Technical and Economic Analysis of EV Charging Stations with Energy Storage System (Interim Report)

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***Abstract*—Electric vehicle (EV) adoption is becoming a crucial element of the transportation industry's low carbon transition to reduce greenhouse gas emissions. However, the lack of public EV charging infrastructure is a major barrier to EV adoption due to range anxiety from EV drivers. EV charging service operators (CSO) require a certain level of demand and pricing to operate profitable EV charging stations. This is especially pressing in developing regions like Southeast Asia where EV adoption is still at a nascent stage. This Malaysia-based study provides insight on the minimum demand levels to breakeven, optimal sizing of energy storage systems (ESS) and compares charging strategies with differing levels of main power grid involvement. The findings show that a minimum number of 11 daily EV customers are required for CSOs to breakeven, and smaller capacity ESS of 50 kWh are sufficient at current demand levels without compromising charging availability. The net economic benefit of a charging strategy with high main power grid involvement is significant, despite the resultant increase in peak hour electricity charges. Sensitivity analysis shows the minimum charging price for CSO to financially breakeven has a logarithmic relationship with daily EV charging demand. The minimum charging price is found to range between 1.45-20.00 RM/kWh.**

***Index Terms*— Charging service operator, electric vehicles, energy storage system.**

1. Introduction

Decarbonization is a growing focus for several emission-intensive industries in an effort to transition toward cleaner alternatives, as the consequences of irreversible climate change edge nearer. The transportation industry has been one of the largest carbon emitting sectors in recent history, emitting 7.3 giga tonnes of the 30.6 giga tonnes of greenhouse gas emissions globally [1]. Emissions from road transport form the bulk of this industry's emissions, emitting 81% of the transportation sector's emissions compared to 8% from aviation transport and 11% from shipping [2].

An electric vehicle (EV) is a vehicle which uses electric motors for propulsion and is powered by a battery. EVs offer a clean alternative to mainstream internal combustion engine (ICE) vehicles, emitting up to 67% less greenhouse gas emissions when compared on a well-to-wheel basis [3]. These EVs are typically charged through private residential chargers installed in homes, or public chargers installed along highways, shopping malls, etc. EV chargers are usually differentiated into slow chargers (< 22 kW) and fast chargers (> 50 kW), with 70% of public chargers today being slow chargers [4].

The availability of public EV charging stations has been noted as a significant deciding factor in EV adoption [4]. In 2021, survey respondents in Southeast Asia cited the "lack of EV charging infrastructure" as the top concern when purchasing an EV (see Figure 1) [5].

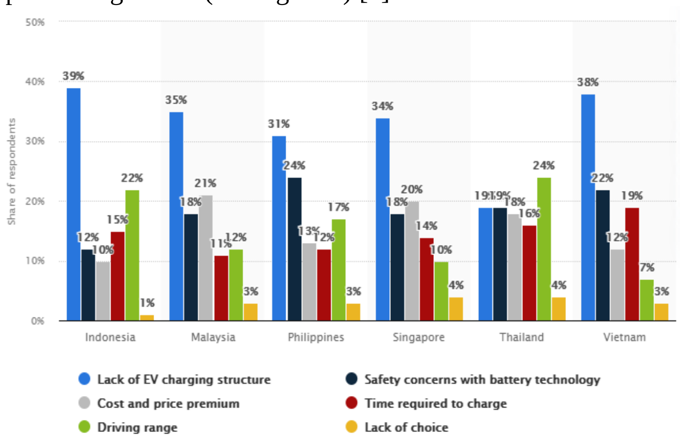


Fig. 1. Deloitte survey on EV customer concerns in Southeast Asia, 2020 [5]

Globally, publicly accessible chargers reached 1.3 million units in 2020 representing a year-on-year (YoY) growth of 45%. Public chargers are projected to reach populations of 14 million slow chargers and 2.3 million fast chargers by 2030 [4]. China and the United States are current leaders in EV charging infrastructure populations, with a majority of publicly available EV chargers being slow chargers. However, EV adoption is still at a nascent stage in Southeast Asia, with market share of EV in Malaysia and Indonesia at 0.05% each; a stark contrast to China where the EV penetration was 5.75% in 2020 [6]. On a global level, BloombergNEF predicts a 13 times increase in the total EV fleet size, from 8.5 million in 2020 to 116 million in 2030 [7]. This growth offers an opportunity for EV charging service operators (CSO) in the Southeast Asia region to build up EV charging infrastructure networks and establish themselves as market leaders in providing for future EV driver needs.

