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Article

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Economic Feasibility of Hybrid Solar-Powered Charging Station with Battery Energy Storage System in Thailand

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ABSTRACT

Developing a public charging infrastructure is essential for the promotion of electric cars (EVs), especially in developing countries. The use of renewable energy sources (RESs), especially solar and the replacement of fossil fuels in EV charging stations has the potential to improve economic efficiency while significantly lowering greenhouse gas emissions and improving urban air quality. Therefore, the purpose of this paper is to investigate the economic feasibility of a hybrid solar photovoltaic (PV) and battery energy storage system (BESS) for environmentally friendly EV charging stations in a university campus under different EV charger utilization rates, electricity costs, and charging types. The results showed that installing a level 2 solar PV charging station at the current subsidized rate provides the most economic benefits, while installing BESS for peak shaving is the least profitable due to the high cost. The sensitivity analysis also revealed that if the cost of the BESS decreases, the IRR of the project will increase. This study aims to promote the development of technologically and environmentally feasible EV charging stations powered by RESs.

Keywords: Electric Vehicles, Solar-powered EV Charging Station, Battery Energy Storage System, Hybrid system, Utilization Rate
JEL Classifications: G0, M2, Q4

1. INTRODUCTION

The transport sector has the highest dependency on fossil fuels of any sector, and in 2021, it was responsible for 37% of the CO_2 emissions that were caused by end-use sectors (IEA, 2022). There are great expectations that electric vehicles (EVs), which are a low-CO_2 alternative to internal combustion engine vehicles (ICEVs), would minimize these emissions (Teixeira and Sodré, 2018). The shift toward EVs is accelerated by government legislation, sustainable development goals, and the net-zero emissions effort. Several countries have already begun to utilize EVs, with 6.6 million EVs sold in 2021 and 2 million EVs were sold worldwide in the first quarter of 2022, representing a 75% increase compared to the same period in 2021 (IEA, 2023). EVs also aim towards net-zero usage of nonrenewable sources including oil, gas, and coal.

As the number of EVs continues to rise, EV charging stations are required to satisfy charging needs of EV drivers (Funke et al., 2015; Zhang et al., 2018). Currently, the majority of EVs charging in Thailand is powered by electricity generated from gas and coal, both of which are substantial contributors to greenhouse gas (GHG) emissions. Renewable energy production is vital for tackling environmental concerns. The integration of renewable energy sources (RESs), mainly solar, into EV charging stations has the potential to improve their economic efficiency while significantly lowering GHG emissions, and improving urban air quality (Shafiq et al., 2022). This could offer other advantages, such as lowering the risk of local grid overloading (Khan et al., 2018), boosting self-sufficiency and enhancing energy self-consumption (Denholm et al., 2013; Gudmunds et al., 2020). Moreover, integrating battery energy storage system (BESS) into these charging stations will improve the share of solar energy provided to EVs while enhancing grid resilience to PV power's natural intermittency (Denholm et al., 2007; Badawy and Sozer, 2022; Eid et al., 2022). To fulfill the net-zero effort, the power generation required for EV charging must also come from RESs such as wind, solar. This will lead to significant reductions in coal, oil, and gas consumption by EVs.

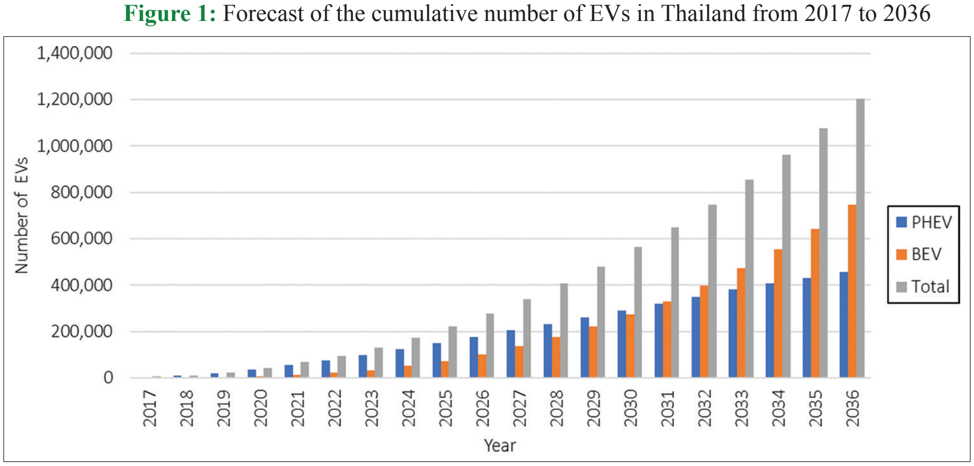
EVs are classified into three types which are battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs) (Miele et al., 2020). Common batteries used in BEVs are lithium-ion battery which have relatively higher energy and power density than other battery technologies. Basically, there are two types of EV charging stations; conductive and inductive charging system. Conductive charging systems are widely utilized as standard devices that induce power by contact. Onboard and offboard integrations are the two most common methods for supplying power to EVs. Onboard charging is mostly used for slow charging, with all charging action occurring within the vehicles, whereas off-board charging provides fast charging. The process of relocating the charger outside the vehicle is referred to as off-board charging (Mastoi et al., 2022). Example of EVs using conductive charging like Tesla Roadster, Nissan Leaf, Chevy Volt.

Currently, the most common types of EVs in Thailand are BEVs, HEVs, and PHEVs. The National Electric Vehicle Policy Committee of Thailand announced in 2021 that 30% of vehicles manufactured in Thailand by 2030 will be zero-emission vehicles (ZEVs). The "30@30" policy aims to transition Thailand to a low-carbon society and to make Thailand the region's manufacturing hub for EVs and auto parts in this region (EPPO, 2022). According to the national Energy Efficiency Plan (EPP2018), the total number of EVs is expected to reach 1.2 million by 2036 as shown in Figure 1. Approximately 50,000 EVs were registered in 2021. In order to manage power supply and EV load charging for the grid reliability, the Thai government approved a provision in 2021 to subsidize the off-peak electricity cost of 2.63 Thai baht (THB)/kWh for low priority smart EV charging at public stations. This provision applies to 24-h controlled normal charging and fast charging and will be implemented for 2 years (MEA, 2021). As of September 2022, the Electric Vehicle Association of Thailand (EVAT) reported that the country has 869 charging stations and 2,572 EV chargers. EA Anywhere company has the highest EV charging station market share (EVAT, 2022). The country's EV charging station market is anticipated to increase at a CAGR of 44.5% between 2021 and 2026, with the EV charging station industry serving as a long-term key market (LHBank, 2022).

Electric utilities are well-positioned to influence the EV industry by collaborating with other market actors to construct transportation electrification initiatives. Electric utilities provide energy to households and businesses and are responsible for metering, billing, and customer service. Due to their inherent involvement in EV infrastructure, electric utilities could play a significant role in EV charging infrastructure development. Electricity Generating Authority of Thailand (EGAT), Metropolitan Electricity Authority (MEA), and Provincial Electricity Authority (PEA) are the three major electric utilities in Thailand. EGAT is a government institution supervised by the Ministry of Energy. Both MEA and PEA are distribution utilities. MEA is responsible for the generation, purchase, distribution, and sale of electricity to the public, enterprises, and industrial sectors in Bangkok, Nonthaburi, and Samutprakan, while PEA is responsible for the remainder of Thailand.

