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PV-ESS design for industrial loads under TOU pricing structure in Thailand

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Abstract

Co-usages of Energy Storage System (ESS) with Solar Photovoltaics (PVs) are proved to provide beneficial results for both distribution and demand sides under proper design system. In this study, PV and ESS sizing are designed to serve industrial loads using Time-of-Use pricing. Our major goal is to lower the electric bill. In the meantime, the sharp load-rising present in daily load is another concern of power quality. The 1-min resolution annual loads of a building in Thailand are investigated and managed via designed control algorithm. The scenarios deploying PV-only and PV coupling with ESS are investigated in order to reduce the annual electric bill. Design selection criteria focus on the cost effectiveness and the ability to improve power quality. Reduction of up to 40% annual tariff could be achieved at the proposed sizing conditions of PV+ESS. The system offers approximately 8-years payback period, however suffers from energy losses. Attempts to change the algorithms for ESS operating schedule have relieved the loss with insignificant amounts. For reasonable saving and faster payback (4.5 years) with minimal energy loss, smaller size of PV is the immediate choice. The power quality requires further in-depth study of the load characteristics for better PV design and more-complicated ESS scenarios.

Keywords: PV-ESS, ESS design, Tariff reduction, Peak shaving

1. Introduction

Concerns on global warming have been driven research aspects as well as policies toward clean energy resources. The mission to reduce greenhouse gas emissions has led to the integration of renewable energy (RE) sources into the power grid [1]. Distributed generation units of renewable based are considered worldwide as an alternative solution to deal with the energy crisis faced by the modern world [2]. Various types of renewable energy at consumers side, especially solar photovoltaic (PV), are used in order to raise the efficiency of energy usage and to reduce electric bill by reducing energy consumption from grid [3, 4]. Moreover, this distributed generator can also increase reliability during fault from main grid by operating in islanding microgrid. Although there are varieties of PV advantages, PV is limited to daytime use. Depending on load types, PV might not be at advantage at all cases, i.e. dominated loads are during the night, thus the off-hour loads must be relieved by grid only. For such a specific case, some projects have deployed the energy storage system (ESS). However, the unit price of the capacity of the ESS system is still expensive at present. PV-ESS sizing design, whose sizing varies with the sizes and the characters of the loads they serve, has become a challenge with both technical and economic aspects being considered.

Solar PV has been promoted for private sector in Thailand for the last 5 years [5]. Especially the number of the solar roofs installed at behind the meter gradually grows. Following the Power Development Plan (PDP) in year 2018, the promising solar will be increased to 100 MW within 25-30 years. The sizing design depends on the tariff structure and electricity tariff structure in Thailand comprises of 3 parts, namely base tariff, automatic tariff adjustment (Ft) and taxes. The base tariff, which reflects the cost of the power construction (power plant and the whole transmission/distribution system) is varied its structure

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between the types of customer services, generally classified by the amount of energy consumption and the voltage level. The Ft part is a variable factor managed by regulator, which is out of customer control and normally adjusted every 4 months. The taxes are calculated from base tariff and Ft combined.

Both PV and ESS could be used in wide range of applications as a stand-alone and in cooperation. Research studies have been explored in various approaches such as technical and economical designs. If classified by load types, these two technologies are often found in small scale and large scale loads.

Examples of small scale loads are often residential loads. The studies mostly look into the loads of an individual household, a small village or community. Many algorithms were developed for smart homes using multi-sources and multi-technologies such as PV and wind turbine with loads management [3, 6-9], solar PV with battery storage [10] were proposed for saving the electric bill. Some studies focused on battery storage system (BSS) design. BSS was used independently in [11, 12] or coupled with solar PV in [10] in order to reduce the demand charge. The system design (sizing) were diverse among different load characteristics. The amount of electric bill saving depends on the tariff structures. Some study considered the cycle life of the battery storage system [13].

Large scale loads are often involved industrial loads as consumer point of views and network loads as the distributors/generators. Both sizing and control algorithm were designed to support loads with the use of the solar PV coupling with the battery storage system [14, 15] With probabilistic load prediction (PLP) and probability density function (PDF), the operator could foresee load and assign the appropriate operating pattern for the storage system via peak shaving [14]. The algorithm in [15] was proposed to determine the maximum revenue within 24 hours of power flowing into grid with the intermittence of PV, whose results showed higher total revenues in the case co-usage of PV and battery system than using PV as extra source alone.

In this study we design the sizing of PV and energy storage system (ESS) to match with the load demands with tariff reduction as our major goal and determine to use the peak shaving technique as to receive a side advantage of improving power quality. The project is as well aimed for the implementation of PV and ESS installation. The current system consists of industrial loads in Thailand which carries approximately 1 MW peak load. In the design methodology, we have divided the study into cases, where the optimization models are developed to evaluate the benefits of using either PV or ESS system on a yearly basis. The realistic building loads of year 2018 are used in the simulation. The real PV data from nearby area is exploited, however estimated as a one-day profile for the whole year. In our studied system, PV is only expected for self-consumption as stated by the local regulation that the system has to be zero-export.

2. Methodology

The required inputs for technical part include loads/PV data and ESS specifications, while the economical part needs the investment costs. The input loads have been collected from a selected building within the industrial estate in Thailand over 1 year period with data resolution of 1 minute. The input PV is measured from a nearby solar farm with 5-minute resolution. As our study cases involve the use of PV-only and PV/ESS coupling, the details of the design methodology of each case are supplied in its own section. ESS operations are determined by the behaviour of 1-minute time step loads. While the final goal is to reduce the tariff, the specific objective of changing the strategy also varies with the situations.

2.1. Input loads characteristics

Original loads were analyzed in order to obtain the initial information for designing ESS operation pattern. Based on the TOU pricing structure, loads could be classified into 2 types; weekday (WD) and weekend (WE) loads. Generalized loads of the building as shown in Fig. 1a) and Fig. 1b) demonstrate the characters of WD and WE loads respectively. WD loads are separated as on-peak and off-peak hours following the designated period and WE loads are assigned as off-peak hours for the whole time. Demand charge is calculated based on the peak power during on-peak hour on weekday.

WD and WE loads represent different characteristics. Daily WD loads always have sharp peak around 7-7:30 AM and normally ramp up and down until 3-4 PM, where another sharp drop occasionally occurs. As for WD loads, the load gradients are not observed. The profiles are rather flat without any specific peak at a certain time. The highest power (denoted as Pmax) of the building of year 2018 reaches 1.1 MW. The lowest power (denoted as Pmin) is recorded to be less than 0.1 MW. Considering WD and WE load types separately, averaged power (denoted as Pavg), minimal power (Pmin) and maximal power (Pmax) are analysed as shown in Fig. 2. Minimal powers occur around 0.2-0.3 MW during both weekdays and weekends. Average powers during weekday (0.4-0.6 MW) are two times the average load during weekend (0.2-0.3 MW). Most of the maximal powers during weekdays range between 0.8-1.0 MW, however also distribute sporadically from 0.2-1.1 MW. The maximal powers during weekend are rather low and range closely to the average and minimal powers, signifying weekend loads being constant. The large gap between Pmax and Pmin has placed difficulty for appropriate PV sizing decision.

