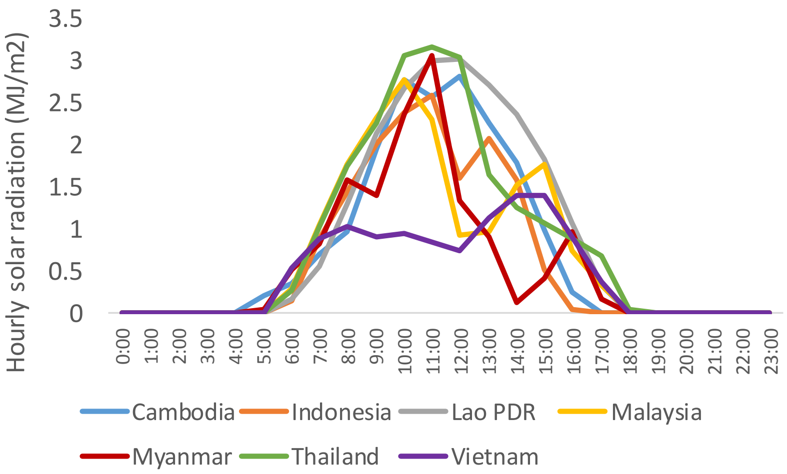
Chapter 4

Assessment of Storage Technologies for Solar PV

4–1 Analysis Overview

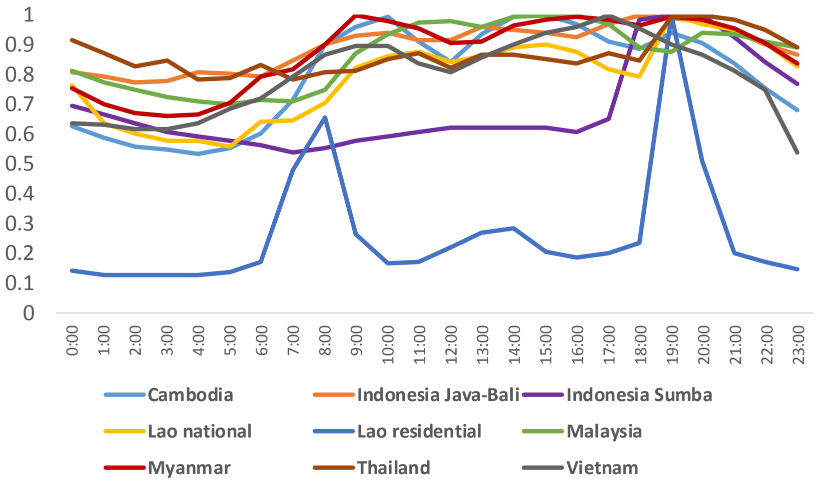
In the power system, the balance between electricity supply and demand must be maintained all the time. However, the output of solar PV depends on the solar radiation condition. That is, generation from solar PV cannot be adjusted according to the load condition and is difficult to predict.

Figure 4–1. Example of Hourly Solar Radiation in ASEAN Countries



Source: Compiled by author using data from New Energy and Industrial Technology Development Organization (NEDO).

Figure 4–2. Example of One-Day Load Curve (Normalised) in ASEAN Countries



ASEAN = Association of Southeast Asian Nations.

Source: Compiled by author using data from various sources including data provided by the participants at the first Assessment of Electricity Storage Technology for Solar PV workshop, data from previous ERIA study, as well as openly published data from utility companies.

Energy storage, especially batteries, is an effective solution to the mismatch between solar output and electricity load. With battery costs falling, the application of batteries – whether at the end-user's side or at the power plant's side – as a way to mitigate solar PV's intermittency in grids has seen rapid growth.

In the first workshop meeting for this study, participants showed great interest in the potential of solar PV and energy storage. At the meeting, three questions were the core of the discussions:

- *How much energy storage capacity will be needed for a certain amount of solar PV?*
- *What will be the economic viability of energy storage technologies?*
- *What are the implications for policymakers*?

The answers to these questions vary significantly depending on the power system and market contexts. For example, since the solar PV and energy storage system is connected to an integrated electricity system and the purpose of energy storage is to help maintain the balance of the whole system, the required energy storage capacity is affected by the load pattern and by how other power generation plants are operated. Therefore, to determine the capacity of energy storage, a complex simulation of the whole electricity system is required.

However, such simulation mentioned above always requires detailed data and information on the whole power generation fleet, the merit order of the generator's dispatching, as well as load pattern, etc. – information that is always not well documented or disclosed within most ASEAN countries. To simplify the calculation and reduce the data requirement, the conditions in which the solar PV and energy storage system operate are predefined in the analysis. Under the presumed cases, the required capacity and the economics of energy storage technologies are calculated.

4–2 Simulation Cases

Three cases are discussed in this study: two cases on utility-scale solar PV power plants, and one case on the household rooftop PV system.

Case 1: Curtailment avoidance (utility-scale solar PV)

The magnitude of solar PV output varies largely within one day. At its peak, the output of solar PV could be higher than what the grid can absorb. To maintain the balance between supply and demand, the excess is usually curtailed (i.e. thrown away) if storage is not available (Figure 4–3). Curtailment leads to less electricity sold to the grid and will ruin the revenue of the solar PV developer. Thus, the high curtailment rate of solar PV is naturally one of investors' emerging concerns.

If an energy storage facility is available, the excess solar PV that cannot be absorbed by the grid may be stored and later released to the grid when solar PV output is low (Figure 4-4). By levelising the output of solar PV using an energy storage system, the effective power generated[4] could increase. However, because of energy losses during charging and discharging, and of the self-discharge of energy storage facilities, not all power generated by the solar PV plants can be fed into the grid.

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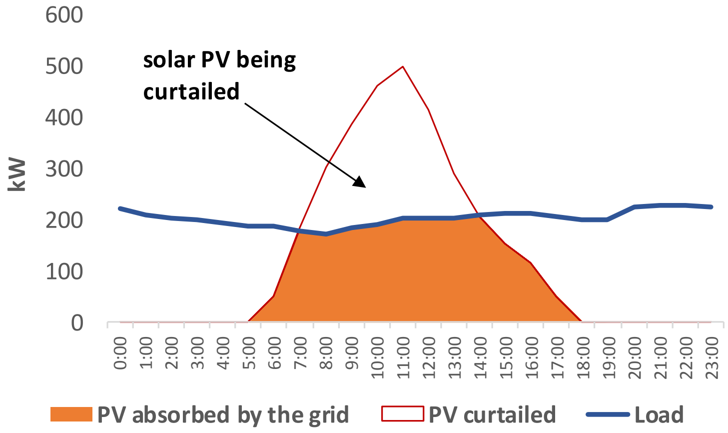
[4] Solar PV power generation that is absorbed by the grid.

