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The role of existing infrastructure of fuel stations in deploying solar charging systems, electric vehicles and solar energy: A preliminary analysis

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ABSTRACT

The lift off point for Electric vehicle (EV) sales is expected in the very near future even with oil prices that stayed cheap last few years and still inexpensive nowadays. Therefore, EV purchasers require convenient access to nationwide public charging stations infrastructure. The aim of this study is to assess the role of existing roofs of fuel Stations in deploying solar assisted electric vehicle charging systems (SAEVCS), electric vehicles and solar energy in Malaysia. PETRONAS petrol stations (PS) nationwide of Malaysia are selected to install solar charging systems on their existing infrastructure as a case study. Hybrid PV-Grid charging system is evaluated under different modes of grid power capacities (0–40 kW). The techno-economic feasibility indices are determined by using HOMER simulation tool. It is found that the estimated net average roof area of all PETRONAS stations is (500 m^2); it will be considered as a representative for the roof area of each PETRONAS station. The produced PV power capacity at each station is found 85 kW. Over 1121 stations until the end of 2015, total PV power capacity is 95 MW with a total annual green energy production of 136 GWh/year; and a total battery bank capacity of 255 MWh. Total CO_2 emissions that can be avoided by the nationwide PV charging systems is 88,559 ton/yr. The results showed that PS-SAEVCS, integrated with limited grid power line of (10 kW) can accommodate up to 2.14% of the initial EV penetration. Taking advantage of the FiT program, the cost of the PV/Grid-10 kW system can be retrieved in 6.3 years whereas the residual period (14.7 years) from the program is a net profit income. The attractive outcome from this study is that SAEVCS can be exploited as a station-to-grid (S2G) technique which is a worthy alternative to vehicle-to-grid (V2G) technology at the early years of system installation (initial stage of EV deployment).

1. Introduction

Transportation is a major source of global warming and pollutant (Mildenberger and Khare, 2000). Researches on finding alternatives have brought strong technological discontinuities to the traditional ways of developing sustainability and its economies (Ray and Kanta Ray, 2011). Researches in technology innovation and management offer multiple definitions of terms around innovation and technology management (Yanez et al., 2010). The emerging technologies and markets have become greater emphasis on engineering, entrepreneurial, and management knowledge practices in order to promise economically important innovations (Kash and Rycroft, 2002; Thukral et al., 2008). Moreover, in the literature, many studies are conducted to analyze the development and marketing of hydrogen (Huétink et al., 2010), low emission vehicles (Wesseling et al., 2014), while others envisage the future of green transportation (Lee et al., 2013) by determining the obstacles precluding the smooth deployment of sustainable mobility (Farla et al., 2010). The electrification of the

Abbreviations: EV, Electric vehicle; ICEV, internal combustion engine vehicle; PS-SAEVCS, PETRONAS Station-Solar Assisted Electric Vehicle Charging System; PS, PETRONAS station; S2G, Station to Grid capability; V2G, Vehicle to Grid capability; FiT, feed in tariff; HEV, hybrid electric vehicle; TCO, total cost of ownership; RES, renewable energy source; TNB, Tenaga Nasional Berhad; PV, Photovoltaic; TRM, Technology road map; MBIPV, Malaysia Building Integrated PV program; NPC, Net present cost; PDB, PETRONAS Dagangan Berhad; BOS, balance of system equipment; EPRI, Electric Power Research Institute; NREL, National Renewable Energy Laboratory; PHEV, Plug in hybrid EV; PEV, Plug in EV; REEV, Range extended EV; COE, the cost of energy; MP10, Malaysia tenth plan; DG, distributed generation; GHG, Green House Gas emission

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Nomenclature

A_{roof}	Roof area under of PV array with two parallel modules (m^2)
L	PV module length (m)
W	PV module width (m)
EV_{NO}	Number of EVs
P_{car}	Number of passenger cars in Malaysia roads
PV_T	PV capacity installed over one PS station (kW)
PS_{roof}	Average roofs area of PETRONAS Stations (m2)
PV_n	Number of PV modules over one PS station
$PV_{tot.power}$	PV total power capacity of PS-SAEVCS in all Malaysia (kW)
PS_{No}	Total number of PETRONAS stations in all Malaysia.
$PV_{tot.annu}$	PV total annual energy of PS-SAEVCS in all Malaysia (kWh/yr)
$PV_{PS.annu}$	PV annual produce energy of one PS-SAEVCS (kWh/yr)
SI_{annual}	Annual system income from feed-in-Tariff ($/yr)
S_{sale}	Selling rate of PV system to the grid ($/kWh)
RT	Retrieving time (yr)

transportation sector with partially and fully electrified vehicles has the potential to decrease global emission of pollutants. On the other hand, technology roadmaps provide a way to identify, evaluate, and select strategic alternatives by mapping structural and temporal relationships among research and development, technologies, potential products, and markets (Radosevic, 1999; Rinne, 2004). Researchers attempted to map multiple views of future images until 2030 using the transition from internal combustion engine vehicles (ICEVs) to EVs (Warth et al., 2013) alongside near future EV market prior to product launch (Orbach and Fruchter, 2011). However, other studies evaluated and compared the technological advancement observed in multiple hybrid electric vehicle (HEV) and full EV market segments over the past of 15 years (Lim et al., 2015) and 25 years (Dijk and Yarime, 2010), respectively.

The problems associated with the widespread deployment of EVs are mostly economical and dominated by two factors. First and foremost, it needs to be economically competitive (from the perspective of consumers) as opposed to the internal combustion engine vehicles (ICEVs) in the context of initial purchasing cost or total cost of ownership (TCO) (BCG, 2009). Fig. 1 describes the vicious loop that is asymptomatic of the EV deployment cost problem (the chicken and egg problem) in the context of factors associated with the smooth and successful EV deployment. Reduced initial cost in turn requires the reduction of the cost of battery packs. Typically, the cost of batteries can be reduced by increasing production size and battery demands, which is the byproduct of increasing the manufacturing and deployment of EVs (BCG, 2010). However, recent publications, articles and industry experts predict strong EV sales growth in the very near future due to fast drop in battery costs, affordable EVs with longer range, huge financial investments to bring more EV models to market (Dearborn, 2015; Hwang, 2016; Tajitsu, 2016; Yang, 2010).