Despite the need for EV charging stations to meet demand, the investment cost of public charging infrastructure is high, including the cost of installing chargers, land rent, and EVSE equipment, and the utilization rate (UR) is frequently poor, resulting in low profitability. The majority of the EV charger's capital cost is made up of hardware. As a result, utilization is critical to achieving economic efficiency. Therefore, our analysis assessed the economic feasibility of hybrid solar PV and BESS system for EV charging station under different utilization rate of two types of EV chargers, including slow and fast charging and two electricity costs namely low priority and time of use (TOU) rates. This study's findings have crucial implications for policymakers and solar PV powered EV charging station investment in Thailand in order to promote the EV business in an environmentally sustainable manner.

Figure 1: Forecast of the cumulative number of EVs in Thailand from 2017 to 2036



This paper will be organized as follows: Section 2 presents a literature review of the solar-power for EV CS, existing solar-powered EV charging station worldwide, recent studies on economic analysis. Section 3 presents the detailed of methodology for the economic analysis. Section 4 shows the economic analysis results and discussions. Section 5 provides conclusions and policy recommendations.

2. LITERATURE REVIEW

2.1. EV Charging Station Infrastructure Overview

EV charging stations are basically recharge facilities for EVs. It is otherwise called Electric Vehicle Supply Equipment (EVSE). A charging point consists of a charging socket, cable, and interface panel in order to supply electricity for the recharging of EVs and plug-in hybrids. The power outlet configuration is determined by the grid configuration, parameters, and transmission standards. Multiple changepoints may exist at EV charging stations. In principle, there are two types of EV charging stations: slow AC charging stations and fast DC charging stations with direct current and high charging power, such as the 170 kW from CCS Systems, as well as Wallboxes in the private sector. Charging types can be classified into three main types, alternating current (AC) Level-1, AC Level-2, and direct current fast charging (DCFC).

- Level 1 (L1) charge cables are provided in every EV. The device is worldwide compatible, requires no installation fees, and can be plugged into any conventional 120-volt outlet with grounding. Therefore, it is utilized the standard 120-volt household plug. With maximum power rating around 2.4 kW. The L1 charger is capable of recharging at a rate of 3-5 miles/h and around 40 miles every 8 h, which is suitable for overnight charging.
- Level 2 (L2) charging stations are the most widespread in both public, residential sites, and workplace and may offer between 3.7 kWh and 22 kWh of electricity at any given time. 240 V, 1-phase, 60 A and 14.4 kW Level 2 charging uses a direct connection to the grid through an EVSE. Furthermore, L2 charging stations are widely used in public-access parking garages and typically charge in 3-4 h.
- Level 3 (L3) charging referred as the fast charging method for charging EVs. It can be seen in both public and commercial sites such as community malls, shopping centers. With DC fast charging, the charge time for a battery from 0 to 80% is usually 15 to 30 min. The last 20% of the battery will always be charged in slow mode. The voltage of Level3 charging typically range from 200 to 600 V and power outputs range from 36 to 240 kW.
- The most common types of home charging are L1 and L2 (LaMonaca and Ryan, 2022). While most public charging stations offer L2 and DC rapid charging (Schroeder and Traber, 2012). To charge a BEV, the EV charging station can provide AC to DC power. For AC power from EV charging station, the EV should come with a built-in onboard charger that converts power from AC to DC, then feeds it into a car DC battery. AC power is more common charging method for BEV. The most common AC charging capacities are rated at 3.7 kW and 22 kW (EV Box, 2021). Table 1 summarized the charging modes, levels, space requirements of EV charging station (Hardman et al., 2018; Salcido et al., 2021).

The most common DC charger types include CHAdeMO, Combined Charging System (CCS), and Tesla Supercharger (Chamberlain and Al-Majeed, 2021). CHAdeMO is the DC charging standard for EVs developed by the CHAdeMO Association (CHademo, 2023), whereas CCS is the open and worldwide standard for EVs in Europe and the United States that combines single-phase, three-phase AC and DC. Tesla Supercharger is Tesla’s proprietary DC charger, which takes only 20-30 min to charge up to 80% of the battery from 0% and around 1 h for a full charge, depending on the battery’s condition, operating temperature, charging rate variation,

Table 1: Summary of charging modes and levels of electric vehicle charging station

Typical location	Charge type	Time to charge 100 miles	Share of charger	Number of parking spaces	Minimum number of spaces with slow charging	Minimum number of spaces with fast charging
Home, work, public parking	Level 1	2–12 h	Slow charger 3.7–22 kW	1	1	
				2–10	2	
				11–15	2	
				16–19	2	
				21–25	3	
				26+	10% of total number of parking spaces	
Work, public, shopping mall	Level 2	30 min–2 h	Slow charger from 3.7–22 kW=33.33% Fast charger 50 kW=66.67%	1	0	1
				2–10	1	2
				11–15	1	2
				16–19	1	2
				21–25	2	3
				26+	3% of total number of parking spaces	7% of total number of parking spaces
Work, public, corridor	Level 3	15–30 min	Fast charger 50 kW	1		1
				2–10		1
				11–15		1
				16–19		1
				21–25		2
				26+		5% of total number of parking spaces

environmental factors, and power conversion efficiency (Collin et al., 2019). Finland and Sweden have the highest utilization of AC charging stations, with average station utilization rates of 11% (Virta, 2022). Utilization rates depend mostly on location, type of use, and pricing. Study in Switzerland showed that the maximum average utilization rate of EVSEs is between 14% and 16%, depending on the day of the week and time of day. The majority of charging takes place Monday through Friday during peak working hours, and on Saturday during the day. The median utilization time in the major cities is longer than the national average (Gellrich et al., 2022).

2.2. Overview of Hybrid Renewable Energy for EVCS

Recently, the government's policies, the sustainability development goals (SDG), and the net-zero emission plan are accelerating the use of EVs to help reduce air pollution and mitigate climate change. Basically, a solar-powered EV charging station is the EV charging station that uses electricity provided by solar power system, and power grid backup. Typically, PV inverter converted the DC output produced by a solar panel to AC output (Khan et al., 2018). The operation of solar-powered charging station has different modes such as unidirectional PV-to-vehicle (off-grid), (PV2V), PV-to-grid (PV2G), bidirectional V2G (Ravi and Aziz, 2022; Rachid et al. 2022), Vehicle-to-vehicle (V2V), PV-to-ESS (Backup), Vehicle-to-home (V2H) (Bhatti et al., 2016; Yap et al., 2022). With battery modes include unidirectional PV-to-battery (PV2B), Battery-to-vehicle (B2V), and Bidirectional grid-to-battery (G2B) for battery mode. Because of advancements in solar technology, bifacial and half-cell monocrystalline panels with a surface area of 2.5 m^2 and a maximum efficiency of 21.5% have become increasingly popular for solar rooftop installation (JASolar, 2022).

