ENERGY AND ECONOMIC ASSESSMENT OF BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) WITH EV CHARGING IN TROPICAL, MARITIME TEMPERATE AND HUMID CONTINENTAL CLIMATES

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ABSTRAK

Industri pembinaan dan pengangkutan merupakan penyumbang utama pencemaran, dan menghadapi cabaran daripada pembangunan pesat dan penggunaan tenaga yang tinggi. Bangunan sahaja telah menyumbang lebih satu pertiga daripada penggunaan tenaga global dan melebihi 36% pelepasan. Kajian ini meneroka penyelesaian yang berpotensi: mengintegrasikan sistem Photovoltaic Bersepadu Bangunan (BIPV) dengan infrastruktur pengecasan kenderaan elektrik (EV). Dengan mengkaji reka bentuk BIPV dalam pelbagai iklim seperti Tropika Pahang, Malaysia, Maritim sederhana Canberra, Australia dan Benua Lembap Örebro, Sweden, kajian ini menyiasat pengoptimuman sistem-sistem ini untuk lokasi berbeza bagi mencapai bangunan sifar bersih dan memenuhi keperluan tenaga isi rumah. Penyelidikan ini mengumpul data mengenai jenis rumah, kecerunan bumbung, penggunaan tenaga isi rumah, jarak perjalanan ulang-alik, dan jenis kenderaan dari setiap lokasi. Saiz sistem PV telah disesuaikan untuk memenuhi sasaran sifar bersih menggunakan data input yang pelbagai ini. Metodologi menganggarkan permintaan tenaga harian untuk isi rumah dan pengecasan EV untuk menentukan saiz sistem BIPV dan menilai parameter tenaga, ekonomi dan alam sekitar. Keputusan menunjukkan sistem BIPV dengan pengecasan EV boleh mengurangkan kos tenaga, meningkatkan prestasi ekonomi, dan mengurangkan pelepasan ke arah mencapai sifar bersih. Di Malaysia yang beriklim tropika, sistem BIPV yang bersambung dengan grid 5.6kWp memenuhi keperluan tenaga harian sepanjang tahun, dengan lebihan tenaga tersedia untuk suntikan ke grid. Di Sweden, sistem 10kWp tidak mencukupi semasa musim sejuk yang teruk tetapi menjana tenaga berlebihan pada musim panas. Panel PV dwimuka meningkatkan pengeluaran tenaga sebanyak 10% berbanding panel monomuka. Di Australia, sistem BIPV 5kWp memenuhi permintaan tenaga harian kecuali pada musim sejuk, dengan penjanaan tenaga tahunan melebihi penggunaan, dan menghasilkan aliran tunai yang positif. Dari segi ekonomi, semua sistem mempunyai nilai bersih positif sepanjang jangka hayatnya, dan dipengaruhi oleh dasar tempatan. Aliran tunai bersih Malaysia dianggarkan pada 13,000 USD, manakala Sweden dan Australia masing-masing mempunyai 45,389 USD dan 24,400 USD. Dari segi alam sekitar, sistem BIPV dengan infrastruktur pengecasan EV menjimatkan 137,321 kgCO_2e di Malaysia, 160,198 kgCO_2e di Australia dan 44,317 kgCO_2e di Sweden disebabkan faktor pelepasannya yang lebih rendah.

ABSTRACT

The construction and transportation industries are major polluters, facing challenges from rapid development and high energy consumption. Buildings alone account for over a third of global energy use and over 36% of emissions. This research explores a potential solution: integrating Building-Integrated Photovoltaic (BIPV) systems with EV charging infrastructure. By examining BIPV designs in diverse climates like Tropical Pahang, Malaysia, Maritime temperate Canberra, Australia and Humid continental Örebro, Sweden, the study investigates optimizing these systems for different locations to achieve net-zero buildings and meet household energy needs. The research gathered data on house type, roof slope, household energy consumption, commute distance, and vehicle type from each location. The PV system size was tailored to meet net-zero targets using this diverse input data. The methodology estimated daily energy demand for households and EV charging to size the BIPV system and evaluate energy, economic, and environmental parameters. Results showed BIPV systems with EV charging could reduce energy costs, improve economics, and lower emissions towards achieving net-zero. In tropical Malaysia, a 5.6kWp grid-connected BIPV system met daily energy needs year-round, with excess energy available for grid injection. In Sweden, a 10kWp system was insufficient during harsh winters but generated excess energy in summer. Bifacial PV panels increased energy production by 10% compared to monofacial panels. In Australia, a 5kWp BIPV system met daily energy demand except in winter, with annual energy generation exceeding consumption, resulting in positive cash flow. Economically, all systems had a net positive value over their lifetime, influenced by local policies. Malaysia's net cash flow was estimated at 13,000 USD, while Sweden and Australia had 45,389 USD and 24,400 USD, respectively. Environmentally, the BIPV system with EV charging infrastructure saved 137,321 kgCO_2e in Malaysia, 160,198 kgCO_2e in Australia, and 44,317 kgCO_2e in Sweden due to its lower emission factors.

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$(1+r)\text{-}t$	The real discount rate corresponding to the cost of capital
B_{EV}	EV battery capacity in kWh
$E_{out/day}$	Net energy output per day
E_{Lost}	Energy Lost in System kWh
$Capital_t$	Total capital construction costs in year t;
$Carbon_t$	Carbon costs in year t;
C_{Bill}	Annual savings on the System
C_{EV}	Cost of EV charging SEK/km or RM/km or AUD/km
$C_{Grid\text{-}A}$	Revenue generated after energy sale to grid RM or AUD or SEK
C_{Import}	Cost of electricity for imported energy MWh
C_{inf}	Total cash inflows in RM or AUD or SEK
$C_{Maintenance}$	Maintenance cost of system over lifetime
$C_{outflow}$	Total cash outflows in RM or SEK or AUD
$C_{Replacement}$	BOS replacement cost respective to PV system
C_{Res}	Annual residential electricity bill in RM or AUD or SEK
C_{System}	Initial cost of PV plant in RM or AUD or SEK
$C_{Transport}$	Annual savings on fuel RM or AUD or SEK
D	Daily commute distance in km
$D_{lifetime}$	Total commute distance over lifetime in km
D_t	Decommissioning and waste management costs in year t
E_0	Energy produced in the first year, kWh
E_{EV}	Daily EV charging load in kWh
EF_{Fuel}	Emission factor for gasoline $kgCO_2/km$
E_{Full}	Full Capacity of system when work 24 hours, kWh
$E_{grid\text{-}Total}$	Energy exported to grid over 25 years
E_H	Daily residential load in kWh
E_{Import}	Net energy imported over 25 years
E_L	Total energy produced over the system's lifetime in MWh
E_n	Energy produced n^{th} year, kWh
E_{Out}	Actual output of the system, kWh
E_{Total}	Daily total load in kWh

F_{Grid}	Grid emission factor of power plant in $kgCO_2e/kWh$
$Fuel_t$	Fuel costs in year t
G_0	Reference Irradiance
GHG_{PV}	Emission reduction by PV plant in $kgCO_2e$
GHG_{EV}	Emission reduction due to avoidance of gasoline in $kgCO_2e$
GHG_{Total}	Total emission reduction by PV plant and transportation in $kgCO_2e$
H_I	Total in-plane irradiation kWh/m^2
n	number of years
NCF	Net Cash flow without discount in SEK
$NCF\text{-}D$	Net cash flow for PV system with discount in SEK
P_0	System power rating in kWp
PB	Payback period without discount in years
$PB\text{-}D$	Payback period for with discount in years
P_{MWh}	The constant lifetime remuneration to the supplier for electricity
R	Range of EV in km
Y_f	System yield
Y_r	Reference yield
δ	Panel Degradation %

LIST OF ABBREVIATIONS

AUD	Australian dollar
BIPV	Building Integrated Photovoltaics
BAPV	Building Applied/Attached Photovoltaics
BOS	Balance of System
DMY	Daily mean yield per day
PGF	Power generation factor
CUF	Capacity utilization Factor
DHW	Domestic hot water
EL	Energy generation over the lifetime in MWh
EM	Daily average energy generation each month in MWh
ES	Energy supplied to grid in MWh
EG	Energy generation in MWh
EV	Electric Vehicle
G_0	Reference Irradiance
H_I	Total in-plane irradiation kWh/m^2
LCOE	Levelized cost of energy (RM/kWh or AUD/kWh or SEK/kWh)
MWh	The amount of electricity produced annually in MWh;
NPV	Net present value
$O\&M_t$	Operation and maintenance costs in year t
OPTA	Optimum Tilt to maximize yearly yield
PB	Payback period without discount in years
PB-D	Payback period for with discount in years
P_{MWh}	The constant lifetime remuneration to the supplier for electricity in MWh
PR	Performance ratio
PV	Photovoltaics
RM	Malaysian Ringgit
ROI	Return on investment
SEK	Swedish currency
TGC	Tradable green certificate

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CHAPTER 1

INTRODUCTION

1.1 Background of the research

Over half of the world's population lives in cities, where they account for 80% of the country's GDP, and this number is predicted to rise to two-thirds by the middle of this century. An estimated 55.3% of people on earth resided in urban areas as of 2018. Urban regions are expected to house 60% of the world's population by 2030, with one in three people living in cities with a population of at least 500,000. In order to fulfill the 2030 Agenda for Sustainable Development, which includes SDG 11, which focuses on Sustainable Cities, and SDG 7, which focuses on renewable and clean energy, cities must become energy efficient (IISD, 2017). Many nations will struggle to keep up with the rate of urbanization and provide for the demands of their expanding urban populations, including those for housing, transportation, energy systems, and other infrastructure (UN DESA, 2018).

Furthermore, cities have an important role in climate change because they emit significant amounts of greenhouse gases from urban activity. Urban regions contribute considerably to global CO_2 emissions, accounting for around 70%. Transportation and buildings are among the most significant sources of these emissions (IPCC, 2022a). According to the World Green Building Council, building and construction are responsible for 39% of all carbon emissions in the world(World Green Building Council, 2019).

In addition, the only way to combat climate change and achieve the goals of the Paris Climate Agreement is to eliminate these emissions (Architecture2030, 2019). According to IEA, under stated policies, global building energy consumption in the residential sector would rise by 83 percent between 2018 and 2040, from 6008 TWh to 11000 TWh (IEA, 2019a, 2021b).

On the other hand, the transportation industry accounts for 24% of direct CO_2 emissions from fuel combustion. Road vehicles (cars, lorries, buses, and two- and three-wheelers) account for roughly three-quarters of CO_2 emissions from transportation(IEA, 2020c).

According to the EIA (Energy Information Administration), the worldwide light-duty vehicle (LDV) fleet had 1.31 billion cars in 2020 and is expected to expand to 2.21 billion vehicles by 2050 (U.S. EIA, 2021). To accomplish a cleaner transportation sector, EVs are being encouraged. In 2020, there were 3.1 million Passenger EV which is expected to reach 14 million by the year 2025 (BloombergNEF, 2021). EVs are poised to play a crucial role in the future as many nations commit to reducing their reliance on fossil fuels. With the growing number of EVs, the demand for home charging infrastructure is also increasing (IEA, 2024). According to the Stated Policies Scenario, in 2030, global electricity demand from EVs for light duty vehicles reaches 377 TWh, about a 18% rise from 2019 levels which is 21TWh (IEA, 2020a). However rising electricity demand was a major factor in the power sector's record-high CO_2 emissions in 2018, but the commercial availability of a wide range of low emissions generation technologies also places electricity at the forefront of efforts to fight pollution and climate change (IEA, 2019b).

Meeting energy demands without compromising the climate has become crucial, as global use of fossil fuels is severely damaging our environment. Decarbonized electricity could provide a platform for reducing CO_2 emissions, with renewable energy playing a major role in providing access to electricity for all (IEA, 2019b). Renewable energy and energy efficiency, in combination with electrification of end uses, are key to a successful energy transition and driving down energy-related CO_2 emissions (T. Zhang et al., 2018). Sustainable concepts like green buildings can significantly alleviate the surge in energy demand worldwide. Additionally, electric vehicles (EVs) offer hope for a clean and long-term solution. More research, development, and innovative government policies can support sustainable energy for buildings and transportation.

As urbanization increases energy consumption, investigating alternate sources that reduce environmental impact becomes critical. Solar power, with its inherent capacity for decentralization and environmental friendliness, emerges as a top contender for urban energy solutions (Etukudoh et al., 2024). Photovoltaic (PV) technology, which transforms solar energy into environmentally friendly electrical energy using sufficient incident solar radiation, is one of the most promising clean energy technologies. PV technology, when combined with traditional construction materials and systems, efficiently captures and utilizes solar energy resources, replacing fossil fuel-generated energy with safe, renewable, and sufficient PV-generated power that can help mitigate climate change. To combat building energy use and promote renewables, Zero Energy Buildings (ZEBs) are gaining traction (Belussi et al., 2019). Integrating solar PV systems directly into buildings offers a comprehensive solution, generating substantial clean electricity to meet building needs.

1.2 Problem Statement

The transportation and construction sectors face significant challenges, including rapid construction, rising energy consumption and costs, and increasing greenhouse gas (GHG) emissions. The buildings sector alone accounts for more than one-third of global energy consumption and emissions, encompassing energy used for construction, heating, cooling, lighting, and running appliances (IEA, 2023). The construction industry, responsible for over 36% of global emissions, has come under scrutiny due to its rapid expansion and pollution levels(Yan et al., 2017). Achieving decarbonization of the building industry by 2050 is crucial, necessitating improvements in building energy performance, reducing the carbon footprint of building materials, strengthening legislative commitments, adopting concrete measures, and increasing investment in energy efficiency(UNEP, 2022).

Simultaneously, the traditional transportation sector, which heavily relies on nonrenewable fossil fuels, faces the unsustainable consequences of increased urbanization, rising fuel prices, inefficient internal combustion engines, and environmentally harmful emissions. In 2019, the combined direct and indirect emissions from industry, buildings, and transportation accounted for 66% of total emissions (IPCC, 2022b). While electric vehicles (EVs) present an environmentally friendly alternative, their sustainability is limited when they are dependent on a fossil-fuel-powered grid. According to the International Energy Agency, EVs are projected to represent more than 60% of global car sales by 2030, necessitating a significant increase in charger installations in buildings. To facilitate charger installation in residential, commercial, and workplace settings, regulatory support for EV adoption is essential. City policies and municipal regulations will drive the adoption of charging infrastructure, particularly in densely populated urban areas. Building codes and regulations will increasingly require the installation of EV chargers in new constructions and renovations(IEA, 2022). Furthermore, the energy demands of transportation and buildings vary significantly across different climates. Addressing these challenges is vital for developing and implementing sustainable solutions in both the transportation and construction industries. Recognizing the substantial differences in energy requirements for transportation and buildings across various climates is essential for creating and executing long-term solutions in these sectors.

1.3 Gaps in existing research

Building-Integrated Photovoltaics (BIPV) for residential energy generation and Electric Vehicle (EV) charging holds significant promise in the realm of sustainable energy solutions." Although solar-powered EV charging is becoming a growing trend and BIPV has shown its promise in building applications, there is still much to learn about how these two systems work together, especially in terms of their energy, economic, and environmental performance. Even though there is growing interest in this integrated strategy, there aren't many studies that are comparable for the chosen areas, according to the literature evaluation.

A particular gap in the literature that prevents a thorough understanding of the technology's potential in this particular socioeconomic environment is the lack of prior research on EV charging in Malaysia using residential BIPV installations. Similarly, a significant research gap exists in Australia due to the lack of studies evaluating the combined energy, economic, and environmental performance of BIPV with EV charging. Moreover, a region-specific gap is highlighted by the paucity of research in Sweden about the performance comparison of monofacial and bifacial solar panels in the context of BIPV with EV charging.

The gaps that have been found highlight the necessity of doing more focused study in the designated zones in order to thoroughly examine the potential, difficulties, and ideal setups of BIPV with EV charging stations. Filling up these gaps will advance our current understanding and make it easier to adopt integrated, sustainable solutions that are specifically suited to Sweden, Malaysia, and Australia's particular needs."

1.4 Significance of this study

This study is important since it is the first to investigate a new field in the context of BIPV (Building-Integrated Photovoltaics) and EV charging for residential use in a place where no such system has been installed before. Even though BIPV has been the subject of several research, the site that was selected offers a hitherto unexplored area and introduces novel protocols and recommendations for the combination of BIPV with EV Charging. Because it covers the important topics of energy, economy, and the environment and offers a thorough grasp of the possibilities for expansion in these fields, this research is very significant.

This research has the potential to have an influence that goes beyond the local context and advances the global objectives of developing carbon-neutral transportation and net-zero energy buildings. The study's conclusions, which clarify the crucial part BIPV may play in lowering CO_2 emissions, have the potential to positively impact society as a whole. Additionally, the study is in line with a number of Sustainable Development Goals (SDGs), such as SDGs 12 (Responsible Consumption and Production), 13 (Climate Action), 11 (Sustainable Cities and Communities), 9 (Industry, Innovation, and Infrastructure), and 7 (Affordable and Clean Energy).Thus, this research is innovative because it has the potential to further our understanding of sustainable technology and offer practical insights that will help ensure a more ecologically conscious and sustainable future for all people on the planet.

1.5 Hypothesis

This study proposes two basic hypotheses. First, building type and location have a favorable impact on the efficiency and efficacy of BIPV technology and EV charging via solar systems. Different architectural designs and geographical contexts are predicted to influence the performance of these integrated systems. Second, the integration of BIPV systems with EV charging infrastructure is expected to be environmentally and economically viable. The study's purpose is to show that integrating these technologies can result in significant energy savings and economic advantages, so contributing to the larger goal of sustainability.

1.6 Objectives

i. To design a BIPV based net zero energy residential building with EV charging infrastructure to meet the daily energy requirements of residential + EV Charging load in three different climatic zones.

ii. To analyse the performance of the above system in the selected climate zones in terms of energy, economic and environmental aspects.

iii. To compare the performances of the BIPV+EV charging system across the three climate zones.

1.7 Scope of this research

This scope of this research lies within below parameters:

i. Design of BIPV+EV charging system

   a. The tropical (Kuantan, Pahang Malaysia), maritime temperate (Canberra, Australia) and humid continental (Orebro, Sweden) have been chosen for the study.

   b. The study is based on national average of commuting distance and energy consumption.

   c. Specific PV panels will be used for BIPV system in each reason due to local climatic conditions and usage pattern.

   d. Study is limited to chosen location. Eg for Malaysia – It is semi urban region. For Australia and Sweden, it is urban.

ii. Performance analysis of BIPV and EV charging

   a. The following technical parameters will be considered for study (Energy yield, performance ratio, capacity utilization factor).

   b. The economic parameters considered for the study are as follows - Payback period, LCOE & cost of EV charging.

   c. GHG Emission, GHG Savings are used for evaluation of the environmental Parameters.

iii. Comparative analysis of the case study based on the various parameters.

CHAPTER 2

LITERATURE REVIEW

2.1 Photovoltaics Installation in Building

BAPV and BIPV are two categories for PV systems based on how they are installed and constructed in buildings. Most current installations use well-known crystalline silicon technology, and rooftop BAPV installations are still the most popular, despite growing interest in BIPV. Therefore, the application of the PV system to the building is one of the most comprehensive solutions in which PV produces a benevolent amount of electricity for building-energy requirements.

2.1.1 Building applied photovoltaics (BAPV)

PV modules are directly mounted to buildings in BAPV system through extra mounting framework and moving rails(Biyik et al., 2017). The BAPV is the approach taken with respect to conventional photovoltaic approaches consists of fitting modules to existing surfaces by superimposition once building has been completed, such as during an energy restoration project (Bourène, 2019). The BAPV modules can help in the planning and implementation of the system during building development. The energy performance assessment of such a system could be done using simulation software's in advance to check its feasibility of the system. The performance of the system would depend on solar radiation of the place, module temperature, its orientation and other climatic conditions of the region where the system is installed. Tilt of the array can easily be adopted independently from the face or roof slope. BAPV systems can be installed on the facades/roofs or any other components of the envelope by supporting structures. These applications are helpful to the energy saving transformation of existing buildings (W. Zhang et al., 2017). The BAPV system can either be directly attached to the roof floor or can be mounted on strong silicon metallic structures as shown in Figure 2.1. This shields the panels from strong winds and keeps them at a certain tilt angle, allowing them to absorb the most solar energy possible for electricity generation. They are responsible for the sole and crucial role of generating energy by absorbing solar energy. These can be removed at any time without compromising the structure's integrity or durability.

Figure 2.1 Building Attached Photovoltaics System (BAPV)

The simplest and most widely used examples of BAPV are roofing solar power stations, which are assembled over the main roof covering. This shares the load requirements of the connected local grid and saves energy. This also reduces the carbon dioxide emissions into the atmosphere protecting the environment against harmful greenhouse gases.

2.1.2 Building integrated photovoltaics (BIPV)

PV cell integration on buildings may be done in four primary ways: on flat roofs, facades, shading systems, and inclined roofs as shown in Figure 2.2. There is no additional space or land area requirement for installation of solar plant. BIPV are seen as either an architecturally integrated aspect of the building's design or as a functional component of its construction(C. Peng et al., 2011). The BIPV system simultaneously functions as a power source and construction material. BIPV systems can reduce material and energy costs, rely less on fossil fuels, emit fewer ozone-depleting pollutants, and enhance the appearance of the building(Strong, 2016). Weather and noise protection, privacy, heat insulation, and other features of traditional building materials must all be included in the BIPV system (T. Zhang et al., 2018). As compared to non-BIPV facades, the BIPV market is still small and the cost of BIPV façade goods is expensive. In addition to producing energy, BIPV concepts have recently gained popularity because of their seamless integration with building envelopes, lower cost compared to PV panel retrofitting, and attractive architectural designs. As the roof space is limited and the façade area is important to achieve optimum energy efficiency, it will be incredibly challenging to incorporate a BIPV system into the building envelope given the current trend in construction designs.

Figure 2.2 Building integrated photovoltaics (BIPV)

Due to growing public awareness of green infrastructure with zero emissions, the business sector will provide the largest share of the BIPV market in 2020. BIPV installations increase the visual attractiveness of business buildings and significantly reduce their power usage, which encourages the spread of the technology throughout the commercial sector. In 2019, the total installed PV capacity reached more over half a terawatt, with 580.1 GW of that capacity coming from grid-connected installations and 3.4 GW from off-grid technology(IRENA, 2020a). BIPV technology still faces obstacles to increasing its applications and becoming ubiquitous, despite its advanced technological state and considerable cost reduction (Martín-Chivelet et al., 2022). Throughout 2014 and 2015, the worldwide BIPV market increased by 35%, from 1.5GW to 2.3GW, according to estimates(Tabakovic et al., 2017). The global market for building integrated photovoltaics (BIPV), which was previously expected to be worth US$17.7 billion in 2022, is anticipated to increase to US$83.3 billion by 2030, expanding at a CAGR of 21.4% from 2022 to 2030(Research and Markets, 2023). The choice of one technology for BIPV depends on type of application, as well as the performance and aesthetical requirements. Table 2.1 below summarises comparison of different features between BIPV and BAPV.

Table 2.1 Comparison of features between BAPV and BIPV

BIPV	BAPV
• Can be integrated to building rooftops, facades, balustrade etc.	• Using mounting equipment and ceiling perforations, indirect integration is possible.
• Wider area can be utilized to produce energy – façade and rooftop	• Can be applied to roof top,
• Aesthetically appealing blended modules:	• Heavy looking
• High Resistance to winds	• Possibility of lift and drag, may affect tilt angle
• On-site clean electricity without requiring additional land area	• Additional land may require generating required energy.
• Lower overall costs than BAPV systems requiring separate, dedicated, mounting systems (Strong, 2016)	• Higher cost as additional rail and mountings will be required.
• Key benefits of BIPV is the contribution into transforming the building into a Net Zero Energy Building(BIPVBOOST, 2020)	• BAPVs only contribute to the environment through producing green energy, not in any other way to the building environment (Jelle et al., 2012) .

Currently there are 4 PV technologies which are commercially available for BIPV application which is shown in Table 2.2.

Table 2.2 Characteristics of commericially availavle BIPV Panels (ICARES, 2019)

Main Characteristics	**Crystalline Silicon (Poly and Mono)**	**Amorphous Silicon (a-Si)**	**Cadmium Telluride (CdTe)**	**Copper Indium Gallium Selenide(CIGS)**
Average BIPV module efficiency	12% to 16% (Gul et al., 2016; Kalogirou, 2009)	6% to 7 % (Dixon, 1981)	14% to 18% (Department of Energy, 2021a)	12% to 14% (Department of Energy, 2021b)
Average temperature coefficient	-0,45%/°C (Multi) and -0,41%/°C (Mono)	0.21%/°C	0.23%/°C	0,35%/°C
Average module degradation rate:	0,5%/y (Poly-cSi) and 0,45%/y (Mono-cSi)	0,85%/year	0,5%/year	0,65%/year
Application	Roof Façade louver, balustrade	Roof , Façade	Roof Façade	Roof Façade
Main Characteristics	High efficiency Lower degradation rate Wide solar spectrum response Mature technology	Low cost Good temperature coefficient	Good temperature coefficient Limited degradation rate	Less energy production process Flexible, Lightweight, Better temperature coefficient Wide-ranging solar spectrum response
Limitations	Limited flexibility in design Non-optimal temperature coefficient in fully integrated condition	Low efficiency High degradation rate Sub-par performances under normal light conditions	Limited efficiency for commercial BIPV Limited solar spectrum response	Limited efficiency for commercial BIPV products Slightly higher degradation rate than cSi products

2.2 Design options for BIPV Modules

A BIPV module's design must be both aesthetically pleasing and capable of producing the greatest amount of electricity yield at an affordable price. (Mittag et al., 2018; Shahid et al., 2018). Also, according to the BIPV standard IEC EN50583, among local RES used in urban settings, PVs appear to have a significant potential to supply sustainable electrical energy by: (i) using urban exteriors already in place without additional infrastructure (ii) providing energy where it is needed, notably with the growing need for electricity in the construction industry, but also for a variety of uses (e.g. production of electrical energy and/or thermal energy for heating or cooling), and (iii) achieving the structure envelope needs(Saretta et al., 2019). Figure 2.3 represents BIPV installation on different surface of the building. The BIPV materials can be attached on these parts of the building:

Rooftops–In such applications, PV material replaces roofing material or in some cases, roof structure itself. Several companies provide an integrated, single-piece solar roof made of laminated glass; others sell solar "shingles" that can be installed in place of standard roof shingles. Due to the shortage of broad area and the abundance of roof space, BIPV is becoming more and more attractive in comparison to utility-scale PV systems. BIPV is space-flexible and may be put on the building's outside, allowing for the integration of energy generation and other building material functions. Possible growth means that product technology and BIPV technology may be combined for improved performance(Haegermark et al., 2017).

Façade–PV can be built into the walls of houses, replacing conventional glass windows with semi-transparent thin-film or crystalline solar panels. Such surfaces have less direct sunlight exposure than rooftop systems, but generally give a larger area (Debbarma et al., 2017a) . PV panels may also be used in retrofit applications to conceal unattractive or deteriorated building exteriors. The facade area becomes increasingly important as the height of the structure increases. Roof area is sometimes quite limited and relatively small in high-rise structures, where the roof is frequently required for the installation of heating, ventilation, and cooling systems. This means that as a building's height increases, so do its facade surfaces. Additionally, as the height of larger buildings grows, façade surfaces are generally less covered by plants or neighbouring buildings, with the exception of megacities (e.g., New York or Toronto), where high-rise structures are frequently surrounded by neighbouring high-rise buildings(Kuhn et al., 2021).

Glazing– Semi-transparent surfaces that produce power and allow light to pass through can be made using very thin solar cells. Greenhouses or PV skylights are also made using them. PV glazing is a cutting-edge technology that, in addition to producing electricity, may lower energy usage for artificial lighting, heating, and cooling(J. Sun & Jasieniak, 2017).

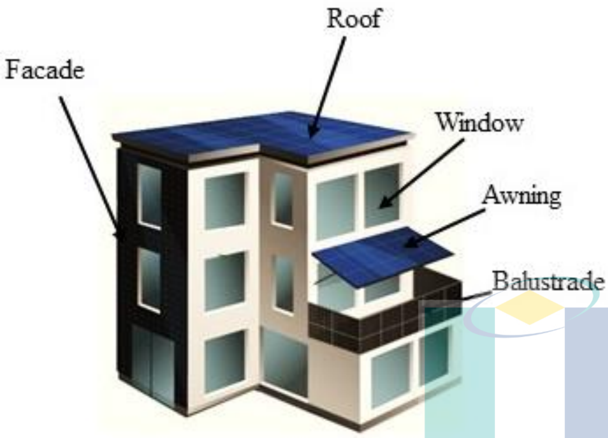


Figure 2.3 BIPV application in a building.

The PV technologies used in the BIPV system fall into two categories: traditional solar cells and developing solar cells. The integration of several PV technologies, including crystalline, thin-film, and organic ones, on various building envelopes is discussed in application (Wójcicki et al., 2022). The outside portion of a structure that divides the interior environment from the exterior is called the building envelope. The three main system envelopes are the roof, facade, and windows of the structure(T. Zhao et al., 2020). Moreover, it may be categorized as a flat or pitched PV rooftop, PV double skin facade, PV glazing that is partially transparent, etc. The demand for and scale of the building, as well as the climate, heavily influence the integration of technology(D. Singh et al., 2021). Under optimal operating circumstances, the PV modules utilized in the BIPV system generate energy at a rate of 13–20% of incoming solar radiation (Ma et al., 2015; Usama Siddiqui et al., 2012). The BIPV system temperature can rise to as much as 80°C in warm locations, (Poulek et al., 2018) which has an impact on the system's performance. A PV module's thermal breakdown rate can be effectively slowed by lowering its surface temperature. Natural or forced ventilation may be used to do this, preventing the modules from heating up while they are in use (Radziemska & Klugmann, 2002).

BIPV is a multipurpose technology used for a variety of things, such as the production of energy, weather protection, noise prevention, thermal insulation, or daylight modulation (A. K. Shukla et al., 2016a). BIPV systems that are incorporated into the roof and the façade serve as a rain screen, while semi-transparent BIPV systems can produce diffused natural day illumination(Agarwal et al., 2014). UV filters, fire prevention, and thermal and noise insulation are all functions of versatile BIPV modules (Ershad et al., 2016) . The fast evolution of PV technology from inflexible, thick solar panels to a variety of flexible semi-transparent in various colours enabled the expansion and transformation of traditional buildings into energy-generating structures(Gautam et al., 2015). The wide range of BIPV solutions available allows for the replacement of numerous building components, including roofs and facades. The building envelope is waterproof and serves as a barrier between the controlled atmosphere of the building and the outside temperature(K. N. Shukla et al., 2015). Furthermore, the facades and roofs govern and control functions like as lighting, ventilation, energy, safety, and privacy protection, among others. It meets the priority of maintaining a suitable internal environment while using the least amount of energy(Athukorala et al., 2015). Below Table 2.3 represent various application of BIPV as building component.

Table 2.3 Various applications of BIPV

Application	Description	Images
Skylight	BIPV technology powers and illuminates the structure. Comparable to the ones utilized in quasi glass facades, this sort of application uses PV modules and structural components.	 Source: Onyx Solar
Shading Systems	PV modules of various forms can be used to shade windows or as part of an overhead glazing system. Because many buildings already have some form of framework to shade windows, using PV shades should not add any additional burden to the building structure. PV shading systems may also employ one-way trackers to tilt the PV array for optimal power while giving varying degrees of shade.	 Source: vitrosolarvolt.com
BIPV Solar Façade	The façade is a building's exterior weatherproof envelope. In modern structures, the facade is frequently linked to the building frame and contributes little to structural integrity. This kind of façade is known as a non-load bearing vertical building enclosure.	 Source: pveurope.eu/
BIPV in-roof	Roofs are ideal for BIPV integration since they receive less shade than ground level. Roofs are usually a large, unused surface for integration. BIPV in a roof system reduces shading and can increase system output.	 Source: NREL
Semi Transparent Facades	It benefits the building by reflecting incoming solar radiation and transporting direct solar heat gain into it. Solar facades that are translucent or semi-transparent convert a portion of the incident sunlight directly or indirectly into electricity or transmit heat energy into the structure using electrical or mechanical equipment.	 Source: www.solarpowerworldonline.com

As indicated in Table 2.4 below, there are a few well-known structures in various nations that have used BIPV on a wider scale.

Table 2.4 Famous Solar Buildings with BIPV

Building: Stadium Panel Type: Roof tile BIPV Location: Taiwan Power: 1.14GW(Synergy Files, 2017) 	Building type: Laboratory Panel: Blue Coloured BIPV Location: Berlin, Germany (*Avancis*, 2020) Panel: 48.60 kWp 	Building : Hospital Panel:Transparent BIPV(Achenza & Desogus, 2015) Location: Florence, Italy Power: 30 kWp (Achenza & Desogus, 2015) 
Building: CIS power Panel: Transparent BIPV Location: Manchester(UK) Power: 390 kWp (Solaripedia, 2009) 	Building: Museum, MNACTEC Panel Type: Colored BIPV Location:Terrassa, Catalunya Power: 38,7 kWp (MNACTEC, 2015) 	Building: Museum, Solar energy Panel Type: monocrystalline BIPV Location: Gifu, Japan Power: 3.4 MW(Inhabitat.com, 2008) 

2.3 Review of BIPV Design and Performance

Different studies have been carried out in relation to the assessment of BIPV across the globe. Today's world is completely depending on energy sector for its development in various means. In most of the countries, fossil fuels contribute to maximum energy production levels, but a recent step towards reducing GHG emission, gave an important and prominent move for the development and use of renewable energy sources in all means (Hayter & Kandt, 2011). In recent years, energy conservation practices were followed in most of the commercial/industrial/residential buildings, these includes natural heating [38], cooling (Enteria et al., 2015), ventilation (Abdallah et al., 2014; Enteria et al., 2015), energy efficient lighting systems (Balachandra & Shekar, 2001), maximizing the day light usage (Yu & Su, 2015), high-performance envelopes (Saidur & Masjuki, 2008; Zhou & Chen, 2010). These energy conservation practices were widely used in most of the developed countries like Germany, Japan, and UK etc. Another most important practices of using renewable energy sources in commercial/residential/industrial buildings are also seen in recent years (Santos & Rüther, 2012). Renewable energy applications for buildings were for power generation, heating and cooling. It is evident that the buildings in most of the developed (Germany, Sweden, France, UK, USA, Singapore etc.) and developing countries (India, Malaysia, Thailand etc.) have the few sustainable features of harnessing energy by the installation of solar photovoltaics, solar thermal collectors (Santos & Rüther, 2012; Takuma et al., 2006) and even wind turbines (Santos & Rüther, 2012). In European countries especially in Germany, it was already demonstrated that the utilization of various renewable energy sources (solar PV/thermal, wind, geothermal and biomass) along with the application of new building technologies (Syed et al., 2009). BIPV serves both for electricity generation as well as the outer layer of the building structure. The parts or components of the PV system form an essential part of the existing or new building with BIPV. PV modules are installed on buildings during the architectural stage in a variety of methods, including roof tops and façades (Solar Edition, 2019). PV modules are used in the place of windows as building materials, these windows are made with PV materials and can even allow the daylight in to the inner area of the building there by reducing energy consumption levels (N. M. Kumar et al., 2018; A. K. Shukla et al., 2016b). Several works were done in the field of BIPV, but still the issues related to the technical and financial viabilities are left unsolved. Due to global warming and the depletion of fossil resources, interest in zero-energy buildings is progressively growing. According to Directive 2010/31/EU, 'Nearly ZEB' means a building that has a very low energy yearly energy consumption, which can be achieved by both the highest energy efficiency and by energy from renewable sources, which shall be 'on-site' or 'nearby'(European parliament and of the council, 2010). In the design and construction realm, for example, Yoo et al. (Yoo & Lee, 2002) presented a building design with PV modules shading the building in the summer to minimize cooling requirements. Wong et al. (Wong et al., 2008) used a semi-transparent PV module on a building's skylight in Japan. In comparison to a roof design utilizing solely an opaque BIPV, the semi-transparent solar skylight permitted 50% radiation transmission and could contribute a maximum of 5.3% of domestic heating and cooling energy consumption under ideal conditions. For a building in Hong Kong, Sun and Yang (L. L. Sun & Yang, 2010) investigated the effects of tilt angles on the energy performance of shading-type BIPV claddings in terms of yearly electricity generation and yearly cooling load reduction. At normal operating cell temperatures, the solar cell temperature of a BIPV module is greater than that of a free-standing PV module. Climate plays an important effect in BIPV system energy output as well as the building's net annual energy consumption, according to the study (Sorgato et al., 2018). Two indicators are used to assess long-term operational performance, which are Daily Mean Yield (DMY), Performance Ratio (PR), as follows. The DMY and PR can be obtained by Eq. (1) and Eq. (2) respectively to analyse the efficiency on the power output of the research PV systems. The study presented a result consistent with monthly irradiation tendency, where the system performance was

$$\mathrm{DMY} = \frac{\mathrm{E_{out/day}}}{\mathrm{P_0}} \quad (1)$$

$$\mathrm{PR} = \frac{\mathrm{E_{out}}/\mathrm{P_0}}{\mathrm{H_I}/\mathrm{G_0}} \quad (2)$$

Previous studies on BIPV design and performance have been summarised in Table 2.5.