Second factor, EV consumers require convenient access to public charging infrastructure (Maia et al., 2015). The deployment of charging infrastructures requires substantial investments amounting to billions of dollars (BCG, 2009). This requires clear approaches that provide payback assurances. The required payback assurances can be guaranteed via extended deployment of EVs within the nation, slight increase of fossil fuel price, reduced electricity price, activating off-peak rate to encourage charging at night, financial incentives for EV purchasers, battery suppliers and infrastructure investors (EPRI, 2010). However, integrating renewable power systems with EV charging stations would help in solving problems associated with the payback assurances. Moreover, utilizing the widespread deployment of petrol stations by using their existing infrastructure (roofs/shades) for installing solar charging stations would solve range anxiety problem and avoid the high initial cost of building new infrastructures for public charging stations.

On the other hand, Malaysia's national oil reserves are diminishing very fast and expected to become an oil importer by the year 2030 (Oh et al., 2010). Recognizing the importance of the renewable and green energy technology to stimulate economic growth, the Malaysian government adopted National Renewable Energy Policy. The highest share in Malaysia RE goals belong to solar energy which will increase drastically from 2016 to 2050. Consequently, Malaysia needs a precise plan for solar energy to achieve total national goals (Chen, 2012; Jacobs et al., 2012). In fact, deploying solar assisted charging stations may play an important role in increasing RE contribution in Malaysia. Moreover, the deployed solar assisted EV chargers with battery storage capabilities can boost the total grid capacity and reduce the gap between peak and valley in the electricity demand pattern (Emanuel, 2014). They can also reduce the possibility of grid-negative impacts during on-peak time, defers expensive utility system upgrades, and support the system's consistency (TVA, 2010).

Based on the above discussion, installing solar assisted charging stations on roofs of the huge number of existing petrol stations would guarantee widespread deployment of charging stations, and

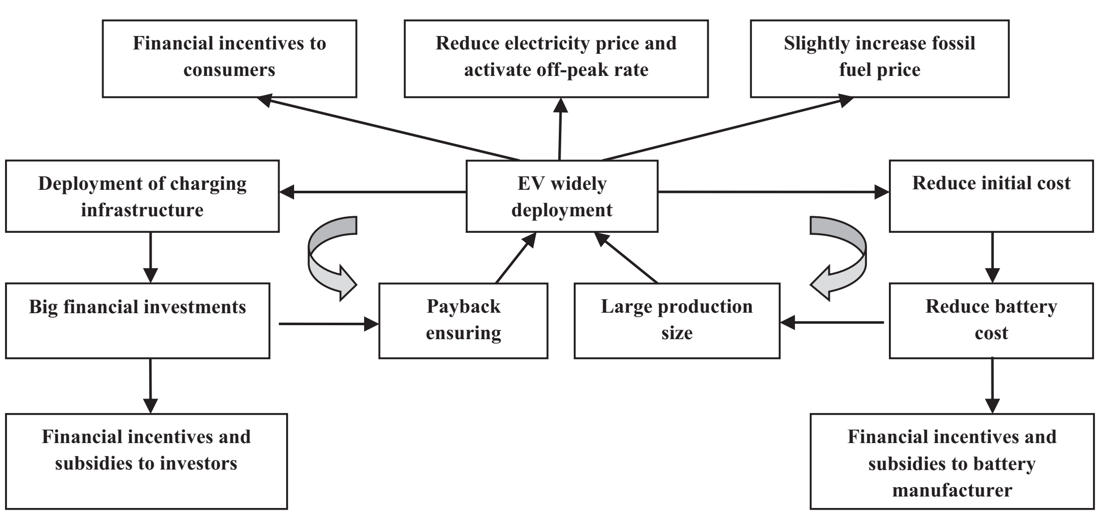

Fig. 1. EV deployment cost problem in terms of the major requirements.

consequently increase the penetration of EVs and RE in Malaysia. In this study, existing retail fuel stations of PETRONAS are chosen as virtual solar assisted charging stations. PETRONAS Dagangan Berhad (PDB) is the principal domestic marketing arm of Petroliam Nasional Berhad in Malaysia (PDB, 2012). PETRONAS has a total of (1121) petrol retail stations nationwide of Malaysia until the end of 2015 (OILTRENDS, 2014).

In the literature, many technical studies (Bhatti and Salam, 2013; Kobayashi et al., 2011; Lee and Park, 2015; Locment et al., 2010; Lukic et al., 2008; Mohamed et al., 2014; Osadcuks et al., 2013; Qifang et al., 2014a; Rasin and Rahman, 2013) and economical studies (Bayram et al., 2011; Guo et al., 2014; Li et al., 2014; Miskovski and Williamson, 2013; Qifang et al., 2014b; Tulpule et al., 2011; Tulpule et al., 2013; Woongsup et al., 2013; Xin et al., 2009) were conducted on the design and sizing of different types of solar-assisted EV charging stations. Among these studies, limited works discussed the coupling of (Grid-PV-Battery-EV) systems (Li et al., 2014; Lukic et al., 2008; Qifang et al., 2014b; Rasin and Rahman, 2013). So, further works to enrich the literature on this regard are desired. This study is a techno-economic feasibility of PS-SAEVCS with battery bank storage integrated with different grid line connection scenarios (0-40 kW). The main preliminary design parameters (input data) to achieve study objectives are monthly average solar radiation over Malaysia, number of PETRONAS stations until the end of 2015, net average roof area of all PETRONAS stations, average travel distance in Malaysia roads, number of passenger cars until end of 2015, percentage of BOS/installation cost of PV system, efficiency of regular EV (km/kWh) and feed in tariff (FiT) program rate schedule. The main outcomes of this study are the total PV power capacity and battery bank power capacity at each station and at nationwide of Malaysia, percentage of EV penetration and payback period.