There are two possible ways for charging EV from PV, namely the PV-on grid and PV-standalone. For PV on-grid, the existing grid can support a solar-powered EV charging station when there is a lack of solar power or when there is a surplus of solar-generated electricity, which can be fed back to the grid through an inverter. Besides, during the absence of vehicle, the electricity from the can be exported to the grid for the monetary gain such as in the form of net metering and net billing. For the PV off-grid, it is typically located in remote area, house area, and standalone individual usage. This type refers to the charging of EV solely by the PV power without the involvement of utility grid. It also can be hybrid generation supported by existing conventional power generation, BESS and other energy sources. In general, solar-powered EV charging station commonly consists of these components:

1. Solar array or solar panels: solar panels consist of PV cells that convert sunlight to DC outputs.
2. Inverter for converting DC to AC for charging.
3. Electric vehicle supply equipment (EVSE): include the charger, the vehicle connector, and the network connection, software, electrical conductors and protocols to safely manage the charging process into EV battery.
4. BESS for storing excessive electricity from solar during daylight and support the solar power system during nighttime.

BESS can be linked to the DC bus for the purpose of storing solar energy. In addition, the installation of a BESS can facilitate peak shaving for EV charging during peak hours (Wallberg et al., 2022). Typically, EV charging stations contribute significantly to the grid's peak demand. Even at low penetration levels, the charging demand of EVs is likely to impact the distribution system and could create new peak loads. If it cannot be managed, it might pose a challenge for cities where the distribution network has limited capacity and/or has times of congestion. A high-performance BESS can "absorb" peak energy loads. This means that the peak energy demand is met by discharging the battery rather than drawing electricity from the grid. Consequently, the storage mechanism saves the charging station operator a substantial amount of money. BESS can then be charged without burdening the grid, such as overnight when fuel pump demand is lower. Previous studies have included different approaches for EV charging with goal of supporting distribution grid. For example, V2G technology for discharging the EVs for peaking shaving or ancillary services (Mojumder et al., 2022; Ravi and Aziz, 2022).

In comparison to traditional EV charging stations, solar-powered charging stations provide a number of advantages. As solar power is one of the clean energy sources, it ensures a carbon footprint of zero because the traditional power system is fueled by fossil fuels like oil, gas, and coal. It gives environmental advantages. Solar-powered infrastructure for charging EVs can also boost local PV energy consumption, minimize charging station reliance on the power grid, and directly cut CO_2 emissions. Solar-powered EV charging can thereby contribute to EVs and society (IEA PVPS, 2021).

2.2.1. Existing solar-powered EV charging station and battery implementations worldwide

There are several solar-powered charging stations that have been developed in various regions of the world. On-grid and off-grid system types are both common for hybrid charging stations (Yap et al., 2022). On-grid solar charging stations can be found in cities, on highways, and in workplaces, and offer L1, L2, L3, and super-fast charging modes. Off-grid stations for rural electrification are located in remote areas and supported by batteries. Solar canopies for EV charging stations are also a popular design for providing shade to vehicles, cutting costs, and reaching grid independence.

In the United States, the number of solar-powered charging stations continuously growing. Envision solar has implemented solar-powered fast charging station with BESS support that does not require a grid connection in California. Tesla built solar powered super-fast charger stations with megapack batteries in California, Arizona, and Tibet. Electrify America has invested 2 million USD in 30 solar-powered EV charging stations in rural California to support Zero Emission Vehicle (ZEV) adoption and develop charging stations equipped with solar canopies that integrate with the local electrical grid. Some of these stations are also equipped with on-site energy storage and DC fast chargers. Solar carport and canopy designs for EV charging stations are also widespread in other countries, such as the Netherlands, Germany, and Australia.

The use of RESs for EV charging is gaining popularity in Asia as well. ATUM Charge is a first solar-powered EV charging station that includes a 5.2kW ATUM Solar Roof for generating electricity in Malad, India. In Malaysia, PLUS Malaysia Bhd (PLUS) launched the country's first solar - powered EV charging station on the North-South Expressway. Table 2 shows the existing solar-powered EV charging station implementations worldwide.

Clearly, RES-powered charging stations for EVs are growing in popularity. Solar PV and BESS are now the most popular integration technologies for EV charging stations. Integrated solar PV and BESS systems are becoming more widespread for both on-grid and off-grid applications, and super-fast charging and solar canopies are being developed continuously.

2.3. Recent Studies on the Economic Feasibility of a Hybrid EV Charging Station Powered by Renewable Energy

Numerous studies on the economic feasibility of EV charging stations have been conducted. Despite their importance, public charging stations suffer from a variety of issues, according to Zhang et al. (2018), including high capital costs such as installation cost chargers, low utilization rates, and thus low profitability. Ilieva and lliev (2016) investigated the financial viability of a solar-powered charging station in Bulgaria and found that a solar-powered EV charging station can be profitable due to the continuous improvements in PV technology efficiency, the extended life of solar modules and other system components, and the decline in PV module prices. Minh et al. (2021) analyzed the technically and economically under various solar radiation conditions in Vietnam using the HOMER software and found that the higher the solar radiation, the higher the investment efficiency, and by optimizing the selection of equipment, the total investment cost could be reduced. Nishimwe and Yoon (2021) developed an optimization framework for profit maximization in the fast charging stations with solar PV and a BESS and the daily power scheduling in the stations. It shows that the fast charging station with the PV and BESS delivered the lowest operating cost because of the flexibility of the BESS and the most profitable in errand distribution scenario.

Another study using HOMER done by Podder et al., (2021) to determine which hybrid solar PV and biogas generator-based charging station was the most economically viable for reducing grid stress. PV systems can give viability; however, BESS is currently not profitable. This study also demonstrated that charging an EV from renewable source produces much fewer emissions than charging from the grid-only. Using the HOMER software tool, a similar feasibility analysis for a solar-powered EV charging station in Shenzhen, China was conducted (Ye et al., 2015). This proposed technology integrated solar PV and satisfied future demands for EVs to handle grid power-related challenges and potentially minimize pollution emission reduction. The University of Palermo in Italy conducted another investigation to design a long-term EV charging station. As a result, the levelized cost of energy is low, requiring a significant initial investment for storage systems (Miceli and Viola, 2017). Another study conducted in the University of Azad Jammu and Kashmir in Pakistan investigated the possibility of designing a solar PV-based EV charging station for security bikes due to its significant potential for solar energy. Aanya et al. (2021) designed an off-grid solar-powered EV charging station utilizing PVsyst in six Indian cities, including the number of cars charged, monthly variation in energy generation, performance ratio, CO_2 emissions reduction, and investment cost per kilometer. This study also found that when monocrystalline modules are employed, the total system generated more energy and saved money. Several studies also indicated that the integration of RESs, such as solar PV, into charging stations is the optimal