1.1. *Background of Yinson Green Technology*

Yinson Holdings Bhd is a Malaysia-based energy infrastructure and technology company publicly listed in Malaysia's Kuala Lumpur Stock Exchange. Yinson operates in 15 countries with primary activities through their offshore production, renewables, green technologies and offshore marine business divisions. Yinson Green Technologies was established in April 2021 and headquartered in Singapore, where they invest in marine decarbonization and clean energy initiatives within the transport and energy business segments [8]. This study is based on an EV charging station operated by

Yinson at Ayer Keroh's Rest & Relaxation (R&R) facility along Malaysia's North-South highway.

2. Literature Review

There is a chicken-and-egg problem hindering the development of the EV industry, between EV drivers who value EV charging infrastructure to curb range anxiety, and CSOs who require a certain level of EV charging demand to operate profitable charging points. Accurate modelling of the economic and technical benefits of operating an EV charging station will be crucial in corporate and government planning for investments.

2.1. *Summary of existing literature*

Studies regarding EV charging stations have largely focused on EV charging behaviour. A study by Chen et al., 2020 [9], provides insight into EV charging behaviour patterns and peak hours in the U.S. by using function principal component analysis approach to study real-world data from EV charging stations.

Bulaeva et al., 2019 [10], identified key performance indicators for CSOs managing a fleet of charging stations in Finland, providing a macro-overview for comparing station performance in a country with mature EV adoption. Through surveys, the study focused on metrics such as charger usage frequency, customer complaints, electricity consumption, payment option preference, etc.

Some studies have modelled technical and financial feasibility of individual EV charging stations. Madina et al., 2015 [11], quantifies the required charging demand and compares charging in different settings. Gjelaj et al., 2017 [12], compares suitability of low-voltage vs high-voltage grid connections to EV charging stations. Ye et al., 2015 [13], created a yearly model using the HOMER software to evaluate the feasibility of a solar-powered EV charging station in Shenzhen City.

Based on the literature review, there has been extensive research and survey on EV charging behaviour patterns, but with few studies modelling the technical and economic feasibility of EV charging stations.

Furthermore, there is a lack of literature on EV charging station modelling that illustrates the hourly energy flow within an ESS-based EV charging station. Existing research on ESS-based EV charging stations do not highlight the key considerations behind sizing the ESS component. Although there is research on the minimum demand level for EV charging for CSOs to breakeven financially in countries such as Denmark, China, etc., there is a lack of similar research in developing regions where EV adoption has yet to pick up. Such a study would bring clarity to EV charging station developers and accelerate EV charging infrastructure in the region.

2.2. *Study objective*

The proposed study incorporates technical specifications and economic parameters to construct the daily 24-hour energy flow between the national power grid, energy storage system (ESS) and EV users. This includes a financial model for each operational year, projecting cash flows to evaluate profitability. The study has the following objectives:

A. Compare effectiveness of different levels of grid involvement in ESS charging strategies.
B. Evaluate charging availability of station based on different demand levels.
C. Determine optimal sizing for a ESS unit within an EV charging station, based on system availability and profitability of different options.
D. Scenario analysis for different demand scenarios, sensitivity analysis of minimum charging price to demand.

The proposed study aims to provide insight for CSOs in sizing an ESS-based EV charging station, suitable pricing of EV charging and sensitivity analysis of profitability in different levels of demand for EV charging in Malaysia.

3. Methodology

The EV charging station in this study is assumed to have three sub-systems: 1) solar power generation, 2) energy storage system, and 3) DC charging points. The PV solar power generation system is connected to the adjacent R&R facility, operating as a separate system from the ESS or DC chargers, as shown below.

Fig. 2. Schematic of PV system connections

The PV array is connected to a DC/AC inverter, where generated electricity is sold to the adjacent R&R facility at 80% of the electricity tariff price for additional revenue. The connections for the ESS and DC chargers are shown below.

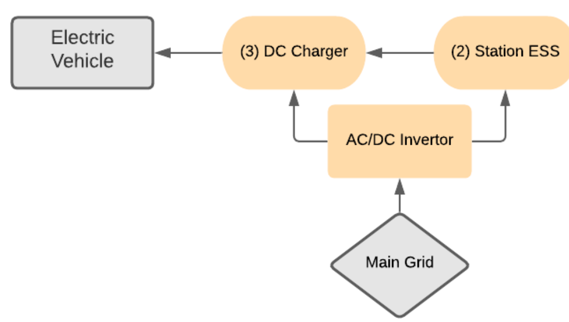


Fig. 3. Schematic of ESS and charger connections

3-phase AC electricity is converted to DC electricity through an AC/DC inverter, connected to the charging station ESS unit and the DC charger directly. The following subsections detail the considerations and formula used in modelling each individual component in the EV charging station.