2. Materials and methods

Fig. 2 outlines the research activities and the overall study evolution methodology. The necessary preliminary data for this study are learned from previous works and used as inputs to estimate some preliminary results, and then the preliminary data and preliminary results are used as inputs again in HOMER simulation tool. The main outputs of HOMER simulation are, electricity production, battery storage capacity, and initial/net present cost (NPC) of one PS-SAEVCS. Google Earth is used to estimate the average roof area of 30 randomly selected PETRONAS stations, which are regarded as being representative of 1121 PETRONAS stations all over Malaysia. The installed PV power capacity over a station is estimated based on the net average roof area, optimum PV array dimensions and optimum tilt angle. The installed PV power capacity over a station is applied in Feed-in Tariff schedule rate to obtain the electricity-selling rate ($/kWh). The payback period and net profit income are estimated based on the electrical production and the offered selling price for the installed power capacity over a PS-SAEVCS during the 21 years of FiT program. The penetration percentage of EVs in Malaysia is estimated based on the electrical production from all PS-SAEVCS nationwide Malaysia.

2.1. PETRONAS fuel stations

Google Earth is used to obtain satellite images of 30 PETRONAS retail stations around Bangi city, Selangor state, Malaysia. These samples are selected randomly within an area of (20 × 20) km^2 around Bangi city as representative of all PETRONAS stations in Malaysia. Fig. 3 illustrates the estimated net area of some PETRONAS stations by using Google image.

Fig. 4 illustrates the results of net roof area of 30 PSs surrounding Bangi city. The measured net roofs area fell between (168–2500) m^2, with an average of 606 m^2. As shown in the figure, all stations are less than 1000 m^2 except two stations exceeded 1000 m^2. To avoid the overestimation of the average net roofs area, these two values are ignored and taking into account the stations with net roofs area that are less than 1000 m^2. So, the average net roofs area (PS_{roof}) that is going to be taken as a design parameter is (514 ≈ 500 m^2). This value (500 m^2) is assumed as a representative average net roof area for each PETRONAS station in Malaysia to install the panels of the PV power system on it.

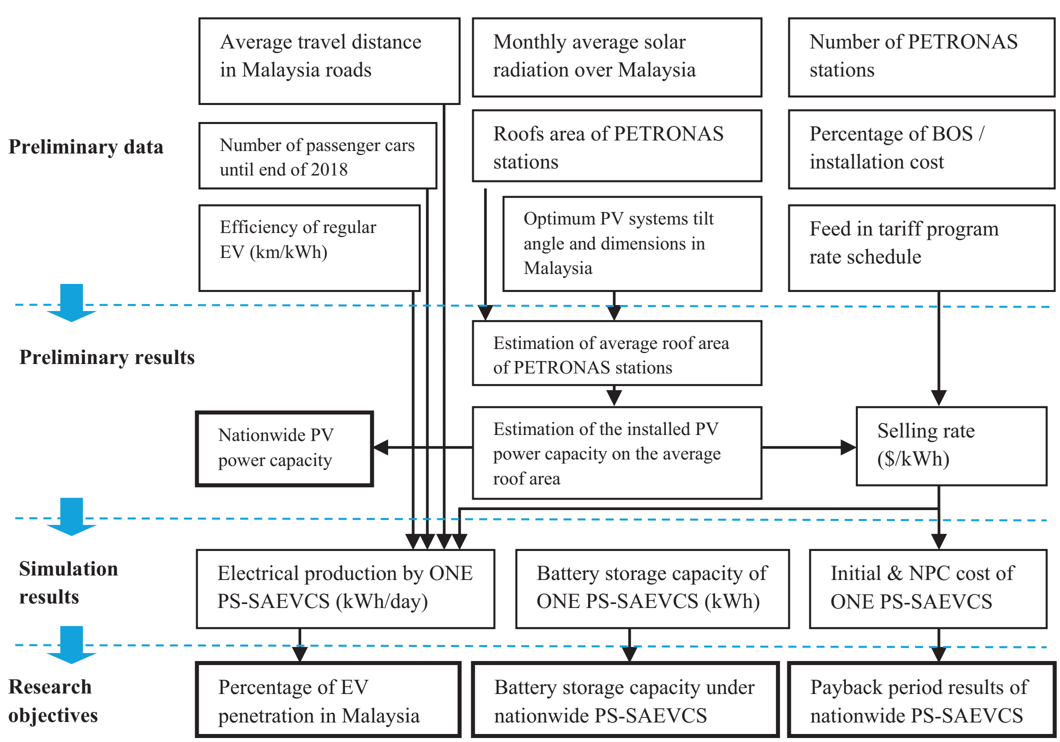

Fig. 2. Block diagram of the study evolution methodology.

Fig. 3. Sample of estimated net roof area of PETRONAS stations by using Google image.

2.2. Solar resources

The observed average monthly solar radiation data of nine cities in Malaysia is reported in (Azhari et al., 2008). Based on the results of this reference, the average monthly solar radiation over Malaysia is plotted and shown in Fig. 5. The annual solar radiation over Malaysia is found (4.89) kW/m^2.

2.3. Main components of the PV power system

The main system components in this work are PV panels, battery bank, and grid-tie bidirectional converter. HY6-72-370M type solar modules are adopted in this study, with a 370 W nominal power, 20.1% efficiency, 1.94 m^2 module area, and US$ 159 module price (Seasun, 2018). Deep cycle Lead Acid battery (RA12-260B) type is adopted in this study, with 12 V DC output nominal voltage, 3.12 kWh energy capacity, and US$ 200 price per unit (RITAR, 2016). Lead Acid battery is cheaper and has a longer cycle life than Li-ion and other batteries, such as Ni-MH (Lowe et al., 2010). Despite its large size and ample weight compared to Li-ion battery, the Lead Acid battery is more suitable for this system, assuming that the bulky feature does not affect the performance of the system. The selected converter in this study is SAJ grid-tie inverter (Suntrio Plus 10k) (Guangzhou Sanjing Electric Co., Ltd, 2018) of 10kWp, costing 100 US$/kW.

Balance of system (BOS) equipment includes electrical works and labor used to integrate the solar modules into the utility electrical system. The average percentage cost of BOS is 29.43%, as learned from (MBIPV, 2014). The PV replacement cost is still the same capital (purchasing) cost, as the installation cost is required only for the first project installation.