Table 2: Existing solar-powered EV charging station implementations worldwide

Company name	Location	Mode	Features	BESS	Reference
Envision solar	California, US	On grid and off grid	Solar-powered charging products include Level 1, Level 2, and DCFC	Yes	BEAM, 2020
Electrify America	California, US	Off-grid and onsite solar canopy	Rural electrification of solar-powered charging station with level 2 speed and FC network	Yes	Electric, 2020
Empower	New York, US	On grid and off grid	EV with solar EV charging station include Level 1, Level 2, Level 3 and V3	Yes	EMPOWER Solar, 2023
Tesla	California, US, Tibet	On grid	Solar Powered Super Charger Station	Yes	Reuters, 2021
ATUM Charge	Mumbai, India	On grid	Solar powered charging station	NA	Visaka, 2023
Fastned	Netherlands	On grid	Solar and wind powered super-FC station and solar canopy	NA	Fastned, 2023
The Ray	Georgia	NA	Solar-powered EV charging station at the visitor information	No	The Ray, 2020
PLUS, Malaysia Bhd (PLUS)	Malaysia	On grid	Solar-powered charging station on highway	Yes	Chargenow, 2018
Volvo Thailand	Thailand	On-grid	Solar carport	No	DEDE, 2023
Paired power	California, US,	On grid and Off grid	Solar-powered pop-up canopy charging station and SEVO SunStation Level 2 Charger	Yes	Pairedpower, 2023
SECAR E-Port	Australia	On grid and Off grid	Solar carport charging station	NA	SECAR, 2018
ELUM Energy	France, Morocco, South Africa	On grid and V2G	Solar-powered charging station	No	ELUM Energy, 2023
Jeep	US and Australia	Off-road trail	Solar-powered charging station	Yes	EV pulse, 2022
MDT-TEX	Germany	On grid	Solar-powered carport charging station	No	MDT-tex, 2023

FC: Fast charging, DCFC: Direct current FC, BESS: Battery energy storage system, NA: Not available, EV: Electric vehicle strategy for maximizing the economic and environmental benefits of EVs and supporting the concept of a smart grid (Amjad et al., 2018; IEA PVPS, 2021; Shafiq et al., 2022). The viability of installing a PV charging station can be determined by a location's influence on irradiance, power pricing, and CO_2 emissions per kWh generated by the local energy mix (IEA PVPS, 2021).

Prior research has demonstrated that the true cost of charging EVs must consider additional factors, such as infrastructure usage rates and a more precise reflection of energy pricing (Zhang et al., 2018; Lanz et al., 2022). The utilization rate of charging infrastructure in the actual world is highly variable, particularly at commercial charging stations. With more expensive technology and no fixed user base, the possibility of underutilization negatively impacting the levelized cost of charging increases. Currently, typical utilization rates of existing infrastructure are around 10% for medium AC charging, 5%-10% for high AC charging, and 1-5% for DC fast charging. High-level EV chargers are more costly than lower-level ones unless their utilization is exceptionally high (Lanz et al., 2022).

3. MATERIALS AND METHODS

This paper was designed to understand the economic feasibility of hybrid solar-powered EV charging station under varying EV charger utilization rate and BESS installation. We aimed to evaluate and compare electric utility's feasibility under two difference modules (slow charge and fast charge) and two electricity costs, namely low priority and TOU rates.

3.1. Study Area, Solar Potential and Load Study

Chulalongkorn University, located in the center of Bangkok, was chosen as the study area to evaluate the PV-powered/Battery hybrid design for an EV charging station. Table 3 presents the data components associated with the location of investigation. Notwithstanding the study's location-specific sample size, the conclusion and methodologies can be applied elsewhere in the world by adjusting the statistics. In Figure 2 shows average solar irradiation, solar panel size, potential parking buildings and car parks for hybrid system EV charging station in Chulalongkorn University campus.

The selected location's monthly average global horizontal irradiance (GHI) was shown in Figure 3. Bangkok has a rooftop solar power output potential of 1.420 MWh/year, with the maximum overall solar PV output occurring in March at 138.8 kWh/m^2.

The load studies in this paper were carried out under hypothetical conditions and were considered in large scale. The EV load was modified from the California's EV charging loads forecast for a typical weekday and weekend in 2025 (California Energy Commission and NREL, 2018) as shown in Figure 4. EV load used in this study was assumed for public charging L2 (in purple) and fast charging (in Green). In weekdays, the electricity tariff used is the time of use (TOU) rate, which is 9:00 AM-22:00 PM on peak and 22:00-9:00 off peak. Weekends are off-peak all days.

3.2. Charging Characteristics

In this study, the operation of a hybrid EV charging station system with L2 and fast charging types was examined. Due to this, as stated in Table 4, only L2 and fast charging were considered for estimating the electric unit in electric charging. Utilizing both charging features, the load factor (LF) for a particular week were estimated.

Furthermore, the installation of two different types of EV charging stations enabled the analysis of each feature's load factor as shown in Table 5. This allowed us to forecast the future electricity needs of each charging station. There are three difference approaches used to evaluate the amount and number of chargers in this study: A represents parking time from 2 h, B represents parking time from 30 min to 2 h, and C represents parking time from 15 to 30 min. The number of charging parking spaces is estimated to account for 10 % of the total parking lot in the area of study.

Based on the load study in Figure 4, we modified the load studies in Chulalongkorn University for both weekday and weekend for three difference schemes as shown in Figure 5.

Furthermore, we assumed that BESS was implemented for peak shaving EV demand reduction and energy arbitrage, which involves charging energy during off-peak hours when tariff rates are low and using it during peak hours when tariff rates are high.

Table 3: Assumptions about the study area

Location	Average solar irradiation (kWh/m^2/day)	Solar panel size (kWp/m^2)	No. parking lots	Roof areas (M^2)
Chulalongkorn University	5.17	0.16	1,800[1]	10,000[1]

Table 4: Load factor of each charging features

Charging features	Load factor (%)
L2 public charging	32.88
FC	37.59

FC: Fast charging

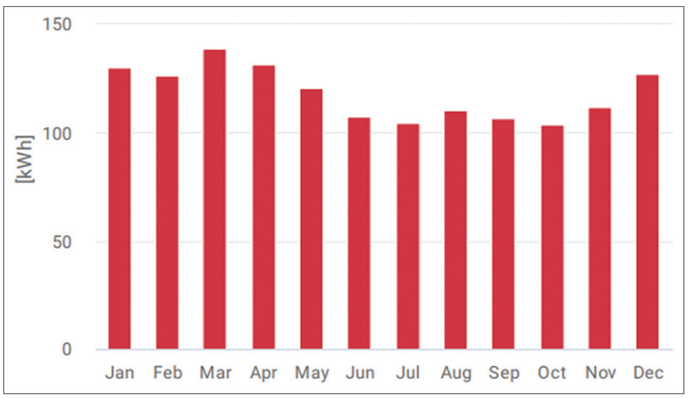
Table 5: Modules of EV charging stations[2]

Charge type	Components	A	B	C
Slow charge	Percentage Installed	10%	3%	0%
	Power (kW)	22	22	22
	Parking lots	180	54	0
	Installed capacity	3,980	1,188	0
Fast charge	Percentage Installed	0%	7%	10%
	Power (kW)	50	50	50
	Parking lots	0	126	90
	Installed capacity	0	6,300	4,500
Normalized power per module (MW)		0.0220	0.0416	0.0500
Load factor (Weekly)		32.88%	36.84%	37.59%

1. Cover only area managed by Chulalongkorn University's Property Management and considered only roof area for solar PV installation.
2. Assumptions based on Salcido, V.R., Tillou, M., Franconi, E. (2021). Electric Vehicle Charging for Residential and Commercial Energy Codes https://www.energycodes.gov/sites/default/files/2021-07/TechBrief_EV_Charging_July2021.pdf[3] PV sizing calculated from the roof area of 10,000 m^2. x solar panel size per m^2 0.16 kWp/m^2.

