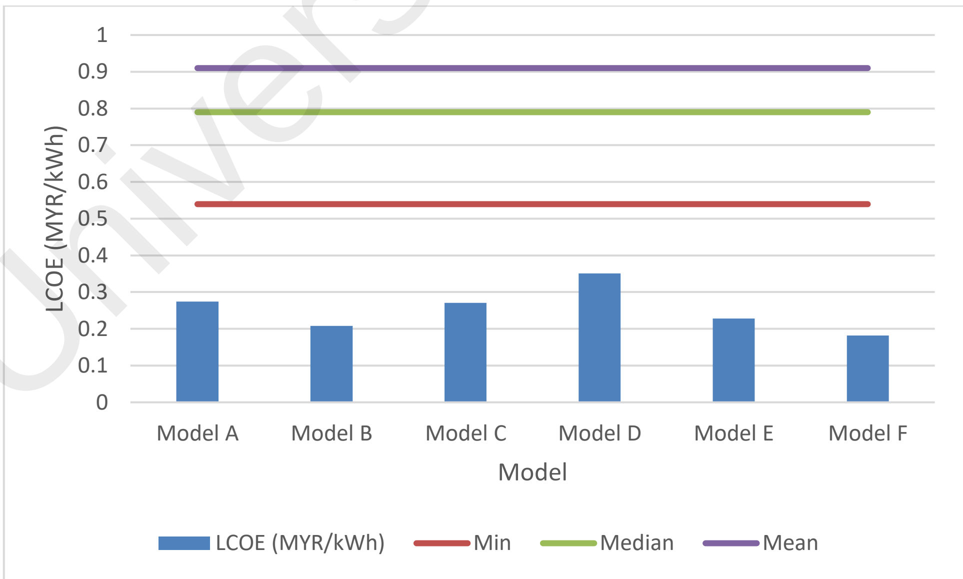

Figure 5.2: Comparison between Simulated LCOE against Available LCOE Data

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This data was back in 2014, and we applied an exchange rate of 1 USD = 4.15MYR to compare the LCOE average against current prices. It can be seen that all of our models are lower than the average LCOE recorded. In the period of time since this report was published, PV technology has improved in terms of efficiency and cost. It is imperative that more studies be done today to give a better benchmark for system designs to ensure we are able to have a better understanding of current market capabilities

This study also did not include optimisers in the study which could have further improve each model's performance. A solar panel optimiser is a device that can be added to one or all panels in a string. Its aim is to increase the output of a solar installation, by bypassing the shaded solar module which allows the system to operate to its full potential. In spite of that, the calculated LCOE is still competitive for the site, but should be another consideration for future studies to consider its costs and benefits.

Whilst our results point towards thin film cells being the best system in terms of PP, ROI and LCOE, there are variables that can be further refined for all systems such as the maintenance cost for different systems, specific degradation rates and loss factors for each PV modules, financing incentives and inclusion of inverters that are optimised for each simulation models.

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CHAPTER 6: CONCLUSION

To relate back to our objectives, we can conclude the following from our research:-

1. At an industrial site, utilising either monocrystalline, polycrystalline or thin-film technologies, we were able to simulate annual potential electricity generation capacity ranging from 1,503 MWh/year to 1,866 MWh/year;
2. By factoring in expected CAPEX and OPEX, the simulated models have an expected payback period of between 9.4 years to 19.8 years, with assumption that electricity will be fully used in the factory to maximise on tariff savings.

Overall, this study developed a method for estimating the BIPV potential of different systems for an industrial plant by using available academic and technical data. We were able to simulate the potential electricity savings and also provide a basis for justifying economic viability for installing such system via our inclusion of ROI and LCOE studies.

This study also benefitted from having a favourable site that has a favourable building orientation which was able to maximise the solar potential. By virtue of being located in an industrial zone, no physical obstructions from tall structures caused shading on the site. This physical and geographic potential considerations should be a major spur for widespread adoption by industrial players looking to reduce their carbon footprint and reduce their electricity consumption from the main grid.

In terms of technical potential, thin films systems gave the lowest capital cost and LCOE among all our simulated models, which indicates that the technology has improved to a point that it is becoming as competitive as the traditional crystalline silicone technology which is the current market leader. More studies should be done on this technology to give more accurate simulations as there is scarce data in terms of its degradation as compared to other technologies.

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The biggest room for further study is on the technical and economic aspect. We could provide more considerations for policies such as rebates, tax deductions and more technical data for losses and degradation to calculate our economic returns. This can be further improved by coalescing industry players and other stakeholders to have a public database that will allow academic studies on the benefits of adopting BIPV systems to meet our national climate goals. Reducing dependency on fossil fuel electricity generations will benefit us in the long run as we will also have better energy diversity.

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