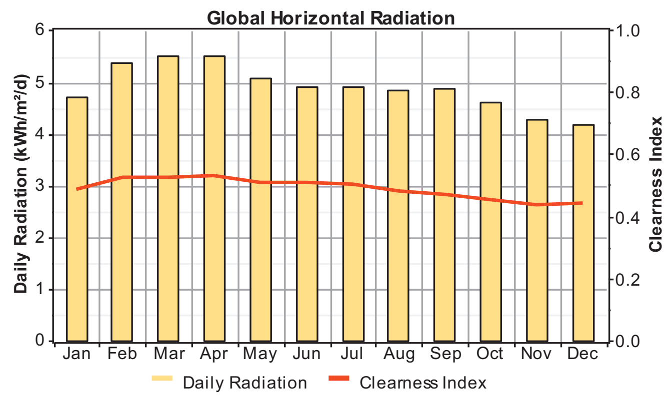

Fig. 5. Monthly average solar radiation (kWh/m^2/d) over Malaysia.

2.4. HOMER simulation tool

HOMER Micropower Optimization Model was developed by the U.S. (NREL) for evaluating design options for hybrid micropower systems (Lambert et al., 2006). HOMER models a physical behavior and system life cycle cost, allowing users to analyze the system's feasibility and compare multiple designs on the account of their respective technical and economical merits (Lambert et al., 2006). In this study HOMER simulation tool is used to optimize the PS-SAEVCS configurations for multiple scenarios.

3. Theoretical background

3.1. PV system installation area

In this work, the flat roof area (A_{roof}) required for installing a string

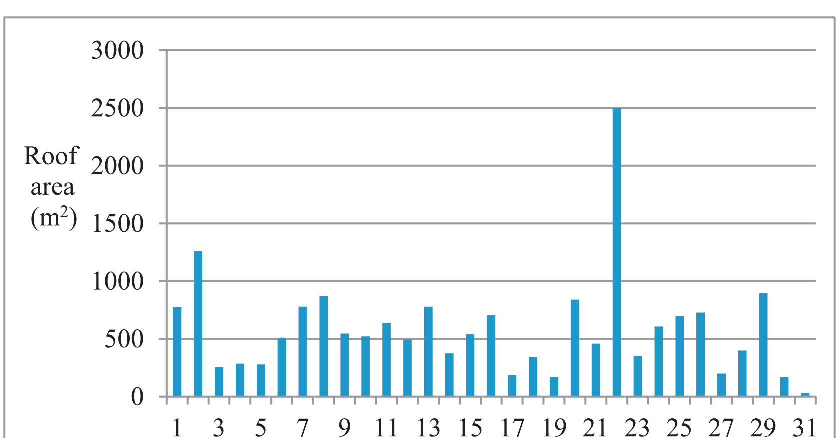

Fig. 4. Net roof area for (30) PETRONAS stations within an area of (20 × 20) km^2 around Bangi city, Malaysia.

of two PV panels, with a total length (2L) and width (W), is determined using Eq. (1). Fig. 6 illustrates the PV sup array of two panels tilted at 7° and 50 cm apart from the next sup array.

$$A_{roof} = (2L\ \mathrm{Cos}\,(7^{\circ}) + 50\ \ \mathrm{cm}) \times W \tag{1}$$

The (50 cm) distance is required as a pass way distance between the PV strings to clean and allow for system maintenance service.

3.2. FiT schedule rate of one PS-SAEVCS

The offered electricity-selling rate S_{sale} (\$/kWh) under FiT rate schedule depends on the installed PV power capacity at one PS-SAEVCS. The total annual electrical production of the PV power system ($PV_{PS.annu.}$) can be translated into an annual PV system income of SI_{annual} (\$/yr):

$$SI_{annual}(\$/yr) = PV_{PS.annu}(kWh/yr) * S_{sale}(\$/kWh) \tag{2}$$

The Retrieved Time (RT (yr)) for initial or total system cost can be determined using Eq. (3):

$$RT(yr) = \frac{\textit{initial or total system cost}\,(\$)}{SI_{annual}\left(\frac{\$}{yr}\right)} \tag{3}$$

3.3. The percentage value of EV penetration

The percentage value of EV penetration in Malaysia can be estimated after obtaining the total number of EVs ($EV_{No.}$) that visit all PS-SAEVCS per day and the number of passengers cars in Malaysian roads (P_{car}) in 2018:

$$\text{Percentage value of EVs\%} = \frac{EV_{No.} * 100}{P_{car}} \tag{4}$$

Based on the fact that the demand for public charging infrastructure is centered on overcoming range anxiety, along with the EPRI study suggesting that 80% of EV owner's prefer home charging (EPRI, 2010). So, an average of 20% of EV owners will charge their cars at public charging stations. The expected percentage of EV penetration in the country will be equal to:

$$\text{Expected percentage of EV penetration}(\%) = \left(\frac{100\%}{20\%}\right) * \text{Percentage value of EVs}(\%) \tag{5}$$

3.4. Photovoltaic system

The PV power of two (HY6-72-370M) modules is 740 W, installed over a roof area (A_{roof}), with a power density (W/m^2) of:

$$\text{Power density} = 740\ \ W/A_{roof} \tag{6}$$

The total PV system capacity PV_T (W) installed in the average roof area of one PETRONAS station (PS_{roof}) is:

$$PV_T = PS_{roof} * \text{Power density} \tag{7}$$

The number of PV modules (PV_n) with a capacity of (370 W) per one module over one PS roof area is:

$$PV_n = PV_T/370\ \ W \tag{8}$$

For all 1121 nationwide PSs ($PS_{No.}$), the total PV power capacity $PV_{tot.power}$ (W) of the nationwide system is:

$$PV_{tot.power} = PS_{No.} * PV_T \tag{9}$$

The total annual electrical energy ($PV_{tot.annu.}$) produced by PV power systems nationwide Malaysia results from the annual electrical production of one PS-SAEVCS ($PV_{PS.annu}$.) multiply by total number of PETRONAS stations:

$$PV_{tot.annu.} = PV_{PS.annu.} * PS_{No.} \tag{10}$$

4. Results and discussions

In this section, the PV-Grid charging system is evaluated under selected range of integrated grid power capacities (0–40 kW) that is expected to be economically feasible. The simulation results were obtained for band of grid line connection capacities (0, 5, 10, 15, 20, 25, 30, 35 and 40 kW). The techno-economic feasibility of each scenario will be analyzed and subsequently evaluated.

Some preliminary results such as flat roof area required for installing a string of two PV panels tilted at 7° and a part 50 cm from next sup array, PV power density, installed PV power capacity and number of required PV modules at each station were determined from the aforementioned equations, and listed in Table 1.