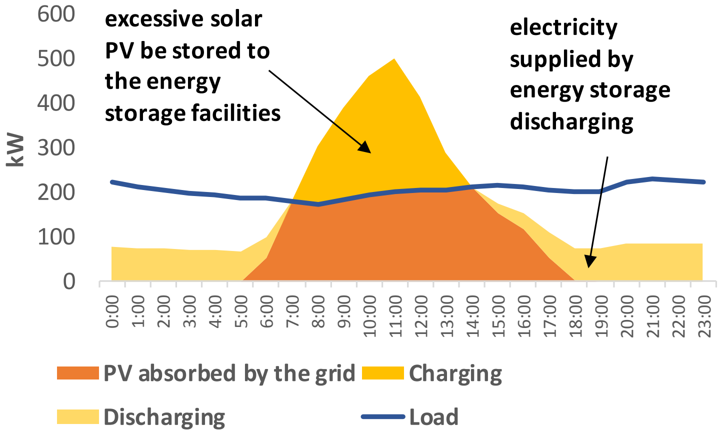
Figure 4-3. Curtailment of Solar PV



PV = photovoltaics.

Source: Author, based on the load and solar radiation data of Malaysia.

Figure 4-4. Using Energy Storage To Absorb the Excessive Solar PV



Source: Authors' analysis based on the load and solar radiation data of Malaysia.

Although the installation of an energy storage facility requires additional investment, the effective solar power generated will also be increased. As a result, if the cost of energy storage facility is low enough, the levelised effective power generation cost (that is, the cost levelised by the power fed into the grid) could be cheaper than that without energy storage (under which case the excess solar PV is curtailed).

The required storage capacity for absorbing all the excess solar PV power is calculated in a simulation study under various curtailment rate assumptions. The curtailment rate of solar PV represents how much of the annual solar PV generated would be curtailed without energy storage. It is calculated using the following equation:

Solar PV curtailment rate *= amount of annual curtailed solar PV/annual total solar PV output*

The economics of energy storage in this case is evaluated by comparing the effective power generation cost (i.e. levelised cost of electricity [LCOE]) of two conditions: (i) without energy storage; and (ii) with energy storage absorbing all the excess solar PV power. Three sets of system cost assumptions (Section 4-4) are applied to calculate the LCOE.

Effective solar PV generation is calculated as follows:

(1) Annual effective power generated without energy storage *= annual total solar PV output – annual total curtailed solar PV*

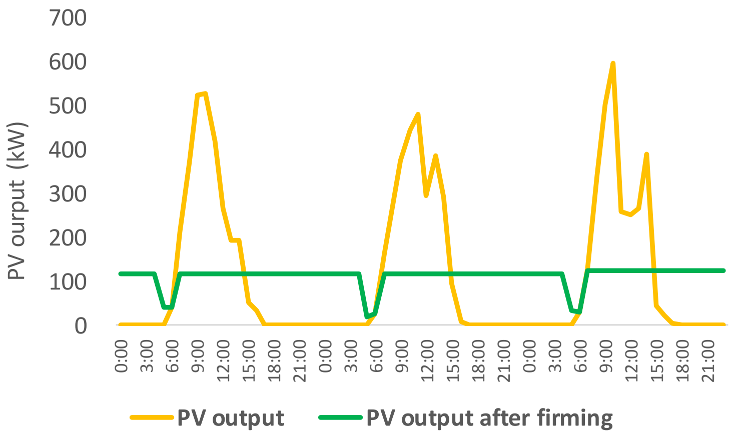
(2) Annual effective power generated with energy storage *= annual total solar PV output – annual total energy losses during charging and discharging – annual total self-discharge of energy storage facility*

Case 2: Capacity firming / output shaping (utility-scale solar PV)

In the management of electric power systems, most electricity demand and supply nowadays are balanced ahead of when the demand really happens. In this process, grid operators aim for a predicable and committed power supply (‘firm’ capacity) for their facilities. Since the power generation of solar PV relies on the condition of the solar radiation, its output is non-firm. The intermittency (‘non-firm’) of solar PV may lead to higher grid operation costs. This is, in fact, one of solar PV’s disadvantages compared with conventional power generation technologies with firm capacity.

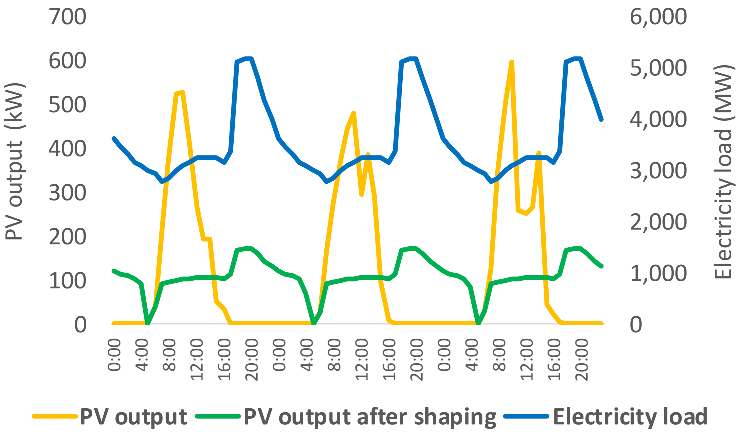
One of energy storage technologies’ applications is renewable capacity firming. By charging (storing peak) and discharging (filling valley), the output of variable renewable technologies can be kept relatively constant (Figure 4-5) or be shaped to follow the load change (Figure 4-6). Paired with an energy storage system, the output of solar PV can be controllable and the possible burden to grid operation may be reduced significantly.

Figure 4-5. Output of Solar PV After Firming by Energy Storage



Source: Author's analysis based on the load and solar radiation data of Malaysia

Figure 4-6. Output of Solar PV after Shaping to Follow Load Change



Source: Authors' analysis based on the load and solar radiation data of Malaysia.

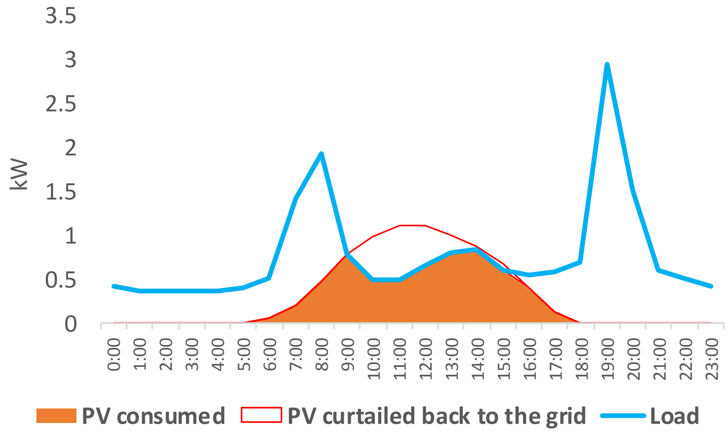
The technical disadvantage of variable renewable technologies can be compensated by pairing with energy storage systems, but this will also increase the cost of renewable power generation.

The simulation of this case aims to find out the energy storage capacity required if one were to shape the output of the overall system into a certain pattern. The economics of energy storage for solar PV capacity firming/output shaping will be evaluated by comparing the LCOE of solar PV + storage with that of conventional power generation technologies, or with wholesale electricity price. Two output patterns –constant output (firming) and load following – are presumed in this simulation. Note that in the first case, the output of solar PV is levelised on a daily basis rather than maintained constant over a whole year, as it is impossible to predict at the beginning of the year, the hourly solar PV output throughout the year.