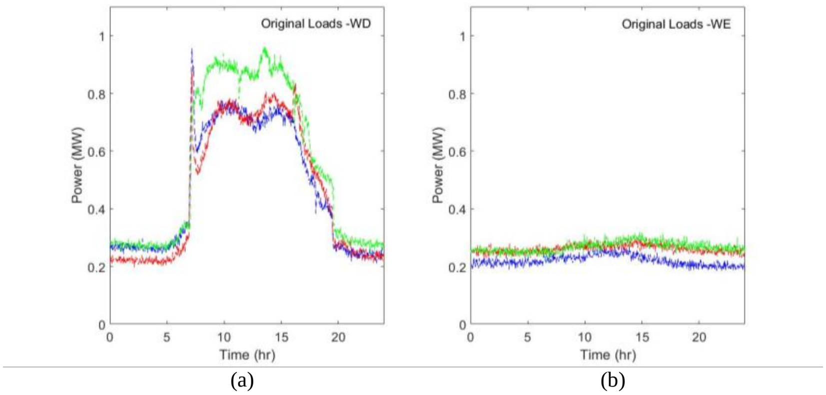


Fig. 1. Random pick of daily original load profiles representing: (a) weekday (WD) and (b) weekend (WE) loads.

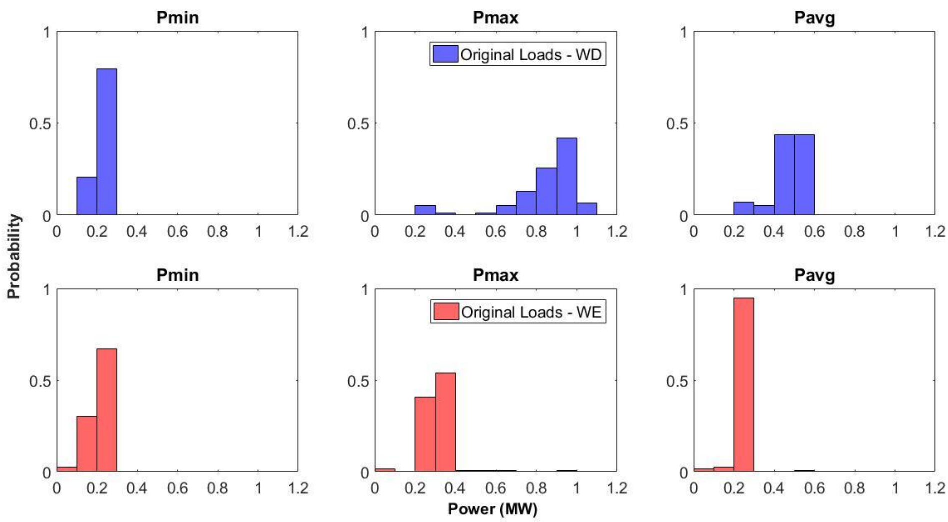


Fig. 2. Histogram analysis of the original load showing probability of Pmin/Pmax/Pavg for weekday (WD) and weekend (WE) loads (WD - Pmax 0.8-1 MW / Pmin 0.2-0.3 MW / Pavg 0.4-0.6 MW; WE - Pmax 0.2-0.4 MW / Pmin 0.2-0.3 MW / Pavg 0.2-0.3 MW)

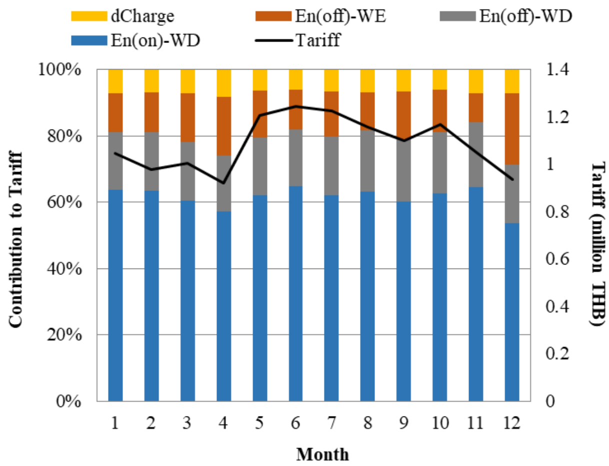


Fig. 3. Monthly tariff and contributions of peak power (dCharge) and energy terms for tariff calculation during on-peak/off-peak hours for weekday (WD) / weekend (WE) load types.

2.2. Time-of-Use tariff structure

Following Time-of-Use (TOU) tariff structure in Thailand, monthly tariff (denoted as Tariff) can be calculated as following.

$$\text{Tariff} = (\text{En(on)}*\text{onTariff}) + (\text{En(off)}*\text{offTariff}) + (\text{Pmax-mo}*\text{dCharge}) + \text{Ft} \quad (1)$$

From the equation, energy during on-peak, En(on) and off-peak, En(off) hours are priced at different rates following on-peak tariff rate (onTariff) being 4.13 THB/kWh and off-peak tariff rate (offTariff) being 2.61 THB/kWh. On-peak periods are from 9 AM – 10 PM of weekdays and off-peak periods from 10 PM – 9 AM during weekdays and 0 AM -12 PM during weekends and special holidays. Demand charge (dCharge), 74.14 THB/kW, is calculated using Pmax-mo, collected from the peak power of the month during on-peak hour.

The energy and the power terms are considered as based tariff which varies with the input loads only. The Ft part varies according to other uncontrollable factors therefore is not included in our study. From eq. (1), tariff reduction can be pursued either via reducing overall energy consumption or reducing the peak power. The strategy for reducing electricity bill will be defined in the later section due to its dependence on the load characteristics.

2.3. Potential benefits of using PV/PV+ESS at the organization

Monthly tariff is calculated with the original load profile via eq. 1, whose results are expressed in Fig. 3. The on-peak energy during weekdays holds 53-60% share of the total monthly energy, while that of off-peak holds 25-27%. The share for off-peak energy during weekends is 15-21%. By using PV alone, energy during on-peak hour could certainly be reduced. The based tariff of the building is calculated to be 13 million THB in year 2018, which deviates less than 0.1% from the actual bills. In details, the energy tariff contributes 93% while demand charge only contributes 7% of the total tariff. Reducing monthly demand charge seems not to put significant effects toward our major goal. However, cutting peak might be an essential option considering the fact that this building serves a number of scientific laboratories and electric consumptions are committed to lab instruments and maintenances. The origin of the sharp peak seen in the morning during the weekday is possibly due to the exhausted chillers being turned on at the beginning of the work. The routine spikes have long affected the quality of the electricity, reflecting not only on the physical state of the sensitive instruments but also on the peculiar experimental data. The instruments being malfunction plus the rising in annual maintenance costs have been subjected to be resolved, enlightening the potential benefits of engaging energy storage into the system. However, using

ESS alone has been proved not to effectively reducing the electric bill in our case. Reducing energy consumption as well as improving quality of the electricity seems to be the potential benefits of PV and ESS coupling usage in this study.

2.4. Studied parameters

These parameters are used as selection criteria for sizing selection.