PV panels type (HY6-72-370M) were considered, with a capital cost of US\$430/kW, plus the average installation work or balance of system (BOS) equipment cost of (2292 \$/kW). The final capital cost of PV panels is equal to \$2722/kW, while the replacement cost remains at \$430/kW, due to the fact that the BOS was only needed for the first project's installation.

The average PV power capacity (85 kW) of one PS-SAEVCS that was applied to the FiT schedule rate of (72 kW–1 MW) are equal to RM1.14, plus RM (+0.26) for installation in buildings or building structures, resulting in a system selling rate (Ssale) of 0.36 \$/kWh (US \$1 = RM3.86 at April 2018).

Under a 10 kW grid line connection scenario, the grid line capacity is similar to the maximum electric power available from the residential three-phase electricity outlet. These features render the system operational in all PETRONAS stations without the additional grid capacity or electricity contract change. It also contributes to the mitigation of the detrimental impact of high-level EV deployment on grid utility. According to the fee schedule for low voltage commercial tariff (TNB, 2016), the cost of purchasing electricity from TNB grid utility is equivalent to 0.136 \$/kWh.

The scenario of 10 kW grid line capacity is subsequently evaluated and discussed thoroughly. Meanwhile, other scenarios are regarded as the final results, as it utilizes similar procedures of evaluation. The 10 kW scenario is initially preferred, as it allows for more than 60% of renewable energy usage in the total system power generation. Moreover, it represents the rate and convenient domestic power connection in electricity standards of three-phase, which is the 380 V AC power outlet.

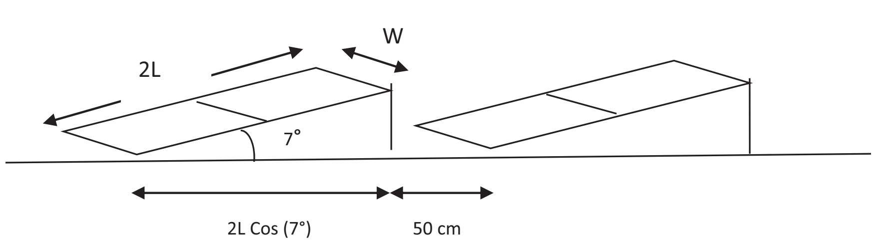

Fig. 6. Flat roof area required for installing a string of two PV panels tilted at 7° and a part 50 cm from next sup array.

Table 1
Preliminary results of installing PV panels.

Parameter	Value	Equation
A_{roof}	4.347 m^2	(1)
Power density (W/m^2)	170.2 W/m^2	(6)
PV_T	85 kW	(7)
PV_n	230 modules	(8)

4.1. One PS-SAEVCS integrated with 10 kW grid line connection

Table 2 shows the optimal configuration of one PS-SAEVCS with limited 10 kW grid line connection. This configuration represents the optimal feasibility out of 21,168 feasible designs evaluated by HOMER simulation tool. It is a cost effective and has a lower net present cost that falls within 85 kW PV sensitivity cases. The design can endure a maximum daily load of 446 kWh/d, and has an initial capital cost of $248,120 and net present cost (NPC) of $274,800 at an operation cost of 1443 $/yr. The cost of energy (COE) is 0.128 $/kWh, while the renewable energy fraction is 67% from the system total energy produced by the PV system and grid line.

The total power capacity of 1121 PS-SAEVCSs nationwide Malaysia is 95.3 MW (Eq. (9)).

4.1.1. Theoretical confirmation

The battery bank autonomy A_{batt} [hours] is the ratio of the battery bank size to the electric load. This value represents the time in hours can the battery bank serve the external load autonomously. HOMER calculates the battery bank autonomy using the following equation:

$$Abatt = \frac{N_{batt} * S_{batt} * (1 - q_{min}) * 24 \frac{hours}{day}}{E_{load}} \tag{11}$$

where N_{batt} is the number of batteries in the battery bank, S_{batt} is the capacity of single battery in the battery bank [kWh], q_{min} is the minimum level of state of charge and E_{load} the primary load (kWh/d).

Battery bank size S_{bank} (kWh) can be calculated as follow:

$$S_{bank} = N_{batt} * S_{batt} \tag{12}$$

where N_{batt} the number of batteries in battery bank and S_{batt} (kWh) the capacity of single battery. The battery bank capacity is related to daily load E_{load} (kWh/d) and battery bank autonomy A_{batt} (hrs) as follow:

$$Sbank = \frac{E_{load} * A_{batt}}{DoD * 24 \frac{hours}{day}} \tag{13}$$

where DoD is the depth of discharge ($= 1 - q_{min}$). The battery bank autonomy A_{batt} is considered in HOMER according to the value that achieves the minimum cost for battery bank in the optimized design. HOMER evaluates the battery bank cost by take the minimum cost for all hourly time steps of the system operation along the project life time. So, we will consider this value of autonomy as the suitable value to calculate the battery bank capacity. In the simulation results of the 10 kW system design, Battery bank autonomy (A_{batt}) is considered as 10.1 h. The battery bank capacity (S_{bank}) and number of batteries in the battery bank (N_{bank}) of (RA12-260D) type with single battery capacity of (3.12 kWh) is shown in Table 3 according to the Eqs. (12) and (13).

These results are close to the simulation results of battery bank capacity (234.6 kWh) and the number of batteries in the battery bank (75 units) for the optimized design of 10 kW grid line scenario of one PS-SAEVCS.

Table 3
The number of batteries and total battery bank capacity.

Parameter	Value	Unit
E_{load}	446	kWh/d
A_{batt}	10.1	hr
DoD	80	%
S_{bank}	234.6	kWh
S_{batt}	3.12	kWh
N_{bank}	75	unit

Table 4
Annual pollution that produced by the grid to supply one PS-SAEVCS.

Pollutant	Emissions (kg/yr)
Carbon dioxide	39,268
Sulfur dioxide	166
Nitrogen oxides	81

Table 5
Annual pollutant that avoided by PS-SAEVCS PV produced energy.

PS	CO_2	SO_2	NO_x
1 station	79 ton	332 kg	162 kg
1121 stations	88,559 ton	372 ton	182 ton

4.1.2. Estimation of EV penetration

Passenger cars in Malaysia travel an average daily distance of 60 km (Osman, 2011). Under EV efficiency of 4.66 km/kWh (Parks et al., 2007), EV requires 13 kWh charging energy. Also, the number of passenger cars in Malaysian roads (P_{car}) is equal to 8,997,562 units, based on forecasting pattern by Jahirul et al. (2007).