Table 2.5 Findings on BIPV design and performance.

Researcher	Study	Findings
(P. Sharma et al., 2020)	The techno-economic performance of a BIPV system with battery energy storage in a South Norwegian home was examined by the author.	Battery storage improves system performance during grid constraints, reveals link between grid and PV output.
(Quintana et al., 2020)	Techno-economic evaluation of BIPV system with grid connected and with storage system	Payback period of ~10 years under the mixed feed-in. Self-consumption mode, over its 20 years operation period for a BIPV system of 35kWp installed in 615m^2.
(Islam et al., 2018)	Design and Analysis of PV Plant	The temperature has a significant effect on the payback period (PB). The power generation is decreased due to an increase of PV cell temperature as a consequence the PB is also increased.
(Arnaout & Ii, 2019)	CdTe, Energy Potential, Payback	CdTe cells offer high energy, low temperature sensitivity, and reasonable payback time.
(Sorgato et al., 2018)	The study scope was to evaluate the technical and economic potential of integrating PV modules on a commercial building façade and roof in six Brazilian cities.	The findings revealed that the analyzed building's annual energy consumption could be met by utilizing the roof and façade for BIPV applications.
(Ritzen et al., 2017)	mc-Si, Investigated the performances of ventilated and non-ventilated BIPV rooftops	The electricity production of a ventilated IPV rooftop was 2.6% higher than that of a non-ventilated rooftop.
(Othman & Rushdi, 2014)	Potential of Roof Top BIPV, Monocrystalline, 5.78kWp System, Flat roof	BIPV application on houses at Eco Setia Park where they registered at an average of 10,450 kWh annually.
(M. Ito et al., 2010)	LCA of VLS-PV system using different PV technology 1 GW system in Gobi Desert	Approximately Payback time for CIGS 1.8 years. And energy pay-back time of SC-Si is 2.5 years. Other PV's approximately 2.0–2.3 years. CO_2 emissions rate is 54 g-CO_2/kW h. CIS shows lower CO_2 emissions rate of approximately 43 g-CO_2/kW h.

Table 1.2 Continued

Researcher	Study	Findings
(G. Gan, 2009)	Effect of an air gap on a PV module's electrical performance.	A 12–16 cm air gap could greatly reduce the overheating problem and increase the electricity generation.
(Ordenes et al., 2007)	mc-Si, pc-Si, a-Si, CdTe, CIS, Investigated the potential of BIPV	For 30% of the running time, the electricity generation exceeds building's demand.
(Kaundinya et al., 2009)	The study scope was to review the literature on decentralized power systems and present the features of several technological alternatives available.	Authors concluded that high electricity costs due to centralized fossil fuel grids in remote regions.
(James et al., 2011a)	The study analysed the installed rooftop prices of building-integrated photovoltaics (BIPV) in the residential sector.	NREL study: BIPV systems offer interesting ROI in US residential market due to multifunctional features.
(Jelle et al., 2012)	Authors discussed the different types of BIPVs, the materials used, and the main options for building integration. It also discusses the future of BIPVs and the potential for improvement.	Jelle reviewed commercially available BIPV approaches, concluding that they have significant advantage over non-integrated systems due to land and stand-alone PV system savings.

2.4 Factors affecting BIPV Performance

Typical PV systems, whether roof-mounted or ground-mounted, are normally built for maximum power production at the lowest possible cost. In contrast, BIPV systems must fit with the geometry, architecture, and construction of an existing or newly constructed building. The effect of envelope geometry(Hachem-Vermette, 2018; Pereira & Aelenei, 2019) and façade system pattern(Centeno Brito & Freitas, 2015; Hachem & Elsayed, 2016; Kacira et al., 2004), such as folded geometry, adaptive BIPV shading (Jayathissa et al., 2017), and adaptive solar façade (Powell et al., 2018)on BIPV performance are investigated. In these studies, the optimum arrangement of solar panels is mainly defined based on electricity generation (Hachem & Elsayed, 2016) or techno-economic analysis (Bakos et al., 2003; Fath et al., 2015; Y. Li & Liu, 2018; Youssef et al., 2016). Unavoidably, many BIPV modules are not only not oriented optimally, but different sizes of modules may be necessary to fit into the given architectural design, and the modules may be subject to shade from neighbouring buildings or other components of the building itself. As a result, there is no all-purpose BIPV module that satisfies all economical, technological, and aesthetic requirements. These circumstances necessitate not just customized module solutions, but also a unique electrical architecture of the BIPV system(Sprenger, 2013).

High-density cities may encounter several obstacles in capturing solar irradiation, which is strongly connected to the available PV installation area and the amount of hindrance (shadings) as a result of dense urban forms. The partial shade impact of PV modules, which plays a crucial role in the efficiency of PV systems due to their non-uniform and dynamic circumstances, is one of the most significant and challenging consequences of dealing with BIPV performance estimation. The majority of the surrounding barriers are trees, power lines, and buildings. Additionally, the building itself is responsible for a 5-10% reduction in overall BIPV performance. PV modules that are partially shaded receive less solar energy, which may cause permanent damage to the module owing to the hot spot effect(Somboonwit & Boontore, 2017).

Correlations for PV-cell operating temperature (Tc) are either explicit, yielding Tc directly, or implicit, including factors like as cell efficiency or heat transfer coefficients, which themselves depend on Tc. To determine the cell temperature in the latter scenario, an iteration procedure is required. There are several models for evaluating

PV-cell temperature in the literature. Models are both explicit and implicit(Achenza & Desogus, 2015). Many research articles deal with the likelihood of the PV module or PV cell temperature T_{pv} and T_c, respectively, for cell types such as mc-Si, pc-Si, a-Si, CIS, CdTe.

Equation provides one of the simplest and most often used ways for calculating Tc. (3).

$$T_c = T_a + \frac{G_m}{800}(NOCT - 20) \tag{3}$$

Where Tc is the temperature of the cell, Ta is the temperature of the air (°C), Gm is the solar radiation (W/m2), and NOTC is the Normal Operating Cell Temperature (°C). If Tc is determined, equation 3 may be used to compute the reduction in performance (4).

$$\frac{PVP_{Tc}}{PVP_M} = 1 - PTC \times (T_c - 25) \tag{4}$$

Where PVP_{TC} is the power of the PV module at Tc temperature, PVP_M is the module's maximum power (i.e. in Standard Test Conditions), and PTC is the power temperature coefficient. It is determined by the type of panel. The following values are for a typical polycrystalline module.

BIPV also faces challenges from the supply-side and the demand-side (T. Chen et al., 2022). In demand side, the electricity demand response and management allow people to choose the time period and flexibly mode of electricity, so the competitiveness of BIPV systems needs to be further improved(Jayathissa et al., 2017). On supply-side, the variability of sunlight and climate difference bring more unpredictable PV power output(Q. Li et al., 2020). Idea of data-driven smart Building-integrated photovoltaic (SBIPV) systems was suggested which could meet future needs on both demand and supply-side (Z. Liu et al., 2023).

Barriers to BIPV Implementation:

Despite the technology advancement in PV, there are still barriers for BIPV implementation as stated by different authors as summarised in Table 2.6.

Table 2.6 Barriers for BIPV

Author	Findings
(Kotarela et al., 2020)	Policies for encouraging BIPV applications have been initiated in recent decades, among which the zero-energy or net-zero energy building is a major concept
(Corti et al., 2020; PVSITES, 2016; Quintana et al., 2020)	• Introducing BIPV-specific building codes • Manufacturing and installing standards • Need for common and standardized methods • Visually acceptable installation of BIPV systems • Customization to fit unusual corners
(Halme & Mäkinen, 2019; Klampaftis et al., 2015)	• Lack of understanding of intricate economic calculations • Lack of information about mounting system of certain BIPV devices • Limited knowledge among decision makers
(Klampaftis et al., 2015)	• Efficiency changes if the solar panels are arranged or coloured • How will the gaps be filled? • What are the costs and benefits? • Which metering systems and rules are applicable?
(Goh et al., 2017)	Affordability, Lack of sustainable material, code and regulation, finance, Lack of Readily Available Accessible Information are some of the barriers in the implementation of BIPV in Malaysia.
(A. K. Shukla et al., 2016b)	Limited public awareness and negative perception of the technology costs also add barriers for BIPV deployment
(James et al., 2011b)	BIPV uptake can be accelerated by introducing BIPV-specific building codes, manufacturing and installing standards and related regulations

2.5 BIPV Powered EV Charging

Technological, economic, and social hurdles surround the integration of EVs, ranging from infrastructure needs to consumer concerns about EV costs, charging times, and the scarcity of EV charging stations(B. Li et al., 2017) safety, reliability, distance range, maintenance service availability, and battery life durability (Karpenko et al., 2018; Rodríguez et al., 2015). The use of PV to charge EVs has been made possible by advancements in power conversion technologies, battery management systems, improved installation techniques, and design guidelines (Branker et al., 2011). There are several reasons why PV integration with EV charging systems is increasing, including continued PV module price decreases, a major growth in EV sales, and worries about greenhouse gas emissions (Bhatti et al., 2016a).

A few survey studies have discovered that EV drivers perceive home charging to be a motivating factor for purchasing an EV when it is convenient to reach(Bailey et al., 2015; Hardman et al., 2018; Nicholas Michael A. et al., 2017). In (von Wirth et al., 2018), The literature research investigating synergy between PV and EVs may be divided into three groups based on study scale: small, medium, and large sizes. PV power availability decreases spinning reserve capacity and increases grid stability (Makena et al., 2012). Using Clean Energy is envisaged to reduce the environmental impacts and improve the overall charging system efficiency (Makena et al., 2012; Schepper et al., 2015). The integration of EVs is expected to pave the way to green mobility with zero carbon emissions (Karpenko et al., 2018). Numerous previous studies examined the architecture of an EV charging station based on solar photovoltaics(Capasso & Veneri, 2015; Choe et al., 2010; Fattori et al., 2014; Gamboa et al., 2010; Goli & Shireen, 2014; Hamilton et al., 2010; Holweger, 2010; Lapsa et al., 2011; Mouli et al., 2015; Noriega et al., 2013). The reciprocal advantage of charging EVs with solar energy has been addressed in (Birnie, 2009; Denholm et al., 2013) where the ability to charge EVs with solar enables for greater penetration of both technologies. Since the transportation industry accounts for almost one-fourth of the world's total greenhouse gas emissions, which are expected to rise from 23 to 50 percent by 2030, reducing CO_2 emissions is an imperative challenge(S. Wang et al., 2014).

Various studies have been done globally on solar powered EV charging, some of the studies are mentioned in table 2.7.

Table 2.7 Review of Solar Powered EV charging

Authors	Study	Findings
(Shafiq et al., 2022)	Study the techno-economics of solar PV-based energy solutions for EV bike charging. Studied two systems –Grid connected with storage and without storage	Electricity cost of grid connected without storage system was lower Renewable fraction of system with storage system was high unto 45% as compared with storage system of 41%. Payback period of grid connected system without storage was 1.5 years whereas system with battery has higher payback period of 7 years.
(Pearre et al., 2011)	Driving data from 484 instrumented gasoline automobiles in the United States is analyzed to determine the range needs of EVs.	Merely 15% of the sample's automobiles are on the road on a typical weekday at 5 o'clock; more than 75% of them are always parked. Drivers progressively connecting between 5 p.m. and 12 a.m. Smart charging, on the other hand, is desirable since it shifts charging to off-peak hours.
(Chandra Mouli et al., 2016)	Authors investigated the possibility of charging battery EVs at workplace in Netherlands using a 10kWp PV system in order to evaluate grid dependency.	The viability of making the EV-PV charger grid independent by incorporating a BESS is assessed. Evaluation of the ideal storage size that lowers grid dependency by 25%
(Bhatti et al., 2016b)	Authors in this paper reviewed EV charging solar photovoltaics and discussed two systems Standalone and only grid connected systems.	It was found that grid connected system was economically and technically feasible whereas standalone system was not feasible due to limited supply and expensive and excess energy cannot be sold to the grid. Stand-alone systems are more prone to losses.
(Prem et al., 2020)	Authors in this paper investigated performance of three different modes, namely stand-alone solar-powered EV charging mode (SPV-EV), Buffer battery to vehicle charging mode (Bb-EV), and Grid to vehicle charging mode (G-EV).	It was found T-source converter to be an ideal choice for EV fast-charging stations. Further benefits include fewer power components, low total harmonic distortion, little ripple, high gain, and quick charging.

Table 2.7 Continued

Authors	Study	Findings
(Grande et al., 2018)	The technological and economic viability of stand-alone PV-BESS to charge electric mobility is examined in this research (EVs) using HOMER.	442,600 kWh of energy are produced annually, with a 7-hour autonomy. Economically, the system payback was determined to be 7 years, and owing to the off-grid technology, there were no CO_2 emissions noted. Off-grid charging stations may be economically and energetically practical.
(S. Khan et al., 2022)	Authors in this paper studies techno-environmental aspects of 1MW BIPV plant with 2 scenarios with fully integrated BIPV vs Semi integrated BIPV with air circulation at university building roof top in Malaysia for EV charging application.	1MW plant can meet daily charging requirement of approximately 4.8MWh for 2000 EV's with seasonal dependency of grid in the month of November.
(A. Singh et al., 2021)	Authors investigated sustainability of 8.1kWp off grid solar powered EV charging with 2 days of autonomy.	Results shows that proposed system can charge 414 vehicles of 30kWh battery annually. Also reduce approximately 7950kg of CO_2
(Ghotge et al., 2020)	The authors investigated the method of using Solar PV to minimize peak power consumption at an EV parking lot.	Forecasting EV charging demand and robust adjustment of the schedule for the performance of the worst possible forecast marginally improved the effectiveness of the scheduling, reducing the peak demand by 39%.
(Esfandyari et al., 2019)	A 10.5kW photovoltaic (PV) array can be combined with 9.6kWh battery energy storage to satisfy the electrical demand of lightweight EV in Dublin, Ireland.	The deployed AC coupled campus charging infrastructure can offer 100% percentage on-site electricity use. The annual unsubsidized excess of PV yield results in CO_2 emission and tax savings of up to 3635.78 kg/kWh and 73 euro/tonnes regularly.
(Fretzen et al., 2021)	Authors in this demonstrated detrimental effects of uncoordinated charging and suggested coordinated charging pattern by modelling EV usage pattern with real world transportation and geospatial modelling of PV generation.	EVs can absorb significantly larger ratios of solar PV generation with a coordinating system. In the case of plentiful solar availability (with a maximum prospective solar portion of 85%). Coordination can improve the feasibility of BIPV systems, which have been shown to be both ecologically and economically advantageous.

Table 2.7 Continued

Authors	Study	Findings
(Bracco et al., 2019)	The authors of this study provided an optimization model for the design of a smart energy infrastructure integrating various technologies to meet electricity demand, taking into account that smart energy infrastructure comprises a solar plant, storage systems, EVs, and charging stations.	The proposed methodology allows for a reduction in the site's energy bill. When compared to the case when all energy is purchased from the external grid, all of the scenarios investigated in this article provided for lower operating costs. It demonstrates that the precise design of a smart energy infrastructure, such as the one described in this study, allows for economic savings while also determining environmental advantages.
(Guzman et al., 2021)	Proposes an aggregation strategy that maximizes a green energy index (GEI) for the smart charging coordination of EVs,	The aggregation technique encourages lower energy use from the main grid. The available PV energy was consumed by EV owners and BIPV users. The GEI's suggested optimization strategy enabled consumers to pay a competitive price for energy even under adverse weather circumstances.

2.5.1 Uncertainty of Solar Powered charging stations

When developing a solar-powered charging station for a residential building, particular challenges appear because the BIPV system should be supplying energy for both consumer buildings and EVs. Sizing the BIPV array while considering all losses from the BIPV array to the inverter output to the EV is one of the main problems. Failure to do so will lead to insufficient energy production, which won't satisfy the needs. Second, solar energy is intermittent since the amount generated on any given day relies on the local weather, including temperature and precipitation. Thirdly, due to the increased power requirements of EV charging, it may have an impact on the functioning of other appliances if done at a time of high peak demand. Finally, the study suggested a BIPV plant based on the constant daily energy need for EV battery charging, which is dependent on daily commuting distance. However, extra energy for home use would be dependent on the grid if the demand for EV charging increases.

2.6 Building integrated photovoltaics and Electric charging vehicle status in selected location

2.6.1 BIPV and EV status in Malaysia

Malaysia's construction sector has been rapidly developing, and energy consumption linked to it is likely to skyrocket. BIPV has significant potential in Malaysia due to predicted increases in power demand, accessible building spaces, and ample solar energy. BIPV can substantially impact the construction sector, potentially replacing some fossil fuel-based energy. BIPV costs can offset construction expenses of building materials and labor, while also generating energy(Debbarma et al., 2017b). Malaysia's equatorial climate, with an average daily solar radiation of 4,500 kWh/m^2 and around 12 hours of daylight(P. Y. Gan & Li, 2008) makes it favorable for BIPV systems.

To encourage Malaysians to adopt renewable energy, the government launched the Net Energy Metering Scheme in November 2016 with a quota allotment of 500 MW till 2020. The principle behind NEM is that the energy from the solar PV plant will be used first, with any excess energy being exported to TNB at the current subsidized cost. On January 1, 2019, the NEM 2.0 was released in an effort to increase NEM adoption. Due to overwhelming response from the PV industry and in an effort to boost the usage of Solar energy, the Ministry of Energy and Natural Resources has launched the new NEM 3.0 initiative to provide energy customers greater options to save money by installing solar PV systems on their rooftops (SEDA, 2020).

Several studies have explored the feasibility of PV systems. Barone et al. analyzed various technical and economic KPIs, suggesting energy management systems can reduce grid power use by 45% to 77%(Barone et al., 2019). Stamatelos et al. studied transient modeling of a power system with EVs, optimized rooftop PV, and heat pumps, finding improved grid stability(Stamatellos et al., 2022). Wi et al. proposed optimal scheduling of EV charging based on predicted PV output and electricity consumption(Wi et al., 2013). Sopian et al. examined a 5.76 kWp grid-connected PV system at UKM, Bangi, Malaysia (Kamaruzzaman Bin Sopian et al., 2007). Othman et al. investigated BIPV applications on different residential rooftops in Shah Alam(Othman & Rushdi, 2014). Islam et al. studied BIPV feasibility in various Malaysian locations, finding the highest energy generation in Sabah and the lowest in Selangor (Islam et al., 2018).

However, no research has considered building and EV charging as a single system, which is a novel aspect of this study.
The transport sector is the second fastest-growing sector in terms of energy consumption, with road transport accounting for over 90% (Ministry of Environment and Water, 2021). The National Automotive Policy (NAP) aims to make the automotive industry a key economic contributor, focusing on energy-efficient vehicles (EEV)(Ministry of International Trade and Industry, 2020). NAP 2020 sets actions to boost EV development, including local battery manufacturing and infrastructure development (Chan, 2021). However, higher prices, a lack of charging infrastructure, and ambiguous regulation limit EV adoption. The government plans to exempt EVs from various taxes and grant income tax relief for EV charging facilities(Gerard, 2021). Higher tax breaks in 2021 led to an 8% rise in BEV sales, although adoption rates remain lower compared to Indonesia or Singapore(Raymond, 2022).

Although Malaysia currently has a low EV adoption rate, this is expected to rise significantly in the coming years(Yamin, 2023). This study sets a precedent by establishing guidelines to assist EV owners and policymakers as demand increases, offering an advantage over previous research. Additionally, this study can serve as a benchmark for future research aimed at enhancing EV charging systems, enabling their seamless integration into the early stages of BIPV design.

2.6.2 BIPV and EV status in Australia

Residential sector has been the primary driver of small-scale renewable investment, with rooftop solar PV installation around one-quarter of all homes(Clean Energy Council, 2021). With over 2 million solar households and penetration levels exceeding 40% of stand-alone residences in some places, Australia dominates the globe in widespread residential PV installation(APVI, 2016). Payback times have shortened in recent years, owing to rising retail power rates and reducing solar panel installation costs(Green Energy Markets, 2019).

Because of knowledge gaps between the PV and construction sectors, there is a lack of BIPV product and standard awareness, as well as optimal project solutions. The Australian government has initiated the BIPV Enabler project, which aims to provide a user-friendly framework for integrating product, policy, technological, economical, and structural data to produce a competitive BIPV offering(ARENA, 2019).

Australia, the world's sunniest continent, has diverse climates including tropical, temperate, arid, and alpine environments, all suitable for solar energy generation. Even areas with less sunlight, like Victoria and Tasmania, have substantial solar energy potential (Clean Energy Council, 2022). Australia receives an average of 58 million PJ of solar radiation per year, nearly 10,000 times the country's total annual energy usage (ARENA, 2014; Flannery & Veena, 2013).

Feed-in tariff programs, once funded by state governments, are now closed to new consumers, though retailers still offer some feed-in tariffs depending on the state and system scale (EnergyAustralia, 2022). Several studies have explored the feasibility of PV systems in Australia. Donald et al. conducted a techno-economic analysis of PV systems with batteries for self-consumption, examining the increasing price of electricity versus falling PV and battery prices (Donald Azuatalam et al., 2018). Hamzah et al. investigated the techno-economic feasibility of a 30MW PV plant in Australia, considering electricity costs and pollutant reduction (Al-Qudah & Fadlallah, 2021). However, no study has yet considered daily residential load and EV charging in a BIPV+EV charging system analysis.

Transport is the fastest-growing and third-largest source of emissions in Australia, following the electricity and stationary energy sectors (Lynskey et al., 2020). Road transport accounted for around 85% of transport emissions (or about 16% of Australia’s total emissions) in 2018(Climate change authority, 2021). Australia's road fleet is among the most energy-intensive in the world. Transitioning from ICEVs to EVs is crucial to reducing road transport emissions. However, EV adoption in Australia is low, with EVs representing less than 1% of new vehicle sales, compared to 3% to 5% in other developed countries(Broadbent et al., 2019). Only 0.6% of Australia's automobile fleet is electric (Rachel Lynskey, 2021). This is expected to improve as more affordable EV models and charging infrastructure become available (ARENA, 2022). EVs offer an environmentally friendly mode of transportation that can greatly reduce the overall carbon footprint (PwC Australia, 2020). In 2021, 31 EV models were available in the Australian market, with 8,688 EVs sold, a 25% increase from 2020(Electric Vehicle Council Australia, 2021).

2.6.3 BIPV and EV status in Sweden

Sweden, ranked fourth in power and heat production, generates 100% of its electricity from low-carbon sources. Due to government initiatives on EV charging legislation and low-carbon fuel standards, Sweden is also ranked second in transportation. The nation aims to eliminate fossil fuels from the transportation sector by 2030, ahead of its 2045 Net Zero goal(KPMG, 2021). Despite a low adoption rate of solar energy at 1%, Sweden's dependency on fossil fuels remains minimal (Swedish Energy Agency, 2022).

Sweden is undergoing an energy transition, moving from fossil fuels to renewable energy. This transition presents challenges for the construction and energy sectors, with the energy sector expected to produce negative carbon emissions(Regeringskansliet, 2019). By 2050, public buildings should use 50% less purchased electricity than in 1995. The industry and construction sectors, which account for about 40% of final energy consumption, must meet specific intermediate targets(Baker McKenzie, 2016). Solar energy contributed 0.2% to total electricity generation, while wind energy made up 10.4%(Holmgren, 2019). The installed capacity of solar systems was 698.05 MW in 2019, or 68 Watts per resident, higher than in Finland and Norway(IRENA, 2020b).

In 2006, Sweden installed around 300 kW of grid-connected PV systems, marking the industry's takeoff. Since then, the number of grid-connected PV installations has increased rapidly, with an average growth rate of about 55% over the last four years(Johan Lindahl et al., 2020). Challenges for PV systems include low yearly irradiation in northern areas, high seasonal changes in solar irradiation, and low energy costs(Jerez et al., 2015). Various studies have examined the feasibility of PV systems in Sweden. For example, Jonas et al. studied PV system optimization in historical buildings (Gremmelspacher et al., 2021) and and Lindahl et al. analyzed the economics of centralized PV parks(Lindahl et al., 2022). Kabir et al. investigated the feasibility of a 40kW PV plant with a 3kWh battery for combined loads in Karlstad and Arlanda, Sweden (Kabir et al., 2021). Public awareness of solar energy is low, and peer effects promoting PV adoption occur primarily through direct interactions (J. Palm & Eriksson, 2018).Municipal actions, such as Malmö's investment in industrial building PV installations, are supporting PV adoption(Gremmelspacher et al., 2021; A. Palm & Lantz, 2020). In order to promote the use of renewable energy on an urban scale and to guarantee financial feasibility, it is crucial to investigate and optimize PV in existing buildings (U. Ali et al., 2020).

Sweden introduced a renewable electricity certificate in 2003 to boost renewable electricity production (Tang & Rehme, 2017). A PV-specific capital investment scheme launched in 2005 further ignited the PV market. Initially, the government funded up to 70% of installation costs, with incremental reductions since then(Johan Lindahl & Cristina Stoltz, 2018). Smaller solar energy producers receive a tax deduction of SEK 0.6 per kWh generated, and financial assistance is available for both private individuals (up to 20%) and businesses (up to 30%) (Baker McKenzie, 2020). In 2021, a new plan offered a tax discount for PV systems, battery storage, and EV charging stations up to SEK 50,000 per taxpayer annually(Energimyndigheten, 2020).

The increasing percentage of EVs has significantly increased energy usage in road traffic, and this trend is expected to continue (Swedish Energy Agency, 2022). EVs are crucial to Sweden's goal of zero-emission targets for 2050. Global EV sales continue to rise, driven by decarbonization efforts and supportive regulations (Virta Global, 2023). Sweden, a leader in EV adoption, offers significant incentives for EV buyers, including up to $6,700 in purchase subsidies (IEA, 2021c). Over 65% of EV users in Sweden have access to charging stations, making EVs a sensible financial choice. The country is also investing in affordable EV technology(Keren, 2018). Public charging infrastructure improvements, particularly in rural areas, are essential to address range anxiety and inadequate home charging options (Egnér & Trosvik, 2018). Sweden aims to become the first fossil-free welfare state, with a goal to reduce domestic transportation's greenhouse gas emissions by at least 70% by 2030 compared to 2010 levels (Carolina, 2023). The country's stringent climate law, enacted in 2018, mandates net-zero greenhouse gas emissions by 2045(IEA, 2021c).

2.7 Review of BIPV simulation tools

Every project is different when it comes to BAPV and BIPV, thus thorough and comprehensive planning is necessary to maximize the efficacy and cost-effectiveness of the design. BIPV planning may be done using a variety of tools that are already on the market. These resources are accessible online, on a Desktop, or as mobile or tablet applications. These solar PV design tools have been used in many studies to 3D model future PV installations and projects and calculate solar irradiance, shading losses, energy output, and financial feasibility. Table 2.8 includes several instances that show the tools specialization. Under the parameters of IEA SHC Task 41 - Solar Energy and Architecture, an extensive study was conducted. Throughout the conceptual phase, preliminary design phase, detailed design phase, and construction drawing phase of a solar project, the research has evaluated and assessed the challenges experienced by architects while utilizing the tools for solar design(Dubois et al., 2010; Kanters et al., 2014). As BIPV systems are frequently a component of a ZEB, a thorough comprehension and modeling of such BIPV systems are required. The time-dependent electrical yield is the simulation's ultimate result, which may subsequently be used to other building simulation software. The difficulty with BIPV modeling is that every project and building has unique features. Simple simulation tools may be utilized for normal PV applications, however the situation for BIPV is frequently far more complicated: The BIPV modules are sometimes partially shaded by adjacent buildings or the building itself, and there are frequently varied module sizes and orientations. All of these result in more intricate module interconnections and inverter specifications that can only be understood through thorough modeling. The next method explains such a thorough BIPV simulation, which is likewise required to accurately anticipate a BIPV system's yield(Brüggemann, 2020). The simplest type of interaction is a 2D design and user interface that displays the azimuth and zenith angles of solar panels. The most popular method for determining the viability of solar systems with fewest shading-producing impediments is this one. This method, however, is unable to comprehend the quality of integration or portray BIPV installations in a building context. Contrarily, 3D building modeling offers such improved characteristics that customers may view BIPV installations that are seamlessly connected with building models. Nevertheless, there are various degrees of integration and interoperability for 3D models of buildings, ranging from complete integration in a 3D CAD environment to a standalone application. Certain software programs, such PV*SOL, Easy Solar App, Skellion, PVSITES-BIMSolar, SolarBIM PV and Construct PV allow users to model BIPV systems on top of building models(Zanelli & Freitas, 2019).

Table 2.8 PV Simulation software's with BIPV simulation feature

Software's	Category	Features
PV*SOL	Major Standalone PV Software	3D Visualizations & Shading analysis Energy, Economics, and environmental analysis. EV energy needs can also be analysed.
PVSITES-BIMSolar	Major Standalone PV Software	3D model and evaluate BIPV projects in terms of: Architectural design, Energy production, Thermal impact, Light transmission
BIMSolar	Major Standalone PV Software	3D Design suitable for BIPV Analysis, Detailed energy and financial analysis
PVSyst	Major Standalone PV Software	Energy, financial, environmental analysis. BIPV Can be analyses in fully integrated and semi-integrated system
PVGIS	Online Tools	BIPV, Energy generation simulation
Skellion	BIM Plug-In	Models can be exported to PVSyst for energy analysis

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section describes the methodology used in this study, which required considerable data collecting from a variety of sources for each site in order to determine daily home energy consumption and electric vehicle (EV) charging energy. PVSyst was then used to do system presizing. Following presizing, the design of BIPV systems for each location was done and optimized to meet the energy requirements. Once the system size was determined, each scenario was analyzed using PVSyst to evaluate energy generation as well as different energy, economic, and environmental characteristics. The research method is depicted in Figure 3.1 below, which depicts the successive stages taken in this study.

The overall methodology of the proposed study is illustrated in Figure 3.1.

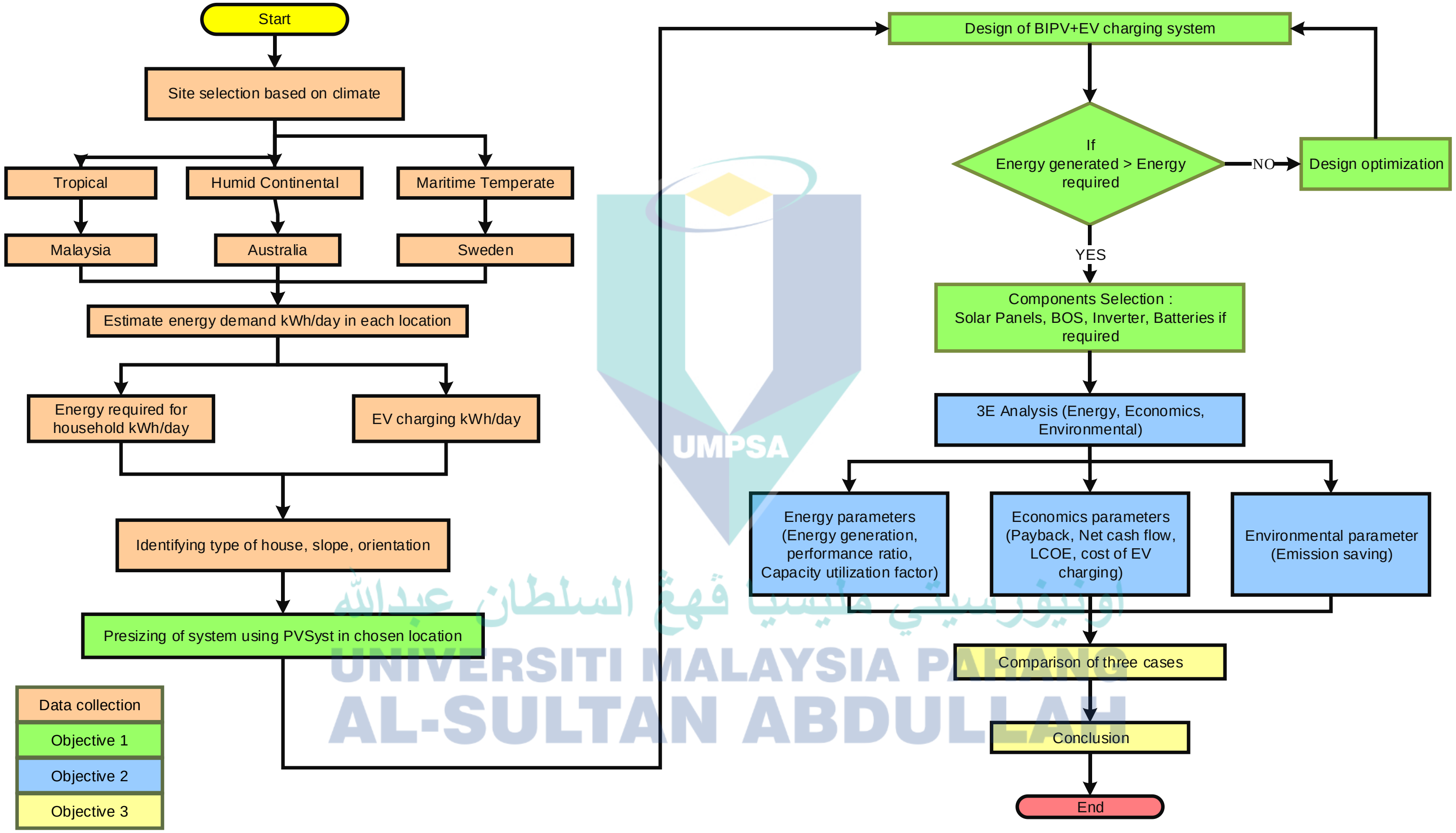


Figure 3.1 Methodology for the research work

3.2 Study locations and climate profile

In this research, tropical (Af), humid continental (Dfb) and maritime temperate (Cfb) climatic zone has been selected for the study as shown in Figure 3.2 and the location coordinates selected using google earth. To perform an assessment study on the proposed BIPV system, locations and installed capacity data are furnished in and the technical specification of the proposed PV module that best match the solar regime of the sites are identified.