Figure 2: Parking buildings and car parks in Chulalongkorn university campus

Figure 3: The monthly average solar global horizontal irradiation in Chulalongkorn University



In this module, BESS was expected to discharge during the peak time and only charge when the energy exceeds the specified peak (new peak value). During weekday off-peak hours, the BESS will charge consistently to prepare the power supply for peak discharge and maintain a state of charge (SOC) between 20% and 80%. Figure 6 depicts an example of a load profile for 30% peak reduction for three schemes in this study.

3.3. Description of the Two Modules Used in this Analysis

3.3.1. Configuration and working principle

The structure of a typical grid-connected solar PV powered EV charging station consisting of the main components of the PV system, the DC-AC and AC-DC inverter, the utility power grid, BESS, and electric vehicles. Due to the declining cost of solar PV systems, the net-zero policy, and the potential system to reduce carbon emissions and the cost of electricity supply, this structure is the best model for EV power supply.

During the day, this model of charging station allows the EV to charge directly from the solar PV system, while charging from the utility grid at night and when the weather is unpleasant. The primary source of electricity for EV charging stations is solar PV and the grid, and the BESS is designed to reduce peak demand and the purpose of energy arbitrage.

Description of the two modules used in this analysis:

Module 1: Solar PV powered based charging station: Both solar PV and the utility grid are employed to charge EVs. If the solar PV system can only generate a limited amount of electricity, not enough to fully charge the EV, the EV is charged using both the PV system and the utility grid. If there is no EV to charge and the solar panel is supplying energy, all PV electricity will be utilized to reduce the facility's electricity bill. The following are the module's assumptions:

- EV charger type: Slow charging, fast charging
- EV charger utilization rate: 6.25% for year 1, 12.5% for year 2, 25% for year 3, 50% for year 4, 100% after year 5 project lifetime 20 years (growth rate 2 times per year)
- EV electricity cost: TOU and low priority rates

Module 2: Solar PV-powered charging station with BESS: BESS installation for EV peak load saving and energy arbitrage. It was assumed to discharge at peak and only charge for energy values greater than the peak value specified (new peak value). In this module, solar PV is not used to charge the BESS because the benefit of solar PV for supplying load is greater than its benefit for energy arbitrage. This module did not consider low priority due to its off-peak rate. Following are the module's assumptions:

- EV charger type: Slow charging, fast charging
- EV charger utilization rate: 6.25% for year 1, 12.5% for year 2, 25% for year 3, 50% for year 4, 100% after year 5 project lifetime 20 years (growth rate 2 times per year)
- BESS: BESS installation for peak shaving purpose for reducing peak demand 30%. BESS sizing was referred to maximum charging.
- EV electricity cost: TOU rate
- C-rate used in each scheme: A = 0.28, B = 0.19, C = 0.24.

3.4. System Parameters

The costs of a solar PV-powered EV charging station system and BESS are shown in Table 6, which is based on the surveyed cost of the Thai solar power market (DEDE, 2020), while the price EV charger of slow and fast charge was from market survey, MEA EV charger price (MEA, 2022), and Wallbox selected by EGAT

Figure 4: Forecasted EV Charging Loads for a Typical Weekday (left) and Weekend (right) in California in 2025

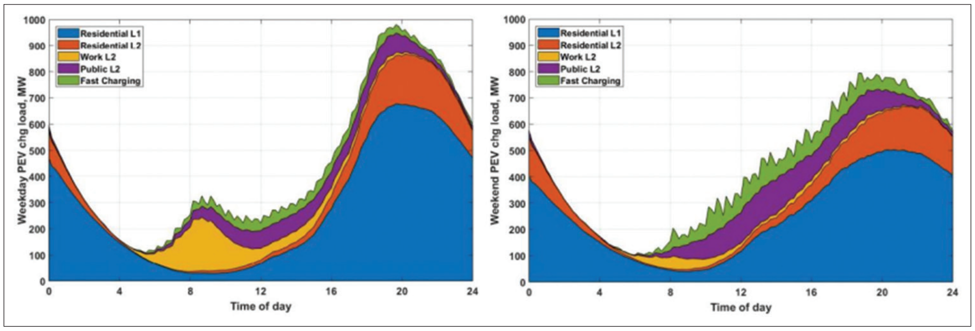


Figure 5: Load profiles in Week day (upper), and Weekend (down) for three schemes

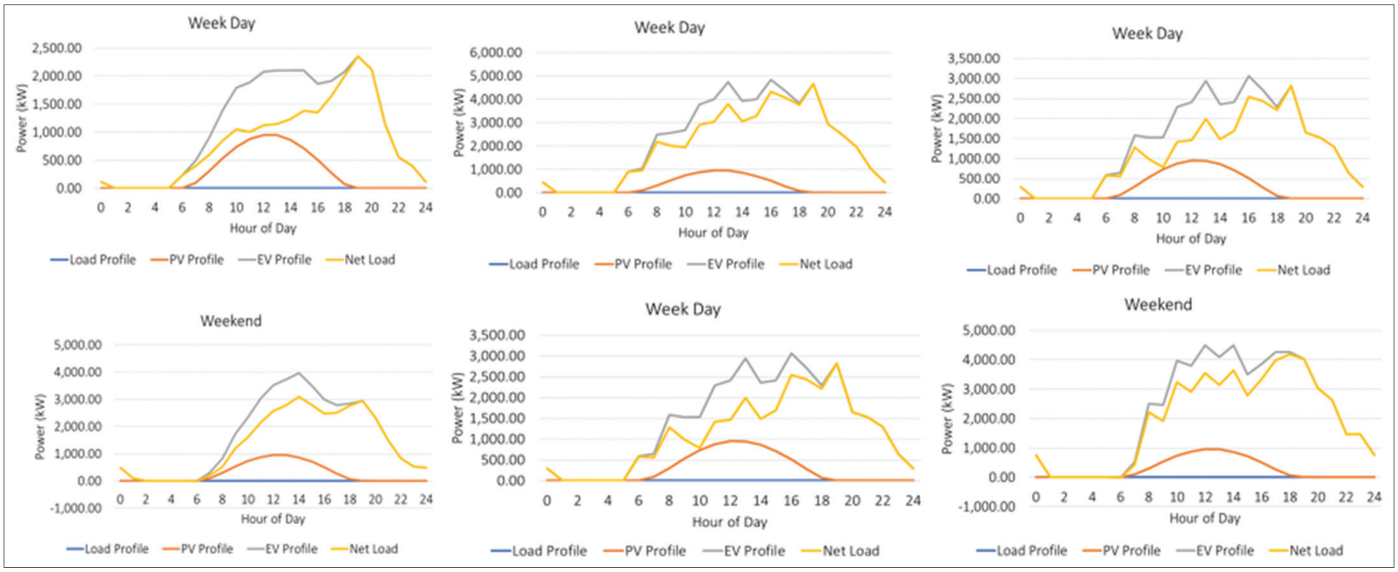
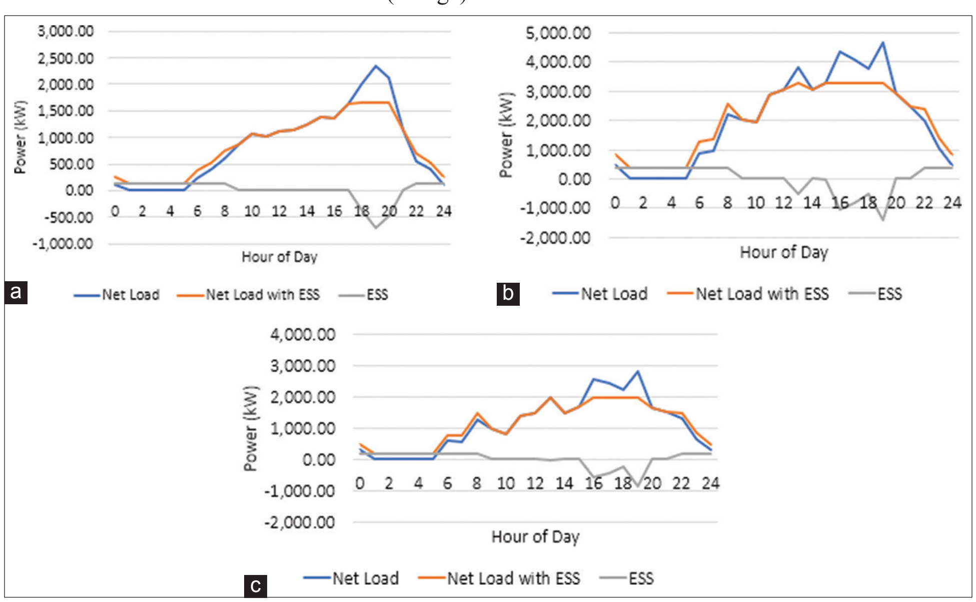