Average daily trip distance of passenger car in Malaysia is 60 km/day. EV load and EV efficiency of 13 kWh and 4.66 km/kWh respectively are enough for 60 km driving. So, the maximum daily charging load (446 kWh/d) obtained from one PS-SAEVCS integrated with 10 kW grid line connection is sufficient to charge 34 EV/day.

For 1121 PS-SAEVCS, the total EVs that are charged daily in Malaysia is 38,114 units, which is equivalent to 0.42% of EV penetration in Malaysia as a result of (Eq. (4)). By considering the EPRI study (which suggest that 80% of EV owner's prefer to charge at home), the aforementioned stations can accommodate 2.14% initial EV penetration in Malaysia (Eq. (5)). This initial EV penetration percentage (2.14%) is a safe deployment without any risk of increasing electricity demand for nationwide PS-SAEVCS public charging infrastructure in country.

This calculation helps estimate the required energy that accommodates specific EV penetration level charging at 1121 nationwide PS stations. Actually, there are many types of public charging opportunities, such as another charging station company, charging in the work place, in shopping centers, and in public parking lots. This means that the EV penetration estimates in this work are limited to the EVs that visit the PS stations daily. Also, the owners of other types of PEVs, like PHEVs or REEVs, are not compelled to stop for recharging, as their vehicles can also run on gasoline. Therefore, they are more inclined to take advantage of cheap and convenient charging at home.

Table 2
Optimum output results of one PS-SAEVCS integrated with 10 kW grid line connection.

Daily load (kWh/d)	PV (kW)	Batteries number	Converter (kW)	Grid (kW)	Initial capital	Operating cost ($/yr)	Total NPC ($)	COE ($/kWh)	Renewable fraction
446	85	75	10	10	$248,120	9671	274,800	0.128	0.67

Table 6
Cost details of one PS-SAEVCS with different grid line capacities.

Grid	Daily charging load	PV capacity	Batteries (RA12-260D)	Converter size	Initial capital cost	Total NPC	Operating cost	COE	Solar fraction
kW	kWh/d	kW	No. of units	kW	$	$	$/yr	$/kWh	
0	267	85	75	0	247,120	271,115	1877	0.218	1
5	356	85	72	5	246,990	272,269	5630	0.162	0.81
10	446	85	75	10	248,120	274,800	9671	0.128	0.67
15	539	85	70	15	247,570	277,488	14,150	0.105	0.56
20	636	85	73	20	248,700	281,897	18,784	0.089	0.48
25	738	85	72	25	248,990	287,260	23,885	0.077	0.42
30	843	85	76	30	250,330	293,936	29,230	0.068	0.37
35	955	85	73	35	250,200	301,388	35,229	0.060	0.33
40	1070	85	75	40	251,120	309,946	41,418	0.054	0.24
Average			73		248,793				

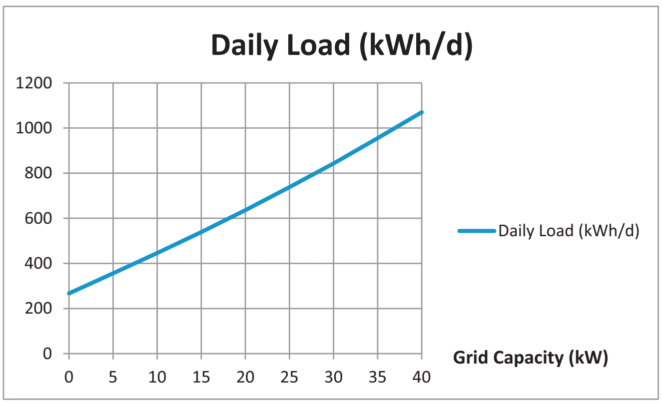

Fig. 7. Linear relation between grid capacity and daily charging load.

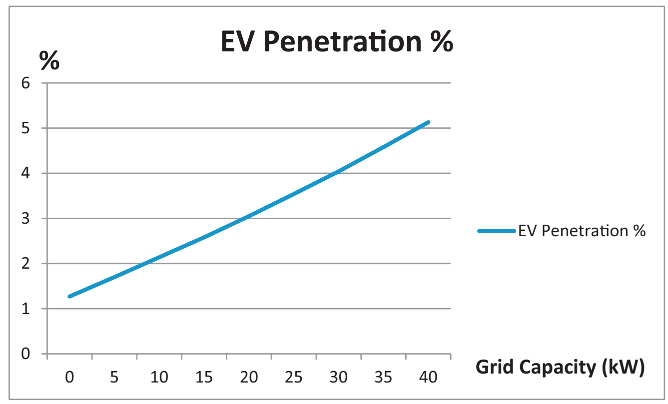

Fig. 8. EV penetration percentage vs. grid capacity for all scenarios.

4.1.3. Total PV energy production

The total annual energy produced by the PV system ($PV_{PS.annu.}$) is 121,304 kWh, with 60,505 kWh purchased from the grid. This amount of renewable energy is equivalent to 67% of the total electricity produced by the system. For 1121 PS stations, there are about 136 GWh annual clean electric energy produced by the PV systems from PS-SAEVCS in Malaysia (Eq. (10)).

4.1.4. Feed-in-tariff applying rate

PV power capacity per one PS-SAEVCS is 85 kW, this power capacity is applied to the feed in tariff (FiT) rate schedule between (72 and 1000) kW. Total annual energy produced by PV system ($PV_{PS.annu.}$) of 121,304 kWh/yr translates to an annual system income (SI_{annual} ($/yr)) and equals to 43,669 $/yr, with a selling rate of S_{sale} (0.36 US$/kWh); determined via Eq. (2). This represents the total income yield from selling electricity produced by one PS-SAEVCS PV system to the grid annually. By using Eq. (3), the initial cost of the optimized design is equal to ($248,120), and is recoverable within 5.7 years. Meanwhile, the net present cost (NPC), which represents the total system cost ($274,800), is recoverable within 6.3 years from the 21-year period of the FiT program. The remaining 14.7 years of the FiT program will be the net profit income to the project, indicating that the system is ensured as a successful investment project.