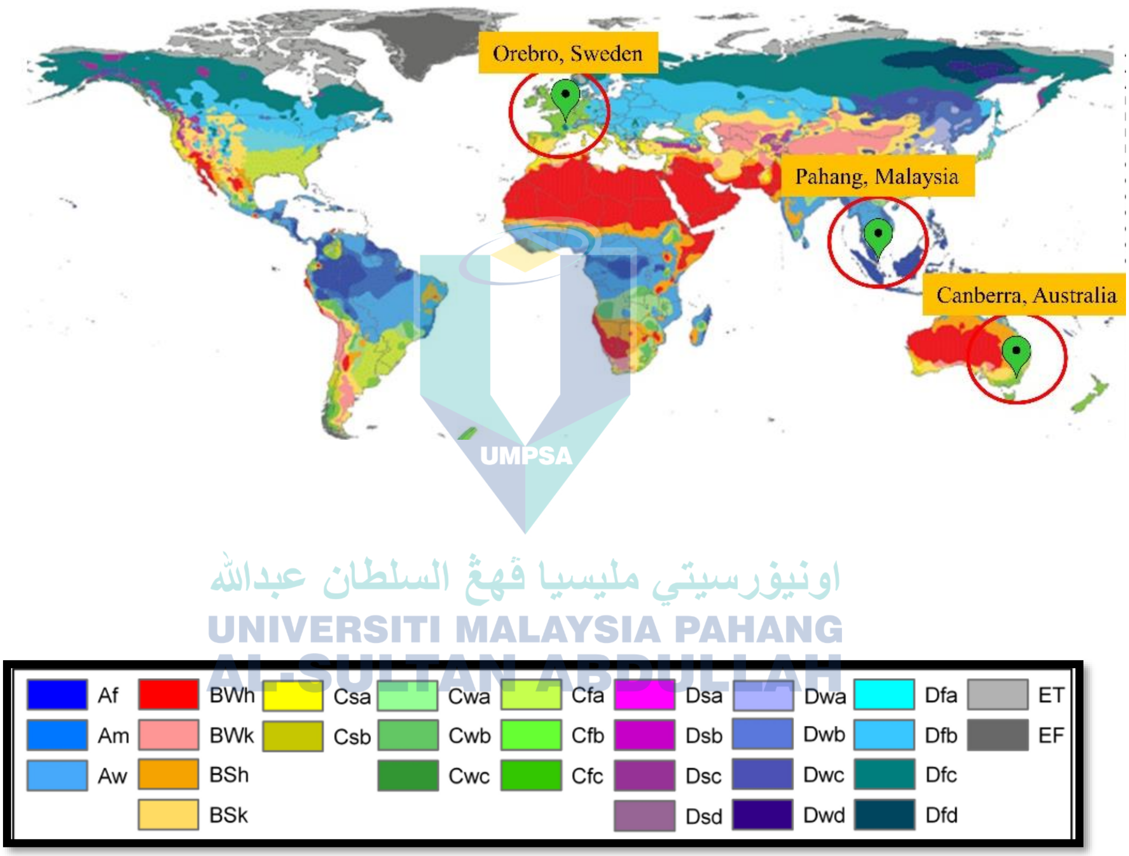


Figure 3.2 World map shows different climatic based on Koppen Classification

3.2.1 Climate profile for Kuantan, Malaysia

Pahang experiences tropical rainforest weather (Classification: Af). The city's average annual temperature is 0.23% lower than Malaysia's averages at 28.05°C (82.49°F). Pahang generally experiences 235.09 wet days annually with average precipitation of 138.06 millimetres. Malaysia enjoys a lot of sunshine, which results in strong solar radiation as show in Figure 3.3.

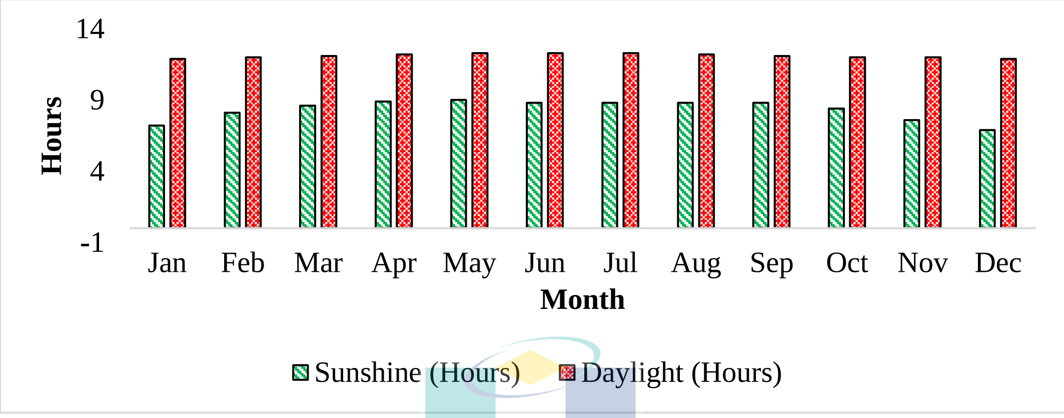


Figure 3.3 Monthly Daylight/Sunshine hours Kuantan, Pahang, Malaysia(Weather Atlas, n.d.-b)

3.2.2 Climate profile for Canberra, Australia

Canberra has a mild and moderate climate and receives a substantial amount of rainfall. Figure 3.4 depicts monthly average sunshine and daylight hours. There is a lot of rain even in the driest month. According to the Köppen-Geiger climate classification, climate is classified as Cfb. The average annual temperature in Canberra is 12.8 °C. Annual precipitation amounts to 589 mm.

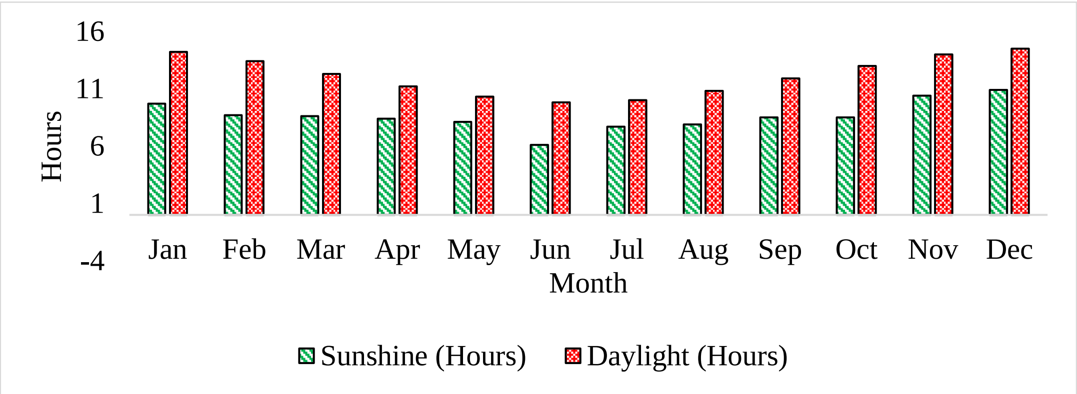


Figure 3.4 Monthly Daylight/Sunshine hours Canberra, Australia(Weather Atlas, n.d.-a).

3.2.3 Climate profile for Orebro, Sweden

The weather in Örebro, Sweden humid continental, with mild to pleasant summers and chilly winters with average temperatures only a few degrees below freezing. July has the greatest average low temperature (12.3° C). January and February are the coldest months (with the lowest average low temperature) (-4.5°C). Weather profile has been depicted in figure 3.5.

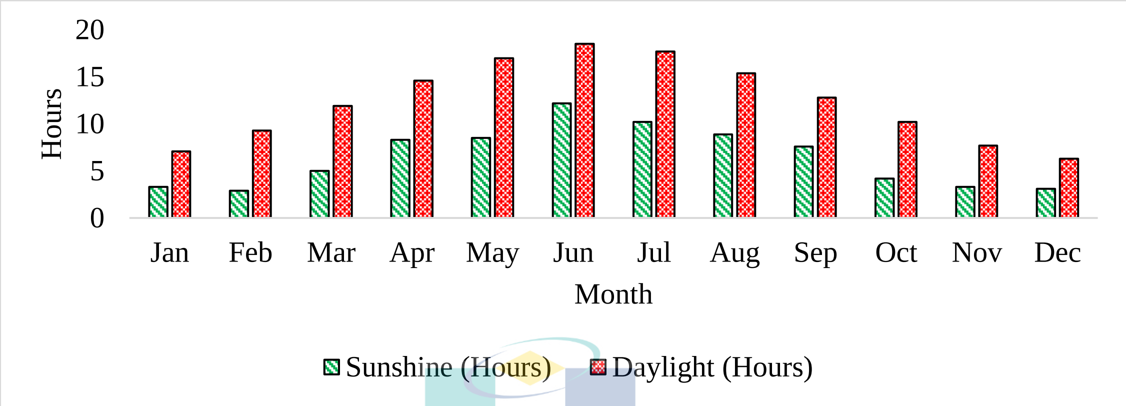


Figure 3.5 Monthly Daylight/Sunshine hours for Orebro, Sweden (Weather Atlas, n.d.-c)

The location which has been chosen listed in below Table 3.1 and the respective solar related parameters has been outlined in table 3.2.

Table 3.1 Site selection with different climatic zones

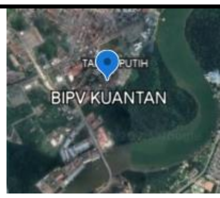
Location	**Latitude and Longitude**	**Climate Zone**	**Elevation(m)**	**Selected Location**
Pahang, Malaysia	3°29'22" N 103°24'09" E	Tropical Rainforest	9	
Canberra, Australia	35°18'44" S 149°06'06" E	Maritime Temperate	580	
Örebro, Sweden	59°15'08" N 15°13'24" E	Humid Continental	28	

Table 3.2 Solar Site Parameters

Parameters	**Unit**	**Pahang, Malaysia (Solargis, 2022)**	**Canberra, Australia (Global Solar Atlas, 2019)**	**Orebro, Sweden (Global Solar Atlas, 2022)**
Direct normal irradiation	kWh/m²	1115.4	2095.8	1055.5
Global horizontal irradiation	kWh/m²	1779.5	1760.8	975.6
Diffuse horizontal irradiation	kWh/m²	931.3	541.5	482.6
Global tilted irradiation at optimum angle	kWh/m²	1781.8	2026	1218.9
Optimum Tilt of PV Modules	OPTA	3/180	33/0	43/180
Air temperature	°C	26.9	12.7	6.8
Terrain elevation	m	9	577	31

3.3 Design of BIPV for residential building with EV charging infrastructure

3.3.1 Layout of BIPV+EV charging

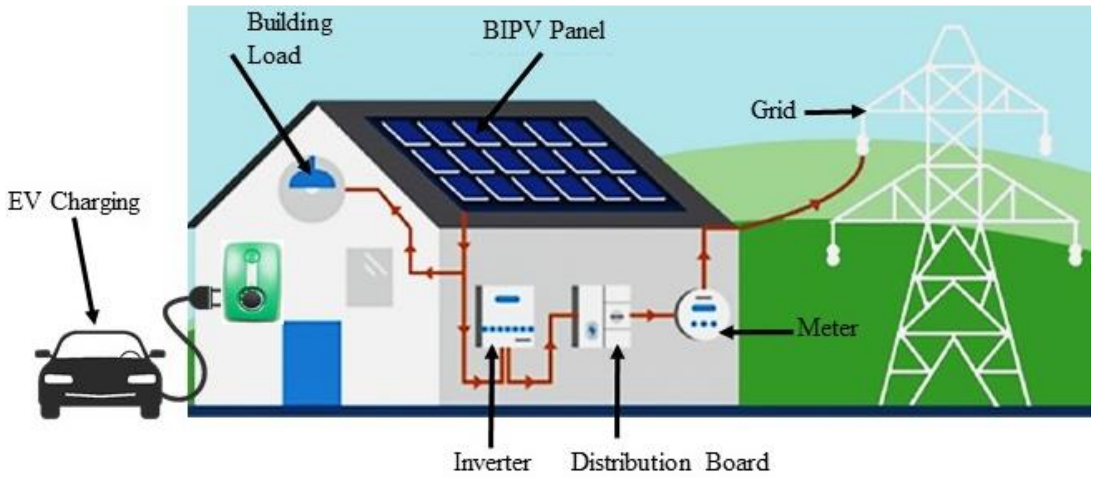


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Figure 3.6 Conceptual photograph of solar BIPV + EV system

BIPV Balance of System: Includes all components other than the solar panels. Balance-of-system components include inverters, batteries, enclosures, disconnects, combiner boxes, charge controllers, meters, wiring & connectors. In both grid-tie and off-grid solar PV systems, solar panels are at the top of the electricity production process.

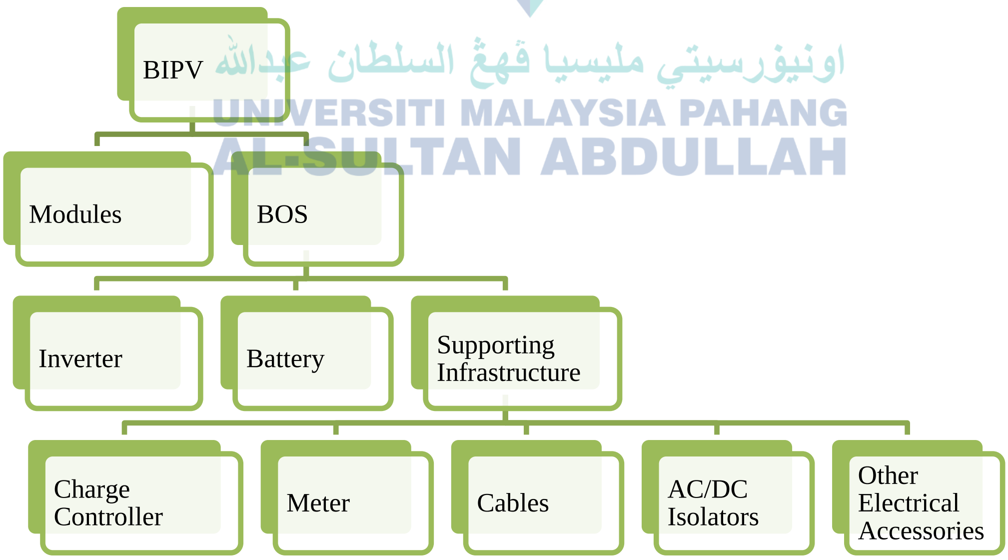


Figure 3.7 BOS Components for BIPV

3.3.2 Building Type

Malaysian Building

An area of 117m^2 (Foo, 2019) and an open gable type, typical Malaysian home with a slope of 10° (Roslan et al., 2016) are taken into consideration in this study. The roof's usable area for PV installation is 59m^2 on each side. The roof is facing southeast at the following coordinates, which have been taken into consideration for study. Although the size of the home may differ, a square area of 10.8 by 10.8 meters has been assumed. The architecture and orientation of Malaysia is seen in Figure 3.8.

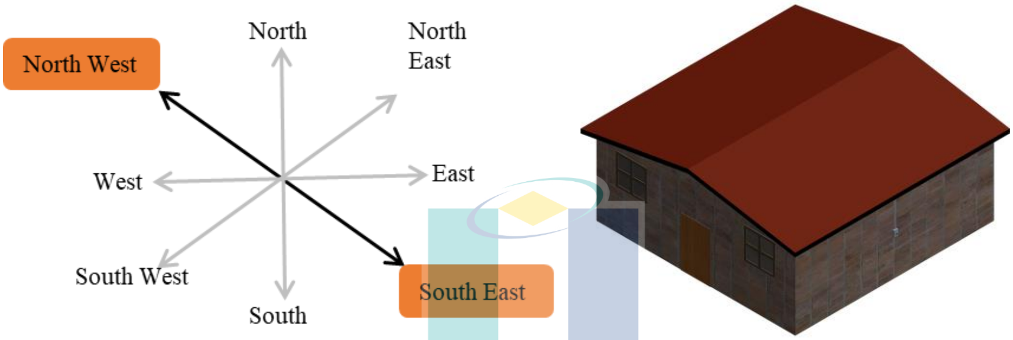


Figure 3.8 Orientation of house roof chosen in Kuantan, Malaysia

Australian Building

This study utilizes a unique Australian house design from Canberra, ACT, featuring acacia-inspired architecture and a 197m^2 floor area. The house's distinctive roof design, with three facets facing different directions, makes it an ideal candidate for this research. The house's dimensions were obtained from a freely available house design database (Australian Government, 2021). Figure 3.9 illustrates the house's design and roof orientation. The building's 14° deviation from north has also been factored into the study.

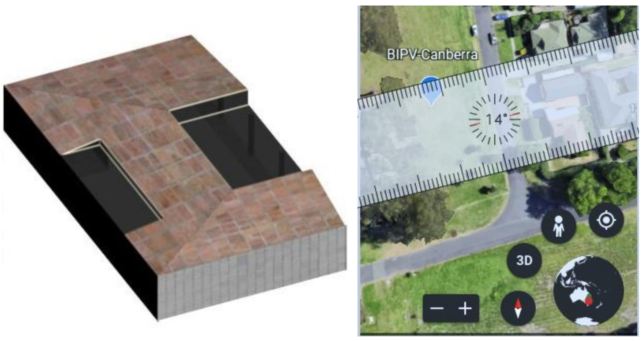


Figure 3.9 Orientation of house roof chosen in Canberra, Australia

Swedish Building

This study employs a typical Swedish house located in Örebro, Sweden. The house features a gable roof with a slope ranging from 15° to 45°, as seen in (Benders.se, 2013), and its orientation faces east of southeast. The house's floor area is approximately 100m^2, based on measurements obtained from Google Maps. According to (Statistikmyndigheten, 2017), the average residence in a multi-dwelling structure measures 68 square meters, while the average one- or two-family house measures 122 square meters. Figure 3.10 illustrates a typical Swedish building along with the orientation of the chosen location.

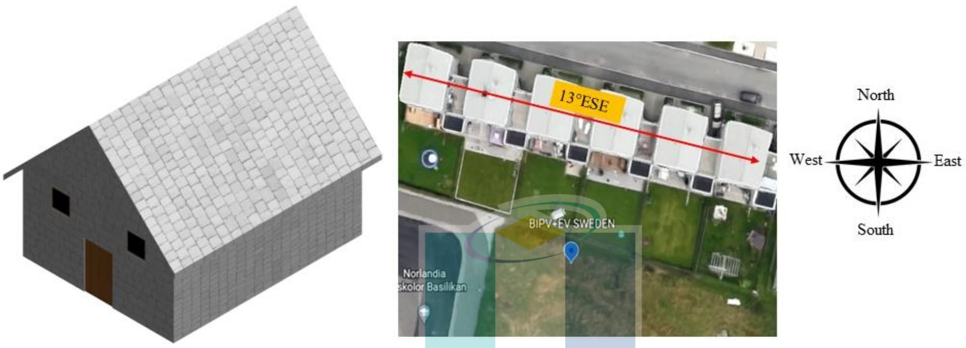


Figure 3.10 Orientation of house roof chosen in Orebro, Sweden

3.3.3 BIPV system sizing

Nominal power Assessment-Grid-Connected and Storage-on-grid system.

Based on the usage and solar irradiation, the peak power of the grid-connected PV systems was calculated. It has been evaluated using peak solar hours ("h"), which correspond to a period of time with a constant irradiance ("I_s") of 1 kW/m^2 and the same actual radiation ("I") (kWh/m^2) striking the surface of the module.

$$h = \frac{I_s}{I} \tag{6}$$

In the absence of power losses P_T, the ideal power delivered by the PV array is computed as follows:

$$P_T = \frac{L}{h} \tag{7}$$

The nominal power under the real condition P_{Nom} is then estimated as follows, taking into account energy losses in the PV system's electronic components (inverter, batteries, charge regulator, link cables, etc.) as well as in the PV system itself (depending on cell temperatures, shading, solar radiation reflections, dirt on module surfaces, etc.).

$$P_{Nom} = \frac{P_T}{\eta} \tag{8}$$

Total energy demand

Total energy demand includes household energy demand and EV charging demand per day represented by below equation 9.

$$\mathrm{E}_{\mathrm{Total}} = \mathrm{E_H} + \mathrm{E_{EV}} \tag{9}$$

Daily EV charging requirement

To find out daily EV charging requirements, below formula can be used(S. Khan et al., 2023).

$$E_{EV} = \frac{B_{EV}}{R} \times D_{day} \tag{10}$$

Charging time can be calculated using below equation 11.

$$Ct = \frac{E_{EV}\ (kWh)}{P_{In}\ (kW)} \tag{11}$$

Size the PV modules

The peak watt (Wp) produced depends on size of the PV module and climate of site location. Panel generation factor should be considered which is different in each site location.

$$\mathrm{PGF} = \frac{\text{Solar Irradiance} \times \text{Sunshine Hours}}{\text{Standard test conditions irradiance}} \tag{12}$$

$$\text{Total Watt Peak rating} = \frac{\text{Solar PV energy required}}{\text{Panel generation factor}} \tag{13}$$

Total number of modules required for the system:

$$\mathrm{N_{Module}} = \frac{\text{System Size, Wp}}{\text{Panel Rating, Wp}} \tag{14}$$

Inverter sizing

The inverter size should be 25-30% bigger than the total Watts of appliances. In case of appliance type is motor or compressor then inverter size should be minimum 3 times the capacity of those appliances and must be added to the inverter capacity to handle surge current during starting (WILES, 2001).

$$\text{Inverter Size} = \text{PV plant size} \times \text{Factor of safety} \tag{15}$$

Battery sizing

The battery type recommended for using in solar PV system is deep cycle battery. Deep cycle battery is specifically designed for to be discharged to low energy level and rapid recharged or cycle charged and discharged day after day for years.

$$\mathrm{B}_{Ah} = \frac{E_N \times \text{Days of Autonomy}}{B_{Eff} \times \text{DoD} \times \mathrm{B}_V} \tag{16}$$

Solar charge controller sizing:

$$R_{Cc} = \mathrm{N}_{\text{String}} \times \mathrm{I}_{\text{SC}} \tag{17}$$

Table 3.3 presents a summary of data collected for different locations regarding household electricity consumption and EV's usage. The study focuses on single-storey houses in Pahang, Malaysia; Canberra, Australia; and Orebro, Sweden.

Table 3.3 Summary of data Collected for the selected location

Location	Type of house	House area (m^2)	Household electricity consumption /(kWh/day)	Car type / brand	Commute per day (Km/day)	Battery capacity (kWh)*	Range (km)*	EV energy required per day (kWh)	Charging Time & Socket Details*
Pahang, Malaysia		117 (Foo, 2019)	14.5 (Hisham et al., 2019)	Nissan Leaf 	38 (Numbeo.com, 2021)	40* (Nissan, 2023)	311*	4.8	Type 2* 7hrs 6.6kW
Canberra, Australia		197 (Australian Government, 2021)	17.55 (Frontier Economics, 2020)	Hyundai Kona Elec. 	32 (Australian Bureau of Statistics, 2016)	39.2* (Hyundai-Australia, n.d.)	312*	4.1	Type 2* 7.2kWh charger
Orebro, Sweden		122 (Statistikmyndigheten, 2017)	27.6 (Paul Zimmermann, 2009)	VW ID3.0 	28.2 (Hiselius & Rosqvist, 2018)	45* (EV Database, 2021)	275*	4.63	Type 2* 7.2 kW AC

*Data from Manufacturers datasheet

3.4 Performance Parameters

3.4.1 Energy Parameters

Annual energy yield

Annual solar power production from a BIPV system that has been installed. It can be expressed on a daily, monthly, or annual basis. It is determined by module specifications and the system's solar irradiation at a certain location(A. K. Shukla et al., 2016b). Value of annual energy has been taken by simulating the system in PVSyst. Losses in PV systems such as tilt, shading, mismatch losses, irradiance losses and temperature impacts (hot spot issues), temperature losses, and DC wiring Ohmic losses, inverter losses, batter losses, maximum power point tracking (MPPT) topology losses affects the output of the system. In this research each loss % has been taken from PVSyst software which varies across different location.

Specific yield

This is the yearly energy yield of a system divided by its nominal capacity. This shows the system's potential under a standard testing condition that takes into account the irradiance and meteorological conditions for a specific location. It is expressed in kWh/kWp.(Akpolat et al., 2019).

$$\text{Specific Yield} = \frac{\text{Annual Energy Yield}}{\text{Nominal Power of Array}} \quad (18)$$

Over time, all solar systems deteriorate. This panel degradation is denoted as δ, and its energy output for year "n" has been calculated using below equation 19(Daniel M. et al., 2016):

$$E_n = E_1 \times (1 - \delta)^n \quad (19)$$

Where E_n is the amount of power produced that year, and E_1 is the amount of power produced in the first year. Therefore, the total power produced over the system's lifetime (n years) is:

$$E_L = \sum_{j=1}^{n} \left[E_1 \times (1 - \delta)^j\right] \quad (20)$$

Capacity utilization factor (CUF)

The ratio of anticipated annual energy generated by a solar PV system to annual energy generation at rated capacity is known as CUF (Khandelwal & Shrivastava, 2018). This is a metric for how well a system functions under ideal circumstances at a certain location. It is expressed as a percentage.

$$\text{CUF} = \frac{E_{Out}}{E_{Full}} \times 100 \tag{21}$$

$$E_{Full} = \text{Installed Capacity} \times 365 \text{ days} \times 24 \text{ Hours} \tag{22}$$

Performance ratio

PR can be defined as the ratio of actual or predicted energy produced by the system to the system under normal operating conditions to the theoretical energy output generated by the system based on local climatic conditions of the place (Marion et al., 2005). It is represented as below.

$$\text{PR} = \frac{\text{Y}_\text{f}}{\text{Y}_\text{r}} \tag{23}$$

3.4.2 Economic Parameters

This section discusses the cost analysis for grid connected BIPV+EV charging systems. Economic analysis is a critical step in the development of a solar photovoltaic project, as it determines whether the project will be financially feasible in the long term. It is useful for users to conduct cost analysis to choose the optimal capacity for their needs. The economic feasibility of a project is determined by its LCOE (levelized cost of energy) and payback time. For this BIPV with EV Charging system, net present value (NPV) is the difference between the current value of cash inflows and cash outflows over time. The project is financially and economically feasible if the NPV is positive. This study includes the initial cost of the system, installation cost, battery replacement costs, annual maintenance cost, and benefits from Feed-in-Tariff to estimate economic indicators.

Payback Period

The payback period is the time it takes to recover the money invested in a project, typically evaluated in years. This is based on the yearly energy savings of the system. The sooner the project's original investment is repaid, the more profitable it becomes.

$$\text{Payback Period} = \frac{\text{Total System Cost}}{\text{Annual Benfits} + \text{Incentives}} \tag{24}$$

Levelized cost of energy (LCOE):

The main instrument for evaluating the plant-level unit costs of various baseload technologies throughout the course of their operational lives is the LCOE. The LCOE represents the financial costs of a general technology, not the expenses of a particular project in a particular market. The LCOE is conceptually closer to the costs of electricity production in regulated electricity markets with stable tariffs, for which it was developed, than to the variable prices in deregulated markets due to the equality between discounted average costs and the stable remuneration over lifetime electricity production, which is at its core. The LCOE idea may theoretically be used in the setting of deregulated markets by changing the discount rate for the hidden cost of price volatility(IEA, 2020b). According to IEA, LCOE equation (25)is represented below(IEA, 2020b):

$$\text{LCOE} = \frac{\sum(Capital_t + O\&M_{\ t} + Fuel_{\ t} + Carbon_{\ t} + D_t) * (1+r)^{-t}}{\sum MWh \times (1+r)^{-t}} \tag{25}$$

Costs for EV charging

An EV’s fuel efficiency is measured in kilowatt-hours (kWh) per 100 kilometres. The cost of energy (in RM per kWh) and the efficiency of the vehicle (how much power is utilized to drive 100 Km) must be known in order to compute the cost per mile of an EV.

$$C_{EV} = \frac{B_{EV} \times LCOE}{R} \tag{26}$$

3.4.3 Environmental Parameters

The substitution of energy from conventional power plants with solar energy for clean electricity has a substantial positive impact on the environment. Additionally, using solar energy to charge EVs contributes to net-zero mobility. Because the BIPV plant employs solar energy to meet the demand for EV charging, emission factors are utilized to calculate the reductions in carbon dioxide emissions that result from not utilizing grid electricity. The average rate of a specific GHG emission for a particular source, expressed in units of activity, is known as an emission factor (UNFCCC, 2017).

GHG Savings

Total annual GHG savings for the proposed system comprises of GHG savings due to BIPV system and use of EV. The equivalent saved CO_2 emissions for PV System has been calculated using below formula.

$$GHG_{PV} = E_L \times F_{grid} \tag{27}$$

$$GHG_{EV} = D_{lifetime} \times EF_{\ Fuel} \tag{28}$$

$$GHG_{Total} = GHG_{PV} + GHG_{EV} \tag{29}$$

CHAPTER 4

RESULT AND DISCUSSION

The design methodology, parameters and the technical specifications for the solar BIPV + EV charging infrastructure in the typical Malaysian, Australian and Swedish house has been discussed in this section.

4.1 Malaysian Case Study

To address user demands in terms of energy, economics, and environmental concerns, various scenarios have been offered in the Malaysian context as shown in table 4.1. From Figure 3.2, it is evident that the minimum daily peak sunshine hours occur in December, amounting to 6.9 hours. Consequently, the battery storage system must supply energy for the remaining 17 hours of non-sunlight, which includes both mid-peak and off-peak hours.

Table 4.1 Proposed cases in Malaysian case study

Case	Case A	Case B	Case C
Description	Grid Connected BIPV with No battery storage	Grid Connected BIPV with battery storage of 75% of total load	Grid Connected BIPV with battery storage of 100% of total load
Conceptual Image			
System Limitations and benefits	Total dependence on grid during night, in case of outage, there will be no electricity.	Can take the load during night peak hours and low peak hours until morning. Also, can provide back up during grid outage. This system cannot provide autonomy.	Case C system provide 1 full day of autonomy when there is no sun. Also, can provide back up during grid outage

4.1.1 Building Load profile

Based on some available literature energy consumption in typical Malaysian house, it varies from smaller single house to double storey terrace house. It has been found that on average typical Malaysian house consumes 14.5kWh electricity on daily basic(Hisham et al., 2019).

The provided figure 4.1 depicts the energy usage pattern for a Malaysian household, represented in a pie chart divided into three distinct categories: Peak, Mid Peak, and Off-Peak hours.

Peak Hours (Red): These are the periods with the highest energy consumption, shown in red. Peak hours occur twice daily, from 11:00 to 12:00 and from 14:00 to 17:00. During these times, the household consumes the most electricity, likely due to increased activity and usage of energy-intensive appliances.

Mid Peak Hours (Yellow): Mid Peak hours are shown in yellow, representing moderate energy usage. These hours span from 08:00 to 11:00, from 12:00 to 14:00, and from 17:00 to 22:00. Energy consumption during these times is higher than off-peak but lower than peak hours, indicating a moderate level of household activity.

Off Peak Hours (Green): The periods with the lowest energy consumption are depicted in green. Off Peak hours cover the longest duration, from 22:00 to 08:00. This is when the household's energy usage is minimal, likely due to reduced activity during nighttime and early morning hours.

The figure highlights the significant variations in energy demand throughout the day. Understanding these patterns is crucial for optimizing energy storage solutions, such as PV System size, battery energy storage systems, to ensure that sufficient energy is available during high-demand periods and to take advantage of lower energy prices during off-peak hours. This can lead to more efficient energy management and cost savings for the household.

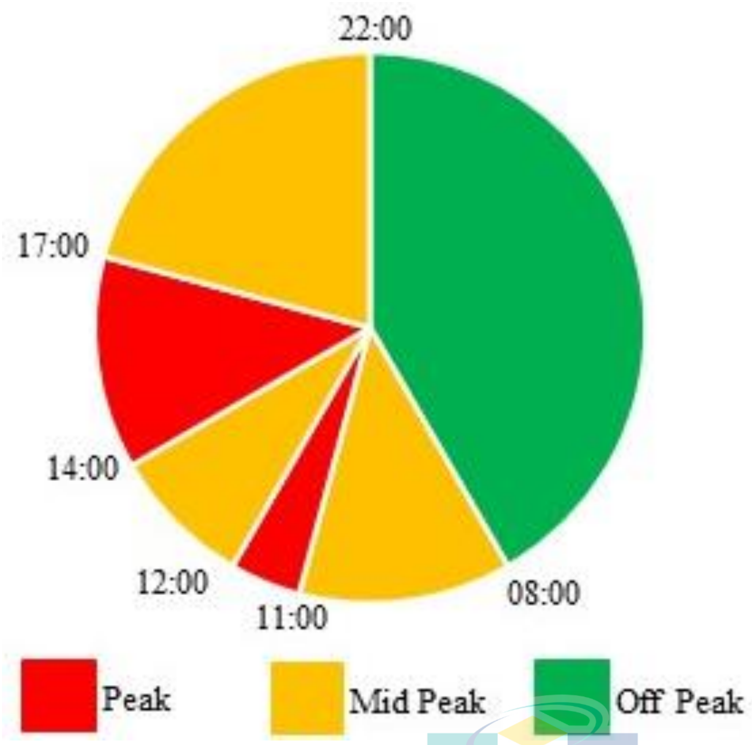


Figure 4.1 Consumer usage pattern or Time of use(TNB, n.d.)

A few of the factors that were taken into consideration in this study when building and modelling the BIPV powered EV charging system are listed in table 4.2. These factors include daily residential load, EV charging load, and EV battery parameters.