3.1. *PV solar power*

The solar power generation system has an installed capacity of 27 kWp, according to the current installed capacity at the Ayer Keroh R&R. Based on the lower bound specific PV power output conditions of 3.58 kWh/kWp/day for the Melaka region [14] and a 90% boost inverter efficiency assumption, the average energy generated per day was estimated to be 86.99 kWh using the following formula:

$$P_{output} = P_{specific,PV} * P_{capacity,PV} \quad (1)$$

The hourly generation profile was produced by applying the average hourly surface irradiation profile for the Ayer Keroh coordinates of 2.3982 N, 102.2219 E in 2019 to the total expected energy generated per day, with the resulting generation profile below.

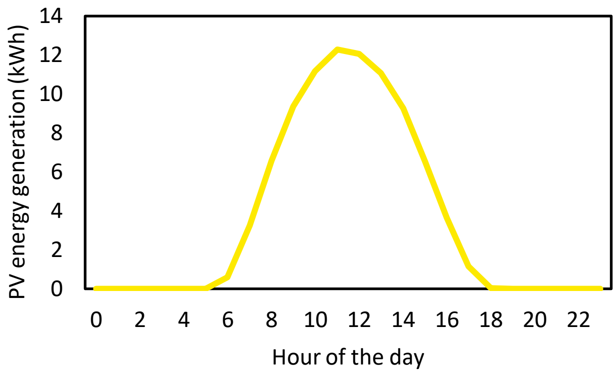


Fig. 4. Hourly profile of solar PV energy generation

3.2. *Energy storage system*

A comparative study was done on ESS of 50 kWh and 300 kWh capacity, based on cost quotations from industry suppliers. Maximum depth of discharge of 80% between 10-90% state-of-charge (SOC) limits, maximum operational period of 90% per year, and End-of-Life (EoL) capacity were applied to each ESS type. Power drawn from the national grid was constrained with an upper limit of 28.8 kW; the maximum rating for the power conditioning system used by Yinson in AC/DC conversion for the 3-phase electricity from the main grid.

Electricity drawn from the grid was modelled for two different charging strategies:

Strategy 1) ESS charging mainly during off-peak hours and during peak hours when ESS SOC limits are reached.

For strategy 1, the energy stored in the ESS is calculated by the following when charging from the grid:

$$E_{ESS,t} = E_{ESS,t-1} + E_{grid,t} \quad (1)$$

where $E_{ESS,t-1}$ is the energy stored at the end of the previous hour, and $E_{grid,t}$ is the energy charged from the main grid. When the ESS is discharging to a customer EV battery, the energy stored in the ESS is calculated from:

$$E_{ESS,t} = E_{ESS,t-1} - E_{load,t} \quad (2)$$

where $E_{load,t}$ is the energy supplied to the EV customer for that hour.

Strategy 2) ESS charging during off-peak hours and peak hour grid electricity direct to DC charger, where ESS discharges to provide for the remaining load.

For strategy 2, the energy stored in the ESS is calculated in the same way as shown in (1). However, the energy stored in the ESS when discharging to the customer EV battery is calculated by:

$$E_{ESS,t} = E_{ESS,t-1} - (E_{peak\ grid,t} - E_{load,t}) \quad (3)$$

Where $E_{peak\ grid,t}$ is the peak hour electricity supplied by the main grid directly to the DC charger through the AC/DC inverter, resulting in a smaller net load on the ESS.

The ESS is assumed to be a single-state system in both charging strategies, either charging from the grid or discharging to users at any point in time.

In addition, three options of ESS are studied and compared. Initial capital expenditure range between RM 472,080-816,235 for the three options, with ESS capacity ranging between 284-354 kWh.

3.3. *DC charger*

A 180 kW DC charger with two charging guns of 90 kW each is used in this study based on the existing setup at Ayer Keroh R&R, which is within the 1C charge rate for the three different ESS options. The battery capacity of the EV customers is assumed to be 54 kWh based on information from Yinson, with a SOC of 20% on entry and 80% on exit assumed. This indicates 32.4 kWh required per user, and is assumed to be charged at 1C, well within the 90 kW rating of the charging gun.

3.4. *Study variables*

The daily number of EV charging station customers and charging price in RM/kWh are the two variables used in the study.