- Reducing demand charge

The peak that results in demand charge occurs during on-peak hour only (implying only weekdays). The only chance that can completely reduce this part of the tariff is the appropriate size of PV and ESS that covers all the peak load situations within the desire-hours. Reducing demand charge might not be a hefty concern toward economic aspects, as its contribution is little. However, the complete reduction implies the loads are leveled to the desire shaving limit, thus reducing overall consumption energy as well as ensuring the power quality. The ability to reduce the demand charge under the specified scenario is counted as a number of months within 1 year time.

- Excess energy of PV

Excess energy from PV results when PV power overcomes the original load, which varies with PV size. Parts of the excess energy are charged into ESS and the dismissed parts are energy loss. Total excess energy (Total EnExcess) and total losses (Total EnLoss) are determined as a yearly basis, varied with PV size, the matching ESS size (Pbatt and Ebatt) and the shaving limit (Psh). Percent EnLoss is calculated to show how much losses are from weekdays/weekends, by comparing the energy loss during weekdays to the energy excess during weekdays and vice versa. The excess energies are sorted as WD and WE. To compare efficiency, the percentage of energy excess charged into the storage (%Use EnExcess) is calculated via

$$\%\text{Use EnExcess} = (\text{Total EnExcess} - \text{Total Enloss}) / \text{Total EnExcess} \quad (2)$$

- ESS operation analysis

In the case with ESS, the power rated and the energy rated of battery are limited during the simulation with the state of charge (SOC), The SOC of the battery is controlled within the acceptation limits, where the maximum SOC allowed (SOCmax) is 90% and the minimum (SOCmin) is 10%. To analyze the operation of ESS, the SOC profile, the charge and discharge state, the power to energy ratio of the operated battery are inspected. While not included in the results, the number of charge/discharged cycles are as well counted as to indicate the ESS performance.

- Payback

For economic aspect, the investment cost, the annual saving and the payback could be calculated via the following equation

$$\text{Inv\_tot} = \text{Inv\_PV} + \text{Inv\_ESS} \quad (3)$$

$$\text{Inv\_ESS} = (\text{ESS\_MW} * \text{Pbatt} + \text{ESS\_MWh} * \text{Ebatt}) * 1.25 \quad (4)$$

$$\text{Inv\_PV} = (\text{PV\_MW} * \text{PV\_produced}) * 1.25 \quad (5)$$

$$\text{Payback} = \text{Inv\_tot} / \text{Annual\_saving} \quad (6)$$

where total investment (Inv_tot) considered the investments on PV (Inv_PV) and ESS (Inv_ESS). The unit price of ESS relies on the size of power (ESS_MW*Pbatt) and the size of energy (ESS_MWh*Ebatt). PV price depends mainly on the power produced (PV_produced) times the unit price of PV (PV_MW). Since the size of the PV and ESS mentioned in this article is the useable size, the factor of 1.25 is multiplied in order to estimate the installation price. Payback in year is the total investment divided by the annual saving. Annual saving is the difference between the orginal tariff of the building and the new tariff under the design scenarios. The current prices information are given in Table 1.

- Levelized cost of Energy (LCOE)

The levelized cost of energy or LCOE is similar to the concept of the payback for energy systems, which combines both the fixed costs and variable costs. LCOE was calculated via

$$LCOE = \Sigma[(I(\tau) + M(\tau)) / (1 + r)^{\tau}] / \Sigma[(E(\tau)/(1 + r)^{\tau}] \tag{7}$$

The total cost associated with the project generally includes the initial cost of the investment expenditures (I), maintenance and operations expenditures (M), which corresponds to the annual tariff in this study. The total output of the power-generating asset includes the sum of all electricity generated (E). The last two important factors to be considered in the equation are the discount rate of the project (r) being 8% and the economic life of the system (τ) of 20 years.

Table 1. Unit cost of PV and ESS system as of 2019

ESS price based on rated power (ESS_MW)	15,000 THB/kWh
ESS price based on capacity (ESS_MWh)	15,000 THB/kW
PV price based on rated power (PV_MW)	30,000 THB/kW

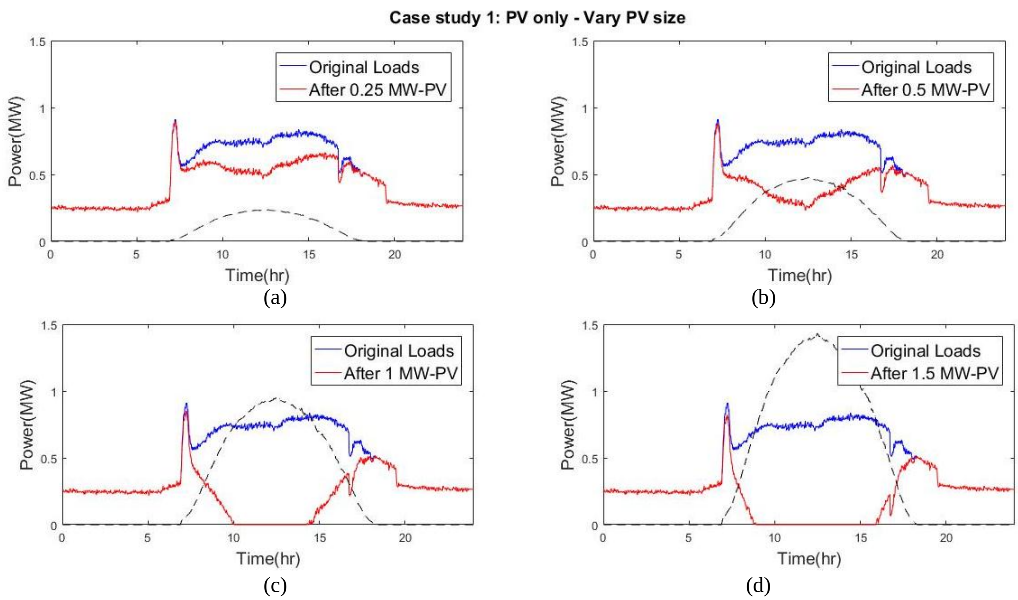


Fig. 4. Original load of a selected weekday plotted against new load after PV at (a) 0.25 (b) 0.5 (c) 1 and (c) 1.5 MW. The dotted line corresponds to the PV profile according to its size.