Daily EV Charging demand:

As the BIPV system size include total energy demand which includes residential energy demand/day and EV charging demand, therefore, EV charging daily demand for Malaysian case, has been estimated using equation 10 and listed in table 4.2.

$$E_{EV} = \frac{B_{EV}}{R} \times D_{day} = \frac{40 \times 38}{311} = 4.8\text{kWh/day}$$

Table 4.2 List of inputs and assumption in Malaysia

Parameters			References
Building	House	Single house	-
	Area	117m^2	(Foo, 2019)
	Roof type	Open Gable, 10°	(Roslan et al., 2016)
	Roof direction	Southeast and Northwest	-
	Building daily demand, E_R	14.5kWh	(Hisham et al., 2019)
EV Charging	Car	Nissan Leaf	-
	Daily Commute distance, D	38km	(Numbeo.com, 2021)
	Daily EV charging demand, E_{EV}	4.8 kWh	-
	Battery Size, B_{EV}	40kWh	(Nissan, 2023)
	Range, R	311km	

4.1.2 BIPV system design

Total demand includes sum of residential energy demand and energy demand for EV charging using equation:

$$E_{Total} = E_H + E_{EV} = 14.5 + 4.8$$

$$E_{Daily} = 19.3\text{kWh/day}$$

Based on above daily load, it can be estimated that annually system must produce 7044.5kWh. But due to degradation in performance of solar panel, annual energy generation reduces over time which can be estimated by using equation 19 and 20. Therefore, system must be oversized to meet the demand 100% at the end of life cycle, in this study 21 years will be considered as per SEDA policy regarding FiT(SEDA, 2019). Using PVSyst presizing, it is estimated that 4.8kWp system can meet energy requirement of 7044kWh annually.

Module selection

Monocrystalline solar panels of 400Wp have been chosen for study. When compared to polycrystalline and thin-film technologies, monocrystalline panels are costlier because of their complex production process and better performance. Recent advances in research have produced thin-film cell prototypes with an efficiency rating of 23.4%. On the other hand, the efficiency range of commercially available thin-film panels is usually between 10% and 13%. Due to their greater efficiency rating, monocrystalline solar panels use fewer panels to produce the same amount of power, making them an excellent option for residences with constrained roof space(Lane, 2023). Monocrystalline PV panels are already matured technology which has high efficiency, nearly average around 15%~20% (American Solar Energy Society, 2021).

Table 4.3 Specification of solar panel in Malaysian case

Panel Specification at STC (1000W/m², 25°C/77°F, AM 1.5)	
Brand	**Jinko Solar**
Country of Origin	China
Models	JKM400M-72-V
Cell type	Monocrystalline panel
Dimensions (mm)	1956x1002x40
Nominal power P_{MPP} [W]	400
Open circuit voltage V_{OC} [V]	49.8
Short circuit current I_{SC}[A]	10.36
Voltage at Pmax V_{MPP} [V]	41.7
Current at Pmax I_{MPP} [A]	9.60
Module efficiency [%]	20.17%
Degradation factor	0.5%

Total number of modules required for the system:

$$N_{Module} = \frac{System\ Size,Wp}{Panel\ Rating,Wp} = \frac{4800}{400} = 12$$

Ideally total 12 Numbers of modules are required to meet the annual energy demand of 7044kWh.

Optimized BIPV system size

Energy generated for the first year is 7044kWh which is taken from PVSyst, but due to panel degradation, annual generated energy will reduce by 0.5% then at the end of 21 years' energy generated by the system can be estimated as below using equation 19:

$$E_{21} = E_1 \times (1 - 0.005)^{21} = 6{,}372\text{kWh}$$

At the end of 21st year, total energy generation will be dropped by 9.5% (rounded off to 10%) as compared to first year. Therefore, PV array must be oversized by 11% to meet the load requirements at the end of 21 years. Therefore, optimized system size will be calculated using equation 30 as below:

$$\text{Optimized System Size } = 4.8\text{kWh } \times 1.11 = 5.28\text{kWh}$$

Optimized number of modules

Using equation 8, optimized number of modules can be re-calculated for oversized system which is rounded off to 14 modules.

$$N_{Optimized} = \frac{System\ Size, Wp}{Panel\ Rating, Wp} = \frac{5280}{400} = 13.2 \sim 14$$

As shown in the calculation, 13.2 number of 400Wp panels were required which has been rounded off to 14. Therefore, the system size becomes 5.6kWp with 14 panels, each having 400Wp.

BIPV Layout

Below figure 4.2 shows module layout for 5.6kWp BIPV system for case A, Case B and Case C.

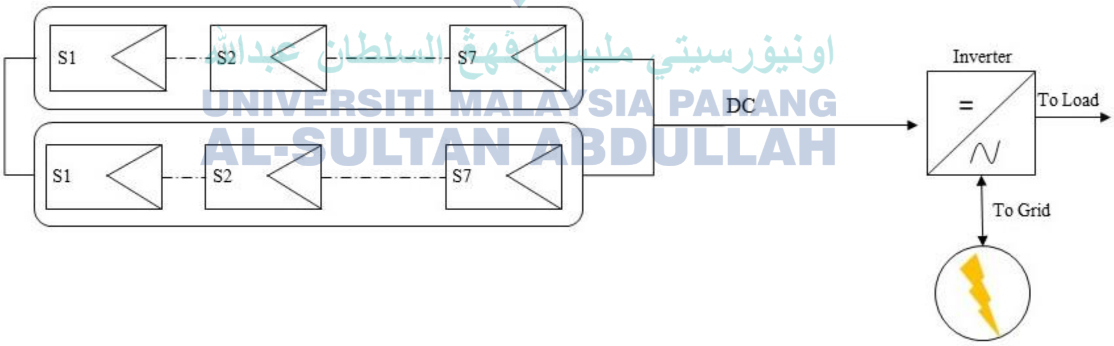


Figure 4.2 Layout of the BIPV system for Case A

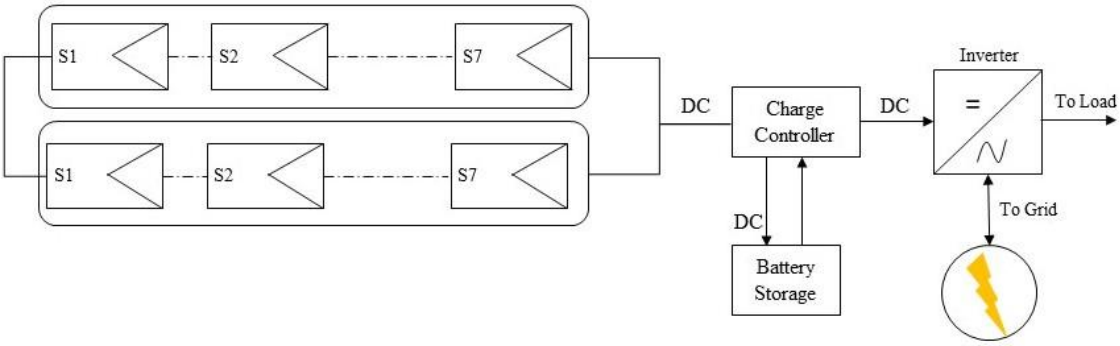


Figure 4.3 Layout of the BIPV system for Case B and Case C

Battery energy storage sizing

Battery Sizing for Case B

Battery sizing in this case is only required to meet the electricity demand for non-sun hours. From Figure 3.2, it can be found that minimum daily peak sunshine hours were observed in the month of December which is 6.9 hours. Battery storage system must be able to provide energy for rest of the non-sun hours which is nearly 17 hours in this case (including mid peak and off-peak hours). Therefore, battery storage system can be designed to meet 75% of the total load (14.45kWh) for non-sun hours. Using the formula 16, preliminary battery sizing calculation has been done using below formula.

$$B_{Ah} = \frac{14{,}450 \ \times 1}{0.95 \ \times 0.8 \times 12}$$

Based on above calculation, a battery pack of 1584Ah is required

Table 4.4 Specifications of the battery [Source- PVSyst 7.2 database].

Parameters	Case B, C
Technology	Lead Acid Sealed
Nominal Voltage	12V
Capacity	200Ah
DoD	80% DOD
Efficiency	95%

Number of batteries required for storage system in Case B:

$$N_{BB} = \frac{B_{Capacity}(Ah)}{Nominal\ Battery\ capacity(Ah)} = \frac{1584}{200} = 7.92{\sim}8$$

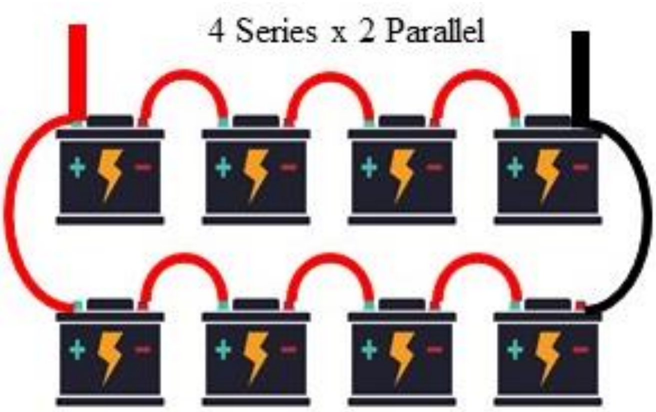


Figure 4.4 Battery layout for Case B

Battery Sizing for Case C

Similar process followed to estimate the number of batteries required to meet 100% of load which is 19.3kWh.

$$B_{Ah} = \frac{19300 \times 1}{0.95 \times 0.8 \times 12} = 2116Ah$$

Number of batteries required for storage system in Case C:

$$N_{BC} = \frac{B_{Capacity}(Ah)}{Nominal\ Battery\ capacity(Ah)} = \frac{2116}{200} = 10.58{\sim}12$$

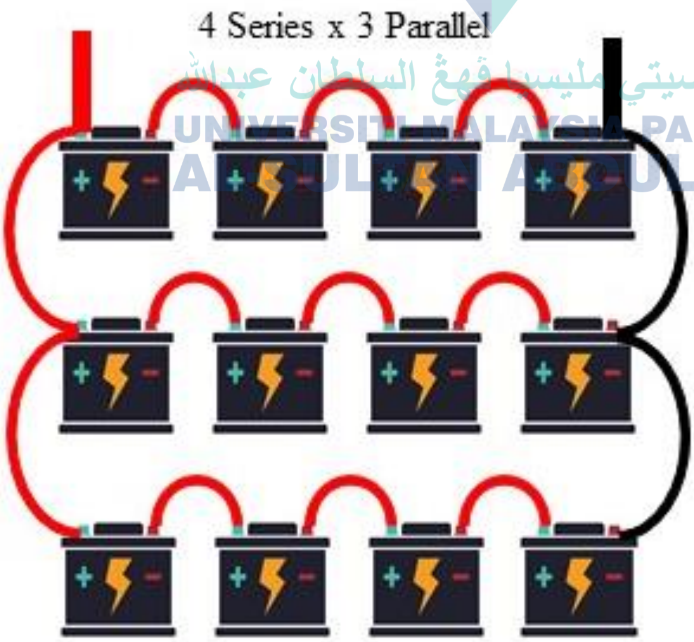


Figure 4.5 Battery layout for Case C

Inverter Selection

A 7kW inverter has been chosen from the PVSyst database with below specification shown in Table 4.5.

Table 4.5 Inverter specifications for Solax 1 Phase X1 Smart inverter

Input		Output	
Recommended max.	10,500 Wp	Rated output power	7,000 W
Max. DC Voltage	550V	Max. apparent power	7,700 VA
Nominal Voltage	360V	Rated output voltage	220/230/240V, 160-
Start-up voltage	100V	Rated AC grid	50 Hz /60 Hz
MPPT voltage range	100 V ~ 530V	Max. output current	33.5A
Number of MPPT	2	Adjustable power	0.8 leading ...0.8
Max. input current	14A	AC Grid connection	Single Phase
Max. Isc per MPP	28A	Max. total harmonic	≤ 3%
		Max. efficiency	97.40%
		MPPT Efficiency	96.8%

4.1.3 Results – Malaysian case study

4.1.3.1 Energy Analysis

The energy production of the system is simulated using PVSyst. System losses and estimated available energy generation of 5.6kWp BIPV+EV charging system in all three cases has been shown table 4.6 below.

Table 4.6 System losses for BIPV System in Case A, B and C in Malaysia

Parameters	Case A	Case B	Case C
Global horizontal irradiation	1813kWh/m^2	1813kWh/m^2	1813kWh/m^2
Global incident in coll. Plane	-0.61%	-0.61%	-0.61%
Far Shading/Horizon	-0.37%	-0.37%	-0.37%
Near Shading Irradiation loss	0.00%	0.00%	0.00%
IAM Factor global	-2.06%	-2.06%	-2.06%
Effective irradiation on collectors	1758kWh/m^2× 28m^2	1758kWh/m^2× 28m^2	1758kWh/m^2× 28m^2
Efficiency at STC	20.24%	20.24%	20.24%
Array nominal energy (at STC) MWh	9.88	9.88	9.88
PV loss due to irradiance level	-0.65%	-0.65%	-0.65%
PV loss due to temperature	-13.00%	-13.00%	-13.00%
Module Quality Loss	0.75%	0.75%	0.75%
Mismatch loss, modules and strings	-2.10%	-2.10%	-2.10%
Ohmic wiring losses	-1.12%	-1.12%	-1.12%
Mixed orientation mismatch loss	0.00%	0.00%	0.00%
Array virtual energy at MPP (MWh)	8.33	8.33	8.33
Inverter loss during operation	-3.33%	-3.33%	-3.33%
Inverter loss due to voltage threshold	-0.04%	-0.04%	-0.04%
Available energy at inverter output (MWh)	8.05	8.05	8.05
Energy Stored into Battery	0	57.3%	62.9%
Battery IN, charger loss	0	-2.33%	-2.57%
Battery global loss	0	-5.65%	-5.13%
Battery OUT, inverter loss	0	-2.85%	-3.32%
Available Energy (MWh)	**8.05**	**7.21**	**7.19**

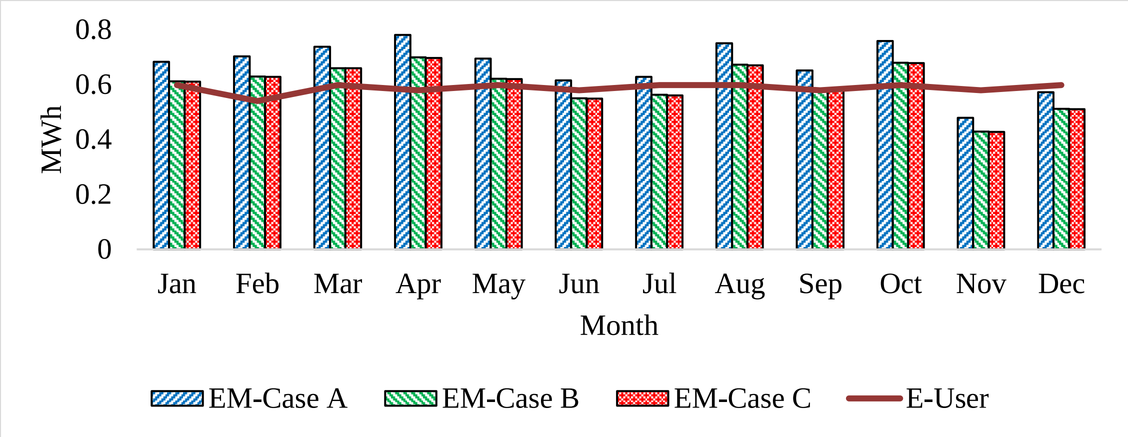


Figure 4.6 Monthly average energy generation after losses in MWh in comparison to user needs

Monthly energy generation has been plotted in Figure 4.6 against user demand in all case A, B and C. Annual energy generated by BIPV system in Case A is 8.05MWh, Case B is 7.21MWh and for Case C is 7.19MWh for the first year and annual usage is 7.043MWh. Considering the degradation of BIPV Panel, the energy generation output will reduce overtime has been estimated using equation 19.

Case A: $E_{21\text{-}A} = 8.05 \text{ X } (1\text{-}0.005)^{20} = 7.28\text{MWh}$

Case B: $E_{21\text{-}B} = 7.21 \text{ X } (1\text{-}0.005)^{20} = 6.52\text{MWh}$

Case C: $E_{21\text{-}C} = 7.19 \text{ X } (1\text{-}0.005)^{20} = 6.5\text{MWh}$

Where E_{21} is energy generation at the end of 21 years by the proposed BIPV system in respective case A, B and C, and has been represented in Figure 4.7.

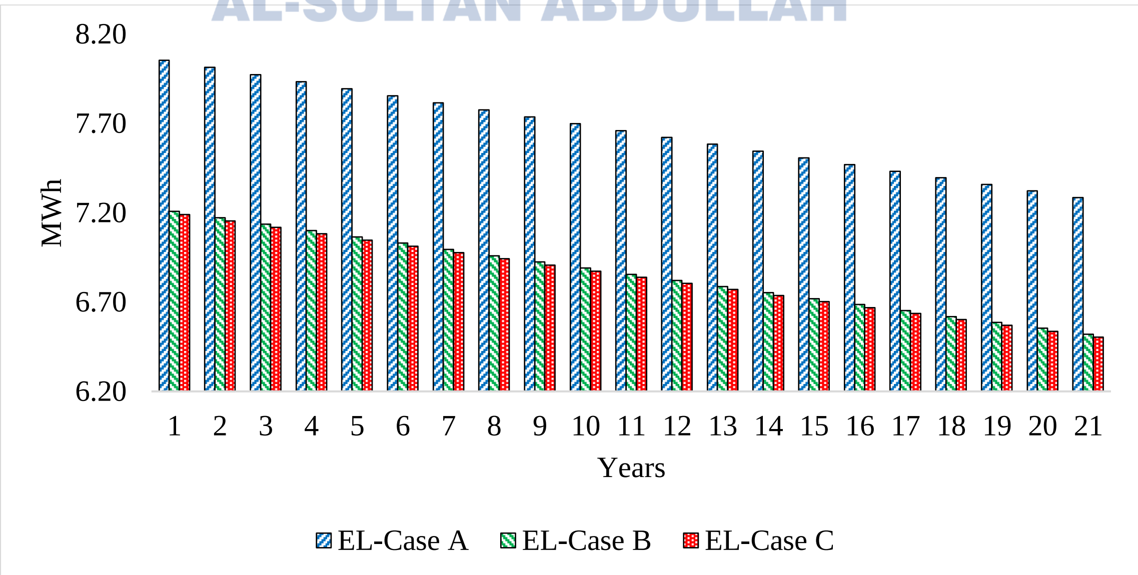


Figure 4.7 Annual energy generation and degradation over lifetime in Case A, B, and C.

Capacity Utilization Factor (CUF)

CUF of the system has been estimated using equation 21 and 22. The plant capacity of the system at full load is 49,056 kWp. So, the CUF for System in Case A is 16.1%, Case B is 14.7% and for Case C is 14.66%. From the result, it can be found that System in Case A has higher CUF than system in Case B and Case C represented in Figure 4.8.

Performance Ratio (PR)

PR of the three systems has been evaluated by PVSyst. This enables the system quality to be compared between various places, different technologies. PR have been plotted in Figure 4.8.

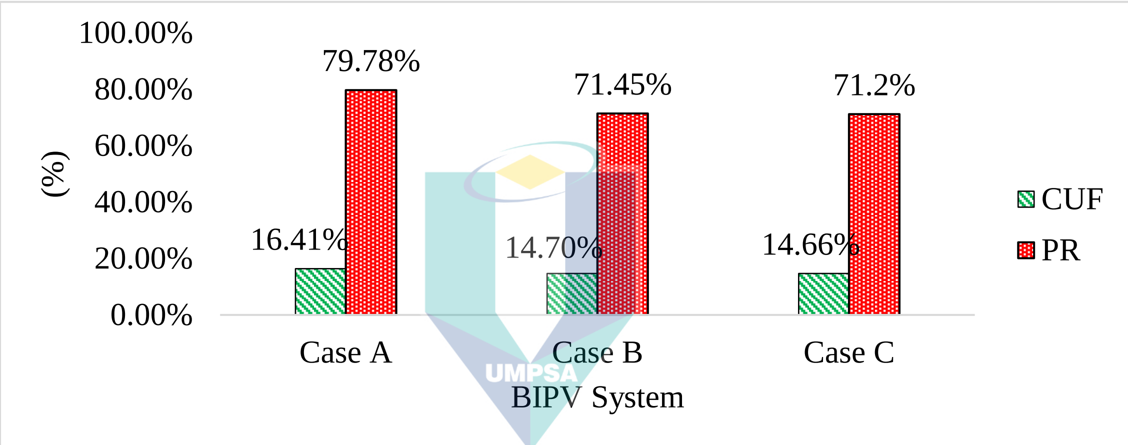


Figure 4.8 Comparison of CUF and PR for System in Case A, B, and C

Net energy supply to Grid

Figure 4.9 below shows the system's net energy exported to the grid during a 21-year period for cases A, B, and C, respectively. It is clear from below figure 4.9 that battery losses reduce the total amount of energy that is accessible annually. Cases B and C have negative net energy exported to the grid, meaning there will be no net benefit for the user.

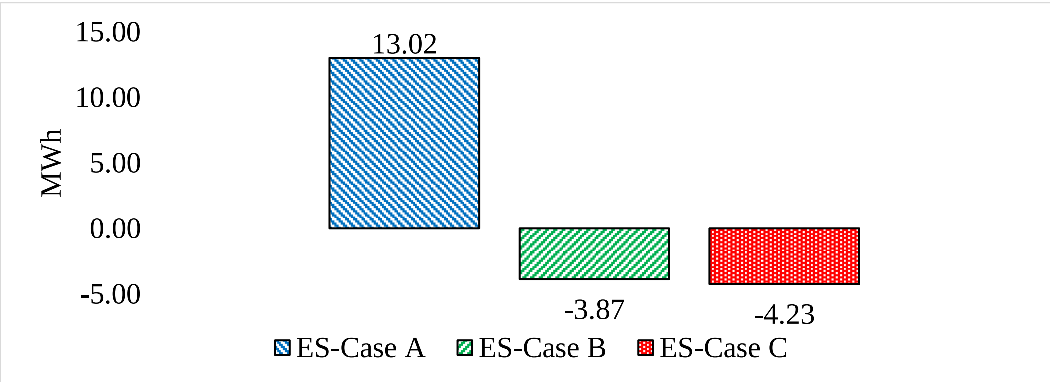


Figure 4.9 Comparison of energy supplied to grid over the lifetime of system.

Within the context of Malaysia, three BIPV systems were investigated in Kuantan, Pahang: Case A, a grid-connected system without battery storage; Case B, a grid-connected system with 75% battery storage; and Case C, a grid-connected system with 100% battery storage. Energy analysis revealed that Case A generated the highest annual energy output, followed by Case C and then Case B. This outcome stems from Case A's absence of battery losses, while Case B and Case C experience some battery-related energy losses. Considering energy production, Case A emerged as the most feasible option.

4.1.3.2 Economic Analysis

Profitability of the installed BIPV system can be indicated by economic analysis. It gives an idea about the recovery of the invested amount and profit gain in any system. The electricity tariff defined by TNB has different rates for the different range of energy consumption, monthly bill has been estimated as per below tariff shown in Table 4.8. An estimated initial cost and installation cost for the proposed BIPV System A, B and C is presented in Table 4.7. For the proposed system, economic analysis includes savings on electricity + savings on fuel.

Table 4.7 Initial Cost Breakdown for Case A, B and C

Items	Unit Price (RM)	Case A		Case B		Case C	
		Unit	Total (RM)	Unit	Total (RM)	Unit	Total (RM)
PV Module	400	14	5600	14	5600	14	5600
Charge Controller	400	0	0	1	5600	1	5600
Inverter	4,200	1	4200	1	4200	1	4200
Battery	2,600	0	0	8	20800	12	31200
Misc.	3,000	1	3000	1	3000	1	3000
Installation	2RM/Wh	-	11200	-	11200	-	11200
Type 2 EV charger	2000	1	2000	1	2000	1	2000
Total Cost			26000		52400		62800

Table 4.8 Malaysia Electricity Tariff (TNB, 2014)

Tariff A - Domestic Tariff	Unit	Tariff
First 200 kWh (1 - 200 kWh) /month	RM/kWh	0.218
Next 100 kWh (201 - 300 kWh) /month	RM/kWh	0.334
Next 300 kWh (301 - 600 kWh)/ month	RM/kWh	0.516
Next 300 kWh (601 - 900 kWh) /month	RM/kWh	0.546

Average monthly bill for the consumption 587.33kWh/month is estimated as RM 225.26 after applying the above tariff. Currently, SEDA approved Feed-in-tariff applications will be paid the FiT for 21 years for renewable energy generation(SEDA, 2019) which will be applied to payback period and net profit.

Cost Savings on Transportation

On an average, 38km daily commute distances is assumed for the proposed systems(Numbeo.com, 2021). A gasoline economical car on average consumes 5.0L/100km of fuel, therefore on average a commuter would spend RM 4.0/day on transportation. Annual savings is estimated to be RM 1460. Data used for the economic analysis has been mentioned in Table 4.9.

Table 4.9 Data used for economic analysis for BIPV+EV Charging system.

Parameters	Case A Grid connected with No battery	Case B Grid connected with 75% battery storage	Case C Grid connected with 100% battery storage
Initial Cost of System (RM), C_{system}	26,000	52,400	62,800
Average cost saving/year, (RM) C_{Res}	2703.12	2703.12	2703.12
Feed-In-Tariff (RM) (SEDA, 2019)	0.528	0.528	0.528
Maintenance Cost/year (RM) $C_{Maintenance}$ (Solar AI Technologies, 2022)	320	320	320
Battery replacement (RM) cost, $C_{Replacement}$	0	20,800	31,200
Cost Saving for (RM) Transportation/Year, $C_{Transport}$	1460	1460	1460

Net Cash Flow

Net cash flow is simply the cash inflows and outflows over the given period. It's an important parameter to estimate the payback period of a project and profit over time.

$$\text{Net Cash Flow} = \text{Total Cash Inflows} - \text{Total Cash outflows}$$

Cash inflows include Savings on electricity bill, transportation and revenue generated by selling energy to grid whereas outflow includes any maintenance cost, replacement cost, buying back energy from grid.

Total bill savings after system installation over lifetime of 21 years has been shown below.

$$C_{Bill} = (C_{Res} + C_{Transport}) \times 21 \text{ Years}$$

$$C_{Bill} = (2703.12 + 1460) \times 21 = \text{RM } 87{,}425.5$$

Since the net exported energy is positive only in Case A, it will be calculated as below:

$$C_{Grid-A} = E_{grid-Total(MWh)} \times \text{FiT (RM)}$$

$$C_{Grid-A} = 13.02\text{MWh} \times 0.528(\text{RM}) = \text{RM } 6872.5$$

Therefore, total savings for 21 years can be estimated as below. Replacement cost and energy import from grid cost is zero in case A. Whereas in Case B and Case C, net exported energy to grid is negative so regular tariff is applied and battery replacement cost has been considered in the estimation.

For Case A,

$$C_{Net-A} = C_{Bill} + C_{Grid-A} - (C_{Maintaince} \times 21) - C_{System} - C_{Replacement} - C_{import-A}$$

$$C_{Net-A} = 87425.5 + 6872.5 - 6720 - 26000 - 0 = \text{RM } 61{,}578$$

For Case B,

$$C_{Net-B} = C_{Bill} + C_{Grid-B} - (C_{Maintaince} \times 21) - C_{System} - C_{Replacement} - C_{import-B}$$

$$C_{Net-B} = 87425.5 + 0 - 6720 - 52{,}400 - 20{,}800 - 844 = \text{RM } 6661.0$$

For Case C,

$$C_{Net-C} = C_{Bill} + C_{Grid-C} - (C_{Maintaince} \times 21) - C_{System} - C_{Replacement} - C_{import-C}$$

$$C_{Net-C} = 87425.5 + 0 - 6720 - 62800 - 31200 - 922 = -\text{RM}14216$$

$$C_{Import} = E_{Import} \text{ kWh} \times \text{Tariff (RM)}$$

$$C_{Import-B} = 3870 \times 0.218 = \text{RM } 844$$

$$C_{Import-C} = 4230 \times 0.218 = \text{RM } 922$$

Payback period has been estimated for System in case A, B and C based on the above parameters represented in Figure 4.10 using equation 24. For Case A, payback period is 6 years, for case B is 19 years and for case C payback couldn't be estimated as it was not able to achieve in 21 years.

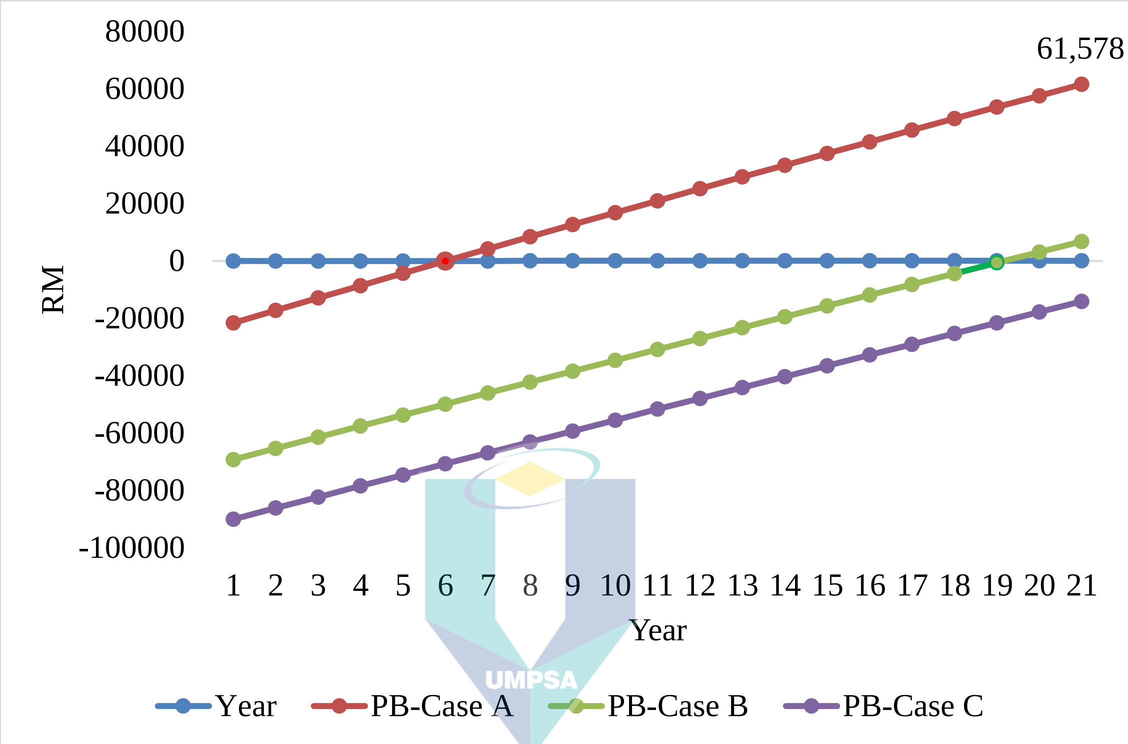


Figure 4.10 Cumulative cash flow and payback for System in Case A, B and C

LCOE of system and Cost of EV charging has been estimated using equation 25 and 26 for the systems in Case A, B and C. It has been represented in below Figure 4.11.

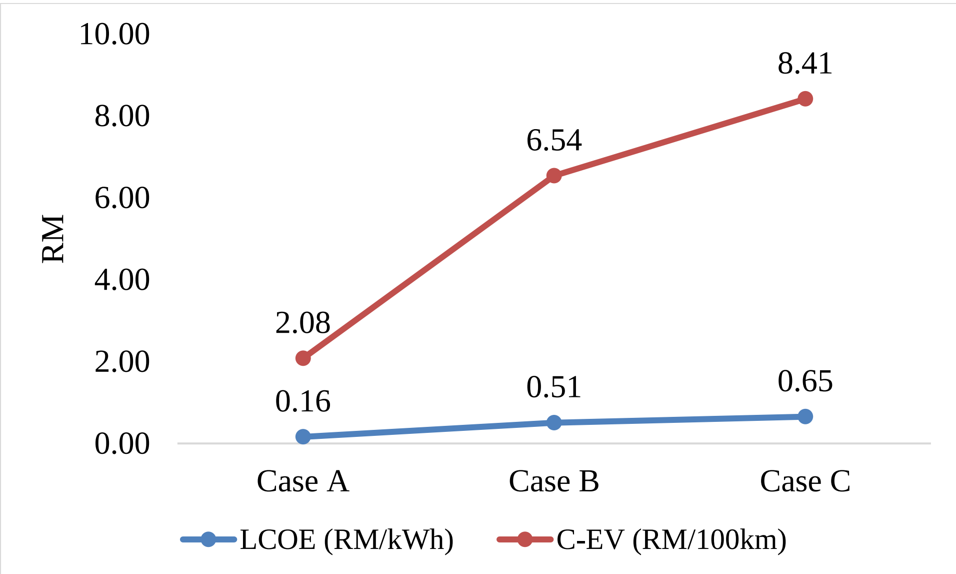


Figure 4.11 LCOE and Cost of EV charging of BIPV systems

In terms of economics, Case A had the lowest LCOE (levelized cost of energy) of 0.16RM/kWh and the shortest payback period of 6 years. Case B had an LCOE of 0.51RM/kWh and a payback period of 19 years. Case C was not economically viable, as it had a negative cash flow and a payback period of more than 21 years. The charging cost for an electric vehicle (EV) was also lowest for Case A, at 2.08RM/100km. Case B had a charging cost of 6.54RM/100km and Case C had a charging cost of 8.41RM/100km.

4.1.3.3 Environment Analysis

The ability to generate clean electricity using solar energy instead of conventional power plants is the environmental benefit that outweighs all others. Additionally, using solar energy to charge EVs contributes to net zero mobility. The carbon-dioxide reduction per kWh to the atmosphere is determined as per Equation 27,28,29 and shown in Figure 4.12.

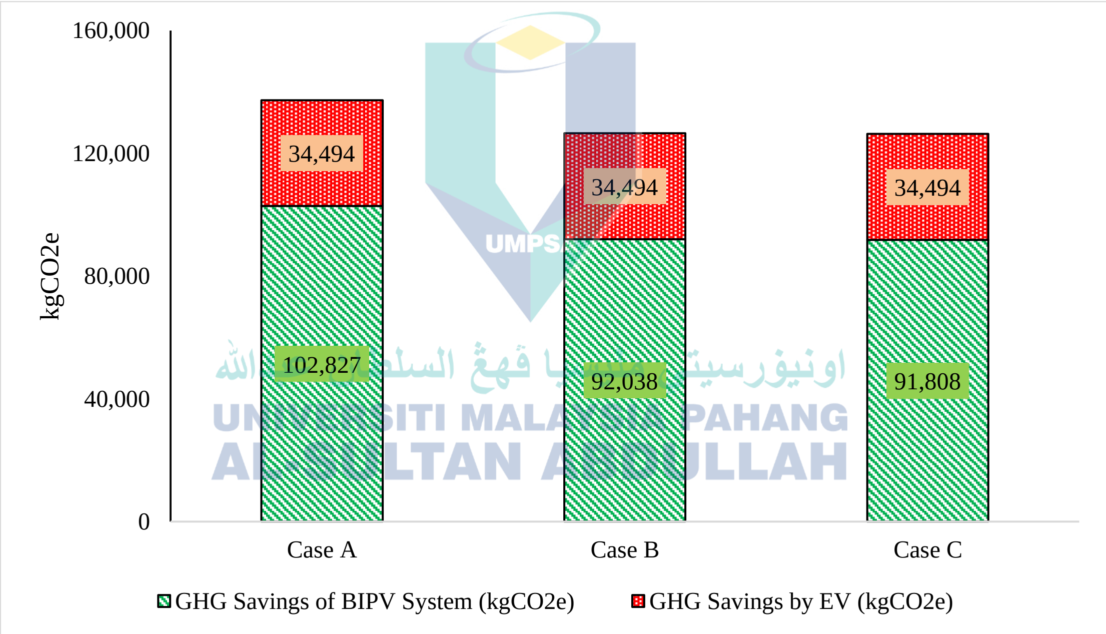


Figure 4.12 Total GHG savings for the BIPV powered EV Charging system

Case A had the greatest reduction in CO_2 emissions of nearly 137,321 $kgCO_2e$, followed by Case C and then Case B. This is because Case A generates the most energy, which reduces the need for fossil fuels. Overall, Case A is the most viable BIPV system from an energy, economic, and environmental standpoint. It has the lowest LCOE, the shortest payback period, the lowest charging cost, and the greatest reduction in CO_2 emissions.