The daily number of customers input is the base year variable, used in modelling the station's daily load profile in its first operational year. In every subsequent operational year, the daily number of customers is assumed to increase by two customers to reflect increasing EV adoption among motorists in Malaysia. In line with Chen's study [9], the EV charging demand is assumed to begin from 9AM onwards.

The charging price to EV customers is also varied to study the minimum breakeven price to charge at different levels of demand. However, the charging price is kept constant at 2.00 RM/kWh when comparing between charging strategies and ESS sizing.

3.5. *Formulas used in economic analysis*

Economic analysis of the EV charging station was evaluated using the internal rate of return (IRR) over a five-year lifetime of the station, as seen below:

$$NPV = 0 = CF_0 + \sum_t^N \frac{CF_t}{(1+IRR)^t} \quad (4)$$

where N is the project lifetime in years, CF_0 is the initial capital expenditure and CF_t is the annual free cash flow for the year *t*. Capital expenditure for the solar PV rectification, DC chargers, ESS and PCS are all based on assumptions provided by Yinson. Here, CF_t is calculated from the operating cash flow shown below:

$$OCF_t = NI_t + Depr_t \quad (5)$$

where $Depr_t$ is the total depreciation of the EV charger and ESS, and NI_t is the net income for that year as calculated below:

$$NI_t = (R_t - Opex_t - Depr_t) * (1 - tax) \quad (6)$$

where R_t is the total revenue generated for year t, $Opex_t$ is the total operating expenditure for year t, and *tax* is the corporate tax rate in Malaysia. Here, R_t is found from:

$$R_t = R_{charger} + R_{facility} \quad (7)$$

where $R_{charger}$ is the revenue generated from the DC chargers and $R_{facility}$ is the revenue generated from the sale of PV generated electricity to the R&R facility at 80% of wholesale tariff price. Similarly, $Opex_t$ is found from:

$$Opex_t = O\&M_{t,PV} + O\&M_{t,charger} + O\&M_{t,ESS} + Opex_{t,grid} \quad (8)$$

where $O\&M_{t,PV}$ is the operating expenditure due to operation and maintenance costs (O&M) for the solar PV system, $O\&M_{t,charger}$ is the operating expenditure for the DC chargers, $O\&M_{t,ESS}$ is the operating expenditure for the ESS and $Opex_{t,grid}$ is the expenses due to peak and off-peak grid electricity charges.

The minimum revenue required for the CSO to breakeven is calculated using the following formula:

$$R_{breakeven} = CF_0 + \sum_t^N Opex_t \quad (9)$$

From here, the charging revenue required over the EV charging station lifetime is found:

$$R_{charging} = R_{breakeven} - R_{facility} \quad (10)$$

The minimum charging price for the CSO to breakeven is then calculated from the formula below:

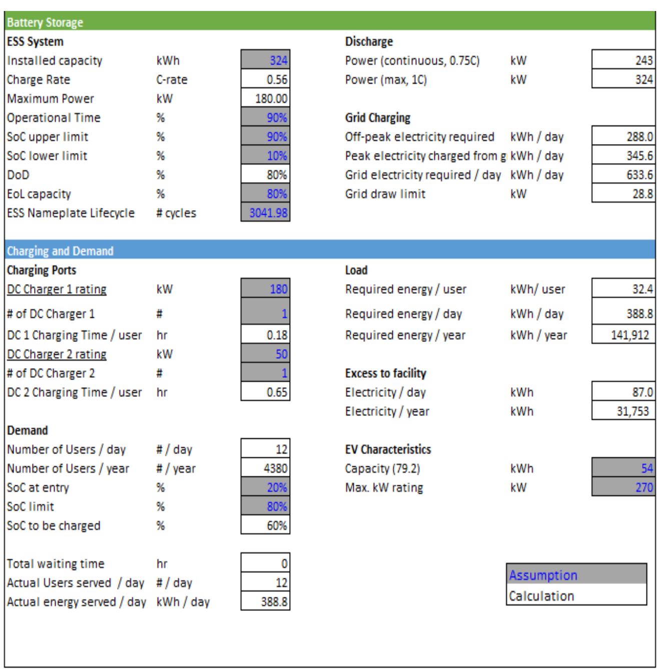
$$Price_{min} = \frac{R_{charging}}{N*(Op_t*365)*E_{day}} \quad (11)$$

where N is the project lifetime in number of years, Op_t is the percentage of a year that the station is expected to be operational and assumed to be 90%. E_{day} is the actual energy delivered to EV customers per day in kWh.