Case 3: Residential solar PV + energy storage (Lao PDR)

Residential rooftop solar PV systems represent the bulk of the solar PV market in Germany and Japan, thanks to their government subsidy. In recent years, driven by the cost reduction of solar panels in places such as Australia, California, or Hawaii – where the solar radiation hours are long and electricity tariff is high – residential solar PV is becoming more popular and cost-competitive compared with electricity supplied by utility companies. However, the off-peak hour (around noon) for residential electricity demand is usually around the same time the output of solar PV peaks. As a result, a significant part of the electricity generated by rooftop solar PV could not be absorbed by the installer and has to be fed back to the grid (where net metering is allowed) or curtailed (where net metering is not allowed) (Figure 4-7).

Figure 4-7. Residential Solar PV Without Energy Storage

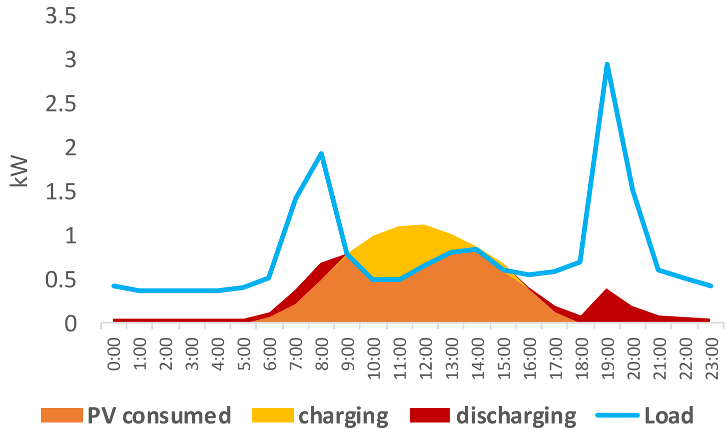


Source: Authors' study based on the load and solar radiation data of Lao PDR.

In places where net metering is not allowed because a significant part of residential solar PV cannot be effectively utilised (either by the household where the panel is installed or by other consumers through the grid), the whole system will be a waste of investment. Meanwhile, in places where net metering is possible, large amounts of solar PV output flowing into the power grid could disrupt the distribution grid's stability. To mitigate the impact on the grid, policies and programmes encouraging self-consumption of residential solar PV are implemented in places with high residential solar PV penetration.

With its price getting cheaper, batteries for residential installation are becoming popular in countries such as Germany or Australia, where the penetration of residential solar PV is high. By pairing with batteries, the excess solar PV power generated can be stored during the day and released during the evening and morning's peaks (Figure 4-8).

Figure 4-8. Residential Solar PV and Energy Storage



Source: Simulation results based on the load and solar radiation data of Lao PDR.

In this case, the self-consumption rate improvement for solar PV as enabled by the installation of batteries is evaluated. The economics of the residential solar PV + battery system is evaluated by comparing the system's power supply cost with the electricity tariff. The simulation of this case covers only Lao PDR because the household electricity demand load curve data is not available from the other countries.

4-3 Methodology

As mentioned earlier, rather than taking all factors into consideration, the simulation in this study focuses only on solar PV and energy storage. The required energy storage capacity is calculated by maintaining the solar PV + energy storage system's output to follow the change in the electricity demand or to form a certain output pattern. The required input data for this simulation consist of one year's electricity demand curve figures, hourly solar radiation data, and technology specifications of solar panel and energy storage technologies.

The solar PV output is calculated by referring to the solar radiation data and technology specification of the solar panel. The required output of solar + energy storage system is determined by using the electricity demand curve data and the assumptions for each simulation case. For example, for the curtailment avoidance case, the output is the adjusted electricity demand; for the capacity firming/output shaping case, the output is the daily constant or load following. Meanwhile, for the residential solar PV + energy storage, the system's output is determined by the household's electricity demand.

Once the required capacity of energy storage is determined, the power generation cost (or the LCOE) of the whole system is calculated using cashflow analysis method. The economics of energy storage is evaluated by comparing the LCOE of the solar PV + energy storage system with different benchmarks.

4-4 Preconditions and Assumptions

(1) Data availability

Data required for the simulation include hourly load curve data, hourly solar radiation data, technical specifications of energy storage facilities and solar panel. Technical specifications were assumed by the authors based on research reports or information published by manufacturers. The hourly electricity load data were collected from various sources (Table 4-1).

Table 4-1. Sources for Electricity Load Data and Solar Radiation Data

	Load curve	**Hourly solar radiation**
Cambodia	Compiled by IEEJ based on data provided by WS1 participant	NEDO
Indonesia	Java–Bali: Compiled by IEEJ from previous ERIA study (ERIA, 2014)	NEDO
	Sumba Island: Compiled by IEEJ based on Hivos report (Hivos, 2011)	
Malaysia	Compiled by APERC based on TNB published data	NEDO

Myanmar	Compiled by IEEJ based on data provided by WS2 participant	NEDO
Lao PDR	Compiled by IEEJ based on previous ERIA study (ERIA, 2014) and data provided by WS 1 participant	NEDO
Thailand	Compiled by IEEJ based on previous ERIA study (ERIA, 2014) and research paper by Baird and Quastel (2015)	NEDO
Viet Nam	Compiled by IEEJ based on data previous ERIA study (ERIA, 2014)	NEDO

APERC = Asia Pacific Energy Research Center; IEEJ = Institute of Energy Economics, Japan; NEDO = New Energy and Industrial Technology Development Organization; TNB = Tenaga Nasional Berhad; WS1 = First Workshop.

Note: *1 TNB: Tenaga Nasional Berhad (largest electricity utility company in Malaysia)

Source: Author.

To reflect the difference in the patterns in electricity load and solar radiation during different seasons or on workday and weekend, the observed data for one whole year is desirable. However, in most ASEAN countries, hourly electricity load data are not disclosed, thus a compromise has to be made by using data samples covering a short period within the whole year (Table 4-2).

Table 4-2. Details of Electricity Load Curve Data

	Load curve type	**Data details**
Cambodia	National	Observed data for one month One week's average daily load curve data are applied to the other months
Indonesia	Java–Bali and Sumba Island	Java–Bali: Two patterns (dry season and rainy season) for the whole year
		Sumba Island: Two patterns (dry season and rainy season) for the whole year
Malaysia	Peninsula Malaysia	Observed data for a whole year

Myanmar	Yangon	Observed data for three months of different seasons (cool, hot, rainy) One week's average daily load curve data are applied to the other months by season
Lao PDR	National load curve and residential load curve	National: Two patterns (dry season and rainy season) for the whole year
		Residential: daily load curve from survey, which is applied to the whole year
Thailand	National load curve	Nine patterns for the whole year: workday, Saturday, and Sunday by three seasons (cool, hot, rainy)
Viet Nam	National load curve	Two patterns (dry season and rainy season) for the whole year

Source: Authors.

Hourly solar radiation data are compiled based on the database of the New Energy and Industrial Technology Development Organization. Conditions of solar radiation could vary significantly even within one country. However, because of the constraint on data availability, the geographical differences in solar radiation data inside one country is not considered in this simulation. For countries where there are missing data, the time slot with missing data were filled out by using values of the same time slot from another day.