Table 2. Comparison of Annual saving, years return and LCOE and excess energy from the installation of various PV sizes

PV size (MW)	Annual saving (THB/yr)	Payback (yr)	LCOE (THB/kWh)	Total EnExcess (MWh/yr)	EnExcess (MWh/yr)	
					WD	WE
0.10	910,459	4.12	51.95	1	0	1
0.25	2,260,044	4.15	19.40	4	0	4
0.33	2,943,557	4.25	14.06	23	3	20
0.50	4,100,860	4.57	8.89	130	19	111
1.00	6,802,409	5.51	4.05	641	187	454
1.50	7,611,025	7.39	2.97	1611	817	794

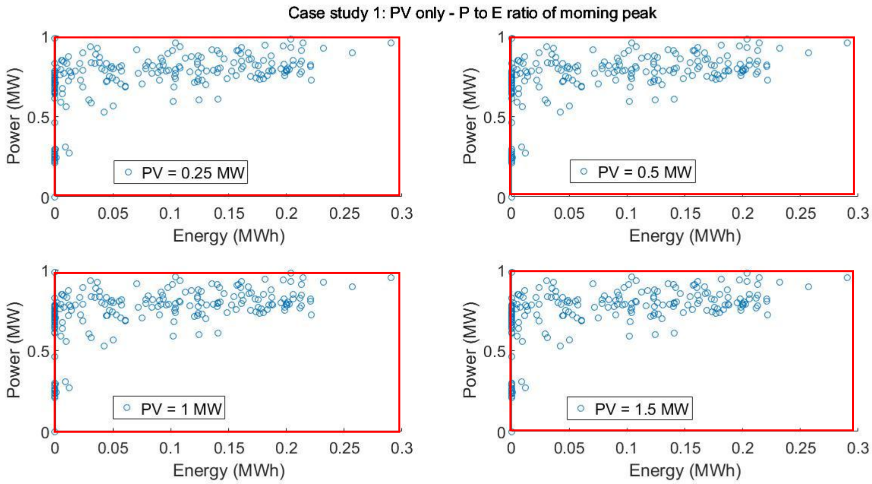


Fig. 5. Power to energy ratio of the morning peak calculated from load after various PV sizes; 0.25 MW, 0.5 MW, 1 MW and 1.5 MW

3. Case Studies

3.1. Case study 1: PV-only

In case study 1, PV-only is selected for the system to reduce the load demands, thus reduce the tariff. According to the load characteristics in the previous section, the selected PV sizings are ranged from 0.25-1.5 MW. All energies produced from the desire PV sizes are dispatched to the building loads, following

$$Pload(t) = Pori\_load(t) - PPV(t) \quad (8)$$

$$Pgrid(t) = Pload(t) \quad (9)$$

where Pload(t) is the load after dispatched by PV at step time t. PPV(t) is the power produced by PV to be dispatched to original building load, Pori_load(t). Pgrid(t) is the final load seen by grid, used to calculate monthly tariff. Annual tariff are calculated and compared their savings upon the various PV sizes.

Examples of 1-day loads (WD) after dispatched power from PV at various PV sizes are depicted in Fig. 4. PV profile on a moderate day is selected from a solar farm in the nearby area. The maximum produced size is 4 MW. The profile is scaled to the selected sizes in the calculation as 0.25, 0.5, 1 and 1.5 MW. Loads are significantly reduced from 10 AM to 3 PM and increasing in the reduction magnitude with larger PV sizes. PV regardless of its size however shows little effects on the morning peak reduction.

The advantages of varying PV sizes are summarized in Table 2. PV helps reducing loads and offers significant annual tariff reduction. The installation of 0.1 MW-PV offers saving of 0.9 million THB per year, which is approximately 7% saving of the annual tariff, while upsized PV would increase even more saving, up to 52% and 58% with 1 MW- and 1.5 MW-PV, respectively. Considering the payback of less than 5 years at PV size smaller than 0.5 MW and less than 10 years for 1 and 1.5 MW, PV investment offers such a good deal, however the comparison of LCOE has suggested to install the minimum size of 1 MW-PV (with LCOE = 4.05 THB/kWh), given the electricity tariff at on-peak hour being 4.2 THB/kWh.

The tendency to install 1 MW-PV also posts another problem. Such PV size fits Pmax of the building and is fully utilized during weekdays. Since WE loads are rather low (Pavg = 0.3 MW), the surplus energy during weekends is without use. While the surplus energies from smaller PV sizes are ignorable, the excess energy of 641 MWh per year generated by the 1MW-PV system is such a significant loss. The loss is more than double when upscaling to 1.5 MW-PV.

The effects of the morning peak are mentioned earlier. Being able to reduce these peaks could be value-added. The peak starts approximately at 7 AM and drops to half of the peak power before ramping up again around 8 AM. In order to remove this morning peak and allow the load to rise continuously, the power to energy ratios are estimated. The results in Fig. 5 suggested ESS of the same capacity despite various sizes of PV, possibly because the peak occurs at the early hour before the PV production. Approximated size of ESS in order to fully cover this peak is 1 MW/0.3 MWh.

Table 3. ESS operating pattern for case study 2

Weekdays (WD)	Weekends (WE)
ESS discharges to perform peak shaving at Psh at SOC>SOCmin. At SOC<SOCmax, ESS is prioritized to charge from excess PV, then from grid but at off-peak hour only.	ESS operates under the same pattern as it does on WD

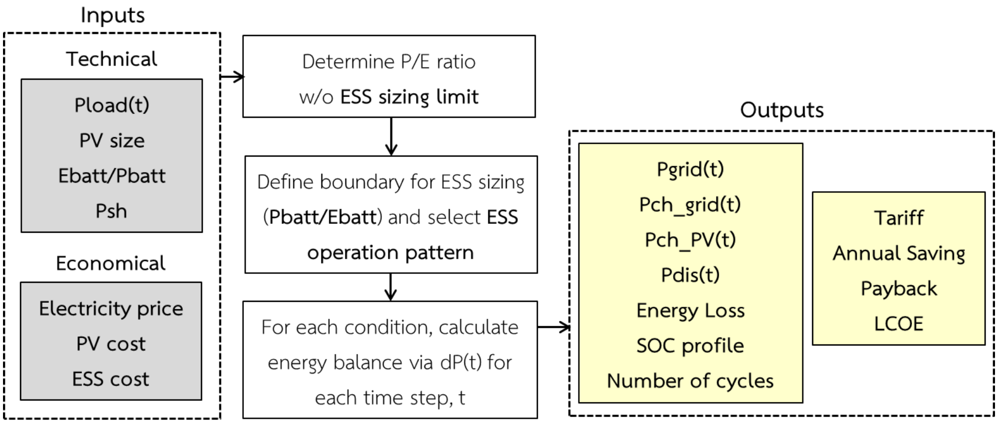


Fig. 6. General algorithm for ESS sizing design, listing input and output parameters

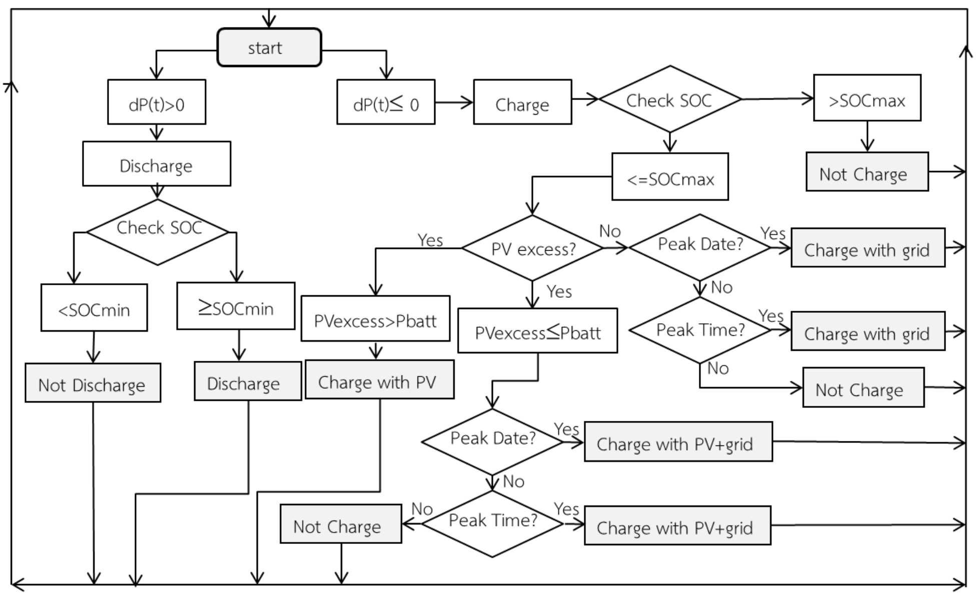


Fig. 7. Operation pattern for charge/discharge schemes for both WD and WE loads in case study 2