The minimum number of daily EV customers required for the CSO to breakeven is found by performing a sensitivity analysis on the IRR of the EV charging station and identifying the breakeven point at which the IRR crossover to a positive value occurs.

3.6. *Model sample*

The inputs above are collated and keyed into the shaded cells of the model as shown below.



Battery Storage					
ESS System			**Discharge**		
Installed capacity	kWh	324	Power (continuous, 0.75C)	kW	243
Charge Rate	C-rate	0.56	Power (max, 1C)	kW	324
Maximum Power	kW	180.00			
Operational Time	%	90%	**Grid Charging**		
SoC upper limit	%	90%	Off-peak electricity required	kWh / day	288.0
SoC lower limit	%	10%	Peak electricity charged from g	kWh / day	345.6
DoD	%	80%	Grid electricity required / day	kWh / day	633.6
EoL capacity	%	80%	Grid draw limit	kW	28.8
ESS Nameplate Lifecycle	# cycles	3041.98			
Charging and Demand					
Charging Ports			**Load**		
DC Charger 1 rating	kW	180	Required energy / user	kWh/ user	32.4
# of DC Charger 1	#	1	Required energy / day	kWh / day	388.8
DC 1 Charging Time / user	hr	0.18	Required energy / year	kWh / year	141,912
DC Charger 2 rating	kW	50			
# of DC Charger 2	#	1	**Excess to facility**		
DC 2 Charging Time / user	hr	0.65	Electricity / day	kWh	87.0
			Electricity / year	kWh	31,753
Demand					
Number of Users / day	# / day	12	**EV Characteristics**		
Number of Users / year	# / year	4380	Capacity (79.2)	kWh	54
SoC at entry	%	20%	Max. kW rating	kW	270
SoC limit	%	80%			
SoC to be charged	%	60%			
Total waiting time	hr	0	Assumption		
Actual Users served / day	# / day	12	Calculation		
Actual energy served / day	kWh / day	388.8			

Fig. 5. Example of model inputs and calculated parameters

The model first takes these inputs and calculates the hourly peak and off-peak grid electricity required, charger demand, resulting load on the ESS and current ESS charge stored in kWh. These calculations are made through nested logic statements and checks on the charge sufficiency in the ESS, if ESS SOC limits are reached, charger unavailability, etc.

The model then outputs the relevant parameters needed for calculating revenue, operating expenditure and depreciation to a cash flow model that evaluates the IRR and breakeven charging price for the EV charging station.

4. Results & Discussion

The hourly profile of the EV charging station was modelled to estimate the charger availability, evaluate the benefits of different charging strategies and calculate the expected profitability over the station's lifetime.

4.1. *Charging strategy*

Two ESS charging strategies were compared; 1) ESS charging mainly during off-peak hours and during peak hours when ESS SOC limits are reached; 2) ESS charging during off-peak hours and peak hour grid electricity direct to DC charger, where ESS discharges to provide for the remaining load. The hourly profile of the EV station ESS in terms of SOC for the two charging strategies, when servicing 8 EV customers starting from 9AM, are shown below.

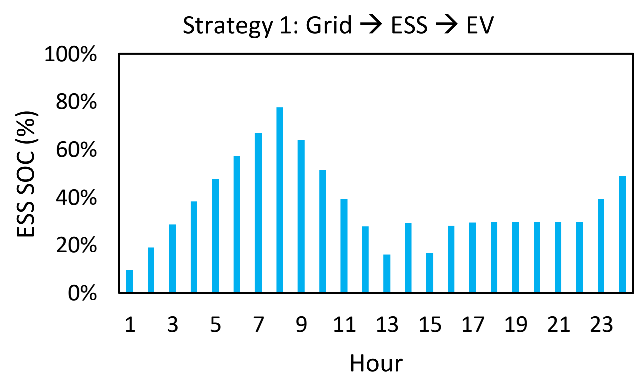


Fig. 6. Hourly profile of ESS SOC for charging strategy 1

Strategy 1 shows the station ESS will have larger fluctuation in its SOC, undergoing more cycles of discharge which leads to faster battery depreciation compared to Strategy 2. The hourly profile of the ESS for the same load is as shown below.