Because of issues with data availability, not all ASEAN countries are covered in the simulation. For some countries (Indonesia and Lao PDR), there is more than one case. It should also be noticed that since arrangements have to be made to complete the missing data for hourly load curve and solar radiation, not all the input data for the simulation are observed data.

(2) Cost assumptions on solar PV and energy storage technologies

Three cases of costs for solar PV and energy storage are assumed in this study. One is based on the current price level; another is based on mild cost reduction from current averages; and the last one is based on expected future cost reduction (Table 4-3). Some of the cost assumptions in the second case have been observed to be already happening in other countries, although outside of the ASEAN region.

Table 4-3. Cost Assumptions for Solar PV and Energy Storage

	Assumption 1: Current price level	Assumption 2: Based on mild cost reduction	Assumption 3: Based on future cost reduction
System cost of utility-scale solar photovoltaic (US$/kW)	1,500	1,000	500
System cost of utility-scale solar photovoltaic (US$/kW)	1,800	1,000	500
Installation cost of battery (US$/kWh)	600	300	100
Installation cost of pumped storage hydropower (US$/kWh)	21	21	21

Source: IRENA (2018); IRENA (2017).

For the utility solar PV, two energy storage technologies – battery and PSH – are covered in the simulation. However, simulation of solar PV + PSH is only carried out for countries with information on PSH projects, either planned or ongoing. For residential solar PV, battery is the only technology considered. Current price and future cost reduction data are from various studies. Assumptions for the mild cost reduction case are set by referencing to low-cost cases being reported. Cost assumption for PSH are set constant for all cases.

4-5 Major Results

Case 1: Curtailment avoidance (utility-scale solar PV)

(1) Required capacity of energy storage

The required energy storage (battery) capacity that prevents curtailment of solar PV under various curtailment rate assumptions are summarised in Table 4-4. Although both the required capacity of battery and of PSH (i.e. only for countries with PSH project information: Indonesia, Thailand, and Viet Nam) were calculated, there were not much differences in the results for the two technologies. Thus, only the results of the battery case are shown here.

Table 4-4. Battery Capacity (kWh) Required to Absorb the Excess Solar PV Under Select Curtailment Rate Assumptions

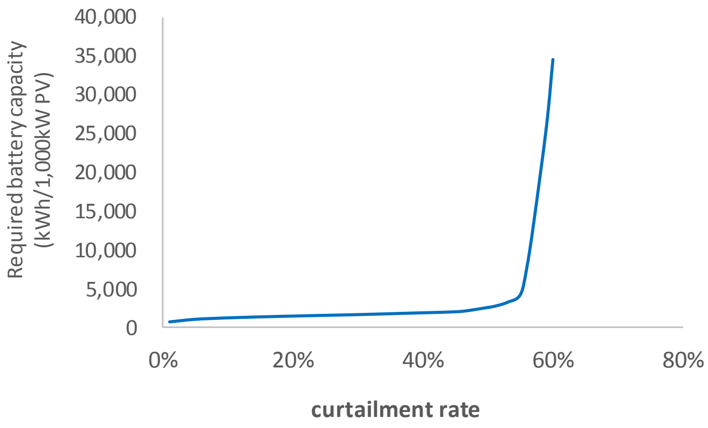
	Required battery capacity (kWh battery/kW PV)				
	Curtailment Rate 20%	Curtailment Rate 30%	Curtailment Rate 40%	Curtailment Rate 50%	Curtailment Rate 55%
Cambodia	1.9	2.3	2.7	8.3	33.3
Indonesia Java–Bali	1.3	1.5	1.7	1.9	2.0
Indonesia Sumba	1.3	1.5	1.7	1.9	2.0
Lao PDR	1.3	1.6	1.8	2.1	15.2
Malaysia	1.5	1.6	1.9	2.6	4.2
Myanmar	1.4	1.8	2.2	4.2	22.0
Thailand	1.4	1.6	1.9	2.2	6.3
Viet Nam	1.1	1.4	1.6	18.5	44.5

Source: Authors' calculation.

The difference in required battery capacity across countries per curtailment rate can be attributed mainly to the magnitude of their solar radiation. The curtailment rate represents the share of annual curtailed solar PV power generated in the total annual solar PV output. For the same solar PV capacity, places with higher solar radiation will generate more power from solar PV (thus, will have higher curtailed solar PV). Therefore, in terms of the required energy storage capacity per kW of solar PV, more capacity is needed in places with stronger solar radiation.

Simulation results also show that the required energy storage capacity increases mildly with curtailment rate until a certain point. Beyond that point, for every curtailment rate increase, a much larger energy storage capacity is required (Figure 4-9).

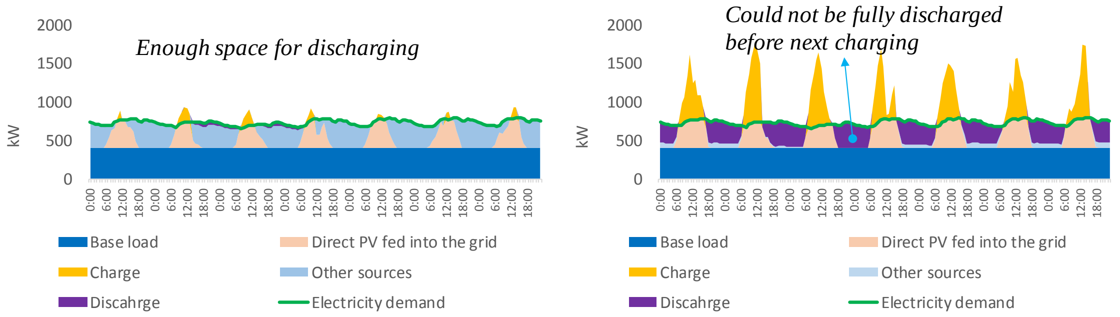
Figure 4-9. Required Battery Capacity per 1000 kW Solar PV By Curtailment Rate Assumption (Example of Malaysia)



Source: Author.

The solar PV stored in the energy storage facility needs to be released to the grid before next charging. When curtailment rate is low, the power stored is also low and the space in the grid to accommodate the discharged power before next charging is enough. However, with the rise in the curtailment rate, the power stored also rises. If the amount of stored solar power exceeds the grid's available capacity to absorb all the need-to-be discharged power, the energy stored in the energy storage system could not be fully released before the next charging. Therefore, larger and larger capacity will be required to store the excess solar PV because the electricity could not be fully discharged from the previous cycle.