Investing on PV system has shown impression toward economic aspects. Nonetheless, if such other concerns as reduction of spikes, energy loss management are taken into account, PV system alone could not take such responsibility. To achieve the above mentioned benefits (shaving off the peaks), coupling with ESS would have been a trended choice. However, the root of the spikes occurring in the morning of weekday could be the results of the rotten chillers. The matter of the investment between PV-alone or PV coupling with ESS and the chiller renovation must be further investigated.

3.2. Case study 2: PV+ ESS for peak demand shaving

The urgent to manage the energy loss during the weekend has suggested the incorporation of ESS with PV. ESS is expected to store the excess PV energy and dispatch to load when appropriate. ESS and PV need to be well designed, since in case of PV size being too small, there would be no need in using ESS due to the lacking of the surplus energy. However, the installation cost of ESS is considered expensive, the design needs to optimize between the expenditures as well as the values gained.

In case study 2, with the selected PV size, we would determine the matching ESS system that would further help reducing the tariff as well as the demand charge. Peak shaving strategic is used in the calculation, where the highest load is limited at Psh, which is determined based on Pmin/Pmax/Pavg of the loads after PV.

The flow chart describing ESS design method is demonstrated in Fig. 6. The peak load shaving concept is used to determine the ESS size without the sizing constraints. Similar analysis as in Fig. 2 has shown that the new statistic for Pmax(WD) is reduced by 1 MW-PV to be 0.6-0.8 MW, Pmin(WD) to be 0-0.1 MW and Pavg to be 0.2-0.3 MW. The peak shaving limits (Psh) are set to be 0.6/0.5/0.4 and 0.3 MW accordingly. With P to E ratio obtained from the simulation, a few ESS sizes are selected based on the ability to cover at least 90% of the occurrences for further limited calculation. With ESS size as boundary limit, another simulation is performed under the assigned ESS operating pattern. The operating schedule for case study 2 is described in Table 3 (whose detailed step is shown in Fig. 7). The fully utilized ESS is set to 90% as maximum state of charge (SOCmax) and 10% as minimum state of charge (SOCmin). Loads after PV are used as input loads (calculated via eq. (8) from case study 1) to calculate dP(t) as following

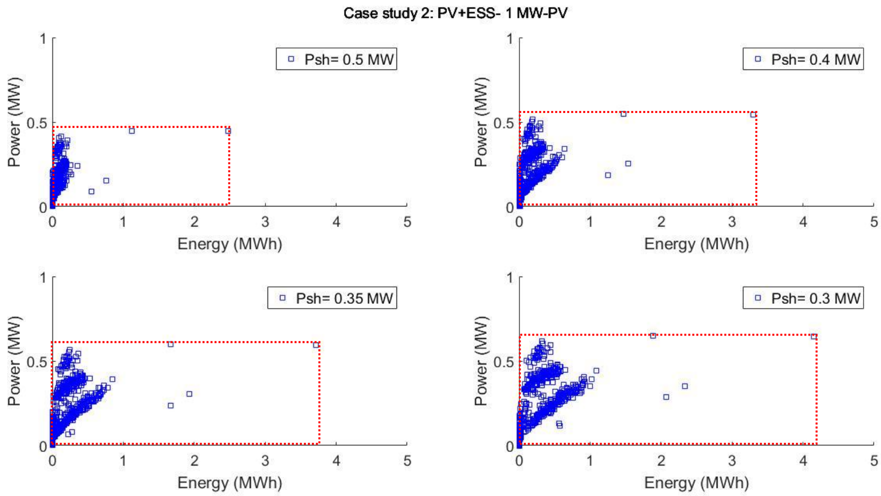
$$dP(t) = Pload(t) - Psh \tag{10}$$

where Pload(t) is the input load used for P to E ratio calculation, defined as load after PPV(t) and dP(t) is the load difference between the input load and load shaving limit, Psh. ESS operates based on the value of dP(t), discharging when $dP(t) > 0$ and charging when $dP(t) < 0$. The charge process is prioritized by the excess PV, while grid charging is allowed at off-peak hour only. Pgrid(t) can be determined via the combination of the input load with additional power charge from grid, Pch_grid(t) and the deduction of the power discharged from ESS, Pdis(t), following

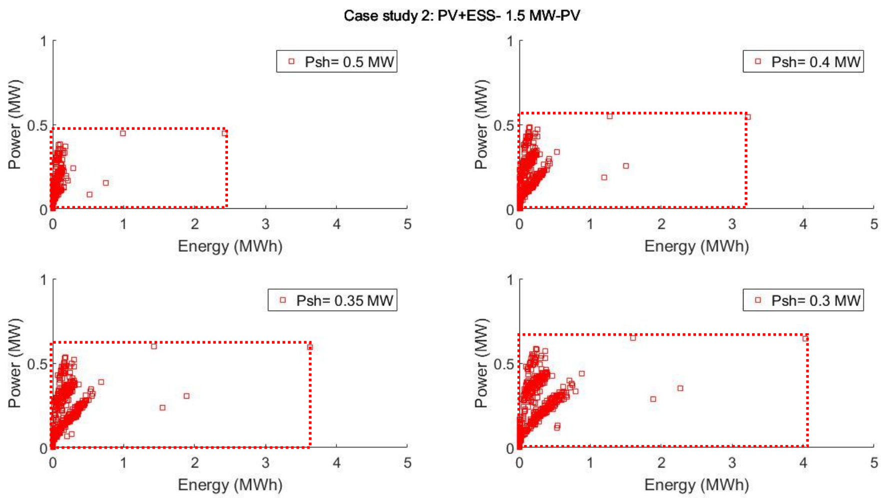
$$Pgrid(t) = Pload(t) + Pch\_grid(t) - Pdis(t) \tag{11}$$

For PV size selection, as seen in case study 1, larger size of PV offers lower LCOE, while takes longer time for payback. Following the algorithm in Fig. 6, the ESS design is without the sizing limit in the first step. Shown in Fig. 8(a) and (b) are the power to energy (P/E) ratio calculated for 1 MW- and 1.5 MW-PVs upon variations of Psh (0.5/0.4/0.35/0.3 MW). To perform shaving at the same Psh limit requires the same ESS size for both PV powers. However ESS capacity also depends on the level of peak shaving; the lower Psh, the higher ESS capacity is required. Regardless of the PV size, to successfully perform peak shaving at 0.5 MW required ESS of 0.5 MW/2.5 MWh in size and 0.6 MW/4.1 MWh for Psh 0.3 MW, assuming all P/E incidents are covered. However, in the actual design schemes at least 90% of the P/E incidents (for Psh 0.3 MW) are considered. For the selected covering incidents, appropriate ESS size are determined to be 0.4 MW/0.25 MWh, 0.5 MW/0.5 MWh, 0.6 MW/0.5 MWh and 0.6 MW/0.75 MWh in order to match with the descending shaving limit for 1 MW-PV. The slightly larger ESS capacities are required in case of 1.5 MW-PV installation. Therefore, considering the payback time and the energy loss (as studied in case study 1), 1 MW-PV is a proper choice of installation. With the selected ESS sizes matched with the fixed Psh as constraints, the calculations are refined upon the design process to justify the decisions.