4.1.5. PS-SAEVCS storage capability and grid connection

The optimized design battery bank of (75) batteries has a nominal

Table 7
Specifications of optimized system configurations for different grid capacity with equivalent daily loads.

Daily load	kWh/d	267	356	446	539	636	738	843	955	1070
Grid	kW	0	5	10	15	20	25	30	35	40
PV	kW	85	85	85	85	85	85	85	85	85
Battery	unit	75	72	75	70	73	72	76	73	75
Converter	kW	0	5	10	15	20	25	30	35	40
Total capital cost	$	247,120	246,990	248,120	247,570	248,700	248,990	250,330	250,200	251,120
Total NPC	$	271,115	272,269	274,800	277,488	281,897	287,260	293,936	301,388	309,946
Operating cost	$/yr	1877	5630	9671	14,150	18,784	23,885	29,230	35,229	41,418
COE	$/kWh	0.218	0.162	0.128	0.105	0.089	0.077	0.068	0.060	0.054
PV production	kWh/yr	121,304	121,304	121,304	121,304	121,304	121,304	121,304	121,304	121,304
Grid purchases	kWh/yr	0	29,137	60,488	94,209	129,131	166,648	205,958	249,082	293,688
Total electrical production	kWh/yr	121,304	150,441	181,792	215,513	250,435	287,952	327,262	370,386	414,992
Renewable fraction		1	0.81	0.67	0.56	0.48	0.42	0.37	0.33	0.24
EV penetration	%	1.27	1.7	2.14	2.58	3.05	3.54	4.04	4.58	5.13
Number of EVs	unit	23,023	30,698	38,458	46,478	54,842	63,638	72,692	82,350	92,266
Battery life	yr	6.0	6.4	7.0	7.5	8.2	8.2	8.6	7.8	7.5
Battery autonomy	hr	16.83	12.12	9.56	7.78	6.88	5.84	5.40	4.58	4.20
CO_2 emissions	kg/yr	0	18,910	39,256	61,142	83,806	108,154	133,666	161,654	190,604

Table 8
Payback periods of all grid capacity scenarios.

Primary load	Grid	Total capital cost	Total NPC	Capital cost payback period	NPC cost payback period
kWh/d	kW	$	$	yr	yr
267	0	247,120	271,115	5.6	6.2
356	5	246,990	272,269	5.6	6.2
446	10	248,120	274,800	5.7	6.3
539	15	247,570	277,488	5.6	6.3
636	20	248,700	281,897	5.7	6.4
738	25	248,990	287,260	5.7	6.6
843	30	250,330	293,936	5.7	6.7
955	35	250,200	301,388	5.7	6.9
1070	40	251,120	309,946	5.7	7

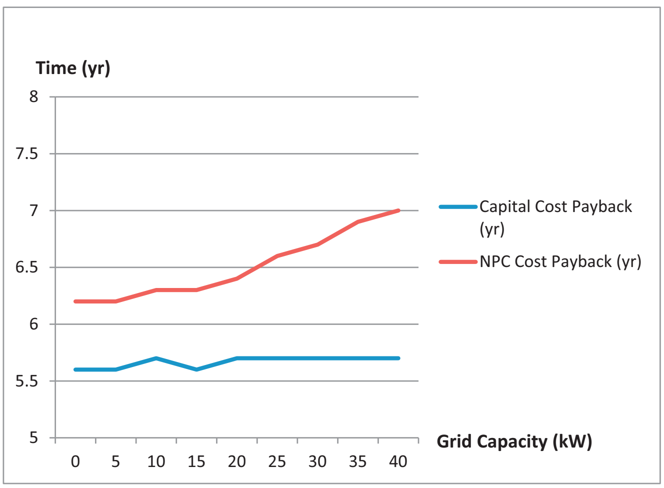

Fig. 9. Payback periods for capital and NPC cost for various grid capacity.

capacity of 234 kWh for one PS-SAEVCS. The storage capacity and limited power grid connection of PS-SAEVCS slowly draws electricity from the grid and injects it rapidly into the EV battery via a rapid charger device. This is quite effective in alleviating the simultaneously large EV charging demand problems associated with integrating EV infrastructure with the grid. The results show that the connection of one PS-SAEVCS with 10-kW grid line produced 60,505 kWh of energy drawn annually from the grid. This total energy is stored in the battery to meet the rapidly charging demand of EVs when PV is available at daytime or assists the battery in meeting the charge demand when PV is unavailable during the nights. This amount of energy represents 33% of the total energy produced by one PS-SAEVCS. The results also show that the drawn energy are smallest on February, March, and April, due to high incidents of solar energy during these months, which translate to maximum PV output power.

4.1.6. Pollution

Table 4 shows the annual estimated pollutant emitted by the grid in supplying one PS-SAEVCS with grid energy fraction. The total amount of pollutant eschewed by PS-SAEVCS is equivalent to the fraction of clean energy produced by the PV system instead of the electricity purchased from the grid. The CO_2 emitting factor of electricity sector in Malaysia is 649 g/kWh, while emitting factors of SO_2 and NO_x are 2.74 g/kWh and 1.34 g/kWh, respectively.

The annual pollutant eschewed by one PS-SAEVCS of 121,304 kWh/yr PV production and 1121 PS-SAEVCSs of 136 GWh/yr PV production are shown in (Table 5).

4.2. Different grid power capacities scenarios

Different grid line connection capacities (0, 5, 10, 15, 20, 25, 30, 35 and 40 kW) are considered in this evaluation. Table 6 shows the maximum daily charging load that the charging system can endure per day for each grid power capacity scenario with the corresponding optimum results of the main the techno-economic feasibility parameters.

The number of batteries in the battery bank shows up-down fluctuation for all scenarios around the average number of batteries (73) versus daily load and grid line capacity. The stability of battery bank size around one value is essentially attributed to the fixed PV power capacity for different system scenarios. It is indicative of the strong relationship between size of battery bank and renewable energy source in the hybrid power systems, irrespective of grid line capacity.

On the other hand, the fraction of renewable energy being used decrease with increasing of grid energy fraction and the stability of the PV energy output. The system shares the produced energy equally from PV and grid at grid line scenario 15 kW. In a 40-kW grid line scenario, the renewable energy fraction takes 24% from the total energy production, indicating that the system keep promising solar fraction in all scenarios.