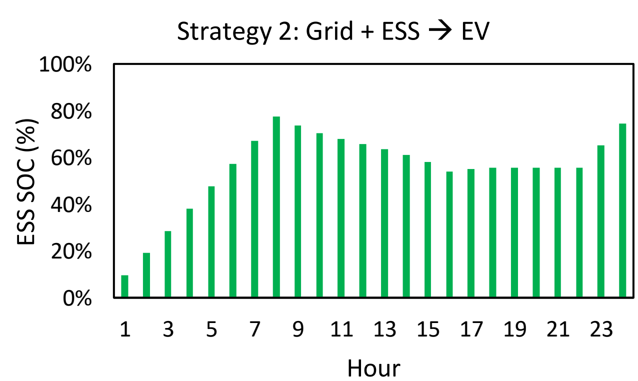


Fig. 7. Hourly profile of ESS SOC for charging strategy 2

The smaller fluctuation in ESS SOC can be seen from the more gradual slopes after 9AM, when demand is expected to begin. However, operating expenditure in Strategy 2 will also be higher due to the continuous consumption of peak hour electricity when there is user demand. At low demand scenarios with less than 14 users, the charging revenue difference due to station unavailability is insignificant. At high demand scenarios with more than 14 daily users, the charging revenue earned using Strategy 1 will be significantly lower due to ESS unavailability. With these trade-offs, the NPV is used to illustrate the overall profitability of each charging strategy in different demand scenarios, as seen below.

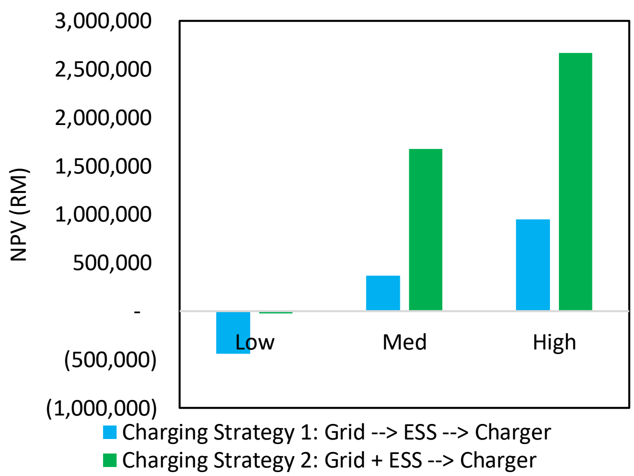


Fig. 8. NPV of EV charging station in different demand scenarios

Strategy 2 of using a combination of direct-to-charger grid charging using peak hour electricity with ESS discharge is found to result in the most profitable outcome, regardless of the level of EV customer demand. As the number of daily customers increase, the greater revenue earned begins to offset the higher operating expenditure from peak hour electricity charges.

4.2. *Availability*

Using charging strategy 2 and a 300 kWh ESS, the theoretical maximum availability was found to be 20-29 users per day, depending on the initial SOC for the ESS at the beginning of the day. At 10% initial SOC, the station will be able to service up to 20 users assuming demand is spread across the day. Two peak hours will be required for re-charging the ESS, as seen from Figure 9 below between 10AM-11AM and 7PM-8PM.

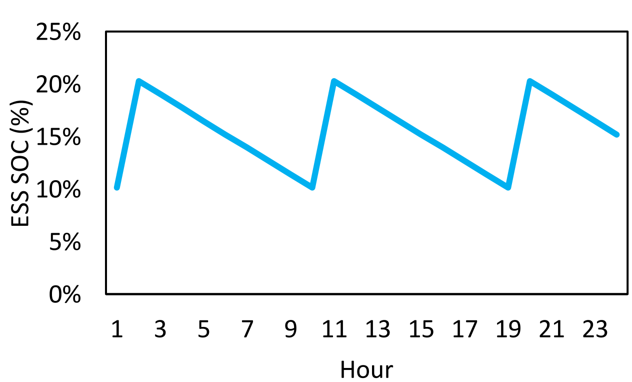


Fig. 9. Hourly profile of ESS SOC in extreme high demand scenario, beginning at 10% SOC

At 80% initial SOC, the station will be able to service up to 29 users and is able to service 14 users continuously before requiring charge from the grid, as seen from Figure 10 below.