Figure 6: (a-c) Load profile for three schemes with BESS installation for 30% peak reduction: Net load (blue) was EV load excluding PV profile, whereas net load with ESS (orange) was derived from net load - ESS



(Wallbox, 2022). PV sizing was derived from roof areas[3]. For the operations and maintenance (O&M) cost of the solar PV system, EV chargers, and BESS includes replacement cost as shown in Table 6. The BESS price is based on utility-scale battery storage market in 2022 (NREL, 2022) as shown in Table 7. The project's lifetime is 20 years. Operating and marketing budget roughly 10-12% of a business's revenue (Bigcommerce, 2022).

3. PV sizing calculated from the roof area of 10,000 m^2. x solar panel size per m^2 0.16 kWp/m^2.

Table 6: Sizing components and cost assumptions used in this study

Component	Size (kW)	Capital cost (USD/unit)	Lifetime (year)	O and M cost (%)	Replacement cost (USD/unit)
EV charger (slow charge)	22	2019.54	10	2.5 of investment/year	2019.54
EV charger (fast charge)	50	29,699.15	10	2.5 of investment/year	29,699.15
PV module	1600	816.73	25	2.3 of investment/year	
Battery (A)	705.30	1475.457	10	2.5 of investment/year	1475.457
Battery (B)	1396.66	2094.07	10	2.5 of investment/year	2094.07
Battery (C)	846.06	2094.07	10	2.5 of investment/year	2094.07
Land use			15% of revenue		
Operation and marketing cost			10% of revenue		
Cost of insurance			0.16% of total investment cost		

O and M: Operations and maintenance, EV: Electric vehicle, PV: Photovoltaic

Table 7: Lithium-ion battery energy storage system price at different C rate ranges

C rate	Range	ESS price (USD/kW)
0.5	0.5≤C	856.85
0.25	0.25≤C < 0.5	1475.46
0.17	0.17≤C < 0.25	2094.07
0.125	0.125≤C < 0.17	2712.68
0.1	0≤C < 0.125	3331.28

ESS: Energy storage system

For assumption rates used in this study are shown in Table 8. The low priority and TOU rates are used to evaluate the economic feasibility of two modules: solar-powered EV charging station and solar-powered plus BESS EV charging station. The electricity user of the study area is of type 4, which is for medium-sized businesses. We assumed in this analysis that the investor is an electric utility. As a result, we adopt the weighted average cost of capital (WACC) of 6.06% from electricity utility data (MEA, 2012). WACC is a measure of the interest rate paid on a company's financing as well as the average after-tax cost of its capital sources. Lowering the WACC benefits the business by lowering its financing costs. We use the same discount rate as WACC.

3.5. Economic Feasibility

The economic analysis of this study is performed using Microsoft Excel, which provides the calculation of net present values (NPV), payback periods (PB), and internal rates of return (IRR) for each technology's investment. For mathematical model of the various economic components utilized to determine economic feasibility in this study: NPV, PB, and IRR as follows.

3.5.1. NPV

The NPV is positive (>0) if the project is economically feasible. The higher NPV suggests the better economic feasibility of operating the charging station (Robinson et al., 2020)

$$\sum_{t=0}^{T} \frac{NCF_t}{(1+r)^t} \tag{1}$$

3.5.2. IRR

The IRR of an investment is the discount rate at which the NPV of the costs (negative cash flows) of the investment equals the NPV of the benefits (positive cash flows). For a project to be considered for selection, the IRR must above the discount rate. The higher the IRR, the larger the economic viability (Kreith, 1980). When IRR is less than the discount rate, it is not economically feasible to operate a charging station. If the IRR is more than the WACC, then the project's rate of return exceeds the cost of capital, therefore the project should be feasible.

$$0 = \sum_{t=0}^{T} \frac{NCF_t}{(1+IRR)^t} \tag{2}$$

Where NCF = Net Cash Flow of a period, r is the discount rate (%), N is the analysis period, T = Period in which the Cash Flows occur

3.5.3. PB

The calculation starts with years before break even (Y^{BB}), which Y^{BB} must meet the equation condition in (3) and (4). Then calculate the remaining months (from year before break-even until breakeven) after break even until month break even (M^{UB}) from equation 5. The PB is then calculated by combining the two values together. The payback period shows the amount of time required to repay the initial investment expenditure (Robinson et al., 2020). It is employed for ranking investments. Power generation with shorter payback periods are logically more economically advantageous than those with longer payback periods. Therefore, a shorter payback period relates with greater sustainability.

Years before break even

$$\sum_{t=0}^{Y^{BB}} \frac{CI_t + O_t}{(1+r)^t} \le 0 \tag{3}$$

$$\sum_{t=0}^{Y^{BB}+1} \frac{CI_t + O_t}{(1+r)^t} > 0 \tag{4}$$

Month until break even

Remaining PB in month

$$M^{UB} = \frac{\left| \sum_{t=0}^{Y^{BB}} \frac{CI_t + O_t}{(1+r)^t} \right|}{\left(\frac{R_{Y^{BB}+1}}{(1+r)^{Y^{BB}}} \right)} \times 1 \tag{5}$$

Total PB in year

$$PB = Y^{BB} + \frac{M^{UB}}{12}$$

Table 8: Rate assumptions used in this study

Components	Value	Unit	Reference
Exchange rate	33.671	THB/USD	BOT, 2023
Low priority rate	0.08	USD/kWh	MEA, 2021
TOU rate (12–24 kV)	Peak: 0.12 Off peak: 0.08 Demand charge: 3.95	USD/kWh USD/kWh USD/kWh	MEA, 2018
EV slow charge – On peak	0.22	USD/kWh	PTTOR, 2022
EV slow charge – Off peak	0.13	USD/kWh	
EV fast charge – On peak	0.22	USD/kWh	
EV fast charge – Off peak	0.13	USD/kWh	
WACC	6.06	%	MEA, 2012
Tax	30	%	Determined by authors
Discount rate	6.06	%	Same rate as WACC