4.2 Australian Case Study

Roof orientation and area has been shown in Figure 4.13. Each face has different area and slope which will be analysed in this scenario to find the best-case scenario. Site coordinates and parameters has been shown in Table 3.1 and Table 3.2

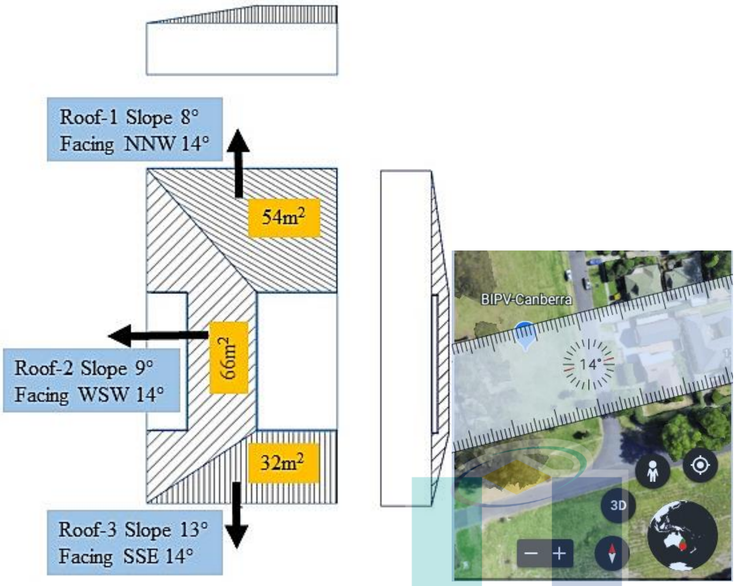


Figure 4.13 Orientation & Area of roof based on Canberra, Australia

4.2.1 Building Load profile

The Australian Capital Territory (ACT's) households consume the most during the winter months. The estimated daily average power consumption for a single storey house in Canberra, Australia is about 17.55kWh/day (Frontier Economics, 2020). Consumption of energy in Australian household varies across different season as shown in Table 4.10.

Table 4.10 Seasonal variation in average electricity consumption in Canberra, Australia (Frontier Economics, 2020)

Summer(kWh) Dec to Feb	Autumn(kWh) Mar to May	Winter(kWh) Jun to Aug	Spring (kWh) Sep to Nov	Annual (kWh)
1258	1550	2168	1431	6407

Hourly load profile

In general, for household, demand for electricity is higher in the evening compared to other hours of the day. A typical household can be categorized in two types: high peak demand household and low peak demand households.

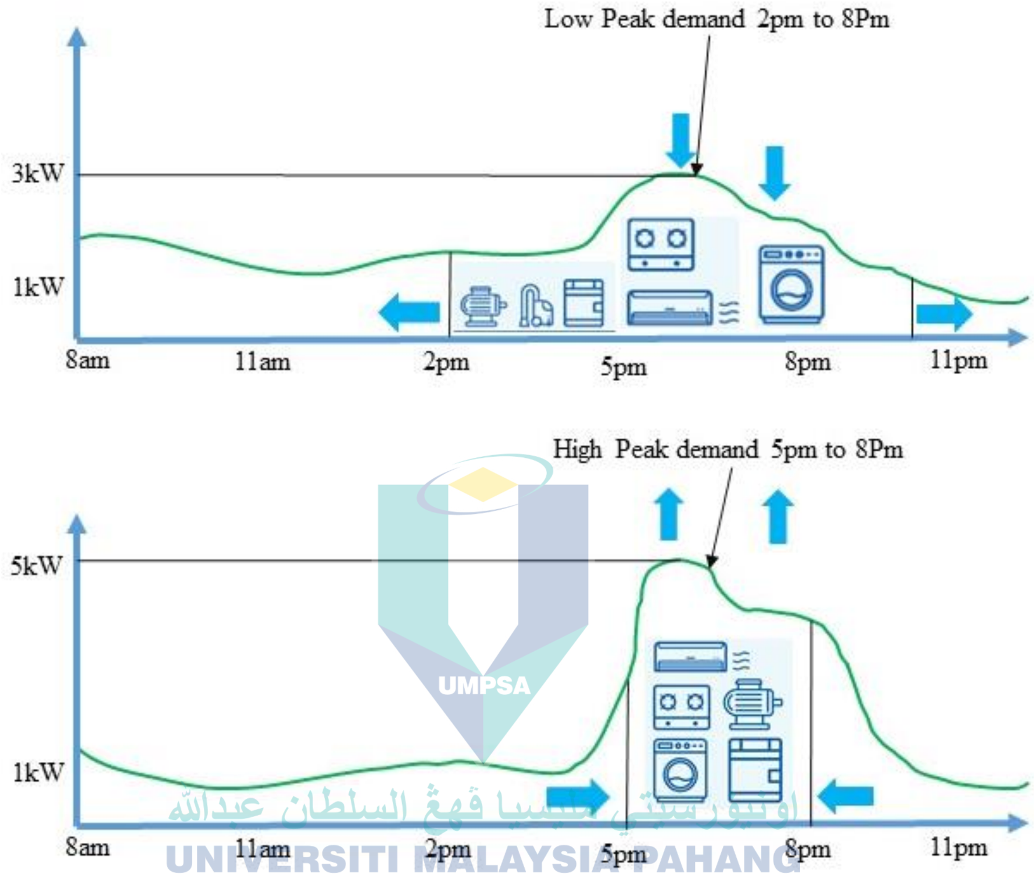


Figure 4.14 Low peak demand and high peak demand household illustration(ActeWagl, 2022b)

Figure 4.14 illustrates the typical usage patterns of household appliances. During the daily peak hour of 5-8pm AEST, high-peak households utilize a majority of their electrical appliances which is more likely to be weekday scenario(S. Lee et al., 2014). This peak-time usage is reflected in their electricity bills. The overall power consumption of a low-peak household is similar to that of a high-peak household, but appliance usage is spread out more throughout the day which can be observed in weekend consumption profile(S. Lee et al., 2014). As a result, their bills have a reduced demand charge. High-peak demand is typically observed during weekdays, while low peak demand is more common during holidays or weekends. High-peak demand profiles show a higher demand at 8am in the morning compared to low-peak demand profiles. At 5pm, both profiles show an increase in consumption, but high-peak demand can reach up to 5kW compared to low-peak demand, which reaches up to 3kW. The disparities are expected given that individuals often get up later on the weekends and spend more time at home between 10:00 and 18:00, whereas on weekdays they tend to spend more time at work or engaging in outdoor activities during the same time period(S. Lee et al., 2014).

Daily EV charging energy requirement:

As this research includes EV charging daily demand, which can be estimated using equation 26. This EV charging consumption will be added to the residential energy demand to estimate total daily energy demand for BIPV system sizing and included in Table 4.11.

$$\mathrm{E_{EV}} = \frac{B_{EV}}{R} \times D_{day} = \frac{40 \times 32}{312} = 4.1\mathrm{kWh/day}$$

4.2.2 BIPV system detailed design

Seasonal consumption has been listed in Table 4.10, which has been used for estimating monthly and average daily consumption profile shown in Table 4.11 below. Estimated EV charging daily demand also has been included in estimation of total energy requirement per day.

Table 4.11 Energy requirements for residential and EV charging in Australia

Month	Monthly Consumption (kWh)	Average Daily Consumption for residential (kWh/day)	EV Charging Energy Demand (kWh/Day)	Total Daily Demand (Residential + EV Charging) (kWh/day)
Jan	433.3	13.98	4.1	18.08
Feb	391.4	13.98	4.1	18.08
Mar	522.3	16.85	4.1	20.95
Apr	505.4	16.85	4.1	20.95
May	522.3	16.85	4.1	20.95
Jun	707	23.57	4.1	27.66
Jul	730.5	23.57	4.1	27.66
Aug	730.5	23.57	4.1	27.66
Sep	471.8	15.73	4.1	19.83
Oct	487.5	15.73	4.1	19.83
Nov	471.8	15.73	4.1	19.83
Dec	433.3	13.98	4.1	18.08
Average daily consumption (kWh/day)		17.5		21.63

Data in Table 4.11 suggests that the daily residential energy consumption is varying for different season, therefore different scenarios have to be analyzed in order to size the system optimally, considering EV charging requirements remains constant. Table 4.12 represents different case scenarios for BIPV system and finding the optimally sized system.

Table 4.12 Load Pattern analysis for system size optimization referring to Table 4.11

Assumption	Scenario 1	Scenario 2	Scenario 3
Housing Load	Average of daily consumption for the year	Maximum daily consumption which is peak in winters	Consumption in Summer (Dec to Jan), Autumn (mar to may) and Spring (Sep to Nov) are considerably less then winter month. Maximum consumption chosen, excluding winter.
Daily Consumption (kWh)	17.5	23.57	16.85
EV charging requirement (kWh)	4.1	4.1	4.1
Total load (kWh)	21.63	27.67	20.95
Effect on overall system sizing for different season	System will be: 3% oversized in Autumn 9% oversized in Spring 19% oversized in summer 22% undersized in Winter	System will be: 32% oversized in Autumn 40% oversized in Spring 53% oversized in summer Exactly matching energy requirements in winter	System will be: Exactly matching energy requirements in Autumn 6% oversized in Spring 16% oversized in summer 24% undersized in Winter
Feasibility of system	System can be feasible in terms of sizing, cost, energy utilization is better than scenario 2	Not feasible, system will be costly, payback period will be higher, has more unused energy	System will be feasible in terms of sizing, cost and energy utilization is better as compared to other two scenarios
Sizing selection	Not Selected	Not selected	**Best case scenario**

Based on above criteria shown in Table 4.12, Scenario 3 has been considered for further study on BIPV+EV charging system sizing and system optimization. Total energy required for PV Sizing is shown below using equation 9.

$$E_{Total} = E_H + E_{EV} = 16.85 + 4.1$$
$$E_{Total} = 20.95kWh/day$$

BIPV with EV Charging system must be designed to meet the daily load of 20.95kWh/day. Based on pre-sizing using PVSyst, a 5.0kWp system will be able to meet the daily requirements.

Module selection

355Wp BIPV monocrystalline panel manufactured by SunPower, California has been chosen for design and simulation due to its availability in Australian market. Monocrystalline technology is more efficient, easily available, and lesser cost compared to other thin film technologies available today. Panel specifications has been shown in Table 4.13.

Table 4.13 Specification of solar panel for Australian case

Panel Specification	
Brand	SunPower
Cell type	Monocrystalline
Dimensions	1690mm x 1046mm x 40mm
Electrical Specification	
Power performance at STC (STC: 1000W/m², 25°C/77°F, AM 1.5) *	
Model	SPR-MAX3-355-BLK
Nominal power P_{Nom} [W]	355
Open circuit voltage V_{OC} [V]	74.3
Short circuit current I_{SC} [A]	6.49
Voltage at Pmax V_{MPP} [V]	59.8
Current at Pmax I_{MPP} [A]	5.94
Module efficiency [%]	20.10%
Panel degradation factor	0.25%

Inverter Selection

Using the safety factor of inverter sizing, a 6.25kW inverter would be suitable for the suggested BIPV system and has been chosen from PVSyst database as shown in table 4.14.

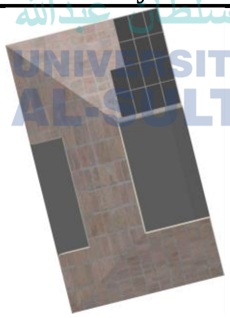
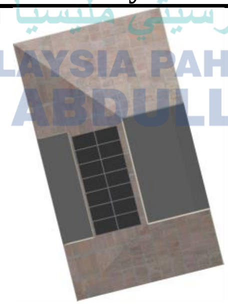
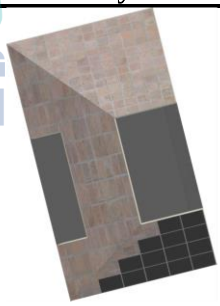
Table 4.14 Inverter specifications for Huawei SUN2000-6KTL-L1

Input		**Output**	
Max. DC Voltage	600V	Rated output power	6000W
Nominal Voltage	360V	Max. apparent power	6000VA
Start-up voltage	100V	Rated output voltage	220/230/240 V
MPPT voltage range	90 V ~ 560V	Rated AC grid	50 Hz /60 Hz
Number of MPPT Tracker	2	Max. output current	27.3A
PV strings per MPPT	1	Adjustable power	0.8 leading ...0.8
Max. input current per MPPT	12.5A/12.5A	AC Grid connection type	Single Phase
Max. Isc per MPP tracker	18A/18A	Max. total harmonic distortion	≤ 3%
		Max. efficiency	98.50%

BIPV System Layout

Three layouts will be studied based on roof faces as shown in Table 4.15 to find the layout with maximum output and will be evaluated in terms of energy, economics and environment. Usable area shown in Table 4.15 is excluding the corners where panels cannot be fitted.

Table 4.15 BIPV installation layout options

BIPV+EV Charging System – Panel Layout			
Layout	**Layout 1**	**Layout 2**	**Layout 3**
Roof Layout			
Mounting	All panels mounted on Roof 1 facing NNW	All panels mounted on Roof 2 facing WSW	All panels mounted roof 3 facing (SSE)
Usable Area	43.2m^2	42.8m^2	25m^2
Module Area	25m^2	25m^2	25m^2
No of Panels	7 Strings × 2 Series = 14	7 Strings × 2 Series = 14	7 Strings × 2 Series = 14

Assumptions for this research

All the inputs which have been considered in the system design has been represented in Table 4.16

Table 4.16 List of inputs and assumption for Australian case

Parameters			References
Building	House	Single house	(Australian Government, 2021)
	Floor area	197m^2	
	Available roof area	Refer Figure 4.12	
	House design	Acacia design- option 1	
	Roof direction	Refer Figure 4.12	-
	Daily energy demand	16.85kWh (Scenario 3- optimized)	Refer Table 4.12
EV charging	Car	Hyundai Kona Elec	-
	Daily commute distance	32km	(Australian Bureau of Statistics, 2016)
	Daily EV charging energy demand	4.1kWh	-
	Battery Size	39.2kWh	(Hyundai-Australia, n.d.)
	Range	312km	
	Charging Time	6hrs 10min	
	Charger Type	Type 2, AC, 6.6kW	

4.2.3 Results – Australian case study

The possibility of a solar PV project is evaluated by its technical, economic and environmental sustainability. The average yearly values of parameters such as energy yield, capacity utilization factor and performance ratio, payback period, LCOE, cumulative cash flow, cost of EV charging and GHG savings has been evaluated in this section.

4.2.3.1 Energy Analysis

The loss parameters values have been taken from PVSyst software for Australian scenario and represented in table 4.17.

Table 4.17 Energy assessment and Loss analysis of Layouts 1,2 and 3 using PVSyst

Parameters	System Layout 1	System Layout 2	System Layout 3
Global horizontal irradiation	1888 kWh/m^2	1888 kWh/m^2	1888 kWh/m^2
Global incident in coll. Plane	6.00%	-2.39%	-11.59%
Far Shading/Horizon	-0.19%	-0.18%	-0.07%
IAM Factor global	-2.73%	-3.32%	-4.57%
Effective irradiation on collectors	1942 kWh/m^2 × 25m^2	1942 kWh/m^2 × 25m^2	1942 kWh/m^2 × 25m^2
Efficiency at STC	20.13%	20.13%	20.13%
Array nominal energy at STC	9.67 MWh/Year	8.86 MWh	7.93 MWh
PV loss due to irradiance	-0.30%	-0.40%	-0.59%
PV loss due to temperature	-7.58%	-7.25%	-6.51%
Mismatch loss, modules, and strings	-2.10%	-2.10%	-2.10%
Ohmic wiring losses	-1.09%	-1.02%	-0.94%
Array virtual energy at MPP	8.74 MWh	8.03 MWh	7.23 MWh
Inverter loss during operation	-1.86%	-1.88%	-1.91%
Night Consumption	-0.16%	-0.17%	-0.19%
Available energy at inverter output	8.56 MWh	7.86 MWh	7.082MWh

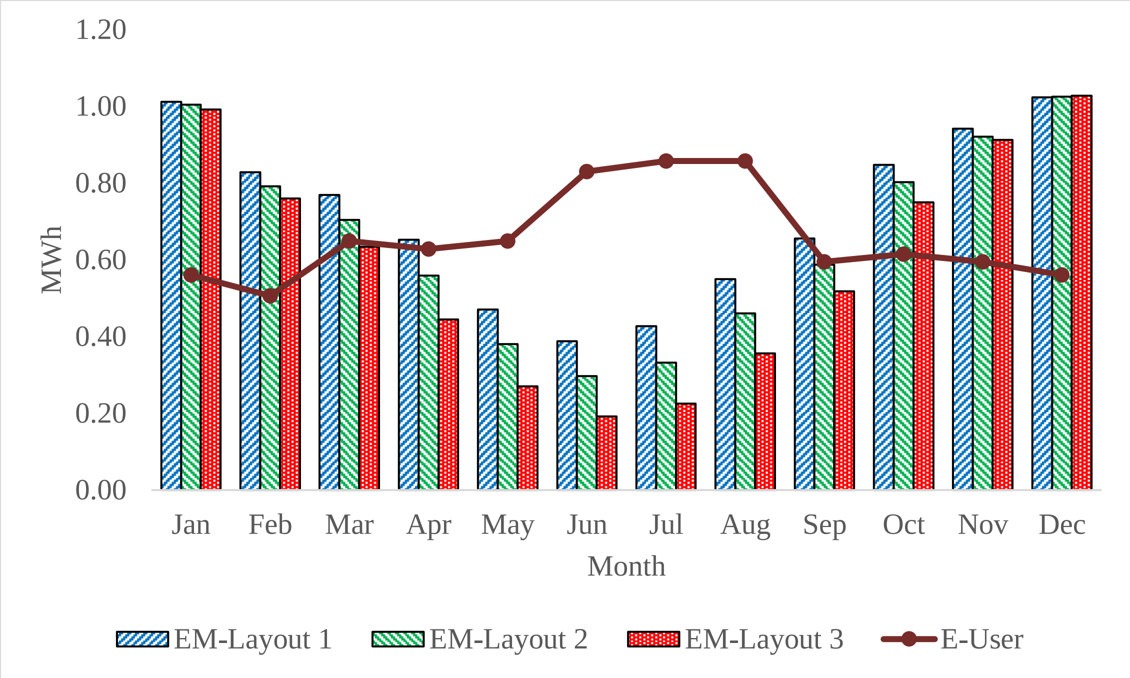


Figure 4.15 Monthly average energy generation for each layout 1,2,3 compared to energy demand by user in MWh.

From the Figure 4.15, it can be found that energy generation by BIPV+EV charging system layout 1 is higher than other two systems on daily basis, also due to higher energy generation it will reduce grid dependency and increase solar revenue. Annually energy generated by BIPV System in Layout 1 is 8.56MWh, Layout 2 is 7.86MWh and Layout 3 is 7.082MWh for the first year and annual user consumption is 7.9036MWh. During the daytime the energy requirements is fulfilled by solar energy and excess will be exported to the grid. But at night the energy requirement will be met by buying electricity back from the Grid.

Considering the degradation of BIPV Panel, the energy generation output will reduce overtime which will affect the exported energy to grid. Panel degradation factor for SPR-MAX3-355-BLK Panel is 0.25% annually which has been applied to estimate the annual energy generation using equation 19 and energy supplied to grid for 20 years presented in Figure 4.16.

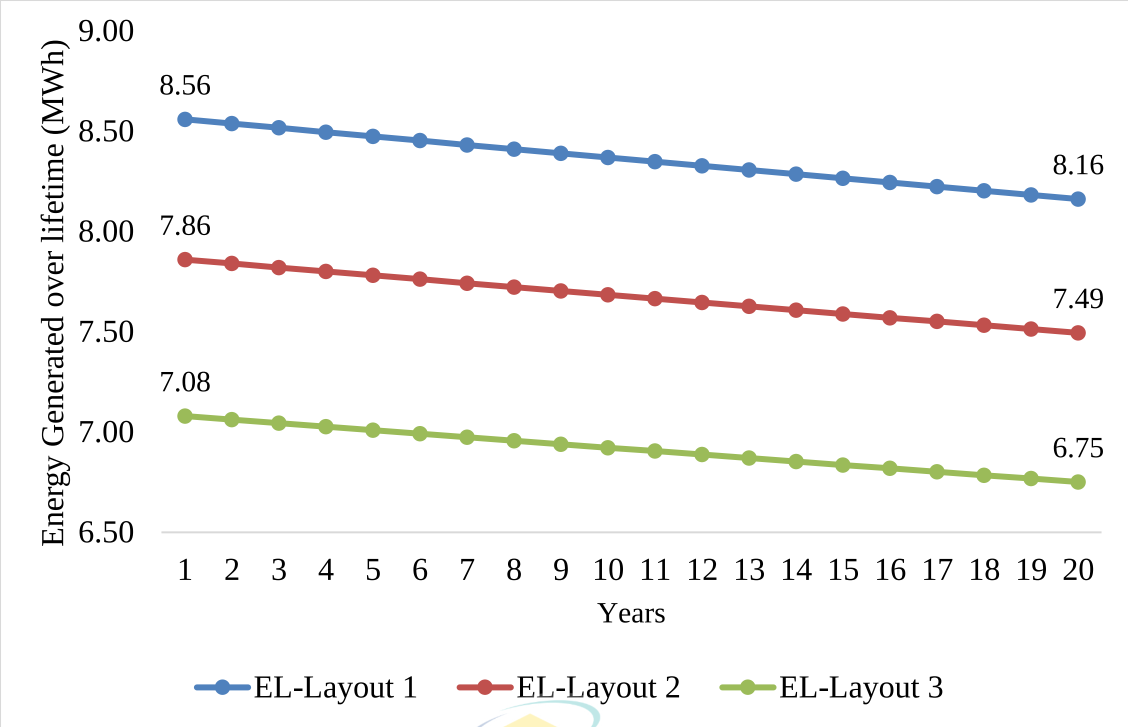


Figure 4.16 Annual energy generation over the lifetime of the system

Using equation 19 and 20 total energy supplied to the system has been estimated. Energy analysis of the 3 layouts presented in Figure 4.17 reveals that only Layout 1, oriented towards NNW, exhibits a net positive energy balance of 9.12MWh, supplying excess energy to the grid throughout the BIPV plant's lifetime. Over the lifetime, layout 2 BIPV system requires 4.55MWh and layout 3 BIPV system requires 19.79MWh. In contrast, Layouts 2 and 3 inevitably require grid dependency as they import energy from the grid.

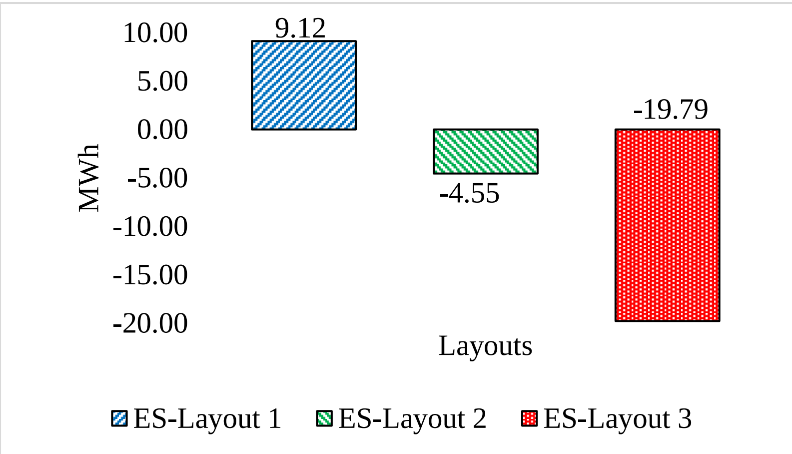


Figure 4.17 Energy supplied to grid in case of layouts 1,2 and 3

From the result, it can be found that BIPV system with layout 1 has better performance in terms of energy generation, higher capacity CUF and PR than the other two systems layout. Therefore, BIPV in system Layout 1 energy results has been taken forward to study economic feasibility and environmental impact. Table 4.18 represent energy utilization for BIPV system in layout 1.

Table 4.18 Daily energy generation, user energy demand, energy from solar, energy supplied to grid and energy buyback from grid

Month	Energy generation layout 1(kWh)	Energy required by user (kWh)	Energy from solar (kWh)	Energy to grid (kWh)	Energy from grid (kWh)
Jan	32.65	18.08	14.19	18.46	3.88
Feb	29.57	18.08	13.54	16.03	4.54
Mar	24.81	20.95	13.97	10.84	6.98
Apr	21.75	20.95	13.33	8.42	7.61
May	15.17	20.95	11.35	3.82	9.59
Jun	12.93	27.67	11.87	1.07	15.80
Jul	13.78	27.66	12.23	1.55	15.44
Aug	17.73	27.66	14.29	3.44	13.37
Sep	21.85	19.83	12.63	9.22	7.19
Oct	27.34	19.83	14.03	13.31	5.79
Nov	31.39	19.83	14.53	16.85	5.29
Dec	33.03	18.08	14.06	18.96	4.01

CUF and PR of the BIPV system

Capacity factor is one of the important parameters to analyze the performance of a system. The plant capacity of the system is 43.54 MWh, calculated using equation 21 and 22. Also, performance ratio of the all the 3 layouts has been evaluated by PVSyst. It has been found that, all the system with different layout has slight variation in performance ratio. Figure 4.18 shows CUF and PR of the 3 layouts.

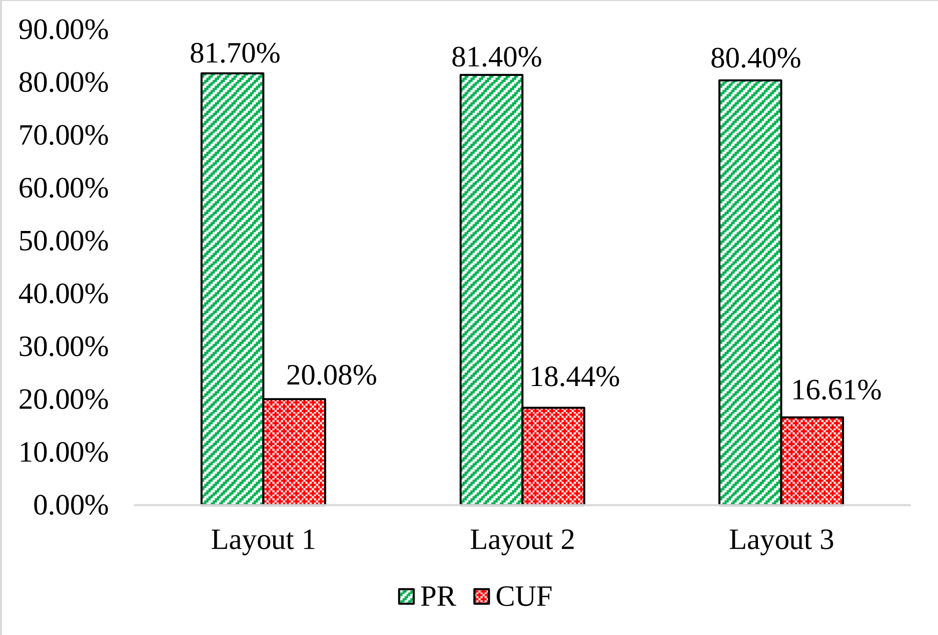


Figure 4.18 Capacity factor utilization and Performance Ratio for 3 Layouts

Energy analysis of BIPV systems with EV charging capabilities in Canberra, Australia, has yielded promising results. The simulation evaluated BIPV systems on three distinct roof orientations to determine the optimal configuration for meeting building energy demands. The BIPV system with EV charging in the NNW-facing Layout 1 produced an annual energy output of 8.56 MWh, outperforming the systems in the other two orientations (WSW and SSE) due to reduced irradiation losses. Capacity utilization factor and performance ratio, as depicted in Figure 4.18, further corroborate the superior performance of Layout 1. Consequently, based on the comprehensive energy analysis presented in Figures 4.16, 4.17, and 4.18, Layout 1 emerges as the most viable option for further economic analysis.

4.2.3.2 Economic Analysis

Economic analysis indicates the profitability of the installed BIPV with EV charging system. It gives an idea about the recovery of the initial investment and profitability of any system. The overall cost break-up of the is given in Table 4.19 for the proposed BIPV system. Savings on household electricity and Savings on transportation has been included in the estimation of all parameters.

Table 4.19 Cost Breakdown for BIPV+EV charging system

Component	Unit price (AUD)	Quantity	Total (AUD)
Module (including installation)	580	14	8120
Inverter	1,365	1	1365
Mounting structure- rails, clamps	400	-	400
EV charger wall box – Type 2	1549	1	1549
Total system cost			11,434

Payback Period

In ACT, retailer has different tariff categories for different packages e.g. Home with all day usage, homes with controlled load, Home time of use, Home Time-of-use with controlled load(ActeWagl, 2022a). In this study, all day single rate category, Solar Plus plan has been preferred for the economic estimation. Regardless of the time of day or year, for the use of electricity, the pricing remains the same. A single rate tariff is often less expensive than peak, but more expensive than off-peak and shoulder tariffs.

Table 4.20 ACT Electricity Tariff (Energy Made Easy, 2022)

Tariff ACT Residential	Unit	Tariff (AUD)
Supply Charge	AUD/day	1.03
All usage (Single Rate category)	AUD/kWh	0.2809
Solar buyback tariff or FiT	AUD/kWh	0.10

Feed-in tariff programs were once funded by state governments in Australia; however, they are now closed to new consumers. Depending on the location and size of your system, some retailers still offer feed-in tariff ranging between 6 to 12 cents/kWh in ACT(Solarchoice.net, 2023). The daily bill has been evaluated using below equation.

$$C_{daily} = (E_{Res} + E_{EV}) \times \frac{AUD}{kWh} + \text{Fixed Tariff} \quad (30)$$

Table 4.21 Net Monthly Bill without BIPV System, with BIPV system and net annual savings

Month	Daily Bill Without BIPV (AUD)	Monthly Electricity Bill Without BIPV (AUD)	Daily Savings after BIPV Installation (AUD)	Daily Revenue generated from FiT (AUD)	Energy Buy back from grid (AUD)	Monthly Bill with BIPV (AUD)
January	6.11	189.35	3.99	1.91	2.12	65.75
February	6.11	171.03	3.80	1.66	2.31	64.57
March	6.91	214.35	3.92	1.14	2.99	92.72
April	6.91	207.42	3.75	0.89	3.17	95.06
May	6.91	214.35	3.19	0.41	3.72	115.47
June	8.80	264.05	3.33	0.13	5.47	164.05
July	8.80	272.83	3.43	0.18	5.37	166.37
August	8.80	272.83	4.01	0.38	4.79	148.39
September	6.60	197.98	3.55	0.97	3.05	91.52
October	6.60	204.57	3.94	1.39	2.66	82.38
November	6.60	197.98	4.08	1.75	2.52	75.51
December	6.11	189.35	3.95	1.96	2.16	66.87
Total Annual Bill (AUD)		2596.07				1228.65
Net Annual Savings (AUD)		1367.42				

Cost Savings on fuel

On an average, 32km daily commute distances is assumed for the proposed systems(Australian Bureau of Statistics, 2016). A gasoline car on average consume 5.0litre/100km(Numbeo.com, n.d.) of fuel, considering that the average gasoline price is AUD1.54/litre therefore on average a commuter would spend AUD 2.4/day on transportation(Numbeo.com, n.d.). Total savings on fuel is estimated to be AUD 876/year by use of EV.

Net Cash flow and Payback period

Net cash flow (NCF) and Payback period of the proposed BIPV+EV charging system has been evaluated using below parameters and has been represented in Figure 4.19. List of parameters has been shown in Table 4.22 which is crucial for economic evaluation.

Table 4.22 Data required to analyse payback period for BIPV system + EV Charging infrastructure.

Required Data	Value	Unit
Cost of BIPV with EV charging system	11,434	AUD
Solar capacity	5.0	KWp
Energy Generation 1st year	8742.0	kWh
Electricity Tariff (AUD/kWh)	0.2809	AUD
Assumed electricity inflation Rate (Swoboda, 2013)	3.00%	%
Average Monthly Bill	216.00	AUD
O&M Cost/year(Solarbay.com, 2020)	46.00	AUD
% Degradation in generation/year	0.25%	%
Feed-In-Tariff	0.1	AUD
Service Life of System	20	Year

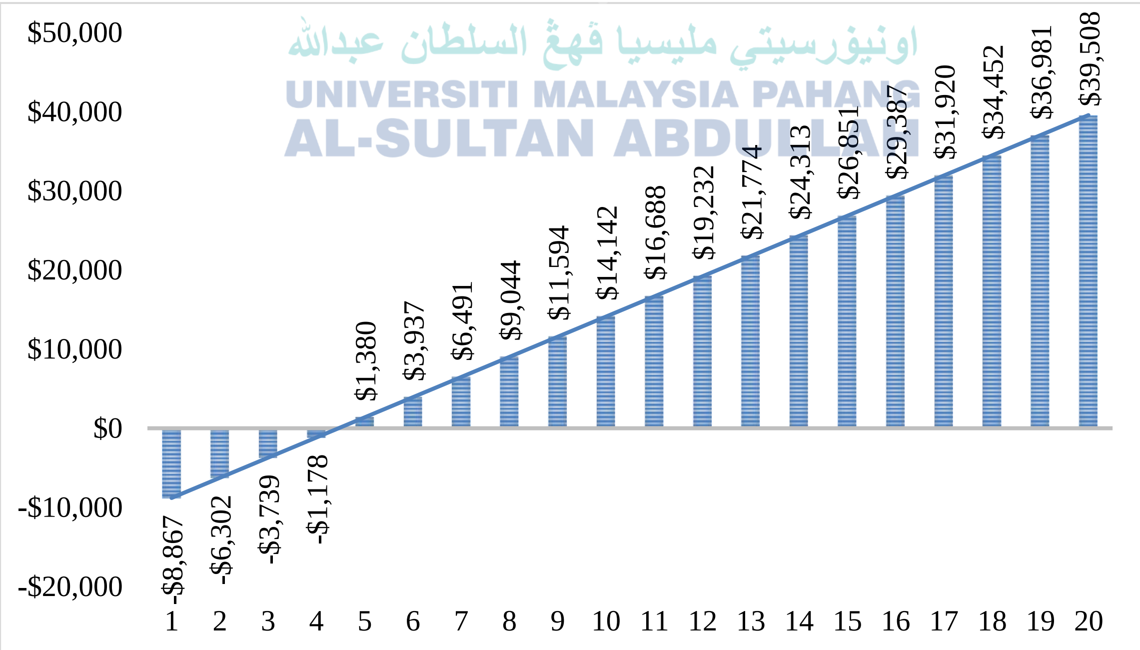


Figure 4.19 Net cash flow and payback for BIPV system – Layout 1

Net cash flow generated over the system's lifetime is 39,508 AUD with payback period of 4.46 years. LCOE of system has been estimated using equation 25 for the BIPV+EV charging systems and it is found that energy price for BIPV with EV charging system is 0.0738AUD/kWh.