Figure 4-10. Battery Charging and Discharging with 10% and 54% Curtailment Rate Assumptions (example of Malaysia)


Curtailment rate = 10%

Curtailment rate = 54%

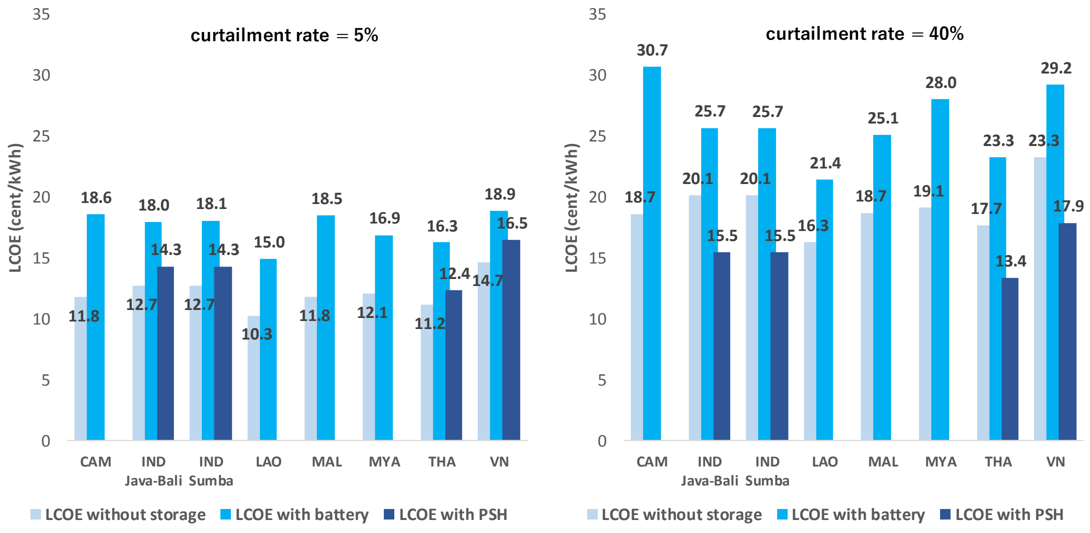
Source: Authors' calculations.

(2) Economics of energy storage

The economics of energy storage is evaluated by comparing the power generation cost (i.e. the LCOE) with and without energy storage. As mentioned above, when calculating the LCOE, the capital expenditure (CAPEX, the initial investment) is levelised by the electricity that will be effectively utilised. The effective electricity output in the solar PV + energy storage system is higher than that in the case with no energy storage (because of curtailment). Therefore, although adding the energy storage system to the solar PV power plant will lead to CAPEX increase, the levelised power generation cost could be lower. The LCOEs of solar PV without energy storage, solar PV + battery, and solar PV + PSH under curtailment rates of 5% and 40% are shown in Figure 4-11 to Figure 4-13, with each figure representing one set of cost assumption.

Figure 4-11. LCOEs With and Without Energy Storage

(PV = US$1,500/kW, battery = US$600/kWh, PSH = US$21/kWh)

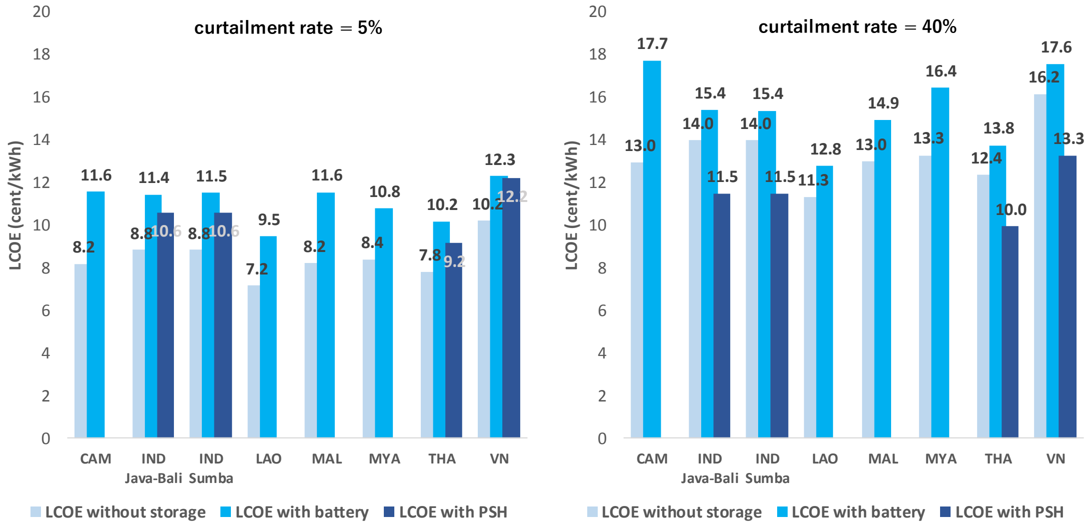


LCOE = levelised cost of electricity; CAM = Cambodia; IND = Indonesia; LAO = Lao PDR; MAL = Malaysia; MYA = Myanmar; THA = Thailand; VN = Viet Nam.

Source: Authors' calculation.

Figure 4-12. LCOEs With and Without Energy Storage

(PV = US$1,000/kW, battery = US$300/kWh, PSH = US$21/kWh)

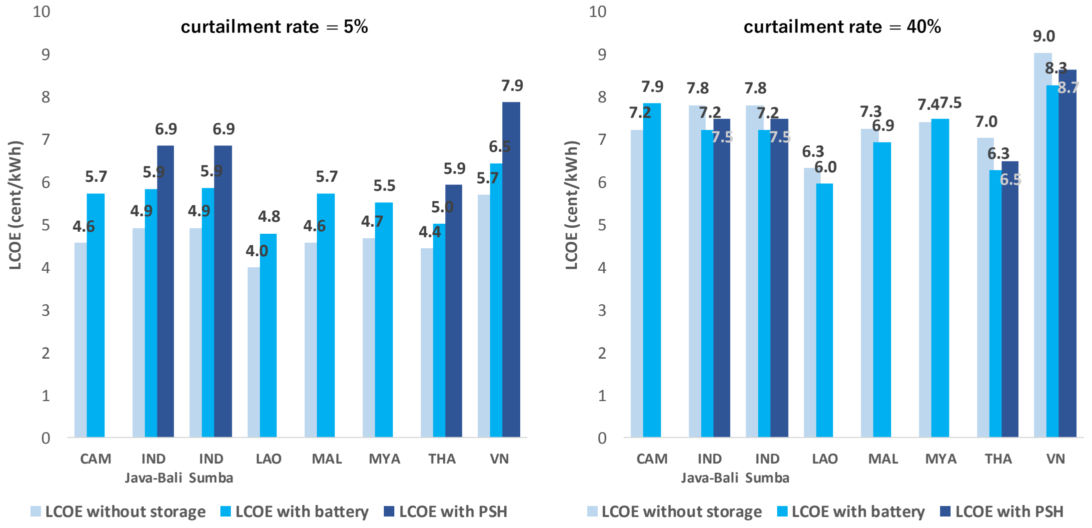


LCOE = levelised cost of electricity; PSH = pumped storage hydropower; CAM = Cambodia; IND = Indonesia; LAO = Lao PDR; MAL = Malaysia; MYA = Myanmar; THA = Thailand; VN = Viet Nam.

Source: Author’s calculation.

Figure 4-13. LCOEs With and Without Energy Storage

(PV = US$500/kW, battery = US$100/kWh, PSH = US$21/kWh)



LCOE = levelised cost of electricity; PSH = pumped storage hydropower; CAM = Cambodia; IND = Indonesia; LAO = Lao PDR; MAL = Malaysia; MYA = Myanmar; THA = Thailand; VN = Viet Nam.