ESS sizing and Psh conditions used in case study 2 as listed in Table 4 are selected based on the 90% covering incidents and the availability in commercial (1C-charge-discharge scheme) as well as the comparison purpose. The max powers of the month regardless of on-peak or off peak period are somewhat reduced with 1 MW-PV installation, as evidenced in Fig. 9. With 1 MW-PV, Fig. 10 and Fig. 11 are the results from the simulation of the two-selected condition from Table 4. Results show plots of original loads versus new loads for 1-week period including WD and WE load types. In Fig. 10, the choice of ESS size (0.5 MW/0.5 MWh) helps chopping the WD loads down to Psh level. The SOC is reduced to only 60% at maximum and stays fully charged for the whole weekends. The charge/discharge behaviors demonstrate the charging frequency of once or twice a day during weekdays and none during weekends, which as well reflect in a number of charge/discharge cycles for the whole year.



(a)



(b)

Fig. 8. Power to energy ratio calculated without energy storage size constraints with varying peak shaving limit for (a) 1 MW-PV (b) 1.5 MW-PV. Dotted line shows the possible storage size to cover all shaving possibilities.

Table 4. Conditions for ESS sizes (specifying Pbatt/Ebatt) and Psh used in case study 2

Conditions	Psh(MW)	Pbatt(MW)	Ebatt(MWh)
1	0.50	0.50	0.50
2	0.40	0.50	0.50
3	0.35	0.50	0.50
4	0.35	0.50	0.75

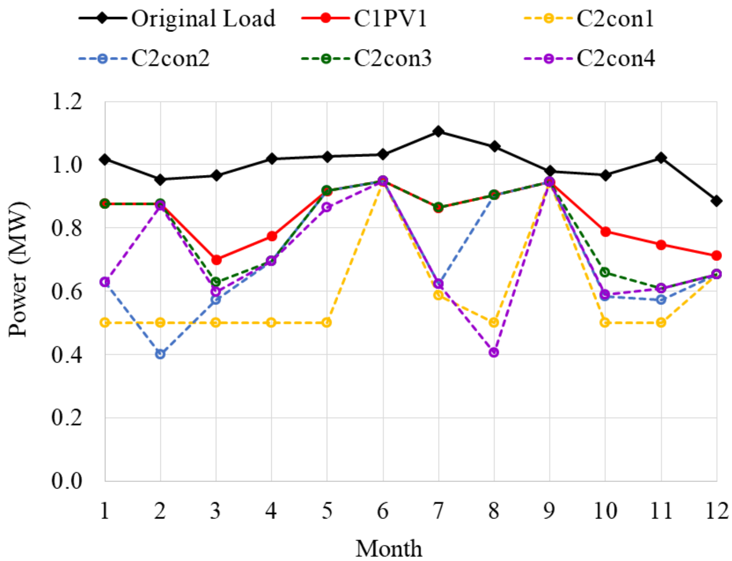


Fig. 9. The max power of the month regardless of on-peak or off-peak period of original loads, case study 1 with 1 MW-PV (denoted as C1PV1), case study 2 condition 1 (denoted as C2con1) and so on.

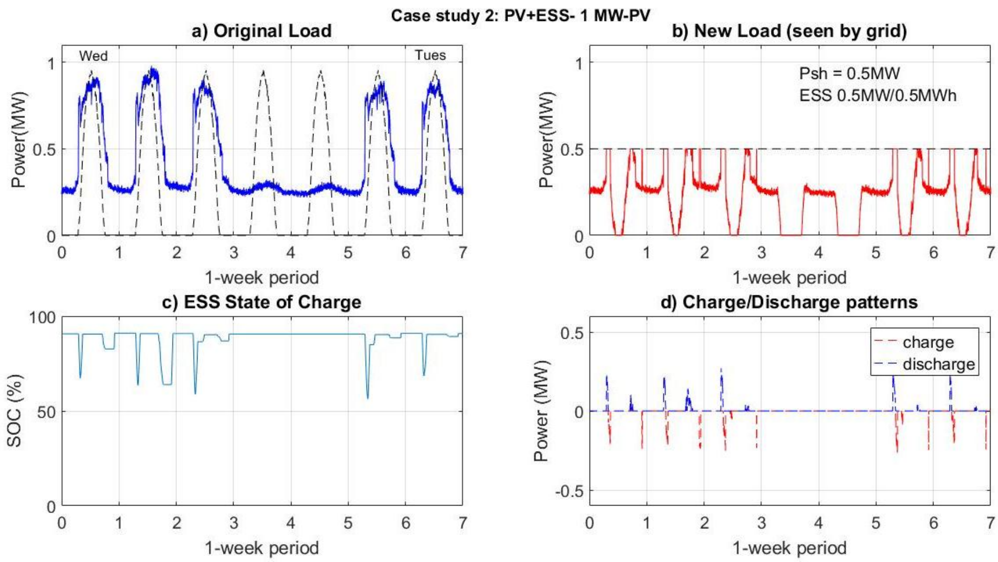


Fig. 10. Random selection of 1-week loads under case study 2 starting from Wednesday (a) Original loads with PV (dotted line) (b) loads seen by grid after 1 MW-PV and ESS 0.5 MW/0.5 MWh to perform Psh = 0.5 MW (c) state of charge (d) charge/discharge patterns