The linear relation between daily load and grid capacity is illustrated in Fig. 7. This relation indicates that increasing grid line power leads to a linear increase of the charging loads that the system can endure per day. Therefore, the system output power is adjustable to the charging demand size and also scalable with the level of EV penetration in the country. For future prospects, increasing the EV level penetration in the country require an increase in the grid energy fraction of PS-SAEVCS. Also, drawing energy from the grid can be limited via night charging, mostly due to the unavailability of solar energy. This energy can then be retrieved during the peak hours of the day. The limited and slow drawing of energy from the grid enhances PS-SAEVCS ability to accommodate more EVs for day charges without disturbing the grid system.

Table 7 collects the specifications of optimized designs for different grid capacity with equivalent daily loads. Limited grid line capacity with ranges of (0, 5, 10, 15… 40) kW scenarios are addressed in the context of equivalent EV penetration in terms of number of passenger cars in Malaysia in 2015 by taking into account the EPRI percentages. The size of battery bank fluctuates around an average of 73 batteries (RA12-260D, 3.12 kWh), which is equal to a total storage capacity of 227.76 kWh. This number of batteries is regarded as the correct number for all scenarios. This is also equal to (9) Nissan leaf battery packs (24 kWh each), or (14) Mitsubishi MiEV battery packs (16 kWh each). This capacity is equivalent to about 255 MWh total capacity of PS-SAEVCS storage system over 1121 PSs in Malaysia.

Also, the penetration of EV in Malaysia demonstrated a directly proportional relationship with the grid line connection capacity, mostly from increased charging power that is available for charging more EVs daily (Fig. 8). This indicates that the system can start with little grid power fraction in cases where EV penetration is minimal. The increased grid fraction depends on the increase of EV penetration in the country.

By using Eq. (3), the capital (initial) and NPC cost of the optimized design of all grid line scenarios, with its payback periods, are shown in Table 8. We can see that the capital cost payback period remained approximately same, at 5.7 years, due to the system keeping similar component sizes, except for the converter, where the price differed along the grid capacity scenarios (Fig. 9). Grid energy purchasing cost resulting from increased grid line capacity and daily charging load appears due to the increased cost of NPC. Therefore, the cost of NPC for all scenarios with increasing payback periods from (6.2–7) years within Malaysia FiT maximum period of (21 years).

This results show that the system manage to economically retrieve its total cost of up to the grid line with 40-kW capacities by selling the PV electrical production to the grid without taking into account the charging service fees. Actually, electricity is not being consumed within the station without EV charging demand, which means that the charging service income must be considered in the net profits of the station economical feasibility. Also, this indicates that the system can start with low grid line capacities according to the daily charging demand or EV penetration level and adjust the charging service fees to be profitable for the station and vehicle owners.

5. Closing remarks

The lessons learned from this work are:

1- The total PV power capacity of (PS-SAEVCS) is 95 MW over 1121 Petronas stations in all Malaysia, with a total annual green energy production of 136 GWh/year. This total power capacity exceeds the country's RES Policy and Action Plan target of 65 MW in 2015.
2- The battery bank capacity of the assisted PV system is equal to 227 kWh for one PS-SAEVCS and 255 MWh over 1121 PSs in Malaysia. This storage capacity can be used as a standby dispatchable energy resource or demand-response energy resource to supply electricity to the grid utility. This capacity is equivalent to about 10,602 Nissan leaf battery packs (24 kWh each), or 15,937 Mitsubishi MiEV battery packs (16 kWh each), which can function as station-to-grid (S2G) to compensate for the well-known vehicle-to-grid (V2G) technology. Unlike V2G, S2G's capability is controllable, dispatchable, less cost, and owned by one party without needing high EV penetration and consequential complex arrangements. On the other hand, the scenario that is economically and technically proper for reusing the depleted EV battery packs (still possess 80% of its initial capacity) is in the form of battery bank in the PS-SAEVCS. This scenario will considerably reduce the cost of the system storage device. Also, it will allow to take full advantage of the battery's full lifetime while reducing the total cost of ownership (TCO) of battery, and consequently, the vehicle.
3- The assisted PV charging systems over all PETRONAS stations infrastructure that are connected to a low limited power grid share (10 kW) can provide an initial EV penetration of up to 2.14% in the country without any noticeable stress on the grid system. However, grid share in PS-SAEVCS has the potential to increase EV penetration.
4- The equivalent NPC cost retrieval provided from the FiT program for PS-SAEVCS connected with 10-kW grid line is 6.3 years. The remaining 14.7 years will be the net profit income from selling solar electricity to the grid in cases with no visible EV penetrations. During EV penetration, the payback income will be recovered from EV charging fees at the stations. This results in profits, on top of realizing the main goal of sustaining the electricity generation mixed with green and environmentally friendly energy source.

Actually, the estimated EV penetration in this work is limited to the EVs visiting the PS stations once per day. Meanwhile, there are many companies, such as (Shell, Esso, BHP, Caltix… etc.) that are capable of using their respective roof structures as public charging infrastructure, which will considerably enhance EV penetration into the country and increase incomes derived from charging services. Also, there are many other public charging opportunities, such as work place, shopping centers, and public parking lots. On the other hand, owners of other PEVs types, such as PHEVs or REEVs, are not compelled to stop for recharging, due to being equipped with gasoline engines, which allows them to take advantage of cheap and convenient charging at home. The government can boost the EV market in the country by offering financial incentives in terms of EV purchasing prices and loans. Grid utility companies, such as (TNB), can positively contribute to this plan by encouraging night charging via the activation of off-peak electricity fees discount, similar to the ones practiced in developed countries.

6. Conclusion

This work evaluates the techno-economic feasibility of integrating PV system with existing PETRONAS fuel stations structures as solar-assisted EV charging infrastructure (PS-SAEVCS) in Malaysia. The preliminary feasibility of the proposed system (PS-SAEVCS) is confirmed in this work, and can enhance the country development plans in:

- The transportation sector by providing nationwide EV rapid charging infrastructure, boosting the efforts of EV deployment in the country.
- Electricity generation and the transmission sector by providing PV Distribution Generation and nationwide battery storage capability for smart grid activation.
- Environmentally by reducing GHG emissions footprint of the country.
- Economically by providing a successful investment model and job opportunities.

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