Cost of EV charging

Cost of EV charging per 100 kilometres has been estimated using equation 26 for BIPV with EV Charging system. It has been found that cost of EV charging is estimated to be AUD 0.95/100km.

Economically, the system cost was the same for all cases. However, the energy generation affected the net profit, payback period, LCOE, and cost of EV charging. The economic analysis showed that the system had a payback period of 4.46 years and a LCOE of 0.74 AUD/kWh, along with a cost of EV charging at AUD 0.95/100km in system layout 1 (facing NNW). The economic analysis was conducted assuming that the FiT (feed-in tariff) would continue for 20 years.

4.2.3.3 Environmental analysis

The most significant environmental advantage of using solar power to generate clean electricity is that it substitutes energy generated by conventional power plants. An emission factor is the average rate of a certain GHG emission for a specific source in terms of units of activity (UNFCCC, 2017). Grid emission factor for ACT, Australia is 790 gCO_2e/kWh(Commonwealth of Australia 2021, 2021). The GHG reduction by the BIPV system to the atmosphere is determined by using equation 27,28 and 29. Also, charging EV through PV power helps in achieving net zero transportation. An average consumption of 5 Liters/100 km then corresponds to 5 l x 2392 g/l / 100 (per km) = 120 g CO_2/km(R. Kumar & Sharma, 2016).

Table 4.23 Total GHG savings for the BIPV+EV Charging system

System	BIPV with EV charging system Layout 1
Energy generation for 20 years	1,67,300kWh
GHG Savings of BIPV System over 20 years	1,32,167kgCO_2e
Total Commute distance over 20 years	233,600km
GHG Savings by EV for 20 years	28,032kgCO_2e
Life cycle GHG reduction (20 Years)	160,198 kgCO_2e

The limitation of the study includes the Greenhouse gases produced during the cell fabrication processes to produce PV modules, BOS and during transportation and disposal has not been considered here. The environmental analysis showed that the system could save an average of 160,198 kgCO_2e over its lifetime.

4.3 Sweden Case Study

In Sweden, house roof slope varies between 15° to 45°(Benders.se, 2013). This research will conduct simulation at 15°,30° and 45° to analyse the best case scenario for meeting residential and EV charging demand. Details of area and orientation has been mentioned in sections 3.3.2.

4.3.1 Building load profile

In this research, daily household energy consumption and daily energy requirement for EV charging has been considered as input for the analyzing total energy requirements. This study is based on daily profile and annual energy profile to analyze the building energy self-sufficiency. The electricity consumption in Sweden is temperature dependent (Svenska Kraftnät, 2021) since a lot of electricity is used for heating. In Sweden, residential housing accounts for 15% of total final energy demand, the majority of which (about 66%) is explained by the need for space heating and DHW. About a third of this is ascribed to space heating, with the remaining amount being DHW(Energiläget, 2022). The estimated annual electricity consumption for a single house in Sweden is about 10.1MWh/year(Paul Zimmermann, 2009) which represents on average of 27.6kWh/day electricity consumption. Hourly profile of a typical Swedish house has been shown in figure 4.20.

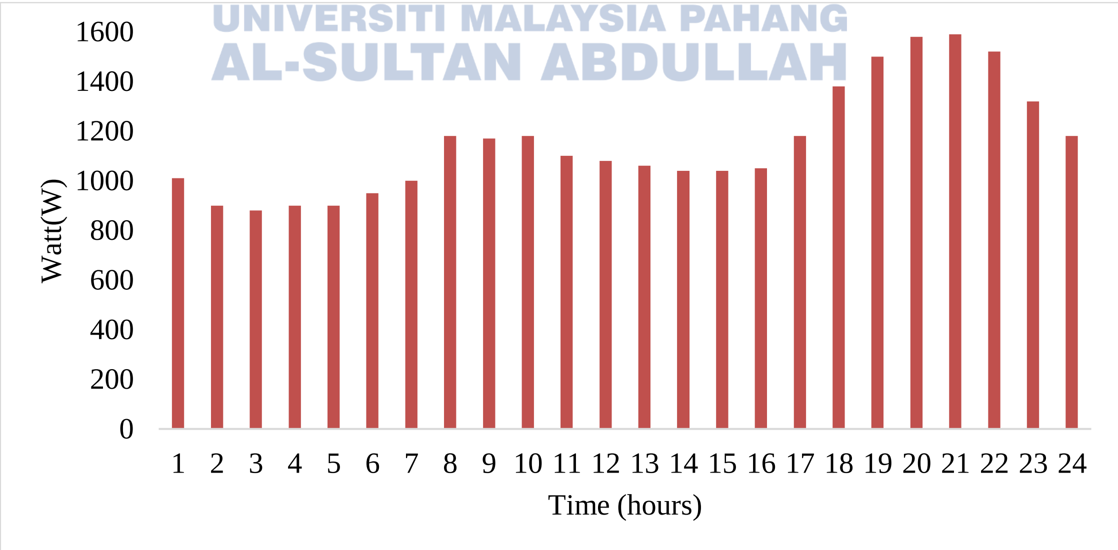


Figure 4.20 Average hourly load curve – Swedish house (Paul Zimmermann, 2009)

The house is where most of the home charging occurs. Charging at work is also relatively common: 35-40% of people surveyed claim to do so daily or weekly(IEA, 2018). In

Sweden, up to 80% of people who use electric cars reside in single-family homes, as opposed to 50% of the general population(IEA, 2018). The discrepancy can most likely be attributed to the greater accessibility of private charging options. Very few electric car owners charge their car at a publicly available street parking place near the house. Most of the time, drivers gradually plugging-in in the evening between 5 pm and 12 am(Pearre et al., 2011). According to the National Travel Survey RVU Sweden 2011-14, the average passenger mileage by car per capita is 28.2 km per person per day(Hiselius & Rosqvist, 2018). Volkswagen ID.3 Pure Performance EV has been considered in this research which has battery capacity of 45kWh with an ideal range of 275km with a consumption of 164Wh/km(EV Database, 2021). However, the range is affected by weather e.g. in cold weather heating is required which reduces the range. This study is considering the ideal range according to the datasheet.

Daily energy required by EV can be calculated using equation 10:

$$E_{EV} = 0.164 \times 28.2 = 4.63\text{kWh}$$

Based on above equation, daily EV charging requirement is approximately 4.63kWh. Therefore, total energy required for PV sizing is shown below using equation 10.

$$E_{Total} = E_H + E_{EV} = 27.6 + 4.63$$

$$E_{Total} = 32.2\text{kWh/day}$$

4.3.2 PV system design

According to the IEA assessment, residential size ranges for single-family homes are 5-10kWp and 10-20kWp, and multi-family homes are 20-50kWp and 50-100kWp(IEA PVPS, 2021). The typical villa system size was nine kWp, which appeared to agree with the typical system size documented in the Svanen database for Swedish single-family housing systems erected in 2019–2020, dominated by monocrystalline panels (IEA PVPS, 2021). This study will proceed considering the feasibility of a 10kWp system towards achieving self-sufficiency of building for residential and EV charging loads.

The study site "Orebro" receives 100 millimeters of snow on average yearly, with most of it falling between December and March. In several studies from snow-rich locations with cold winters, PV systems suffer significant annual energy output losses, as reported in the literature. Snow's effect on solar panels depends on how the array is set up and how much sunshine hits each cell. Strong correlation exists between a cell's maximum throughput current (I) and the sun irradiation that it receives(Y. J. Wang & Hsu, 2010). According to research conducted in Truckee, California, snow can cause yearly losses of 12-18% for tilt angles ranging from 39 degrees to 0 degrees (flat). The study also discovered a direct link between tilt angle and energy loss, but the relationship is modified by parameters such as array height and row spacing (Powers et al., 2010). Lorenz et al. (Lorenz et al., 2012) studied the impact of snow on photovoltaic (PV) output in northeast Germany. They assumed that snow covered the PV panels 100% of the time when the air temperature was below zero degrees Celsius. This assumption decreased the root mean square error (RMSE) of intra-day hourly prediction values at a single site level from 11% installed power to around 7.5%. In another study [68], a PV test platform with seven modules at four different tilt degrees (0°, 15°, 30°, and 45°) was set up in Calumet, Michigan, USA, to track energy loss from snowfall for a year. According to the findings, snow-related yearly energy losses for tilted, unobstructed modules varied from 5% to 12%, with the sharpest tilt angle incurring the most negligible energy loss. Additionally, significant losses of up to 9.3% have been documented in moderate climates, compared to plants in mild temperatures, which generally have annual losses of less than 2% (Marion et al., 2013). As a result, the panels can continue to be blanketed with snow until the surrounding air is warm enough for clearing to happen. As expected, ambient temperatures nearing zero degrees Celsius have a significant impact on how quickly PV panels clean(Pawluk et al., 2019). These studies and their published findings suggest that snow losses might significantly affect energy yield and the investor and site owner's financial situation. Therefore, it is reasonable to consider snow effects when planning PV locations and to factor them into estimates, financial ROI calculations, and LCOE calculations. The plant's design criteria and technical details also affect how quickly snow is cleared. In general, but not always linearly, larger tilt degrees result in shorter snow cover times. Hence, this study includes the simulation of different roof slope and fixed azimuth. The impact of slope and azimuth on energy generation will be analyzed while comparing performance of mono-facial monocrystalline panel with bifacial monocrystalline panel in all conditions. A total of 6 cases with different conditions of panel tilt (15°,30°,45°), azimuth (-77°), and technology selection have been considered in this study, as shown in Table 4.24.

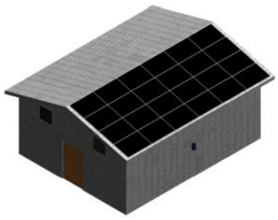
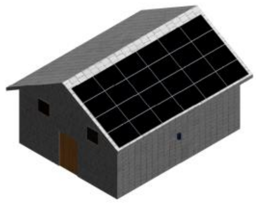
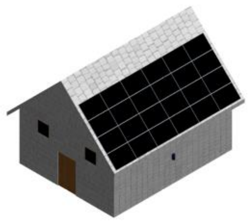
Table 4.24 Possible cases for study for Swedish house

Case	Tilt/Azimuth	Technology
1	15 / -77°	Mono
2	30 / -77 °	Mono
3	45 / -77 °	Mono
4	15 / -77°	Bifacial
5	30 / -77 °	Bifacial
6	45 / -77 °	Bifacial

PVSyst student version 7.2 database has been used to select panels, batteries and inverters; further detailed simulation is carried out in the same software. This program collects meteorological data, device architecture, shading testing, loss determination, and economic assessment within a specified region. The simulation is run monthly for a year, and the results are summarized and stated in detail.

To design PV system, the Trina Solar monocrystalline monofacial solar panel TSM-410 DE09.05 with efficiency of 20.5%, panel degradation of 0.55% and Bifacial solar panel TSM-DEG15MC-20-(II)-410 with efficiency of 20.2%, panel degradation of 0.5% has been selected from PVSyst database. The maximum power capacity of both panels is 410Wp at STC. Each monofacial panel requires $1.76m^{2,}$ and the bifacial panel requires $2.03m^2$. Monocrystalline technology is more efficient, readily available and less expensive than other thin-film technologies. Monofacial solar cells only capture photons that hit the device's front surface. In contrast, the front and rear sides of a solar module's bifacial solar cells concurrently capture light from direct and reflected radiation. Bifacial solar cells also have the advantage of having lower operating temperatures and higher maximum power output due to reduced infrared absorption in the absence of aluminum back metallization(Huebner et al., 1997; Obara et al., 2013; Yang et al., 2011). Results and studies have demonstrated that bifacial modules can generate 10–20% more electricity than monofacial panels. The additional power may be as much as 30–40% if conditions are ideal and single-axis trackers are used(Lusson, 2020). Accordingly, Kostal Piko -10 three Phase Inverter has been chosen, a 10kW inverter with an MPPT Voltage range of 90 V ~ 560V, maximum efficiency of 98.5% with 2 MPPTs have current input of 12A each MPPT. Table 4.25 represents various building layouts and available area for PV system installation.

Table 4.25 Representation of building and required area

PV System Layout			
Layout	Layout 1	Layout 2	Layout 3
Roof Layout			
Roof Slope	15°	30°	45°
Usable Area	67.8m^2	75.6m^2	92.6m^2
Module layout	11 Strings × 2 In Series = 22 Units	11Strings × 2 In Series = 22 Units	11 Strings × 2 In Series = 22 Units

Assumptions in this research

Table 4.26 shows list of parameters that have been considered in this study for designing and simulating the PV System for residential and EV Charging energy requirements**.**

Table 4.26 Inputs and assumption for the system simulation

	Parameters		**References**
Building	House	Single house	(Benders.se, 2013)
	Available Roof Area	Shown in Table 4.25	-
	House design	Typical house with gabled roof	(Benders.se, 2013)
	Roof Direction	Refer figure 3.10	-
	Building daily load	27.6kWh	(Paul Zimmermann, 2009)
EV Charging	Car	Volkswagen ID.3 Pure Performance	-
	Daily Commute distance	28.2km	(Hiselius & Rosqvist, 2018)
	Daily EV Charging load	4.63kWh	-
	Battery Size	45kWh	(EV Database, 2021)
	Range	275km	
	Charging Time	Refers to Table 3.3	
	Charger Type	Refers to Table 3.3	

4.3.3 Results – Sweden case study

The possibility of a solar PV project is evaluated by its technical, economic, and environmental sustainability. The average yearly values of parameters such as energy yield, capacity utilization factor and performance ratio, payback period, LCOE, cumulative cash flow and GHG savings has been studied for the chosen location with two different PV technology to analyze the feasibility of system.

4.3.3.1 Energy Analysis

Energy analysis has been estimated considering losses in each case and available energy at inverter output has been taken for further analysis. The energy production of the system is simulated using PVSyst. Figure 4.19, it shows that energy generation by PV System with EV charging system layout 1 is higher than other two systems on daily basis, also due to higher energy generation it will reduce grid dependency and increase solar payback revenue. Table 4.27 below shows comparison of loss with respect to each case.

Table 4.27 Loss analysis of different cases 1-6 in Swedish case study

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Global horizontal irradiation (kWh/m^2)	932	932	932	932	932	932
Global incident in coll. Plane	2.1%	2.0%	-0.45%	2.10%	2.00%	-0.45%
Far Shading/Horizon	-0.01%	-0.03%	-0.06%	-0.01%	-0.03%	0.06%
Near Shading irradiance loss	0.00%	0.00%	0.02%	-0.35%	-1.48%	-2.96%
IAM Factor global	-3.97%	-3.09%	-2.67%	-3.93%	-3.09%	-2.71%
Ground reflection on front side	0.00%	0.00%	0.00%	0.12%	0.68%	1.77%
Bifacial Panel	-	-	-			
Global incident in ground (kWh/m^2)	-	-	-	579 on $143m^2$	576 on $143m^2$	575 on $143m^2$

Table 4.27 Continued

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Ground reflection loss	-	-	-	-70.00%	-70.00%	-70.00%
View factor for rear side	-	-	-	-67.20%	-69.28%	-72.85%
Sky diffuse on rear side	-	-	-	1.45%	8.61%	24.81%
Beam effective on rear side	-	-	-	1.67%	16.34%	45.41%
Shading loss on rear side	-	-	-	-5.00%	-5.00%	-5.00%
Global irradiance on rear side(kWh/m^2)	-	-	-	150	150	218
Effective irradiation on collectors (Wh/m^2 X 53m^2)	914	921	902	912	914	891
Efficiency at STC (%)	20.08	20.08	20.08	20.17	20.17	20.17
Array nominal energy (at STC efficiency)	9.64	9.72	9.52	10.87	11.04	11.14
PV loss due to irradiance level	-1.76%	-1.72%	-1.75%	-1.62%	-1.62%	-1.60%
PV loss due to temperature	-4.29%	-4.71%	-4.90%	-4.09%	-4.29%	-4.11%
Module quality loss	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%
Mismatch loss, modules and strings	-2.10%	-2.10%	-2.10%	-2.10%	-2.10%	-2.10%
Mismatch back irradiance		0.00%	0.00%	-1.45%	-1.67%	-2.13%
Ohmic wiring losses	-0.72%	-0.77%	-0.80%	-0.77%	-0.81%	-0.81%

Table 4.27 Continued

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Array virtual energy at MPP(MWh)	8.88	8.91	8.71	9.89	10	10.06
Inverter loss during operation	-4.83%	-4.85%	-4.91%	-4.70%	-4.69%	-4.67%
Night Consumption	0.00%	-0.17%	0.00%	0.00%	0.00%	0.00%
Available energy at inverter output (MWh)	8.45	8.48	8.28	9.42	9.53	9.59

Figure 4.21 depicts that during month from April to august, system will generate sufficient energy to meet the user needs while in other months' energy generation is too low which can only meet between 9% in January to 56% in September, therefore remaining energy will be imported from grid.

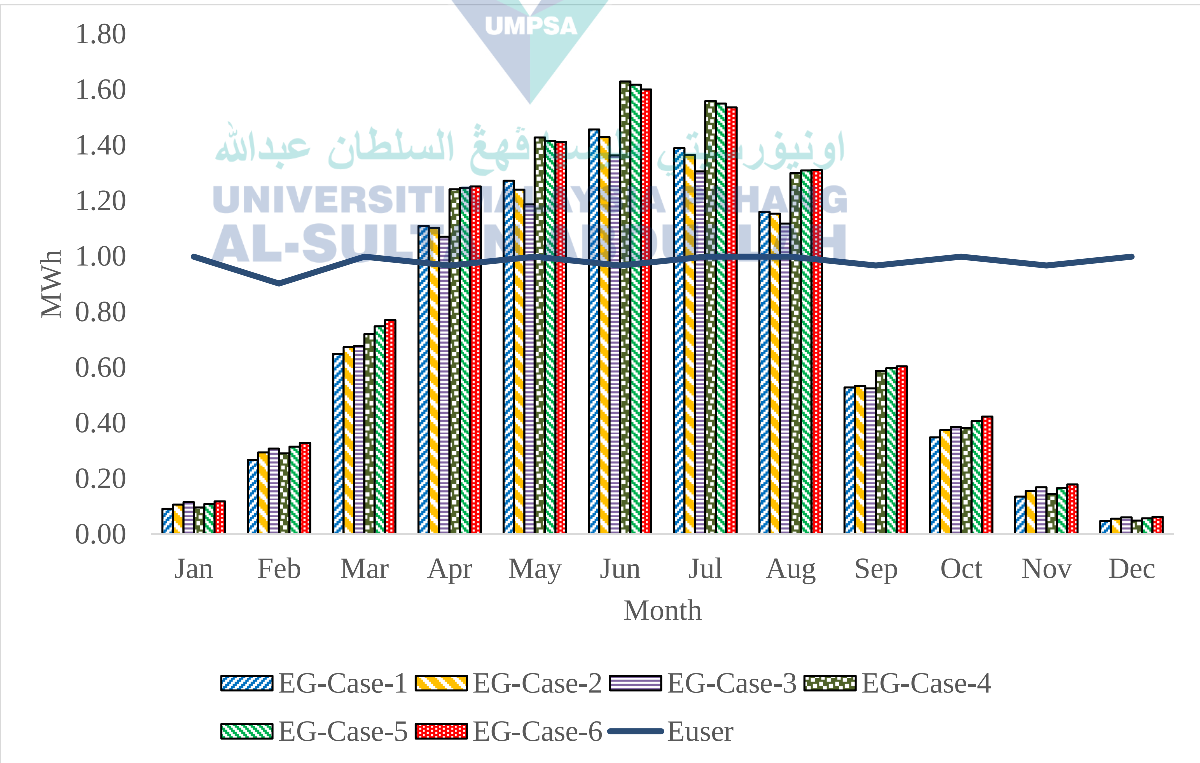


Figure 4.21 Monthly average energy generation for each case compared to energy demand by user in MWh.

Figure 4.22 shows that energy generation by PV systems for bifacial panels are higher than system with mono-facial panel. PV systems in all the cases are not able to meet the energy demand, therefore energy from grid is required to meet the excess energy.

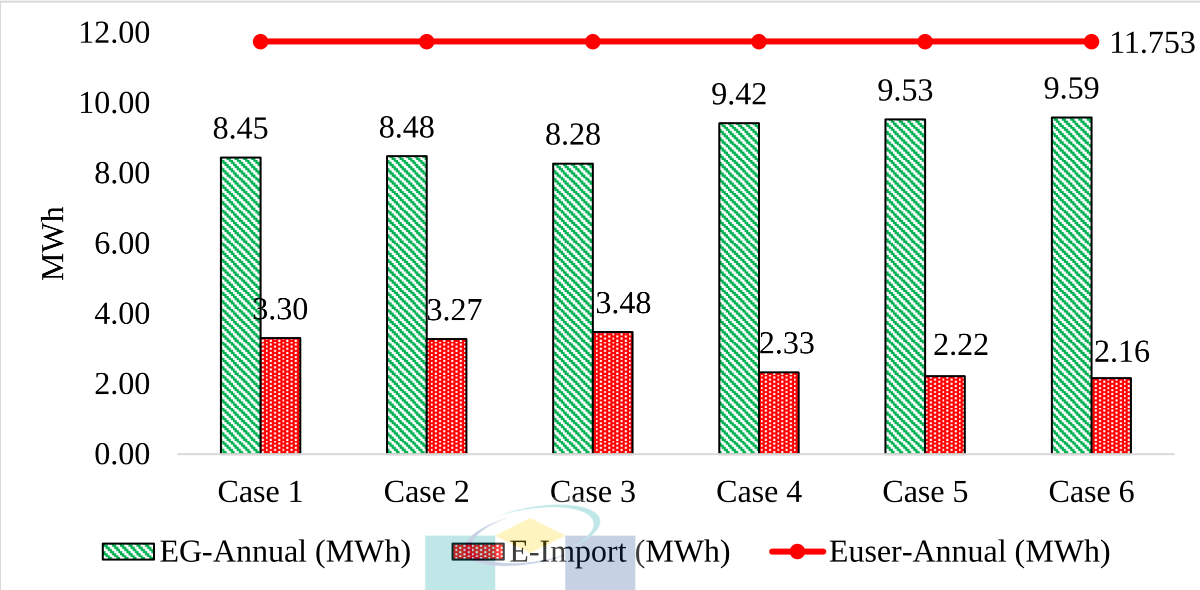


Figure 4.22 Comparison of annual energy generation and energy imported from grid vs user needs in MWh.

Considering the degradation of PV Panel, the energy generation output will reduce over the lifetime which will affect the imported energy from grid. Panel degradation factor has been applied to estimate the annual energy generation in figure 4.23.

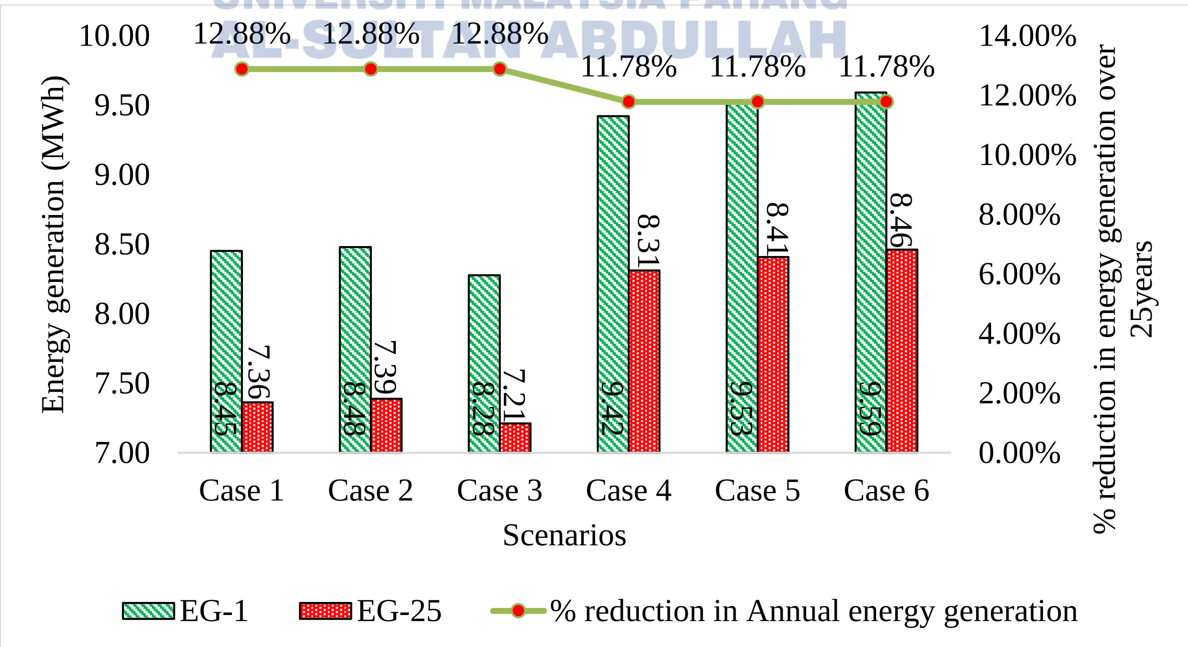


Figure 4.23 Annual energy generation comparison between 1st year and 25th year.

Capacity Utilization factor and Performance ratio

At full load, the system's plant capacity is 92,505.6 kWh. Figure 4.24 depicts the CUF and PR for System in Cases 1 through 6.

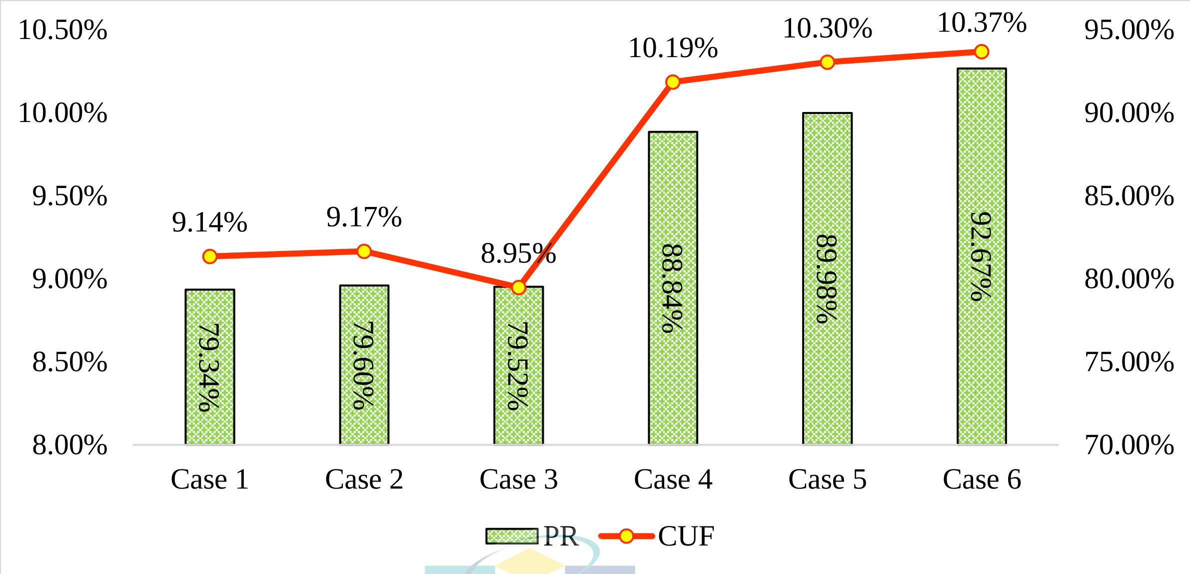


Figure 4.24 Comparison of CUF and PR of different cases

A grid-connected 10 kWp PV system with EV charging for a typical house in Sweden was investigated. The study investigated the energy, economic, and environmental aspects of the system. Six cases were studied, with two different technologies: monofacial and bifacial monocrystalline. Bifacial PV systems generated a minimum of 10% more energy than monofacial PV systems. Figure 8 shows the average daily energy generation by the PV systems and compares it with the user needs. It was observed that during the summer months from April to August, the system was able to generate sufficient energy to meet the daily energy demand of 32.2 kWh.

However, for other months, the energy generated by the PV systems in all cases was not able to meet the building and EV charging demand. Therefore, grid dependency of the PV system cannot be avoided, as excess required energy must be imported from the grid. Figure 4.19 shows the annual energy generation and energy imported from the grid. Case 6, which is a bifacial PV system with a roof slope of 45°, generated the highest energy of 9.59 MWh annually, while case 3 generated the least annual energy of 8.28 MWh. However, none of the systems were able to meet 100% of the annual energy demand of 11.753 MWh.

The performance ratio of all monofacial monocrystalline panels is approximately 79%, while the performance ratio of all bifacial monocrystalline panels is found to be higher, ranging between 88% and 92% due to high energy yield. Figure 10 shows that the reduction in energy generation by the PV system for the monofacial panel was 12.88% after 25 years, while the % drop in energy generation by the bifacial PV system was 11.78%. This means that the bifacial PV system performed better in terms of meeting energy needs.

The CUF of the PV system is found to be approximately 9.4% for case 4 to 10.88% for case 6. Net cash flow, LCOE, and payback period are important economic performance indicators in many other PV-based grid-connected residential studies.

4.3.3.2 Economic Analysis

Profitability of the installed PV system can be indicated by economic analysis. It gives an idea about the recovery of the invested amount and profit gain in any system. The average price of electricity in Sweden, in June of 2022, has been 0.2525€ per kilowatt hour equivalent to 2.79SEK/kWh(Countryeconomy.Com, 2022). Cost estimate for system has been presented in table 8. Estimated system breakdown cost is shown in below table 4.28 (Soft costs taken from IEA report (Johan Lindahl et al., 2020)).

Table 4.28 Initial Cost Breakdown for PV System with Monofacial versus Bifacial panel

PV System	Case 1,2,3	Case 4,5,6
Hardware	SEK	SEK
Module type	Monofacial	Bifacial
Modules cost	58,630	104,390
Inverter	28,995	28,995
Mounting materials	4012.8	4012.8
Other electronics	15734.4	15734.4
Subtotal hardware	107372.2	153132.2
Soft costs	Average [SEK/Wp](Johan Lindahl & Cristina Stoltz, 2018)	Average [SEK/Wp]
Installation work	3.5	3.5
Permits and reporting	0.13	0.13
Working travel time	0.23	0.23

Table 4.28 Continued

PV System	**Case 1,2,3**	**Case 4,5,6**
Planning and sales	0.48	0.48
Shipping to customer	0.16	0.16
Travel costs	0.09	0.09
Other	0.04	0.04
Supplier margin	1.17	1.17
VAT	3.22	3.22
Subtotal soft costs	9.02	9.02
Total (SEK)	202,623.4	248,383.4
System Size(Wp)	10560	10560
EV Charger price	7345	7345
Total System Cost (SEK)	209,968	255,728

PV installations are eligible for a 15% tax deduction, whereas electric car batteries and charging stations are eligible for a 50% tax deduction. Private individuals are eligible to claim this deduction once per person and per year. The maximum permitted amount per year is 50,000 SEK. Also, excess PV electricity can be injected into grid with offers from utilities, 0.6 SEK/kWh + Green certificates + Feed in compensation from the grid owner(Johan Lindahl et al., 2020).

On an average, 28.2km daily commute distance has been considered for calculation as reported in literature(Hiselius & Rosqvist, 2018). Gasoline price in Sweden is 20.3 SEK/liter taken on April 17,2022(Globalpetrolprices.com, 2023). An economical car on average consumes 5.0L/100km of fuel, therefore on average a commuter would spend SEK 39.76/day on transportation. Accordingly, annual savings have been estimated at SEK 10,449/year.

Table 4.29 Data used for economic analysis of the PV system with EV Charging infrastructure

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Years of Service, N	30	30	30	30	30	30
Initial Cost of System, C_{system} (SEK) Without discount	179,968	179,968	179,968	255,728	255,728	255,728
*Initial Cost of System, C_{system} (SEK) With discount 15%	152,973	152,973	152,973	217,369	217,369	217,369
Electricity bill saving/year (1st Year), C_{Res} (SEK)	23578.5	23658.5	23094.4	26288.2	26594.1	26759.3
Maintenance cost/year $C_{Maintenance}$ SEK/kWp/yr) (Johan Lindahl et al., 2020)	64	64	64	64	64	64
Cost saving for transportation/year, $C_{Transport}$ (SEK)	10,449	10,449	10,449	10,449	10,449	10,449
Cost of energy import annually (1st Year), C_{import} (SEK)	9,212	9,132	9,696	6,503	6,197	6,032

*Represented discount rate of 15% on capital cost of system.

To analyze economic aspects of the proposed PV System, Net cash flow, LCOE and payback period will consider both cases of capital cost without discount and with 15% discount.

Net cash flow and payback

The payback period is the time it takes to recover the money invested in a project, typically evaluated in years. This can be estimated using equation 24. This is based on the yearly energy savings of the system. The sooner the project's original investment is repaid, the more profitable it becomes. This Sweden case consider two scenarios where users has discount from the government and other case is when there is no discount as shown below.

$$\text{PB or PB} - \text{D (years)} = \frac{C_{\text{system}}}{\text{Annual profit (SEK)}} \qquad (31)$$

Net cash flow is simply the cash inflows and outflows over the given period. It's an important parameter to estimate the payback period of a project and profit over time.

Similarly, net cash flow over lifetime has been estimated for two conditions without discount and with discount on capital investment.

$$\text{NCF or NCF} - \text{D} = C_{inflow} - C_{outflow} \tag{32}$$

Cash inflows include savings on electricity bill, transportation and revenue generated by selling energy to grid whereas outflow includes any maintenance cost, replacement cost, buying back energy from grid. Total bill savings after over the lifetime of 25 years (based on Solar panel datasheet) can be estimated using equation 34.

$$C_{Bill} = (C_{Res} + C_{Transport}) \times 25 \text{ year} \tag{33}$$

Replacement cost has not been considered. Furthermore, net cash generated over the lifecycle of 25 years has been evaluated as per below equation 34:

$$C_{Net} = C_{Bill} + C_{Grid} - (C_{Maintaince} \times 25) - C_{System} - C_{Replacement} - C_{import} \tag{34}$$

$$C_{Import} = E_{Import} \text{ kWh} \times \text{Tariff (SEK)} \tag{35}$$

$$E_{Import} = \sum_{j=1}^{n} \left[E_0 \times (1 - \delta)^j\right] - (E_{user} \times 25) \tag{36}$$

Energy generation will reduce overtime due to panel degradation while energy import will increase from the grid over the life cycle of the plant which affects the economics. Following equation 34, cumulative cash flow over 25 years has been represented in figure 4.25 and figure 4.26 respectively. The graph depicts the cash flow from the start of system installation, which was negative until the initial investment was recovered, and profit was made over the lifetime. Intercept with the year axis is the payback period for all the system along with net cash flow which has been further represented separately in figure 4.27.