Source: Authors’ calculation.

Solar PV + energy storage becomes more cost competitive when curtailment is higher. This is because high curtailment rate means less effective power generation (thus, high levelised power generation cost). Since the unit CAPEX of PSH is lower, solar PV + PSH is more cost competitive than solar PV + battery when the cost of battery is still high. However, it should be noted that the capacity of a PSH plant is usually much larger than that of battery, which means that all the PSH plant's capacity being dedicated to one solar PV power plant is highly unlikely. In this study, when calculating the LCOE of solar PV + PSH instead of CAPEX of the whole PSH plant, only the CAPEX for the capacity being utilised is counted.

Although the unit CAPEX of PSH is much lower than that of battery, the PSH's round-trip efficiency is lower than of batteries. Thus, more electricity will be lost during the charging/discharging process of PSH than that of batteries. In addition, because of its complexity and large size, PSH has a much higher operation and maintenance cost than do batteries. When the cost of batteries becomes low enough, the solar PV + battery will become more cost competitive than solar PV + PSH (Figure 4-13).

The cost competitiveness of energy storage under various assumptions of curtailment rate for each country/region is shown in the Annex of this publication. Figure 4-14 further depicts the evolution of the difference in LCOEs between solar PV + energy storage and solar PV without energy storage when there is an increase in curtailment rate. When the difference is larger than zero, LCOE of solar PV + energy storage is higher than that of solar PV without energy storage. This means that adding energy storage to avoid curtailment is not economically viable.

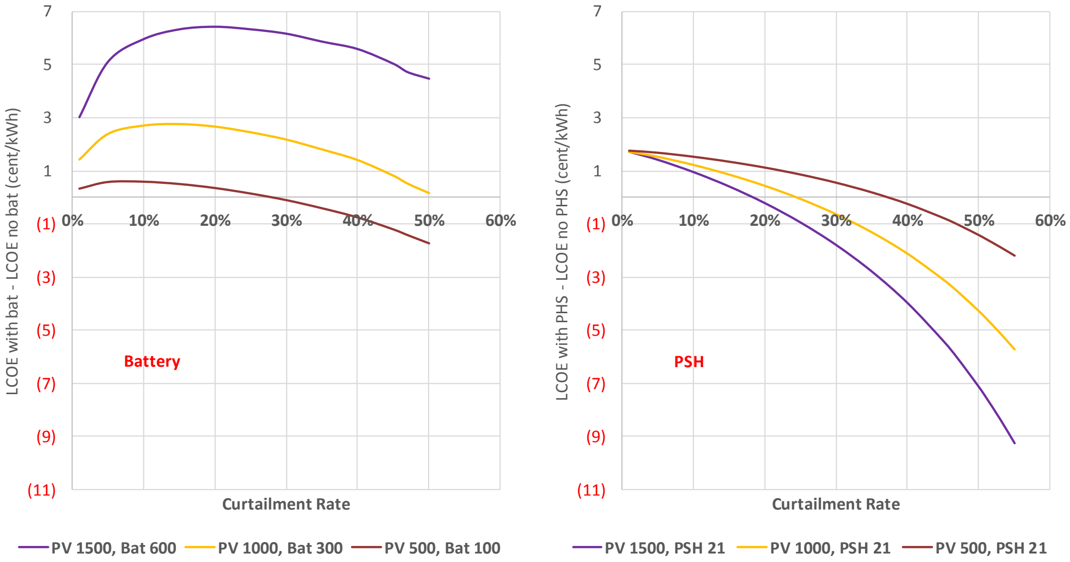
On the other hand, when the curve goes into the negative range, energy storage for curtailment avoidance is more cost competitive even when the initial investment is higher.

Case 2: Capacity firming/output shaping (utility-scale solar PV)

(1) Required capacity of energy storage

Simulation results on the required battery capacity per kW of solar PV for capacity firming and for output shaping (load following pattern) are presented in Table 4-5. As with Case 1, calculations were done for both the cases of battery and PSH, but because both presented similar results, only the findings on batteries are discussed in this report.

Figure 4-14. Evolution of Economic Viability of Energy Storage for Curtailment Avoidance (Example of Thailand)



Source: Authors' calculation.

Table 4-5. Required Battery Capacity (kWh) per kW of PV for Capacity Firming and Load Following

	Required battery capacity (kWh battery/kW PV)	
	Capacity firming	Load following
Cambodia	2.5	2.4
Indonesia Java–Bali	2.0	2.0
Indonesia Sumba	2.0	2.1
Lao	2.2	2.1
Malaysia	2.0	2.1
Myanmar	2.3	2.2
Thailand	2.2	2.1
Viet Nam	1.8	1.7

kWh = kilowatt-hour; kW = kilowatt; PV = photovoltaics.

Source: Author's calculation.

In the capacity firming case, the solar PV + energy storage system has a daily constant output, to smoothen out what is originally a reverse bell-shaped solar PV output (on a sunny day). However, since the firming is done on a daily base, the magnitude of output from day to day could be different depending on that day's solar radiation condition.

In the load following case, the required energy storage capacity is determined by the solar PV output pattern and electricity load curve.

It should be noticed that since the firming is carried out on a daily base, the result represents the maximum value of each day's energy storage requirement in one year.

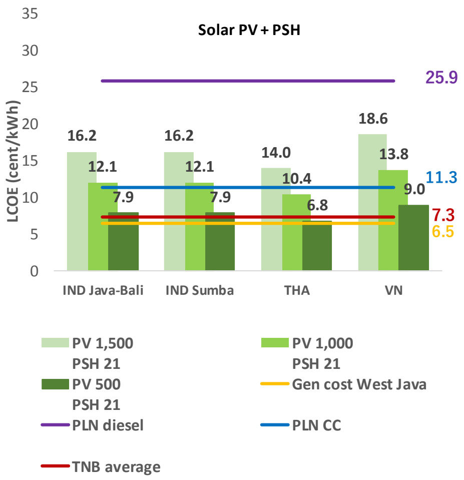
(2) Economics of energy storage

Paired with energy storage, the output of solar PV can be controllable, thus giving it an overall advantage over conventional power generation technologies.

At current average solar PV and battery price levels, the LCOE of solar PV + battery system in most ASEAN countries is higher than US$0.26/kWh, which is even higher than the LCOE of diesel power generators in some countries. However, with the solar PV cost of US$1,000/kW and battery cost of US$300/kWh, the system's LCOE can be reduced to less than US$0.18/kWh, which is lower than that of diesel power generators in some countries but still more expensive than conventional power generation technologies. If further cost reduction of both solar PV and battery is realised (i.e. solar PV at US$500/kW, battery at US$100/kWh), the output controllable solar PV + battery system can be as competitive as conventional power generation technologies in most ASEAN countries.

If PSH is available, the solar PV + PSH system could achieve lower LCOE with the same output pattern as that of solar PV + battery. However, for the same solar PV system cost but where the battery cost is reduced to US$100/kWh, results show that the power generation cost of the two options will be at the same level.