TOU: Time of use, WACC: Weighted average cost of capital, MEA: Metropolitan Electricity Authority, EV: Electric vehicle

Table 9: Assumptions on environmental and social benefits

Key benefits	Estimated saving	Reference
EV - fuel saving	413 USD/Car/Year	Malmgren (2016)
EV - Avoided GHG emission	86.6 USD/Car/Year	
EV - economic development	96.5 USD/Car/Year	

GHG: Greenhouse gas, EV: Electric vehicle

3.6. Sensitivity Analysis

We performed a sensitivity analysis on the IRR/peak shaving ratio and revealed that the percentage of peak shaving affects c-rate and BESS pricing. Given that the purpose of BESS installation is to reduce peak demand by 30% (base case), we investigated the impact of BESS pricing on economic feasibility. As stated in Table 5, based on the C Rate, the price of BESS ranges from $856.85 to $2,094.07 (a decrease of 0%), in the base case.

3.7. Environmental and Social Benefits Assumptions

It is critical to reduce GHG emissions from power generation systems in order to maintain a sustainable ecosystem. Conventional power plants such as oil and gas generate vast quantities of GHG such as CO_2, SO_2, and NO_x. RES generates no pollutants and offers a solution for sustaining an environmentally power generation system. As indicated in Table 9, we examined the environmental benefits based on four indicators by multiplying them with the load factor and total number of EV chargers in each scheme.

To calculate the amount of CO_2 of the proposed system can be calculated as

$$CO_2 \text{ emissions} = A \times E_f \qquad (6)$$

Where E_{f} = emission factor of kg CO_2 emission per kWh, A = Activity data

4. RESULTS AND DISCUSSION

4.1. Scenario 1 – Solar PV Charging

Table 10 shows the findings of a twenty-year economic analysis of a solar PV powered charging station with 1,600 kW. The electricity generation is 2,488,320 kWh/year from the solar PV system, which is 25.02% of the total electricity demand. The PV installation capacity and EV charging profile were considered as a study area profile without considering the initial load. EV charger utilization rate was 6.25 % in year 1, 12.5 % in year 2, 25 % in year 3, 50 % in year 4, and 100 % after year five. The plant factor was 16.21% in first year. Considering NPV, IRR, and PB, the most economical installation was slow charging of 22 kW for 180 units at a low priority and TOU rate. The subsidized low priority rate provided a favorable financial return due to a shorter payback period than the TOU rate in all schemes. It is likely unfeasible to install fast chargers due to their high cost. In both schemes, the subsidized low priority rate provided a greater financial benefit than the TOU rate, given the off-peak rate is 24 h. Thus, the investment in level 2 solar PV charging stations on university campuses and in Bangkok is highly feasible and can develop in the coming years.

This scenario, which is similar to studies in Bulgaria, China, and Vietnam, as well as current solar-powered EV charging station deployment around the world, revealed that investing in solar-powered EV charging stations is both economically feasible and attractive. The driving force of PV technology efficiency, the declining price of solar panels and other system components, and the trend of GHG abatement are further arguments that such investments are economically sensible.

4.2. Scenario 2 – Solar PV Charging Station with BESS Installation

The BESS installation in this system was used for peak shaving by 30% of EV load and the purpose of energy arbitrage. Table 11 shows the economic results of a solar PV charging system with BESS installation at campus over a period of twenty year. The NPV, IRR, and PB revealed that slow charging with BESS 705.30 kW and TOU rate offered greater financial benefits than the other two schemes. In a while, the installation of pure fast-chargers provided the least financial return. However, it can be observed that none of the schemes with BESS installation have a negative NPV. Considering the current trend of declining BESS prices, this technology could become economically viable in the near future. In the meantime, it would be challenging for investors to generate a profit; thus, the installation of BESS should be supported by government or organization funding, thereby creating a market that drives down the price of BESSs.

4.3. Sensitivity Analysis

As shown in Figure 7, the sensitivity results of IRRs for peak shaving showed that IRRs ranged within the range of -4.80% to 45.5%. When

Table 8: Rate assumptions used in this study

Components	Value	Unit	Reference
Exchange rate	33.671	THB/USD	BOT, 2023
Low priority rate	0.08	USD/kWh	MEA, 2021
TOU rate (12–24 kV)	Peak: 0.12 Off peak: 0.08 Demand charge: 3.95	USD/kWh USD/kWh USD/kWh	MEA, 2018
EV slow charge – On peak	0.22	USD/kWh	PTTOR, 2022
EV slow charge – Off peak	0.13	USD/kWh	
EV fast charge – On peak	0.22	USD/kWh	
EV fast charge – Off peak	0.13	USD/kWh	
WACC	6.06	%	MEA, 2012
Tax	30	%	Determined by authors
Discount rate	6.06	%	Same rate as WACC

TOU: Time of use, WACC: Weighted average cost of capital, MEA: Metropolitan Electricity Authority, EV: Electric vehicle

Table 9: Assumptions on environmental and social benefits

Key benefits	Estimated saving	Reference
EV - fuel saving	413 USD/Car/Year	Malmgren (2016)
EV - Avoided GHG emission	86.6 USD/Car/Year	
EV - economic development	96.5 USD/Car/Year	

GHG: Greenhouse gas, EV: Electric vehicle

Figure 7: Percentage of peak reduction: Comparison of IRR across the three difference schemes

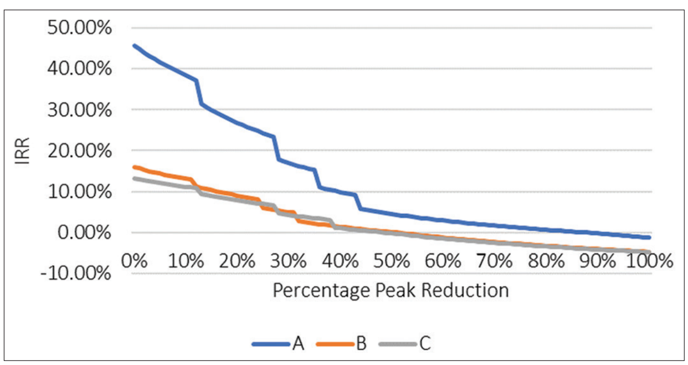
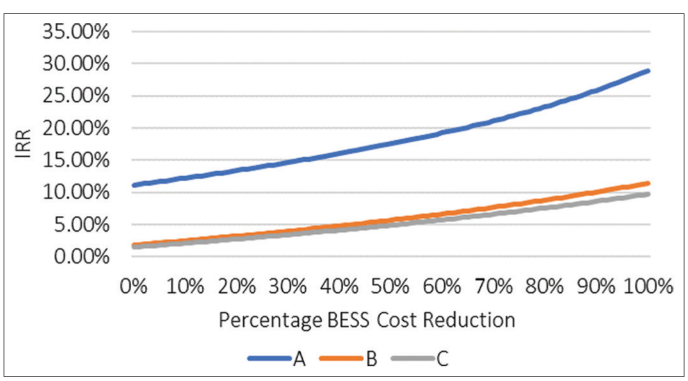