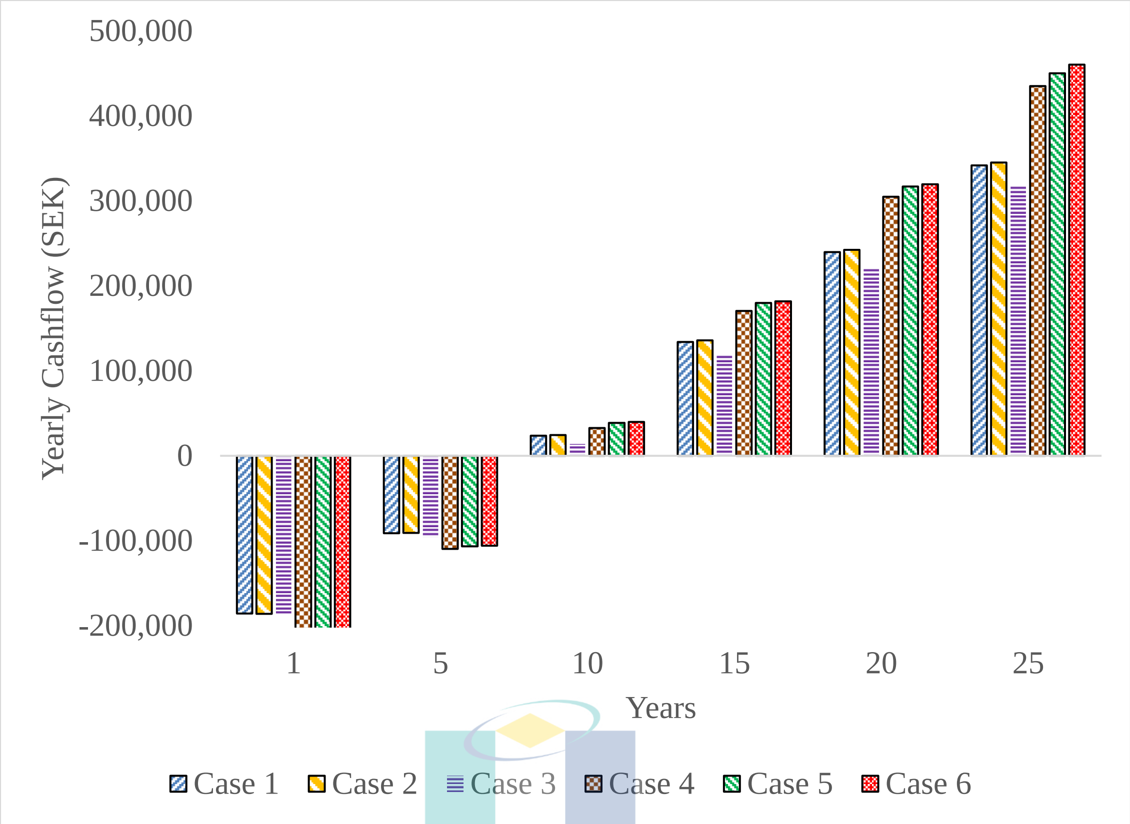


Figure 4.25 Cumulative cash flow all cases for PV system without discount

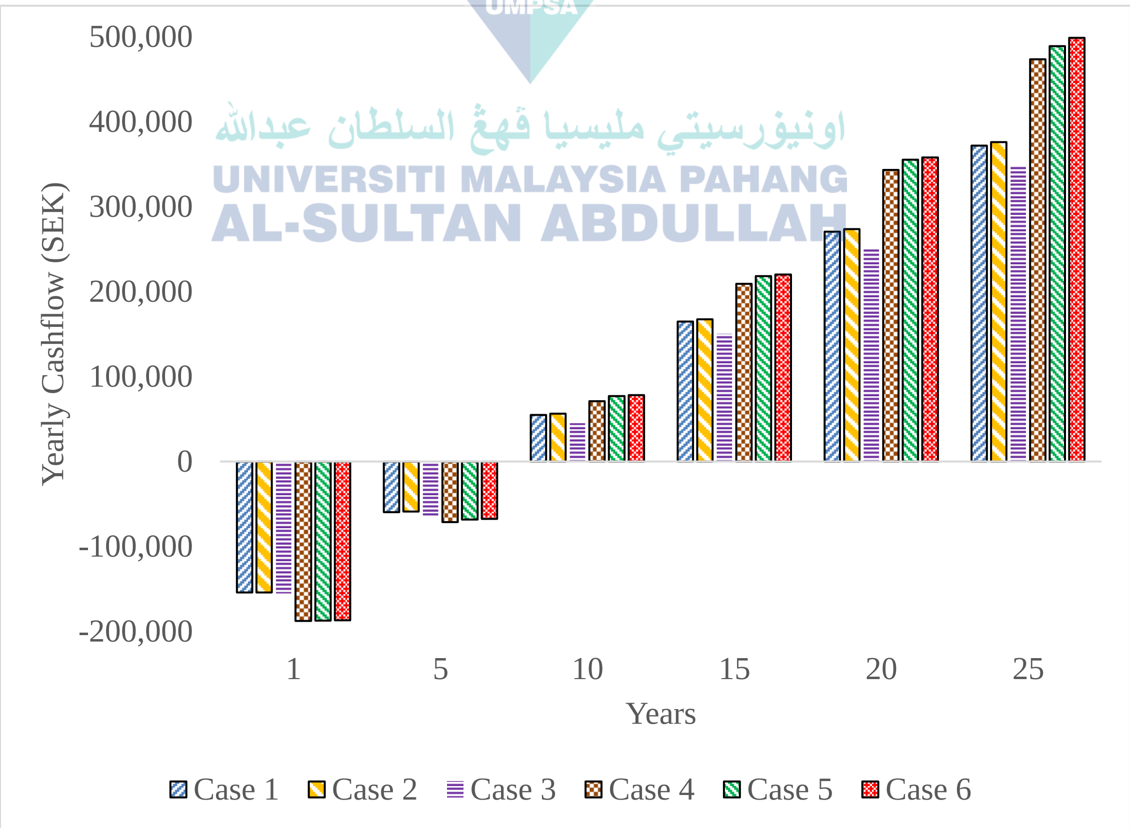


Figure 4.26 Cumulative cash flow all cases for PV system with 15% discount

Figure 4.27 below represents total profit generated in 25 years shown in y-axis on left of the PV system with payback period in years in y axis on right. PV system with discount and without discount has been shown on x-axis. PV system with discounted system cost has reduced payback period and higher net profit. systems with discounted prices exhibited higher returns, totalling SEK 497,108 in Case 6. Case 2 also presented a viable scenario, with a cumulative cash flow estimated at SEK 375,849. The payback period for all systems is depicted in Figure 4.26, illustrating that PV systems with discounted prices have a shorter payback period of 7.3 years in Case 6, compared to 7.5 years in Case 2.

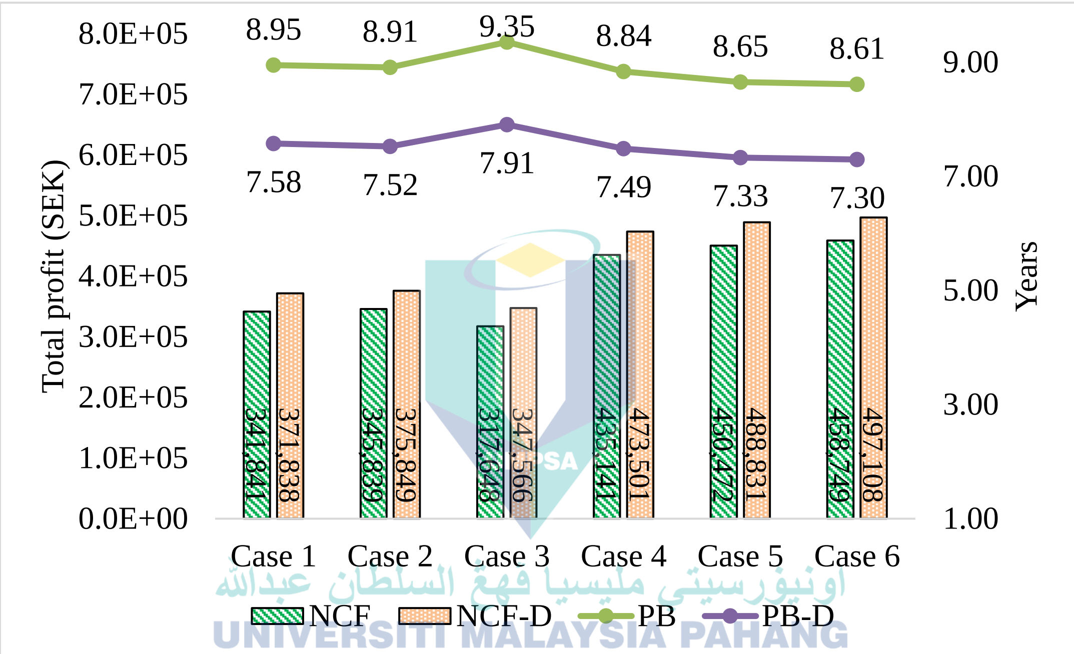


Figure 4.27 Comparison of net cash flow and payback period for PV systems without discount and with 15% discount

The LCOE for the system ranged from 0.8988 to 0.9851 SEK/kWh for PV systems with discounted rates, slightly higher at 1.057 to 1.159 SEK/kWh for systems without discounts. The EV charging cost was least in Case 2 at 14.707 SEK/100km and highest in Case 6 at 16.121 SEK/100km for the discounted system. The net cash flow over the PV system's lifespan varied between SEK 317,648 for Case 3 and SEK 458,749 for Case 6 without discounts.

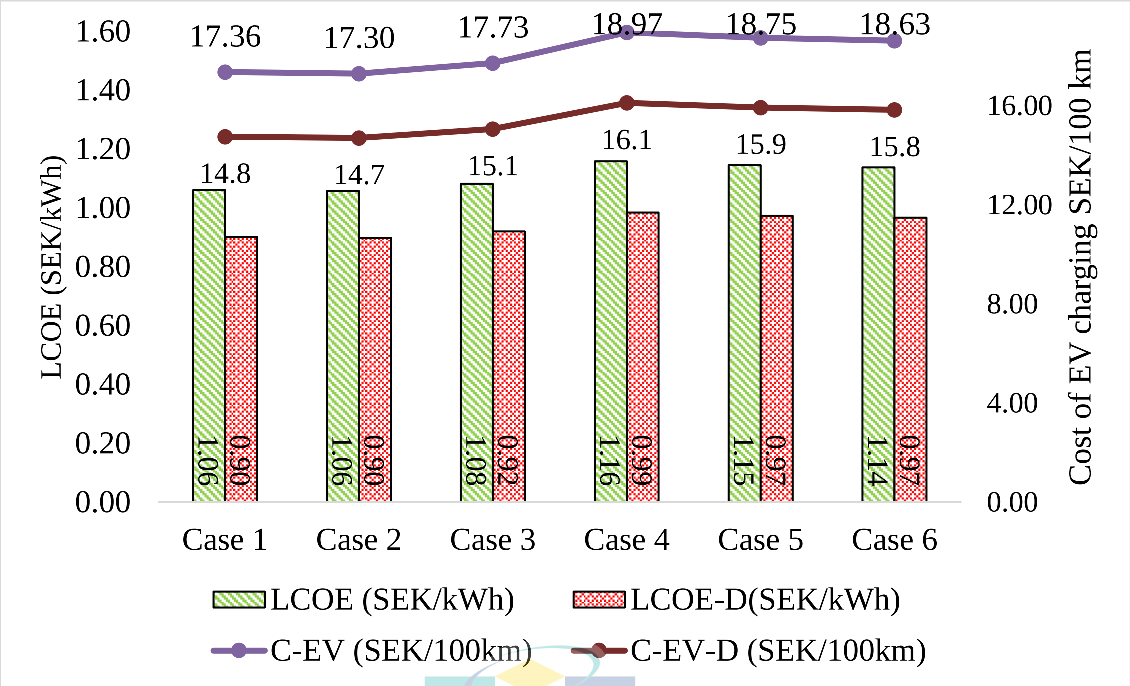


Figure 4.28 LCOE and cost of EV charging of the PV system without tax discount and with 15% discount

Conversely, Policies related to discounts or tax rebates on components can play a crucial role in reducing the payback period and enhancing profitability for homeowners.

4.3.3.3 Environment Analysis

Sweden had average emissions in 2021 of 29 g CO_2eq/kWh. Hydropower (46.7% of total energy production) was the main renewable energy source, accounting for 68% of all energy production. Sweden is a leader in the development of renewable energy(www.nowtricity.com, 2022).

GHG Savings by EV

In 2020, new passenger car emissions in Europe decreased by 12% to 107.5 gCO_2/km on average, following a modest increase in emissions from 2017 to 2019 that brought them up to 122.3 gCO_2/km. For the years 2020–2024, Regulation (EU) 2019/631 establishes a fleet-wide objective of 95 g CO_2/km, and stronger fleet-wide targets for 2025 and 2030(European Environment Agency, 2023).

The ability to generate clean electricity using solar energy instead of conventional power plants is the environmental benefit that outweighs all others. Additionally, using solar energy to charge EVs contributes to net zero mobility. The carbon-dioxide reduction per MW power to the atmosphere is determined as per Equation 27,28,29 and has been represented in figure 4.29.

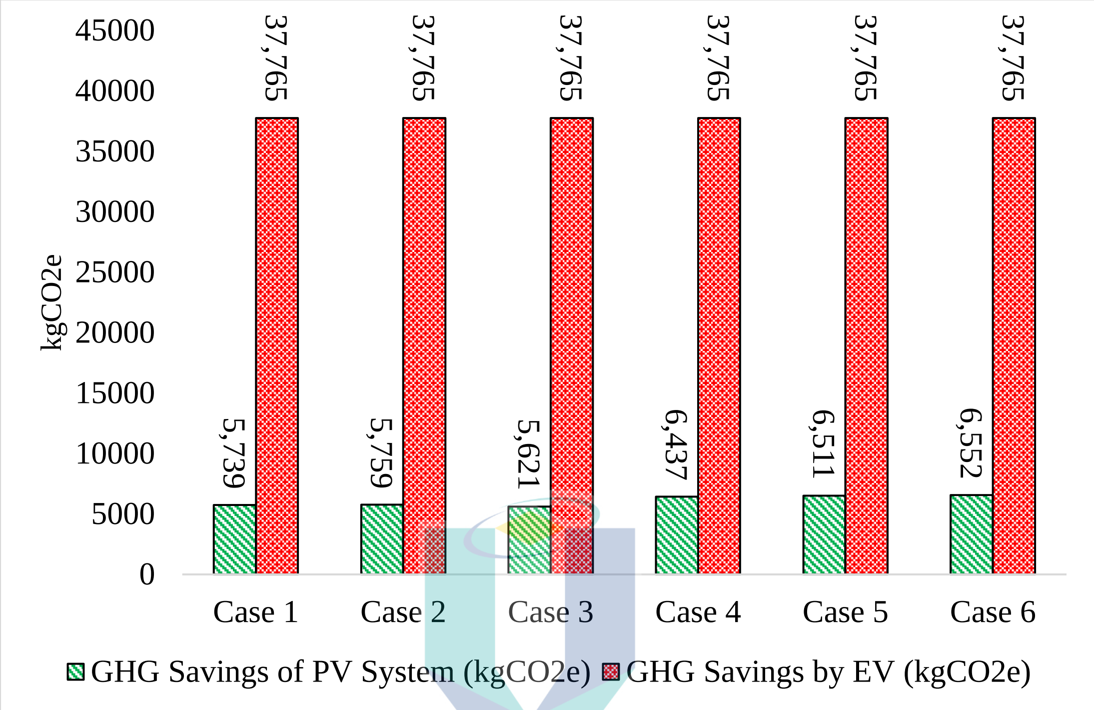


Figure 4.29 Total GHG savings of the PV system for Residential and EV charging load and fuel.

In Sweden case study, the decrease in greenhouse gas (GHG) emissions ascribed to photovoltaic (PV) systems is comparably smaller. This is due to the fact that a large amount of the region's power is generated from sources with lower related emissions.

4.4 Comparison

All the case studies looked at the possibilities of BIPV systems with EV charging to minimize energy prices, pollution, and grid dependency. Although the studies have yielded encouraging outcomes, there are several limits to the study. One problem is that the investigations only looked at a single region. It is likely that the outcomes would differ in other regions with varying climatic circumstances. Furthermore, the research did not take into account the expense of battery storage in all cases. Battery storage might boost system performance, but it would also raise the cost. Despite these limitations, research has indicated that BIPV systems with EV charging have the potential to be a low-cost approach to cut energy expenses and emissions. According to the studies, BIPV systems with EV charging can also assist to make homes more sustainable.

In Malaysia, the study found that a grid connected BIPV system with no battery backup was the most cost-effective option. The system was able to meet the annual energy demand of the household and had a payback period of 6 years. In Canberra, Australia, the study found that a BIPV system with EV charging on a roof facing NNW was the most efficient option. The system was able to meet the annual energy demand of the household and had a payback period of 4.46 years. In Sweden, the study found that a grid connected BIPV system with a bifacial PV panel and a roof slope of 45° was the most efficient option. The system was able to generate the most energy and had a payback period of 7.3 years. To compare the performances of all systems, below Table 4.30 summarizes the parameters taken from best-case scenario of all the three locations. As the local units has been used for economic analysis, for comparison purpose, all the comparable parameters have been unified e.g. all currency in USD and plotted in graphical form.

Table 4.30 Comparison of best-case scenario in each location.

Location	Kuantan, Malaysia	Canberra, Australia	Orebro, Sweden
System type	Grid-connected BIPV system	Grid-connected BIPV system	Grid-connected BIPV system
System size (kWp)	5.6	5	10
Panel Technology	Monocrystalline Silicon	Monocrystalline Silicon	Bi-facial Monocrystalline Silicon
Annual energy generation (MWh)	7.043	8.56	9.59
Payback period (Years)	6	4.5	7.3
Exchange rate in USD as on 05/12/23	1RM = .21USD	1AUD = 0.66 USD	1SEK = 0.095 USD
LCOE	0.16RM/kWh	0.074 AUD/kWh	0.9678 SEK/kWh
LCOE (USD/kWh)	0.0336	0.4884	0.091941
Cost of EV charging	2.08RM/100km	0.95AUD/100km	15.84SEK/100km
Cost of EV charging (USD/100km)	0.4368	0.627	1.5048
Net cash flow	61,578RM	39,508AUD	497,108SEK
Net cash flow (USD)	12,931	26,074	47,225
Lifetime consideration	21	20	25
GHG saving ($kgCO_2e$)	137,321	160,198	44,317

Figure 4.30 presents a fascinating comparison between BIPV system size and annual energy generation across the three regions. We observe that Australian systems boast the most compact size, followed by those in Malaysia, while Sweden's systems are significantly larger. This difference can be attributed to Australia's abundance of daylight hours, allowing for higher energy output with a smaller system footprint. Conversely, Sweden's low winter sunlight translates to the least efficient BIPV system, despite its larger size. Australia and Malaysia are the most viable possibilities in terms of energy generation, since they provide a balance between system size and energy output.

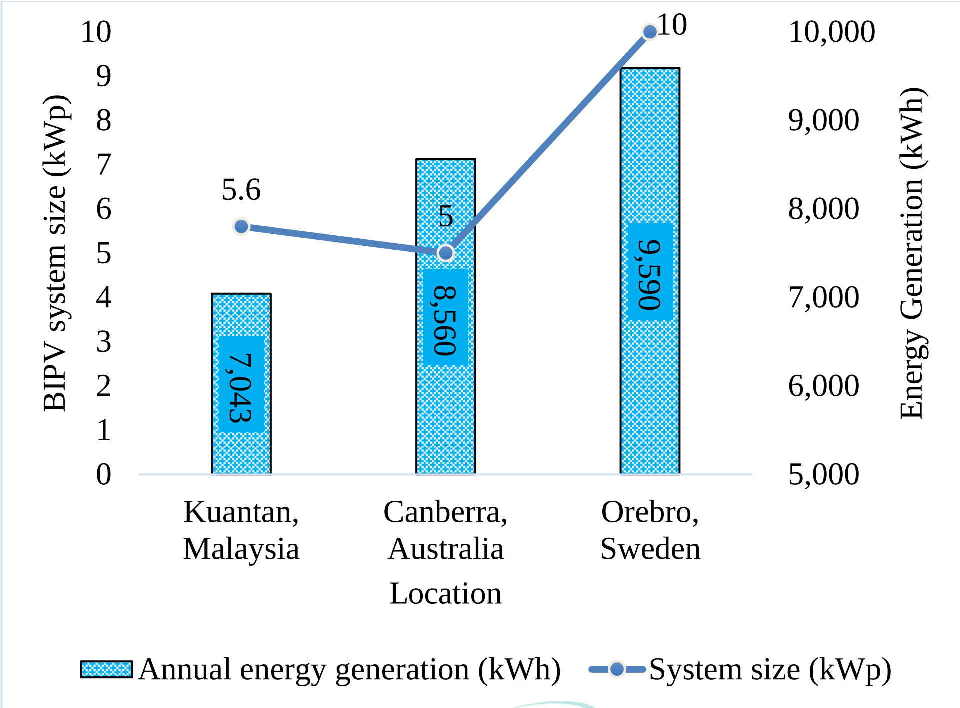


Figure 4.30 Comparison of BIPV system size and annual energy generation in selected location

Figure 4.31 and Figure 4.32 present an economic comparison of the three locations. Notably, plant lifetimes vary due to differing local policies. The Swedish scenario offers the highest net cash flow, driven by generous incentives and discounts on solar components. While the payback period is longer in Sweden due to the higher initial investment, it remains a viable option due to the system's substantial lifetime profitability. Conversely, the Australian system boasts the smallest size and lowest investment, resulting in the fastest payback and significant cash flow. However, across their lifetimes, all three systems demonstrably generate positive returns for homeowners. Among the three locations, the Malaysian case exhibits the most favorable outcome in terms of both LCOE and EV charging cost.

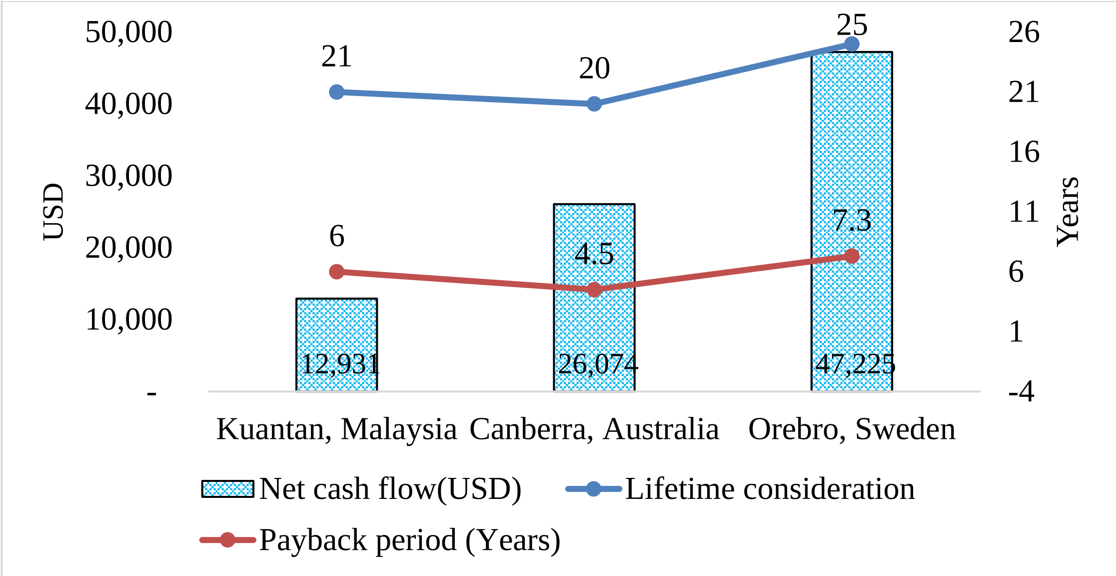


Figure 4.31 Comparison of plant lifetime, payback period and net cash flow

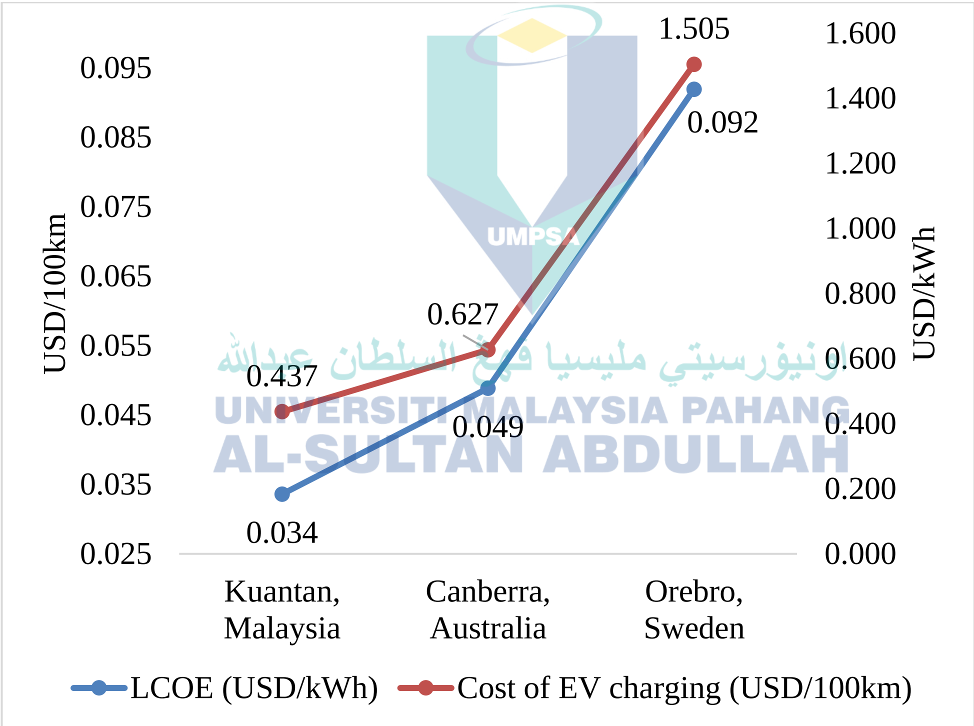


Figure 4.32 Comparison of LCOE and Cost of EV charging

Figure 4.34 compares the net GHG emission savings from the BIPV plant due to energy generation and by use of EV over the lifetime. Australian case proved to be the best in terms of GHG savings as the grid emission factor is highest followed by Malaysian scenario. It can be observed that Swedish case shows least GHG emission savings due to the country dependency on energy through renewable source.

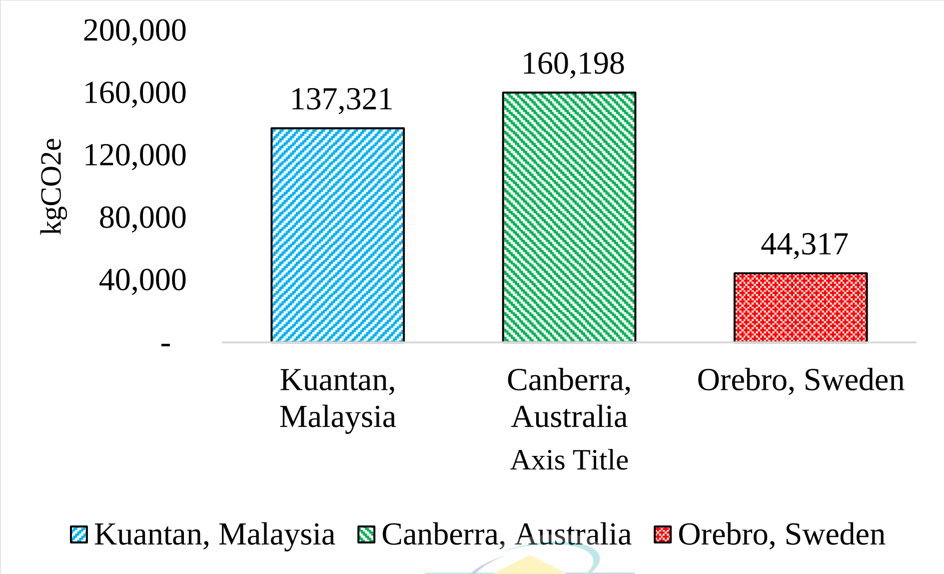


Figure 4.33 Comparison of GHG emission savings in $kgCO_2e$

Across the studies, optimal system design emerged as highly dependent on location and climate. In Malaysia's hot, humid climate, a system without battery backup might suffice. Conversely, Sweden's cold, snowy conditions necessitate battery backup for year-round household energy security. Therefore, considering energy, economic, and environmental assessments, Australian scenario appear most favorable for such systems.

CHAPTER 5

CONCLUSION

This research investigated the use of building-integrated photovoltaics (BIPV) with electric vehicle (EV) charging in three different climates: tropical (Malaysia), humid continental (Australia), and maritime temperate (Sweden). The goal was to achieve net zero energy buildings and net zero transportation, which contribute to Sustainable Development Goals (SDGs).

It was discovered that each nation has various climatic characteristics, demand profiles, and driving habits. As a result, each case's PV system design was unique. While the grid-connected BIPV system was created in Malaysia with and without energy storage, the BIPV system in Australia was designed, assessed for three distinct orientations, and optimised to optimal energy utilisation. Due to snow in the winter, Sweden's PV system was designed and evaluated with three alternative slope and azimuth configurations using monofacial and bifacial panels to satisfy energy demand. To determine which nation has the most potential to fulfil the SDGs 7 and 11, all of the aforementioned were assessed for their impacts on the energy, economics and environment.

In Malaysian context, 5.6kWp grid connected system without battery backup was most feasible in terms of 3E analysis have annual energy generation of 8.05MWh as battery losses was avoided and have higher PR and CUF of 79.78% and 16.4% respectively. Economically, LCOE was 0.16RM/kWh, lower payback period of 6 years, lower EV charging cost 2.08RM/100km and environmentally, estimated GHG savings of 137,321kgCO_2e over period of 21 years which was highest compared to same size BIPV systems with battery backup.

While in Australian case, roof facing NNW (North of north west) was found to generate maximum energy of 8.56MWh by the 4.9kWp BIPV system which was sufficient to meet residential load and EV charging load. Peformance ratio(PR) of the system was found to be 81.7% and CUF of 20.08%. Economic analysis of the proposed cases showed that BIPV with EV charging has a payback period of 4.46 years and a levelized cost of energy (LCOE) of 0.74 AUD/kWh. The cost of EV charging and operating is nearly negligible for both the systems, at an average of AUD 0.94/100km. This compares to an average cost of AUD 7.7/100km for a gasoline car. GHG emission savings from the BIPV system has significant impact compared to same energy generated by coal plant, estimated to reduce 160,198 kgCO_2e over the lifetime.

In Swedish context, 10kWp PV system with monofacial and bifacial panels was studied to achieve the maximum energy output as during winters there is snow and lesser sunlight hours. Due to that, grid dependency cannot be avoided as PV system output was not sufficient. However, results shows that energy generation of bifacial panels was 10% higher than monofacial panels. At the same azimuth, bifacial panels performed better at a greater slope of 45°, generated annual energy of 9.59MWh, but monofacial panels performed better at a 30° slope with 8.48MWh annual energy generation. PR of bifacial PV plant was ranged between 88% to 92% whereas monofacial PV plant PR was found to be 79% approximately. In terms of economics, eventhough bifacial panels were expensive, it was found to be feasible when long term net cash flow generated was highest. On the otherhand, LCOE of 0.8988SEK/kWh and cost of EV charging 0.1471SEK/km was lesser in monofacial PV plant. Environmentally, due to low grid emission factor, GHG reduction due to transportation was higher compared to PV system as grid emission factor for Sweden very low.

The research have also demonstrated that BIPV with EV charging stations has potential economic and environmental performance. The results of this research suggest that BIPV with EV charging can be a feasible way to achieve net zero energy buildings and net zero transportation in different climates. However, the specific design of the PV system will need to be tailored to the specific conditions of each country.

Also, the study on BIPV with EV charging systems in Malaysia, Australia, and Sweden have shown that these systems have the potential to contribute to the following sustainable development goals:

- SDG 7: Affordable and clean energy. BIPV systems can help to reduce reliance on fossil fuels and provide clean energy for homes and businesses.
- SDG 13: Climate action. BIPV systems can help to reduce greenhouse gas emissions and mitigate climate change.

- SDG 9: Industry, innovation, and infrastructure. BIPV systems can help to promote sustainable industrialization and infrastructure development.
- SDG 11: Sustainable cities and communities. BIPV systems can help to make cities more sustainable by reducing energy consumption and improving air quality.
- SDG 12: Responsible consumption and production. BIPV systems can help to promote sustainable consumption and production patterns by reducing waste and pollution.

Overall, the research points to the possibility of a large contribution to sustainable development from BIPV with EV charging infrastructure. However, this study's scope was confined to BIPV system modelling and optimisation for EV charging and everyday household energy needs. Therefore, utilising the mathematical framework provided in previous publications, the study's future focus may include integrating household energy management systems for the optimisation of the suggested system.

Limitations and future scope of the research

The process presented in considered a case study of a Swedish household with following limitations. However, the methodology presented can be implemented to other countries as well using country specific input data.

I. Input data for the simulation work depends on the data available through various literatures has been presented in table 4.26.

II. Energy analysis has been conducted based on pre-defined losses in the software output which may vary based on actual conditions.

III. Cost of the system has been taken from online sources for economic analysis which may affect accuracy of the results. The inflation rate has been excluded in the economic analysis.

IV. Fuel price is dynamic in nature and usually changes over time. In this study, fuel price has been considered based on specific date and time and considered contact for the lifetime.

V. Environmental GHG emission reduction is based on the result achieved through software simulation; actual results may vary. Result in this paper could be used as a benchmarking for further research.

VI. The limitation of the study includes the Greenhouse gases emitted during the fabrication of PV modules cells, BOS and during transportation and disposal are not considered here.