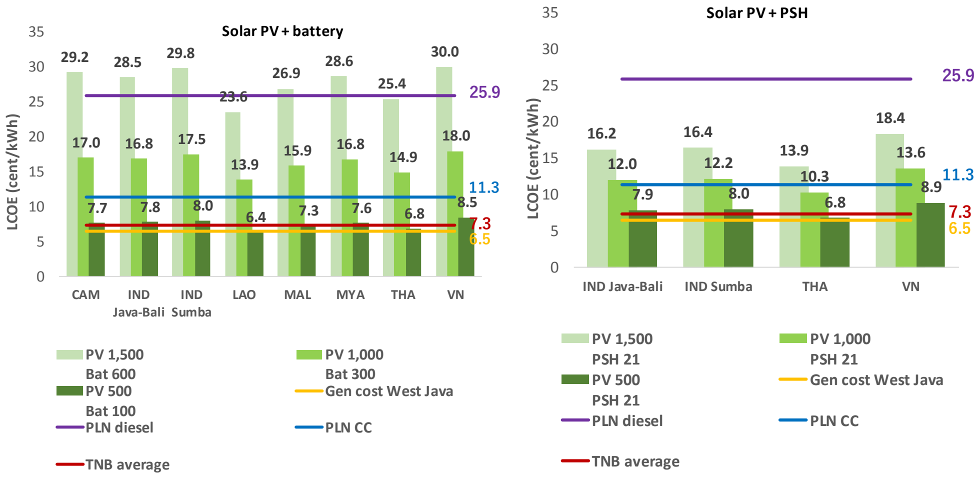
Figure 4-15. LCOE of Solar PV + Energy Storage for Daily Capacity Firming



CC = natural gas combined cycle; PSH = pumped storage hydropower; PLN = Perusahaan Listrik Negara (Indonesian government owned utility company); PV = photovoltaic; TNB =Tenaga Nasional Berhad (largest electricity utility company in Malaysia).

Source: Authors' calculation; ASEAN Centre for Energy (2016); Ministry of Energy and Mineral Resources of the Republic of Indonesia (2017).

Figure 4-16. LCOE of Solar PV + Energy Storage With Load Following Output



CC = natural gas combined cycle; PSH = pumped storage hydropower; PLN = Perusahaan Listrik Negara (Indonesian government owned utility company); PV = photovoltaic; TNB =Tenaga Nasional Berhad (largest electricity utility company in Malaysia).

Source: Authors' calculation; ASEAN Centre for Energy (2016); Ministry of Energy and Mineral Resources of the Republic of Indonesia (2017).

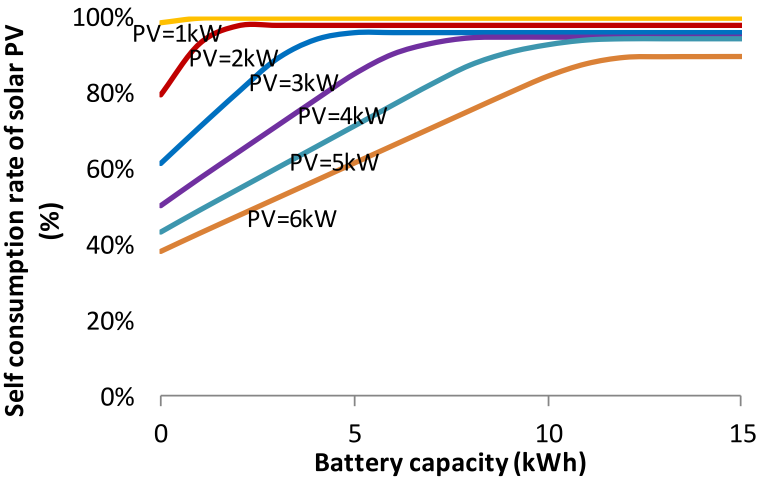
Case 3: Residential solar PV (Lao PDR)

(1) Improvement of self-consumption of residential solar PV

Power from residential solar PV systems that is fed back to the grid is one of the concerns in grid stability. In some ASEAN countries, net metering (fed-back power from household PV panels to the grid) is not even allowed. However, because the peak time of the solar PV output does not match the time when household electricity demand peaks, the self-consumption rate (i.e. the solar PV generation used by the consumer compared with the total solar PV power generation) of residential solar PV is usually low.

The self-consumption rate of residential solar PV can be effectively improved by pairing with battery storage systems. For a typical household in the suburban region near Vientiane in Lao PDR, the peak load is around 3 kW. If the household installs a 4 kW solar PV system, which is the average size of residential solar PV in Japan, the self-consumption rate would only be around 50% when there is no battery. However, the self-consumption rate can be improved to 85% with a 5 kWh battery (Figure 4-17).

Figure 4-17. Self-Consumption Rate of Various Solar PV and Battery Combinations



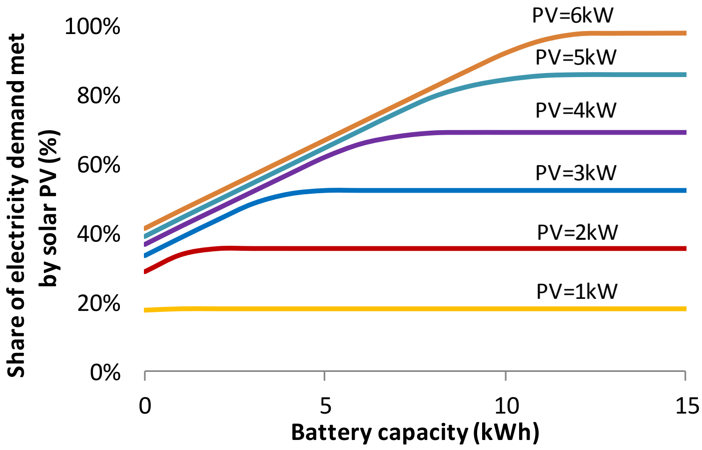
PV = photovoltaic; kWh = kilowatt-hour.

Source: Authors' calculations.

Figure 4-17 depicts the self-consumption rate under various solar PV + battery combinations of a household in Lao PDR with a peak electricity demand of 3 kW. For the same solar PV size, the self-consumption rate is improved by increasing the battery's capacity. However, because of the energy lost during charging and discharging, self-consumption rate settles at a certain level despite the additional battery capacity.

Although its self-consumption rate is low, bigger solar PV can supply larger output to the household's electricity demand, which can be further increased when equipped with a battery. In countries where there is a shortage of electricity supply, this can help relieve the grid's pressure for supply. For the household in Lao PDR, a 6 kW solar PV system with a 12 kWh battery can supply around 98% of the family's annual electricity demand.

Figure 4-18. Share of Electricity Demand Met By Solar + Battery System



PV = photovoltaic; kWh = kilowatt-hour.

Source: Author's calculation.