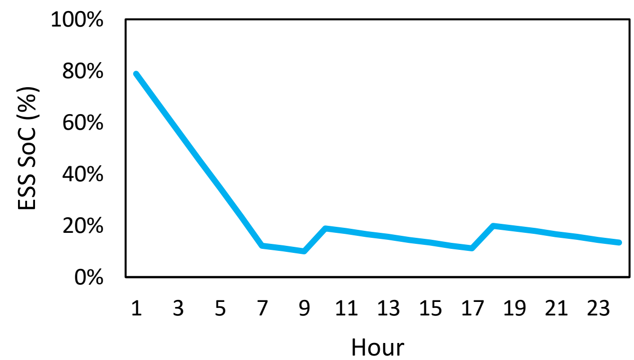


Fig. 10. Hourly profile of ESS SOC in extreme high demand scenario, beginning at 80% SOC

Between 12AM-7AM, two EV customers are assumed per hour. This results in an 11% decrease in ESS SOC per hour, as illustrated in the steep decline in Figure 10. Between 7AM-11PM, one EV customer is assumed per hour. This results in a smaller 1% decrease as the main grid provides most of the load, illustrated in the gradual slopes in Figure 9. While it is unlikely for the daily EV customer demand to be more than 10 in Malaysia, CSOs can increase the availability of their EV charging station by either installing a higher power rating grid connected inverter or installing a larger capacity ESS. However, these options also raise the initial capital expenditure significantly. Thus, the targeted revenue growth from greater availability must be balanced against the costs involved in upgrades. This trade-off is illustrated in the next section.

4.3. *Economic analysis*

Comparing between a 50 kWh and a 300 kWh ESS, the 50 kWh ESS system experiences larger depth of discharge than the 300 kWh system, especially at levels of high demand. The depth of discharge is unlikely to be cause for concern if the load is shared with the main grid directly connected like in charging strategy 2 (see Figure 11 below).

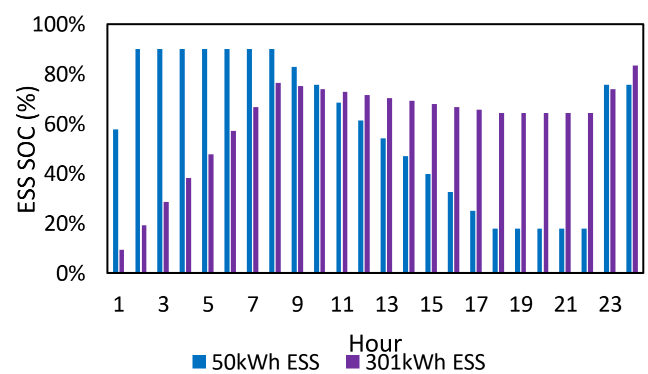


Fig. 11. Hourly profile of ESS SOC for 10 customers per day when using charging strategy 2

Here, the decline in ESS SOC is gradual regardless of ESS capacity, as the main grid is able to provide for most of the load. It is observed that even up to 10 daily EV customers, the smaller 50 kWh capacity ESS is able to provide the required energy and has sufficient capacity that does not affect charging station availability. However, if charging strategy 1 is used where the full load is borne by the ESS, the depth of discharge in the 50 kWh capacity ESS would be significant and cause unavailability of the charging station (see Figure 12 below).

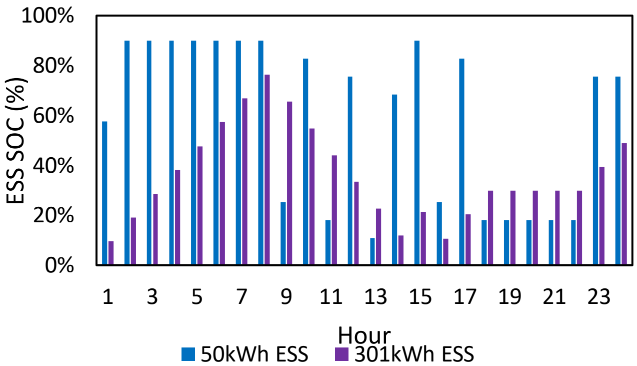


Fig. 12. Hourly profile of ESS SOC for 10 customers per day when using charging strategy 1

The large difference in capital expenditure required between different capacity of ESS indicates that the 50 kWh capacity ESS has a smaller minimum charging price for the CSO to breakeven than the 300 kWh option.

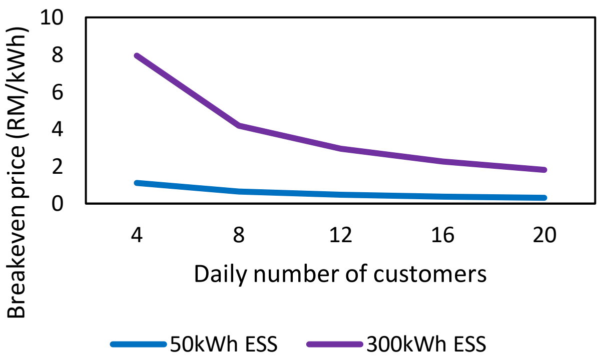


Fig. 13. Minimum charging price for charging station to breakeven, RM/kWh

The resulting difference in minimum charging price is most notable at low demand levels, where charger availability is not an issue for the station using a 50 kWh ESS and hence, no difference in charging revenue earned. However, the economic case for using a larger capacity ESS grows with a higher number of daily EV customers, where the larger capacity ESS provides greater charger availability and results in significant revenue gains.