VII. Cost of EV has been excluded.

VIII. Energy management of the PV system with EV charging has been excluded

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APPENDIX A : LIST OF PUBLICATIONS

1. Khan, S., Sudhakar, K., & bin Yusof, M. H. (2023). Building integrated photovoltaics powered electric vehicle charging with energy storage for residential building: Design, simulation, and assessment. *Journal of Energy Storage*, *63*, 107050. https://doi.org/10.1016/J.EST.2023.107050

2. Khan, S., Sudhakar, K., Yusof, M. H. bin, Azmi, W. H., & Ali, H. M. (2023). Roof integrated photovoltaic for electric vehicle charging towards net zero residential buildings in Australia. *Energy for Sustainable Development*, *73*, 340–354. https://doi.org/10.1016/J.ESD.2023.02.005

3. Khan, S., Sudhakar, K., & Yusof, M. H. bin. (2023). Comparison of Mono and Bifacial Modules for Building Integration and electric vehicle Charging: A Case Study in Sweden. *Energy Conversion and Management: X*, 100420. https://doi.org/10.1016/J.ECMX.2023.100420

4. Khan, S., Sudhakar, K., & Hazwan Bin Yusof, M. (2022). Techno-Environmental Analysis of Facade Integrated Photovoltaics and Electric Vehicle Charging for University Building. *Mathematical Problems in engineering*, *2022*. https://doi.org/10.1155/2022/7186009

5. Khan, S., Sundaram, S., Sudhakar, K., & Hazwan Bin Yusof, M. (2023). Review of Building Integrated Photovoltaics System for Electric Vehicle Charging. *The Chemical Record*, (Accepted)

APPENDIX B : REVIEW OF PHOTOVOLTAIC TECHNOLOGY

Solar cells are usually given the name of the semiconducting material that they are composed from. In order to absorb sunlight, these materials must possess qualities. Solar cells are divided into three generations:

Table B.1 Generations of solar cell (Pastuszak & Węgierek, 2022)

1st Generation (Wafer based) and year	2nd Generation (Thin film) and year	3rd Generation and year	4th Generation (under development)
• Monocrystalline Silicon , Year 1918 (Müller & Friedrich, 2005) • Polycrystalline silicon - Year 1954 (Photovolt & Green, 2005)	• Amorphous silicon (a-si) – Year 1990(Zou et al., 2010) • Cadmium telluride (CdTe) – Year 1972 (Romeo & Artegiani, 2021) • Copper indium gallium selenide (CIGS) – Year 1988(Rau & Schock, 2005) • Copper zinc tin sulfide (CZTS) – Year 1988(K. Ito & Nakazawa, 1988) • Gallium indium phosphorus (GIP) – year 1959(Weinberg et al., 1986) • Gallium arsenide (Ga-As) – Year 1965(Andreev, 2012)	• Dye-Sensitized solar cell - Year 1991 (Çakar et al., 2022) • Quantum dot PV – Year 2011 (NREL, 2013) • Perovskite solar cells – Year 2006 (Ozdemir, 2022)	• Carbon nanotube • Graphene and its derivatives • Metal nanoparticles and metal oxides

First generation

The first generation of photovoltaic cells are made of materials made of thick crystalline layers of silicon (Si). Monocrystalline and polycrystalline silicon, as well as single III-V junctions (GaAs), are included in this generation(GaAs)(Richter et al., 2013; Suman et al., 2020). The most widely utilized material for commercial applications is silicon (Si), and products based on silicon account for about 90% of the photovoltaic solar cell market (Sampaio & González, 2017).

Monocrystalline silicon solar cells are created by growing Si blocks from tiny monocrystalline silicon seeds and then cutting them into monocrystalline silicon wafers via the Czochralski technique. Monocrystalline material is extensively utilized because it is more efficient than multicrystalline material. Stringent material purity standards, high material consumption during cell manufacture, cell manufacturing methods, and limited module sizes made of these cells are key technological obstacles connected with monocrystalline silicon. Monocrystalline silicon solar panels are characterized by an efficiency range of 15% to 24%, a band gap of approximately 1.1 eV, and a lifespan of around 25 years. These panels offer distinct advantages, including stability, superior performance, and extended longevity. However, they also come with certain limitations, such as higher manufacturing costs, increased temperature sensitivity, potential absorption issues, and material loss(Pastuszak & Węgierek, 2022).

High-purity silicon is melted and crystallized in a large crucible using a directed solidification method to generate multicrystalline silicon blocks. Because there is no reference crystal orientation in this technique, as there is in the Czochralski process, silicon material with various orientations is generated. P-type Si substrates doped with boron are the most often utilized base material for solar cells. In comparison to p-type substrates, n-type silicon substrates are utilized for the manufacturing of high-efficiency solar cells, but they bring extra technical hurdles, such as ensuring homogeneous doping along the silicon block(Goetzberger et al., 2003). Polycrystalline silicon solar panels offer an efficiency range of 10% to 18%, a band gap of approximately 1.7 eV, and an anticipated lifespan of around 14 years. They present several advantages, including a simplified manufacturing process, cost-effectiveness, reduced silicon waste, and superior absorption compared to monocrystalline silicon panels. However, they also exhibit certain limitations, such as lower efficiency and increased temperature sensitivity(Pastuszak & Węgierek, 2022).

A monocrystalline silicon wafer has a single, uniform colour, but in polycrystalline silicon, the different grains are visibly distinct. There are lattice mismatches at the grain borders, which cause many faults there. Because of the Shockley-Read-Hall recombination, polycrystalline silicon has a shorter charge-carrier lifetime than monocrystalline silicon. The lifespan of the charge carriers is shortened in materials with greater grain boundaries. As a result, the recombination rate is significantly influenced by grain size (Smets et al., 2018). The main advantage of monocrystalline cells is their high efficiency, which is nearly average around 24.4% in laboratory condition (Philipps et al., 2023).. whereas for polycrystalline silicon commercial module efficiency is 20.4(Philipps et al., 2023).

Bifacial technology

According to the National Renewable Energy Laboratory (NREL), switching from monofacial to bifacial architecture can boost the energy yield of PV power plants by up to 30% (Dullweber & Schmidt, 2016; X. Sun et al., 2018) with a moderate increase in production costs(IEA, 2021a).

The first patented bifacial solar cell design, devised by Hiroshi in 1960(Hiroshi, 1966), utilized a p+ junction on both sides of an n-type silicon wafer, with contacts attached to the cell's edge. Luque et al. were the first to introduce this design in scientific literature, recognizing its potential to significantly enhance the energy output of photovoltaic (PV) systems(Luque et al., 1980). Cuevas et al. (Cuevas et al., 1982)showed that by concurrently gathering direct and albedo radiation from the rooftop and nearby areas, a focusing device may augment albedo radiation, permitting a 50% increase in electric power output.As a result, it was shown that bifacial solar cells can lower area-related costs for PV systems while increasing the power density of PV modules relative to monofacial cells (Kreinin et al., 2011).

Even though similar cell designs were later studied, bifacial photovoltaics did not gain widespread acceptance until the PERC cells were manufactured on an industrial scale. PERC technology was created in the lab in 1989 to overcome the following two restrictions(Blakers et al., 1989) : (i) Rear-side recombination at the full-area aluminum back contact (ii) Partial absorption of infrared light at the rear, by introducing localized metal contacts and partial passivation at the rear side of the cells. But before process advancements allowed PERC cells to be produced in large quantities, 25 years of development were required. Al-BSF (Aluminum back surface field) cells are being swiftly replaced by monofacial PERC cells in industrial manufacture(IEA, 2021a).

As to the International Technology Roadmap for PV (ITRPV), photovoltaics (PV) accounted for 50% of the global PV market in 2019 and are expected to reach around 80% in the upcoming years(VDMA - Photovoltaic Equipment, 2020). Monofacial PERC is very close to its maximum efficiency limit of 22.5%, nevertheless. Since the potential for bifaciality (rear efficiency divided by front efficiency) in PERC cells is around 80%, one option to increase their output power is to make them bifacial (PERC+)(Deline et al., 2019). Changing the monofacial production line to bifacial has no substantial impact on manufacturing costs (IEA, 2021a).

It has been proposed to employ bifacial PV modules not just for utility-scale power production systems, but also for agriculture, water, and building settings(Kopecek et al., 2021; Mouhib et al., 2022). The bifacial modules have previously been proposed for usage in buildings in a variety of configurations, including vertically placed in conjunction with green roofs(Baumann et al., 2019), integrated on the roof to boost power generation in countries with limited land (Mehadi et al., 2021) or as solar shading (Yoo & Choi, 2021). Chen et al. (M. Chen et al., 2021)investigated the integration as skylight and curtain wall as well as the relationship between bifacial gain and internal daylighting.

When compared to mono-facial PV devices, bifacial PV modules can enhance performance by 10% and 15% for 25 and 45 tilt angles, respectively. Bifacial PV modules are ideal for use as a building envelope due to their increased power generation and unique power generating properties(M. Chen et al., 2021).

Bifacial PV modules are largely studied for their outdoor performance(Park et al., 2019)(Park et al., 2019). Corrado Comparotto (Comparotto et al., 2014)examined how well an n-type bifacial PV module performed outside at various heights. If the module was 64 cm above the ground, the power of irradiance was 9.7% higher than if it was at 0 cm above the ground. A few researchers were integrating bifacial photovoltaic modules with structural elements. Green roofs and bifacial PV modules were integrated by Thomas Baumann. When comparing the yearly power output of the bifacial PV module mounted vertically in the east-west direction to the monofacial module in the south direction, the reflectance of the ground and shadow is less than 0.2 (Baumann et al., 2019). Yoo performed optimization of a BIPV system using bifacial solar cells. When the BIPV was utilized as a shade device, it was discovered that bifacial PV modules improved power by 14%(Yoo, 2019).

The need for additional research is particularly clear in high-albedo settings(Andrews & Pearce, 2013) where little work has focused on bifacial modules, including both artificial environments(Brennan et al., 2014), (e.g. white commercial rooftops(Muehleisen et al., 2021) or low-concentration substrates(Hollman & Pearce, 2021)), and natural environments (e.g. desert(Baloch et al., 2020)) and snow covered terrain(Bembe et al., 2018)). Due to the albedo effect, areas with a lot of snow may be even more appealing for bifacial PV applications. A major factor in overall bifacial gain (Marion, 2019; Taomoto et al., 2016) and there are some signs that snow enhanced albedo speeds up snow clearing due to backside surface heating (Burnham et al., 2019) are the increased amounts of incident light reflected upward. The number of solar projects being installed in snowy environments has led to an increase in interest in this area (Andrews et al., 2013; Andrews & Pearce, 2012; Marion, 2019; Townsend & Powers, 2011). This is because financing large-scale PV projects requires accurate snow (Hashemi et al., 2020; Hosseini et al., 2018; Noord et al., 2021). Snow has the ability to totally obstruct solar radiation reaching the PV panel or module, hence its presence affects how much power is produced. Double digit yearly energy losses can arise from ill-designed systems, such as ones that permit ground interference that keeps snow from sliding off modules(Heidari et al., 2015).

Second generation

Thin-film technologies, also referred to as the second-generation PV technology. Compared to the wafers that serve as the foundation for first-generation PV, these solar cells are comprised of significantly thinner films. As a less expensive alternative to crystalline silicon cells, thin-film photovoltaic cells based on CdTe, copper indium gallium selenide (CIGS) or amorphous silicon have been produced. At the disadvantage of reduced efficiency, they offer higher mechanical properties suitable for versatile applications(Smets et al., 2018). Despite the fact that the first generation of solar cells was an example of microelectronics, the development of thin films demanded new methods of growth, which allowed the industry to embrace other disciplines like electrochemistry(Kuczyńska-Łażewska et al., 2021). They have several advantages such as less loss in performance under overcast cloudy climatic conditions and partial shading from obstacles (Gottschalg et al., 2013; Taraba et al., 2019), employ lower semiconductor material and hence lower production cost, manufacture of transparent or translucent modules using laser scribing (Sebastian & Sivaramakrishan, 1991; A. V. Shah et al., 2004).

Amorphous solar cells made on amorphous silicon are less expensive and more commonly available. The efficiency of amorphous silicon solar cells has a theoretical limit of about 15% and realized efficiencies are now up around 6 or 7%. (Dixon, 1981). The maximum advantage of these cells is that amorphous silicon can be deposited on a wide range of substrates, both rigid and flexible. The panels made from amorphous silicon solar cells come in a variety of shapes, such as roof tiles, which can replace normal brick tiles in a solar roof (Kalogirou, 2009).

CdTe-based PV is considered a thin-film technology because the active layers are just a few microns thick, or about a tenth the diameter of a human hair. Cadmium telluride (CdTe) is a single-junction solar cell having 1.45 eV bandgap energy. It is a direct bandgap semiconductor nearly ideal for optimal conversion of solar radiation into electricity. The record efficiency for a laboratory CdTe solar cell is 22.1% by First Solar. First Solar also reported its average commercial module efficiency to be approximately 18% at the end of 2020 (Department of Energy, 2021a). The major limitations of CdTe cells are its instability and toxicity of cadmium which makes it less suitable for PV application(Garcia, 2021).

CIGS has high light absorptivity and 0.5 μm of CIGS can absorb 90% of the solar spectrum (Kazmerski et al., 2008). CIGS (in-film panels) have high light absorptivity, can absorb up to 90% of the solar spectrum, have a high capacity and stability for generating electricity, are inexpensive to produce, and have a quick energy recovery time (Kazmerski et al., 2008). AM1.5 cell efficiencies for CIGS of up to 22.6 percent, as certified in 2016, are the result of ongoing research and development (Jackson et al., 2016). (CIGS-based PV technology has not yet reached its full potential despite its high efficiency level. An efficiency level close to 30% would be technically possible if all loss mechanisms were addressed simultaneously. The CIGS solar cell efficiency of 22.6 percent is a global record for any thin-film technology, surpassing that of polycrystalline silicon (21.9 percent) (Siebentritt, 2011). Preliminary data has shown that CIGS has lesser Global warming potential (GWP) than other technologies. (Average values for GWP CIGS are 23.92 gCO_2eq/kWh, for a-Si is 31.5 gCO_2eq/kWh, for CdTe is 24.1 gCO_2eq/kWh, for Mono-Si, the average values for GWP is 64.8 $gCO_2eq/$ kWh and for poly-si is 54.6 gCO_2eq/kWh(Lunardi et al., 2021) . Penetration of thin film is currently 5% of the total PV market share (Alice, 2020).

Scientific community has recently been very interested in absorber materials that are non-toxic, affordable, and readily available. The quaternary semiconductor Cu_2ZnSnS_4 (CZTS) has become a viable choice for solar absorber components. Each component of CZTS is inexpensive, less harmful, and readily available on Earth. To deposit the CZTS thin films, a variety of methods, including vacuum and non-vacuum based approaches, have been investigated. The maximum efficiency achieved by this pure CZTS thin film solar cell using kesterite as the base is 8.4%. This efficiency, meanwhile, pales in comparison to the CIS and CIGS thin film solar cells, which are now commercially available and have conversion efficiencies above 15%(Suryawanshi et al., 2013).

With the exception of having alternating elements' atoms at its lattice locations, GaAs has a zinc blende crystal structure, which is comparable to the cubic crystal structure of diamond. In GaAs, every Ga atom has four As neighbors, whereas every As atom has four Ga neighbors, in contrast to c-Si, where each Si atom has four neighbors of the same sort. GaAs is substantially denser than silicon, having a density of 5.3176 g/cm3 (Si: 543.07 pm, 2.3290 g/cm^3), and a slightly higher lattice constant of 565.35 pm. Wide bandgap materials, like silicon, with a bandgap of 1.12 eV, have the added benefit of becoming more semi-conductive at higher temperatures. The thermal production of carriers overtakes the purposefully doped amount of carriers at higher temperatures. As a result, GaAs solar cells are now the norm for use in extreme temperature ranges(Brozel et al., 1996; Ghandhi, 1994). Gallium is far less prevalent in the Earth's crust than silicon, which is extremely plentiful(Smets et al., 2018). GaAs thus is an extremely pricey material. Arsenic is very poisonous, and there is considerable evidence that GaAs may cause cancer in humans(Tanaka, 2004). Sasaki et al. reported an efficiency of 45% for CPV using solar cells built for concentrator applications, such as InGaP/GaAs/InGaAs inverted triple-junction (Sasaki et al., 2013).

Third generation

The third generation of solar cells—which also includes tandem, perovskite, dye-sensitized, organic, and emerging concepts—represents a range of approaches, from inexpensive low-efficiency systems (dye-sensitized, organic solar cells) to pricey high-efficiency systems (III-V multi-junction cells), for uses ranging from building integration to space applications. Because of their low commercial penetration, third-generation photovoltaic cells are frequently referred to as "emerging ideas," despite the fact that some of them have been studied for more than 25 years(Dunlap-Shohl et al., 2019).

Dye-sensitized solar cells are inexpensive and can turn solar energy into electricity. It corresponds to the third iteration of solar cells, which are concerned with environmental friendliness and ease of fabrication(Ambapuram et al., 2022). In essence, the DSSC structure is made up of three sandwich-like components: the dye-sensitized photoanode, the counter electrode, and the redox electrolyte. Charge injection and light absorption are carried out by the dye-sensitized photoanode, redox pair reduction by the counter electrode, and dye reduction by the redox electrolyte or hole transporting substance(H. Peng et al., 2017). The counter electrode must exhibit greater conductivity, superior catalytic activity for electrolyte regeneration, and excellent stability performance as a feature. For the creation of counter electrodes, platinum is a well-researched electrocatalytic active material that has shown greater power conversion efficacy. Its restricted stability and greater expense prevent its wide range of applications(Ambapuram et al., 2022). The efficiency of current DSSCs has reached up to to 12% by using Ru(II) dyes, but this is still less than the 20–30% efficiency provided by first- and second-generation solar cells, such as other thin-film solar cells and Si-based solar cells(K. Sharma et al., 2018).

As a result of their size-dependent optoelectronic characteristics, quantum dots (QDs) have the potential to be solar energy conversion agents. Due to simple and inexpensive production methods, QD-sensitized solar cells (QDSSCs) are prospective contenders to satisfy the rising need for sustainable energy. Several other QD types, including CdS/CdSe, CuInS2, PbS, Zn-Cu-In-Se, and perovskite QDs, have been investigated (PQDs). Due to their performance, low cost, and ease of manufacturing, Cd chalcogenide-based sensitizers, particularly CdS and CdSe (CdTe), are the favoured options for solar cell devices out of all QDs. Despite its immense potential, implementing solar energy on a broader scale is extremely difficult due to the price and efficiency of existing photovoltaic cells (PVs)(N. Ali et al., 2016). According to research from NREL, quantum-dot solar cells can theoretically achieve maximum conversion efficiencies of up to 66% under concentrated sunlight, which is twice what is possible with conventional solar cells at this time (31% for first- and second-generation solar cells currently on the market)(NREL, 2013).

Fourth generation

Fourth-generation photovoltaic cells are also known as hybrid inorganic cells because they combine the affordability and flexibility of polymer thin films with the stability of organic nanostructures such as metal nanoparticles and metal oxides, carbon nanotubes, graphene, and its derivatives. These objects, often known as "nano-photovoltaics," may reflect photovoltaics' bright future(Wu et al., 2020).

Among the new-generation photovoltaic devices that convert solar energy into electricity, organic solar cells (OSCs) are being widely investigated owing to their low production cost, facile fabrication procedure, abundance of raw materials, easy scalability, lightweight, excellent flexibility and environmentally friendly nature (Gusain et al., 2019; S. L. Lee et al., 2020; X. Li et al., 2021; D. Liu et al., 2021; M. N. Shah et al., 2021; Shoyiga et al., 2021).

Despite having a lower projected cost of < \$0.07/Wp relative to < \$0.35/Wp for commercially available silicon solar cells (Riede et al., 2021), the power conversion efficiency (PCE) of state-of-the-art OSCs (18–25%)(Cho et al., 2020; Rollet, 2020; Salim et al., 2020) is still lower than that of commercially available silicon-based solar cells (above 26%) (Andreani et al., 2019). In addition, when compared with silicon solar cells, OSCs suffer from poor long-term environmental stability, which limits their commercialization(Burlingame et al., 2020; L. X. Chen, 2019; Duan & Uddin, 2020; Y. Wang et al., 2021). Hence, this has prompted significant research interest in developing highly efficient and sustainable devices through approaches, such as incorporating novel materials into the different components of OSCs, to overcome the limitations of the commonly used traditional materials.

In this respect, carbon-based materials, such as graphitic carbon nitride, carbon quantum dots, carbon nanotubes (CNTs) and graphene(Hu et al., 2020; Jeon et al., 2019; Nguyen et al., 2019; Pan et al., 2021; Qin et al., 2020; Shin et al., 2021; Subramanyam et al., 2019; Vercelli, 2021), have attracted considerable research attention due to their unique physicochemical properties, low-cost, natural abundance of carbon, non-toxicity and compatibility with large-scale solution synthesis (Delacou et al., 2017)). Among these, CNTs are more appealing owing to their large specific surface area, tunable band gap, high optical transmittance in the visible region, competitive electrical conductivity, high charge carrier mobility, excellent flexibility and superior mechanical, thermal and chemical stability(D. Khan et al., 2018; Oseni et al., 2018).

Graphene:

Graphene is a carbon-based material whose atoms are organized in a hexagonal pattern. It has a graphite-like structure, yet its density is the same as carbon fiber, and it is up to five times lighter than aluminium. This nanomaterial is classified as 2D since its thickness is as thin as a carbon atom. On the other hand, despite its thinness, it has a strength of up to 200 times that of steel. To the list of graphene's properties, we must add that it is a good conductor of heat and electricity, as well as transparent, waterproof, and flexible.

Researchers have examined the efficiency of graphene in solar cells by using it on a thin film-like photovoltaic cell known as a "dye-sensitized solar cell." The scientists changed the solar cell by adding a sheet of graphene and covering it with indium tin oxide and plastic transparent backing(Ahmed, 2021) .

Since the properties of graphene are fundamentally related to its fabrication process, a judicious choice of methods is essential for targeted applications. In particular, highly conductive graphene is suitable for use in flexible photovoltaic devices, and its high compatibility with metal oxides, metallic compounds, and conductive polymers makes it suitable for use as a selective charge-taking element and electrode interlayer material(X. Li et al., 2010).

In the past two decades, graphene has been combined with the concept of photovoltaic material and is showing a significant role as a transparent electrode, hole/electron transport material, and interfacial buffer layer in solar cell devices. We can distinguish several types of graphene-based solar cells, including organic bulk heterojunction (BHJ) cells, dye-sensitized cells, and perovskite cells. The energy conversion efficiency exceeded 20.3% for graphene-based perovskite solar cells and reached 10% for BHJ organic solar cells. In addition to its function of extracting and transporting charge to the electrodes, graphene plays another unique role—it protects the device from environmental degradation through its packed 2D lattice structure and ensures the long-term environmental stability of photovoltaic devices(Geim & Novoselov, 2007). For PV technology, graphene offers a lot more because of its flexibility, environmental stability, low electrical resistivity, and photocatalytic features, while having to be carefully and deliberately designed for the targeted applications and specific requirements(Eswaraiah et al., 2011; Mahmoudi et al., 2018).

One problem for graphene application is the absence of a simpler, more reliable way to deposit a well-ordered monolayer with low-cost flakes on target substrates having various surface properties. The other problem is the adhesion of the deposited graphene thin film, a subject that has not yet been studied properly. Graphene’s major disadvantage is its poor hydrophilicity, which negatively affects the design of devices processed in solution, but that fact may be overcome through modifying the surface by non-covalent chemical functionalization(Pastuszak & Węgierek, 2022). The growing interest in BIPV systems has contributed to the overall development of photovoltaic technology, which has led to lower costs, increasing the feasibility of investment. Most of the standard second-generation technologies show efficiencies of 20–25%, and while they are expensive, the cost of silicon cells has come down and it is the improvement of silicon technologies that is now one of the key research directions(D. Sharma et al., 2021) .

Carbon nanotubes

CNTs, one of the stiffest and strongest materials ever discovered, consist of a cylindrical nanostructure of hexagonally oriented carbon atoms and can be classified as either semiconducting or metallic depending on their length, diameter and arrangement of hexagonal rings (Alturaif et al., 2014).

CNTs can be deposited onto various components of organic solar cells by using different techniques, such as spray coating, dip coating, spin coating, sputtering and CVD(D. Khan et al., 2018). However, the insolubility in organic solvents, entanglement and poor alignment of CNTs, in addition to the presence of metal impurities, are the main limitations for the incorporation of CNTs into various layers of OSCs. These limitations cause unfavourable short-circuits, surface charge carrier trapping and reduction in charge carrier mobility, thereby increasing leakage current and recombination pathways(Oseni et al., 2018). CNTs, are more appealing due to their solution process ability, non-toxicity, the natural abundance of carbon, low-cost, competitive optoelectronic properties and excellent stability. However, the efficiency of CNT-based OSCs is still relatively lower than that of the state-of-the-art OSCs fabricated with traditional materials due to drawbacks, such as the relatively low visible region optical transparency of CNT-based electrodes and charge transport layers, which limit the passage of incoming photons to the active layer, thereby reducing the exciton generation rate, and hence lowering the photo generation of current(Muchuweni et al., 2022).

APPENDIX C : REVIEW E-MOBILITY & EV CHARGING

Electric mobility is a subset of "sustainable mobility," which refers to a group of transportation methods (and generally, an urban mobility system) that can lessen the negative effects that private vehicles have on the environment, society, and the economy (such as noise and air pollution, traffic jams and the degradation of urban areas due to the displacement of pedestrians by vehicles). Since the transport sector accounts for 27% of global final energy consumption there are great reasons for energy efficiency via electrification. Researchers have stressed the benefits of transitioning from traditional gasoline automobiles to EVs in order to minimize greenhouse gas emissions from the transportation industry. The paradigm shifts from conventional to electric cars has several environmental and economic benefits. EVs produce no exhaust emissions, which improves air quality and reduces health hazards; they also help the country lessen its dependency on foreign fossil fuels(Robinson et al., 2014). EVs are exhaust-free vehicles, in contrast to conventional automobiles. They emit less pollution than gasoline-powered automobiles, even when the electricity they require comes from fossil fuels. As a result, EVs are a preferred substitute for people who want to reduce their carbon footprint(Waseem et al., 2023). One of the most significant barriers to e-mobility adoption is a lack of adequate infrastructure, such as charging stations. However, as the number of electric cars grows, the need for charging and energy rises too. Management of charging patterns to reduce GHG emissions from electricity generation (as well as stress on distribution networks) will become increasingly more essential as the number of BEVs grows in the future(EEA, 2016) . In order to handle unidirectional power flows from the high-voltage transmission grid to customers, low-voltage (LV) or medium-voltage (MV) distribution grids are primarily used to connect PV installations and EV charging points. In order to handle the voltage drop along the distribution feeders before reaching the customer, the distribution grid was created(Bollen & Hassan, 2011). EV charging loads have a detrimental influence on numerous distribution network properties, including voltage profile and peak load [40]. Charging the EV via the electrical grid places an additional stress on the utility, especially during high demand periods(Kelman, 2010; Lindgren et al., 2014). Regional studies have been made regarding the impact of EV charging on the electric distribution system for several regions and countries, e.g.

Netherlands (Lojowska et al., 2012), Portugal(Lopes et al., 2011), Germany (L. Zhao et al., 2010), Belgium (Clement-Nyns et al., 2010), United States(Sortomme et al., 2011) and Canada(Kelly et al., 2009).

Increased demands, like those required for EV charging, cause the feeders' current to increase and the voltage reduces as a result (Deilami et al., 2011). Previous studies in the field have only examined one or a small number of low voltage(LV) grids (Dallmer-Zerbe et al., 2014; Lim et al., 2015; Van Der Burgt et al., 2015). In (Dallmer-Zerbe et al., 2014), To prevent overstepping the voltage boundaries in an LV grid, active power limitation of EV charging and reactive power regulation were applied. In (Van Der Burgt et al., 2015), a tool was created to simulate the effects of distributed generation (DG) and EV charging (3.7 and 22 kW) on LV grids. Few studies suggest that the most typical method for charging EV's is to charge them at home using level 1 or level 2 chargers. Many nations provide financial assistance to EV buyers who want to install a Level 2 charger in their residence. If a driver has access to a designated, off-street parking space, usually a driveway or garage, they can install home charging. When BEVs are charged during periods when the supply of renewable electricity exceeds the demand (for example, in the middle of the day when solar photovoltaic (PV) generation is available), this excess will be integrated into the grid, resulting in a grid mix with lower GHG and air pollutant emissions on average(EEA, 2016), however BEV charging at night, which coincides with peaks in other energy consumption, will frequently have significant GHG emissions since the additional demand is frequently satisfied by carbon-intensive sources of electricity like gas- and oil-fired power stations(electrive.com, 2016). According to a survey on energy efficiency and renewable energy in the USA, most EV charging sessions took place in residential areas, and around 80% of the established charging infrastructure is for home charging(Franke & Krems, 2013; Wood et al., 2018). Unfavorable impact of EV charging loads on different parameters of the distribution network like voltage profile (Geske et al., 2010) and peak load (McCarthy Dean & Wolfs Peter, 2010) has been studied. Utilizing full grid capacity to charge an EV will affect the usage of other appliances used in household at the same time. To overcome the issue of extra burden on grid, smart charging can be proposed to charge vehicle in non-peak hours or BESS can be used to make the EV charging independent of grid.

Levels of EV Charging

Different organizations, including AIS, SAE, and IEC, have governed EV charging. EV charger specifications has been defined in standards SAEJ1772 and IEC62196 (IEC 62196-1:2014, 2014; SAE, 2017) which specifies that dedicated EV socket-outlet and plug must be permanently installed with control and protection function. A charging Level refers to the voltage and power of the charging system. The greater the voltage, the more power the system can send and, as a result, the faster it can charge. Table 2.8 below summarizes different level voltage and power output along with charging time.

Table C.1 : EV charging level (IEC: Geneva, 2010)

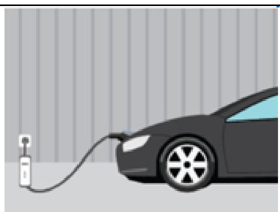
	Charger Level	Voltage Power	Charging Time (Hr)	Range Miles/hour	Primary Location
	Level 1	120V 1.3~2.4kW, 1 Phase On Board	20 to 22	2 to 5	Residential
	Level 2 (AC)	240V 6.2~7.7kW 1Ph or 21kW 3Ph On Board	6 to 8	10 to 30	Residential Public, Work
	DC Fast Charging	480-600V 50~350 kW Off Board,	0.2 to 0.5	150 to 350+	Public

Table C.2 Pros and Cons of EV charging level (Savari et al., 2023)

Level	Pros	Cons
1	Affordable solution may provide drivers a full charge overnight for daily commute. No need for expert installations or updates.	Longer charging time
2	Faster charging than Level 1. It takes about 2-4 hours for a full charge with a rate of up to 25 miles per hour.	Requires installation of a 240V circuit by expert. May involve an upgrade your existing electrical panel.
3	Excellent for longer road trips or rapid charging when traveling. It's the quickest charging option available.	Non compatibility with some EV port. Higher implementation and electricity costs.

Type of Chargers

Rapid Chargers

The quickest way to charge an EV is via a rapid charger, which is frequently available at highway rest stops or areas near major thoroughfares. Fast DC chargers use either the CHAdeMO or CCS charging protocols and deliver power at 50 kW (125A). Depending on the battery capacity and initial state of charge, both connections can normally charge an EV to 80% capacity in 20 minutes to an hour. Power output from ultra-rapid DC chargers is 100 kW or more. Although alternative maximum speeds between these numbers are feasible, these are commonly either 100 kW, 150 kW, or 350 kW. The battery capacity of more recent EVs have increased, but these quick charge points represent the next generation and can maintain shorter recharging times.

Figure C.1 Types of rapid chargers

Fast Chargers

Rapid chargers are usually rated at 7 kW for 1 phase system or 22 kW for 3 phase system. Although the great majority of fast chargers use AC power, some networks are installing 25 kW DC chargers with CCS or CHAdeMO interfaces(Zapmap, 2023). Charging duration varies depending on unit power and EV OBC, however a 7-kW charger can recharge a compatible EV with a 40 kWh battery in 4-6 hours, while a 22 kW charger would recharge it in 1-2 hours.

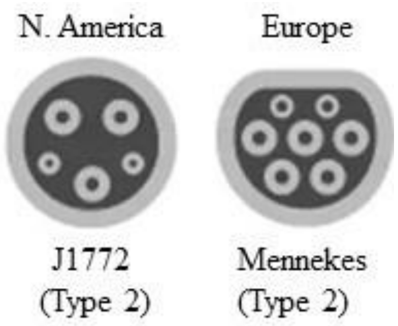


Figure C.2 Type 2 charger's socket

Slow charger

Most slow charging equipment have a rating of up to 3 kW, which is a rounded figure 2.7 that covers most slow chargers. Slow charging is really done between 2.3 to 6 kW, while the most frequent slow chargers are rated at 3.6 kW(16A)(Zapmap, 2023). Depending on the charging device and the EV being charged, charging periods vary, but a full charge on a 3-kW unit will normally take 6 to 12 hours. Many owners charge their electric cars overnight at home using the highly popular slow charging technique.

Figure C.3 Type 1 charger

Mode of Charging

The charging MODE refers to the electronic communication between the vehicle and the power supply. The purpose of the communication is to avoid overcharging and to ensure safety in general.

Table C.3 Mode of Charging (BEAMA, 2015; IEC: Geneva, 2010)

Charging Mode	Description	Maximum Current and Voltage, Connector
Mode 1	conductive connection between a standard socket-outlet of an AC supply network and EV without communication or additional safety features	230V AC, 13A from a BS1363 3 pin domestic socket-outlet, 16 A BS EN 60309-2 socket-outlet
Mode 2	conductive connection between a standard socket-outlet of an AC supply network and EV with communication and additional safety features	230V AC, 13A or 16A from a BS1363 3 pin domestic socket-outlet, 32A A BS EN 60309-2 socket-outlet
Mode 3	conductive connection of an EV to an AC EV supply equipment permanently connected to an AC supply network with communication and additional safety features	32A and 250 V AC, 1-phase 63 A and 480 V in 3-phase. IEC 62196 Type 2 connectors
Mode 4	conductive connection of an EV to an AC or DC supply network utilizing a DC EV supply equipment, with (high-level) communication and additional safety features	Very high voltage and Current 125A, 500V Providing a rapid charge. Type 3, CHADeMO, CCS -1, CCS-2 IEC 62196-3

Table C.4 Findings EV and charging infrastructure.

Authors	Context	Findings
(Ghotge et al., 2020)	EV charging	Forecasting EV charging demand and robust adjustment of the schedule for the performance of the worst possible forecast marginally improved the effectiveness of the scheduling, reducing the peak demand by 39%.
(Hussain et al., 2019)	Storage System	Most of the literature has suggested stationary energy storage and fast charging systems to overcome challenging problem.
(Hardman et al., 2018)	EV Charging	Charging of EVs occurs at home 50–80% of the time, 15–25% of the time at the office, and 10% of the time at other places (such as a supermarket or park)
(Goldin et al., 2014)	EV Charging	The implementation of more home charging (HC) infrastructure could increase EVs' adoption rate, especially in cities.
(Peterson & Michalek, 2013)		
(Tulpule et al., 2013)	PV based charging	Confirms feasibility of PV-based infrastructure, benefits to EVs' drivers and the garage owner and the need for an optimal charging controller
(Veneri et al., 2012)	Range & Battery level	According to Veneri et al. (2012), Commuters do not exceed 50 km in 80% of the cases.
(Birnie, 2009)	Solar to Vehicle, Area of $15m^2$	The results showed that the yield energy is enough to drive EV commuters to and from work given that they live within a radius of 24 km of their work.