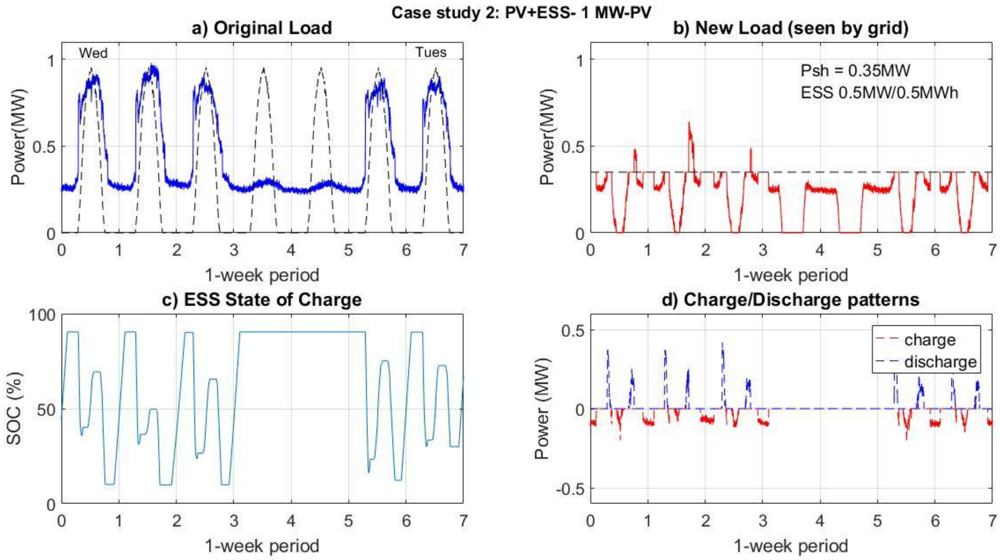


Fig. 11. Random selection of 1-week loads under case study 2 starting from Wednesday (a) Original loads with PV (dotted line) (b) loads seen by grid after 1 MW-PV and ESS 0.5 MW/0.5 MWh to perform Psh = 0.35 MW (c) state of charge (d) charge/discharge patterns

Table 5. Comparison of payback, LCOE, the number of months that cannot perform 100% shaving and energy loss for 1 MW-PV and Psh/ESS sizing conditions as specified in Table 4 for case study 2

Condition	Payback (yr)	LCOE (THB/kWh)	Month w/ dCharge (#)	Total EnLoss (MWh/yr)	Percent EnLoss (%)		%Use EnExcess
					WD	WE	
1	8.26	4.05	1	638	98%	100%	<1%
2	8.24	4.04	9	625	92%	100%	2%
3	8.21	4.03	10	617	87%	100%	4%
4	8.83	4.01	9	615	86%	100%	4%

Table 6. ESS operating pattern for case study 3

Weekdays (WD)	Weekends (WE)
ESS discharges to perform peak shaving at Psh at SOC>SOCmin. At SOC<SOCmax, ESS is prioritized to charge from excess PV, then from grid but at off-peak hour only.	ESS discharges to load when Pload(t) > 0 at SOC>SOCmin. ESS is not allowed to charge from grid. ESS is allowed to charge from excess PV at SOC<SOCmax only

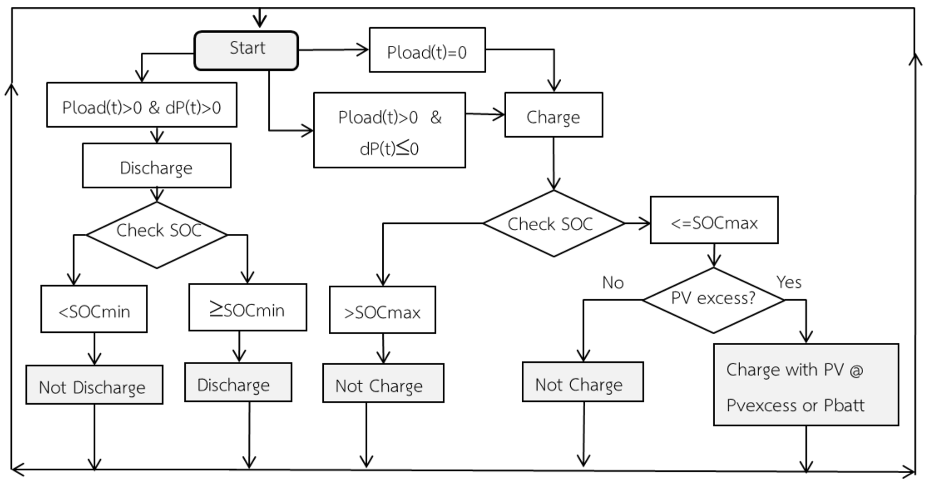


Fig. 12. Operation pattern for charge/discharge schemes for weekend (WE) loads in case study 3

Other results are summarized in Table 5. In term of savings, all conditions save approximately 53%, improve by 1% when compared to the integration of PV alone in case study 1. The annual savings result in the same length of payback times and slightly longer for those with larger ESS capacities. LCOEs also do not make significant differences; LCOEs for all conditions are already lower than the on-peak hour tariff. What we should concern is the demand charge that cannot be reduced despite the integration of ESS. At Psh lower than 0.5MW, the demand charge are charged at Pmax>Psh for 9-10 months out of a year period. This issue might not be considered serious by economic aspect, since demand charge costs only 7% of the monthly tariff. Those unshaved peaks would however appear as spikes, reflecting in poor electricity quality instead.

Energy excess from 1 MW-PV is 641 MWh/year. When there is no ESS, the excess energy becomes the total energy loss, where the losses during WE and WD are 454 and 187 MWh/year respectively. With ESS 0.5 MW/0.75 MWh and Psh 0.35 MW, the maximum loss reduction is 2% (from 641 to 625 MWh/year). Percent EnLoss shows that 100% of the energy excess during WE becomes energy loss. The results imply that WE excess energy is never charged into ESS, as ESS stays idle most of the times under the operation pattern in case study 2. These results suggest that the differences in the load characteristics of WD and WE loads require ESS to operate differently.

3.3. Case study 3: PV+ ESS –changing control strategy

In case study 3, there is a change in the operation pattern in order to solve the energy loss problem and increase the frequencies of ESS operations. In this case, the operation pattern for WD loads follows case study 2, ESS discharges when load is higher than the shaving limit, while that for WE is adjusted to discharge when loads exists (Pload(t)>0). The detailed patterns are described in Table 6. The ESS operation pattern for WD loads follows Fig. 7, while the details for WE loads are shown in Fig. 12. In this case, ESS discharges when Pload(t)>0 and dP(t)>0. The charge case is operated under 2 circumstances, i.e. Pload(t)>0 and dP(t)<=0 and when Pload(t) = 0. ESS is restricted to charge from excess PV only.

According to Fig. 13, SOC shows that ESS is more efficient use during weekends in case study 3. From the strategy, at the start of WE (i.e. 0:00 AM of Saturday) ESS starts to dispatch energy to any Pload(t) and drains until empty during the low load hours. According to the selected ESS size, the dispatched energy has lasted approximately 1.30-2 hrs and ESS is not allowed to charge unless from PV system, thus stays at SOCmin state until PV starts again in the morning. ESS is then continuously charged to SOCmax due to zero load (load after PV=0) and discharged to the existing Pload(t) when there is no PV until SOCmin again.

Table 7 has summarized the results for case study 3 in the similar manner to Table 5. With other parameters slightly improved, here we would discuss only the energy loss issue. The use of excess energy is increased from 1-4% in case study 2 to 8-13% in case study 3. Although there is less energy loss in case study 3 but the amount of energy loss is still significant even under the change of control strategy. The previously selected ESS sizes are probably not suitable with the alternating strategy.