Figure 8: Percentage BESS cost reduction: Comparison of IRRs across the three difference schemes



compared to the base scenario of 30% peak shaving at 0% cost reduction, it was estimated that using BESS to reduce peak demand by a greater amount would result in a lower IRR for the project, because BESS is required to be larger in all three schemes. With the high cost of BESS implementation, the share of BESS benefits obtained may be reduced. Thus, a BESS price sensitivity analysis was conducted to determine the effect of BESS pricing on IRR when

Figure 9: Environmental and social benefits

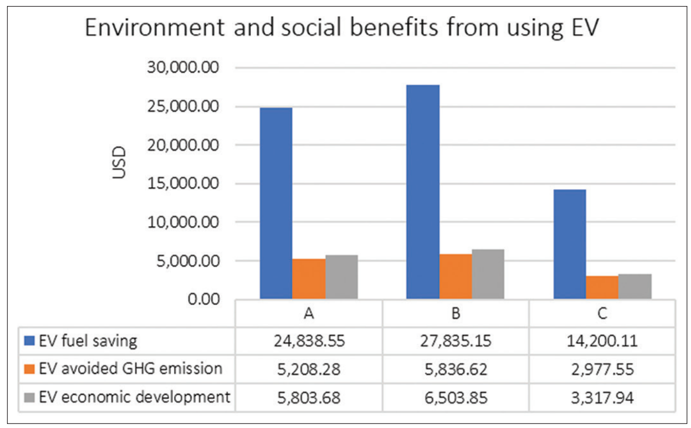
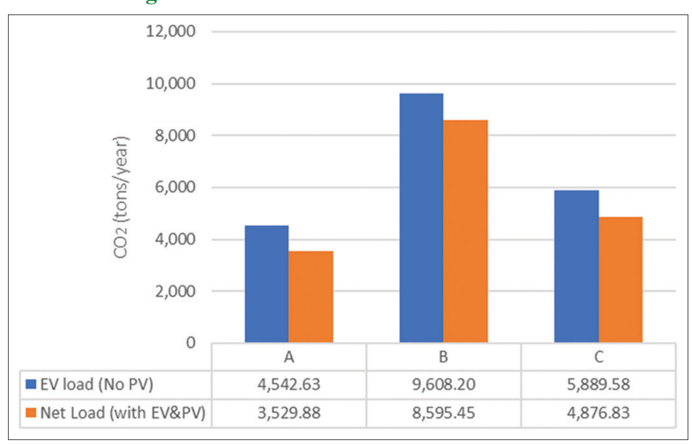


Figure 10: Emission reduction in each scheme



a business installs and operates BESS. As shown in Figure 8, the IRRs for varied percentages of BESS cost reduction ranged from 1.42 % to 28.92 % across three schemes. The project's IRR will increase when the price of the BESS lowers. Slow charging was also demonstrated to be more feasible than fast charging in most cases.

4.4. Environmental and Social Benefits Assumptions

The RESs are the most environmentally friendly and effective replacements for traditional energy sources, and they have numerous beneficial benefits on the planet, including a significant cut in GHGs, which is crucial for addressing climate change (Al-Shetwi, 2022). The proposed systems accounted for the key

Table 10: Solar photovoltaic+charging station: Comparison of the net present value, internal rates of return, and payback with the low priority and YOU rate for three difference schemes

Electricity cost Scheme	Low priority			TOU		
	A	B	C	A	B	C
NPV (USD)	6,185,723.21	6,932,908.05	4,033,178.84	4,332,155.24	2,849,332.58	1,831,077.23
IRR (%)	29.61	16.61	14.65	25.72	11.23	10.61
PB (years)	4.10	7.2	10.4	5.2	13	13.5

NPV: Net present value, PB: Payback period, IRR: Internal rates of return, TOU: Time of use

Table 11: Solar photovoltaic charging station with BESS installation: Comparison of the net present value, internal rates of return, and payback period with the low priority and YOU rate for three difference schemes

Electricity cost Scheme	TOU rate		
	A	B	C
NPV (USD)	3,355,591.33	2,689,003.552	966,435.78
IRR (%)	17.32	10.72	8.5
PB (year)	6 0.9	13.7	16.6

NPV: Net present value, PB: Payback period, IRR: Internal rates of return, TOU: Time of use

benefits of EVs in terms of fuel savings, reduced GHG emissions, and economic growth, as well as the usage of solar PV for avoided greenhouse gas emissions throughout project lifetime 20 years.

As shown in Figure 9, the data demonstrated that EV adoption had a positive impact on fuel savings, avoided GHG emissions, and economic growth. Scheme B produced greater environmental benefits than other schemes due to its higher average vehicle usage and greater number of EV charger units. Thus, the use of solar PV systems with increased capacity in EV charging stations can reduce the rate of grid power consumption and the amount of GHG emissions produced during operation.

To analyze the CO_2 emission reduction of using solar PV for EV charging station, the emission factor is considered to be 0.407 tons of CO_2 per MWh (EPPO, 2022). So, the emission of proposed system was 0.407 kg CO_2/kWh x 2,488,320 kWh (annual solar output) = 1,012,746.24 kg CO_2/year. Figure 10 presents the CO_2 emission reduction in difference schemes.

5. CONCLUSION

This study presented the economic feasibility of a hybrid solar-powered EV charging station under varying EV charger utilization rates and BESS installation by comparing two difference charging types and electricity cost in Chulalongkorn University. According to the solar resource data, the area has a substantial solar energy potential and provide economic efficiency. NPV, IRR, and PB were utilized to evaluate the feasibility of the investor's perspective. We found that level-2 solar PV-powered stations with the current subsidized rate are the most attractive to investors, followed by TOU rates with a payback period of 4.10 and 5.20 years, respectively. In addition, installing a solar PV system at an EV charging station can minimize the quantity of CO_2 emitted by the utility grid. This also encourages the use of RESs for low-carbon mobility, which contributes to the significant advantages of EVs in terms of fuel savings, reduced greenhouse gas emissions, and economic growth. In addition, EV Charging stations qualify for carbon credits because they provide EVs with renewable energy. By selling carbon credits, charging station owners have the option to earn a greater return on their investments.

However, due of the high cost of installing BESS for peak shaving, it is not currently economically feasible, although it may become so in the future if it gets less expensive. Similarly, installing fast chargers is not feasible in comparison to slow charging because they are substantially more expensive. The utilization rate of an EV charging station is an important factor in boosting the financial return of an EV charging station. A variety of factors influence utilization rates, including location, efficiency, and cost. Higher utilization rates directly result in increased revenue for owners of EV charging businesses.

We also investigated the effects of peak shaving percentage on IRRs. As the percentage of peak shaving increased, the IRRs generally decreased because BESS is required to be larger. This implies that the percentage of peak shaving influences the pricing of c-rate and BESS. Larger BESS sizes require costly investments. The introduction of ancillary services to the grid, such as frequency regulation, could significantly increase the project's profitability.

Future study will focus on developing a business model with an appropriate pricing structure for EV consumers. In addition, it is essential to identify the challenges and barriers for solar PV-powered with BESS EV charging stations, to perform a social acceptance survey, and to conduct a feasibility analysis of a RES hybrid system EV charging station with different modules and charging prices.

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