Comparing between the three ESS options of 284-354 kWh, Option C of 324 kWh was found to be most profitable with the highest IRR at each demand level, assuming the same charging price of 2.00 RM/kWh in all cases. This is illustrated in Figure 14 below.

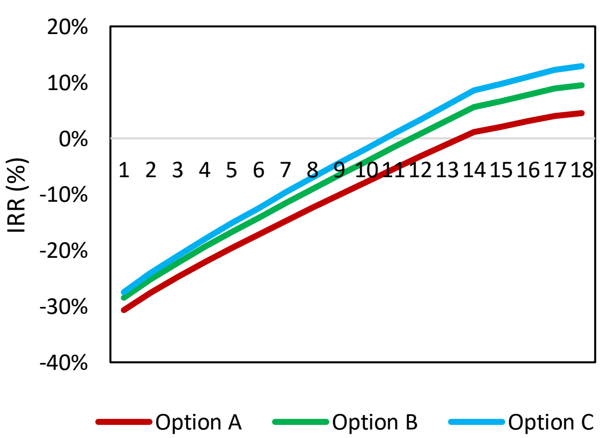


Fig. 14. Sensitivity of IRR to number of daily EV customers, %

The IRR was found to increase by 3% for every additional daily customer for the EV charging station up till 15 customers, after which any additional daily customer will only result in smaller IRR increments of 1%. From Figure 13, it is observed that a minimum of 11 daily EV customers is required for the CSO to breakeven when RM2/kWh is charged.

Varying the daily number of customers using an ESS from Option C, the minimum charging price was shown to have a logarithmic relationship with daily demand, ranging from 20.00 RM/kWh to 1.45 RM/kWh at 18 daily customers.

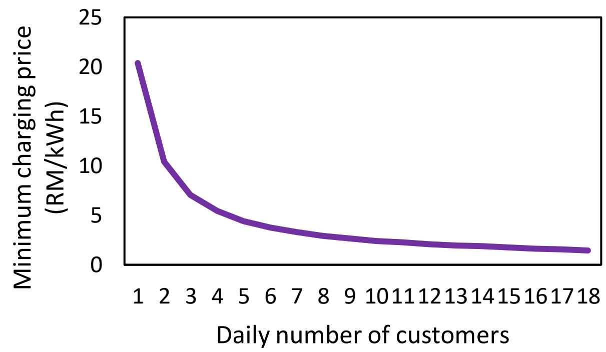


Fig. 15. Sensitivity of minimum charging price to demand level

Here, it is observed that the minimum charging price is still extremely high if the number of daily EV customers is below 10, requiring a charging price of 2 RM/kWh to breakeven in a scenario of only 2 daily customers.

5. Conclusion

With EV adoption still in its early stage in Malaysia, this suggests that the capital expenditure and operating expenditures associated with operating an EV charging station are still too high to justify a large capacity ESS being used. With a small capacity ESS of 50 kWh being sufficient even up to 10 daily EV customers, CSOs in Malaysia should look toward capping their initial capital expenditure outlay with small ESS options before upgrading them if necessary. Charging strategies with greater main grid involvement are shown to have a net benefit at high daily demand levels, as the revenue gain from greater availability offsets the increase in operating expenditure associated with peak hour electricity charges.

6. Schedule for 2nd Semester

Date	Description
10–14 Jan	Discuss available data for further study into micro-grid connected EV charging station
17–21 Jan	Finalize data and scope for study continuation
24–28 Jan	Further literature review on micro-grid connected EV charging station
31 Jan–4 Feb	Data collection
7–11 Feb	Final thesis draft (Introduction and literature review)
14–18 Feb	Data collection

21–25 Feb	Model improvements
28 Feb–4 Mar	Revise final thesis draft based on CELC
7–11 Mar	Model improvements
14–18 Mar	Analysis of results
21–25 Mar	Analysis of results
28 Mar–1 Apr	Analysis of results
4–8 Apr	Writing of results & discussion
11–15 Apr	Final review of thesis with supervisors
18-22 Apr	Final thesis submission

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