Expanding ESS capacity is expected to help reducing the wasted energy. Table 8 lists the newly determined ESS sizes matching with the 1 MW-PV in order to reduce the energy loss. The conditions are operated following the pattern in case study 3 and focus only for the energy loss problem. The simulation is performed to find the ESS size that maximizes the use of the excess energy. Upon the similar variations of the shaving limit, the smallest ESS size to reach the goal is 0.5 MW/5 MWh, forming a C/10-rate ESS system. As shown in Table 9, the use of the excess energy is 46% for condition 5 and increases up to 64% for condition 8. Percent Enloss indicates that more of WE energy excess is charged into ESS instead of going wasted. Demand charge reductions are effective for condition 5, 6 and 7. LCOEs indicate the good economic values for all conditions, however the paybacks of 17-18 years, as a results of the price of the C/10-rate ESS system have somewhat derails the decision for the investment**.** The expanded capacity has solved the energy loss problem to some extent, implying that the specific operation pattern requires its corresponding ESS size, however in this case is positioning the economic aspect in despair. For the optimized values, the case has to be further investigated in details.

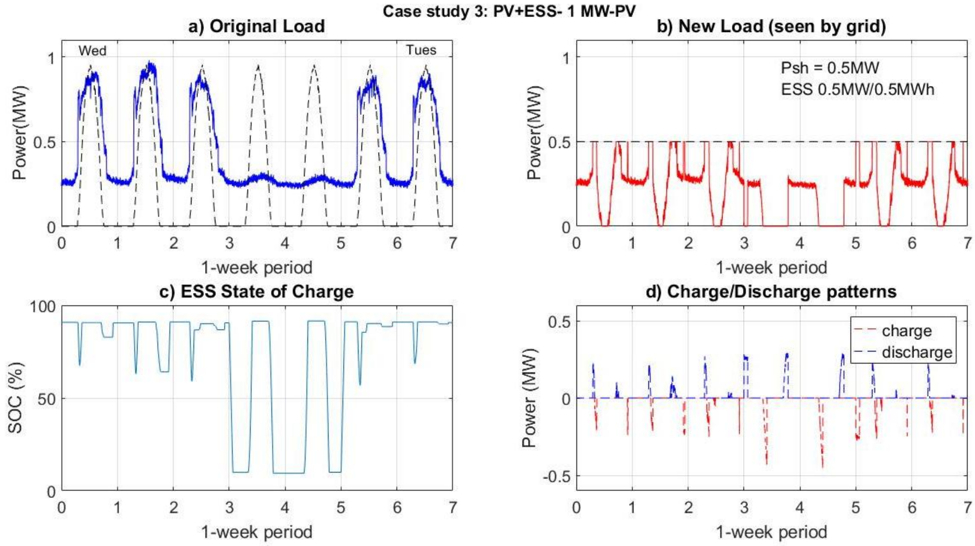


Fig. 13. Random selection of 1-week loads under case study 3 starting from Wednesday (a) Original loads with PV (dotted line) (b) loads seen by grid after 1 MW-PV and ESS 0.5 MW/0.5 MWh to perform Psh = 0.5MW (c) state of charge (d) charge/discharge patterns

Table 7. Comparison of payback, LCOE, the number of months that cannot perform 100% shaving and energy loss for 1MW-PV and Psh/ESS sizing conditions as specified in for case study 3

Condition	Payback (yr)	LCOE (THB/kWh)	Month w/ dCharge (#)	Total EnLoss (MWh/yr)	Percent EnLoss (%)		%Use EnExcess
					WD	WE	
1	8.11	3.99	1	592	98%	90%	8%
2	8.09	3.99	9	580	92%	90%	9%
3	8.06	3.98	10	571	87%	90%	11%
4	8.62	3.93	9	557	87%	85%	13%

Table 8. Adjusted conditions for ESS sizes (specifying Pbatt/Ebatt) and Psh to solve energy loss problem for case study 3

Conditions	Psh(MW)	Pbatt(MW)	Ebatt(MWh)
5	0.50	0.50	5.0
6	0.40	0.50	5.0
7	0.35	0.50	5.0
8	0.30	0.50	5.0

Table 9. Comparison of payback, LCOE, the number of months that cannot perform 100% shaving and energy loss for 1MW-PV and Psh/ESS sizing conditions as specified in Table 8 for case study 3

Condition	Payback (yr)	LCOE (THB/kWh)	Month w/ Demand Charge (#)	Total EnLoss (MWh/yr)	Percent EnLoss (%)		%Use EnExcess
					WD	WE	
5	18.50	3.71	0	349	95%	38%	46%
6	18.03	3.63	1	327	84%	37%	49%
7	17.67	3.57	1	285	74%	32%	56%
8	17.44	3.52	6	229	57%	27%	64%

4. Conclusions

The first mentioned goal of this study is to reduce the electric bill by using either PV or PV+ESS along with the TOU pricing structure. Other benefits, in case of achievement, could add the significant value for the project. Under all proposed case studies as well as the conditions, the annual tariff is reduced at least 40% which is the convincing amounts. The 0.5 MW-PV could be installed as a stand-alone just for the purpose, although the LCOE value suggests the contradiction. With LCOE concerned, the PV size could be increased to 1 MW, but the system would suffer from the energy loss. With the aid of the ESS and various control strategies, ESS size as large as 0.5 MW/5 MWh plus 1 MW-PV is required to minimize the loss, which boosts the payback period up to the unacceptable point. The balance between the power quality (as represented by the absent of peaks/spikes), the optimized usage value (as represented by the minimum energy loss) and the acceptable payback seems to be out of our investigated scope.

The further load characteristics investigation reveals that the unique loads of this building could not be treated with a simple system. If peak loads are defined as Pload(t) > 0.8 MW, they possibly occur 3 times a day during weekdays, i.e. 7-8 AM, 11 AM-2 PM and 3-4 PM.

The intended ESS size for installation of 0.5 MW/0.5 MWh with the appropriate Psh, is originally prepared for the 7-8 AM peaks only. After cutting the peak, ESS would alternate its state between peak shaving and being charged with the excess PV energy, as the situations allow. With 1 MW-PV installed, ESS would be fully charged by mid-day and loads rarely exist at the times, thus ESS stays idle. During mid-day period, the loads after 1 MW-PV are often zero. The loads after PV reappear after mid-day, as the original loads either continue to ascend or remain within the peak loads region instead of gradually descend at this time. The currently-full storage would discharge to perform peak shaving until it reaches SOCmin and by 3-4 PM there is no chance for re-charging as PV energy is weakened, while another sudden drop-and-rise loads occasionally occur, therefore they are left unshaved.

At current state if the annual tariff needs be reduced, installing 0.5 MW-PV would be the best choice. For power quality, the storage system should be in co-operation, however with a more complicated operation patterns. Such other techniques as loads shifting or loads leveling instead of a single peak shaving limit might be more suitable in order to deal with the large gap between WD and WE loads. With the plan to upsize PV to 1 MW, the energy loss issue would require the loads/PV predictions and the more complicated ESS control strategies. The improved model is expected to serve further implementation plan and be applied for different loads types from other buildings within the industrial estate.

Conflict of Interest

The authors declare no conflict of interest regarding the publication of this article.

Author Contributions

All authors were involved in the process of data collection. The corresponding author developed the model in order to analyze the data and wrote the paper. The co-authors had provided advices on the structure of the paper. The final version was approved by all authors.

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