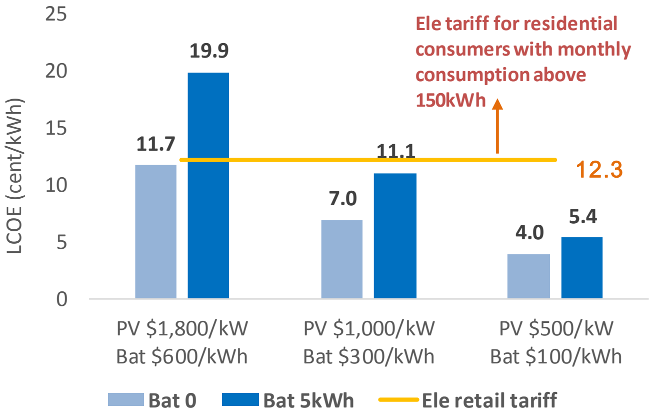
(2) Economics of energy storage for residential solar PV

The economics of solar PV + battery depends on the system's cost as well as on whether net metering is allowed and how that is compensated. From the solar PV installer's perspective, if the excess solar PV can be sold back to the grid at a higher price (such as the feed-in-tariff policy in Japan for residential solar PV), there is no need to install a battery. However, in this case, the total cost of power supply will increase, and the additional cost will be shouldered by customers with no solar PV installations.

Otherwise, if the solar PV installer is not allowed to feed back the excess solar PV to the grid, or if it is allowed but the fed-back electricity will not be compensated as much as the electricity tariff, the incentive to install a battery starts to grow.

In places where net metering is allowed but the excess solar PV electricity is not compensated, the incentive for battery installation depends on whether the solar PV + battery could produce electricity much cheaper than the price of electricity from the grid. For example, in the case of Lao PDR, at current cost of solar PV and battery, electricity produced by a system consisting of a 4 kW solar PV and 5 kWh battery system is much higher than the electricity tariff. If the costs can be reduced to US$1,000/kW for solar PV and US$300/kWh for the battery, the system starts to be competitive compared with that of grid's electricity. If the cost will be further reduced to US$500/kW for solar PV and US$100/kWh for battery, the solar PV + battery system could produce cheaper electricity (Figure 4-19).

Figure 4-19. Power Generation Cost Of Solar PV and Solar PV + Battery Under Various Cost Assumptions (Solar PV 4 kW, Battery 5 kWh)



PV = photovoltaic; kWh = kilowatt-hour; LCOE = levelised cost of electricity.

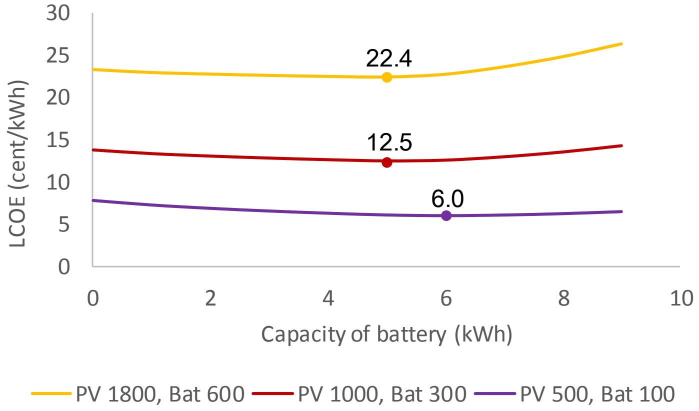
Source: Levelised cost of electricity (LCOE) results by author; information on electricity tariff from first workshop participant.

Figure 4-20 shows the power generation costs of the solar PV at various sizes of batteries for the same household and solar PV system (4 kW) but under a scenario where net metering is not allowed. If net metering is not allowed, excess solar PV will have to be curtailed, which means the improvement in self-consumption rate is the improvement in effective solar PV generation. The LCOE results suggest that although a battery system is an additional initial cost, the levelised power generation cost of the system is lower than that of a system without a battery because of the increase in effective power generation.

The self-consumption rate will improve at a lesser rate with every kWh of battery size increase (Figure 4-17). The same is true with the effective solar PV power generation. Therefore, there is an optimal combination of size of solar PV and of battery that can minimise the system's power generation cost. For a 4 kW solar PV system, the size of the battery that has the least generation cost is 5 kWh or 6 kWh, depending on the cost of both the solar PV and battery.

If net metering is not allowed, the power generation cost of residential solar PV + battery under current prices would be much higher than the electricity tariff in Lao PDR. When the system cost for solar PV and the battery changes to US$1,000/kW and US$300/kWh, respectively, the system starts to be competitive with the grid's electricity.

Figure 4-20. Power Generation Cost Of Solar PV + Battery When Net Metering Is Not Allowed (Solar PV 4kW)



LCOE = levelised cost of electricity; PV = photovoltaic.

Source: Authors' calculation.

4-6 Summary

One of the issues associated with high solar PV penetration is that the output of solar PV during its peak time could exceed the system's capacity to absorb. Excess solar PV generated that cannot be absorbed by the grid is usually curtailed. However, a high curtailment rate can ruin RE developers' revenue stream and discourage new investments on solar PV. Thus, one of energy storage technologies' applications is to avoid curtailment.

In this study's simulation, the required energy storage capacity to absorb the excess solar power under various assumed curtailment rates are calculated. For ASEAN countries covered in the simulation, a 1.1 kWh–1.9 kWh of energy storage capacity per kW of solar PV is required to avoid a 20% curtailment rate. To deal with a 40% curtailment rate, a 1.6 kWh–2.7 kWh energy storage per kW of solar PV would be needed. The result also shows that the required energy storage capacity to avoid curtailment of solar PV starts to increase sharply after the curtailment rate gets to a critical point.

The economics of energy storage in curtailment avoidance application is evaluated by comparing the LCOE without energy storage with LCOE of solar PV + energy storage. The comparison is done under three sets of cost assumptions for solar PV and energy storage.

Simulation results suggest that when curtailment rate is low, the installation of energy storage to avoid curtailment is more costly (than without energy storage) even in the lowest-cost case in this simulation. When the curtailment rate becomes higher, energy storage could be an economically viable measure to avoid curtailment. However, the viability is different from country to country depending on the system costs of solar PV and energy storage as well as the curtailment rate.

Another issue with solar PV is its intermittency, which can cause additional cost to grid operations. By pairing with energy storage systems, solar PV can the mitigated intermittency and reduce the negative impact on the grid stability. In the simulation, two cases on the solar PV and energy storage mix were discussed: daily capacity firming and electricity load following.

To achieve the specific output pattern for daily capacity firming, every kW of solar PV will require 1.8 kWh–2.5 kWh of energy storage. For load following, every 1 kW of solar PV would require 1.7 kWh–2.4 kWh of energy storage.

At current average prices of US$1,500/kW for solar PV and US$600/kWh for battery, the LCOE of the solar PV + battery system in most ASEAN countries is higher than US$0.26/kWh. However, such system can be competitive against diesel in some countries if both the solar PV cost and battery cost are reduced to US$1,000/kW and US$300/kWh. In this scenario, the system's LCOE becomes less than US$0.18/kWh.

Nowadays, solar PV's system cost can be as low as around US$1,000/kW in more mature markets such as Germany, China, and India.[5] Although the cost of batteries varies widely depending on the type, the Li-ion battery installation cost can go as low as US$200/kWh.[6]

If further cost reduction is realised (where the costs of solar PV and battery become US$500/kW and US$100/kWh, respectively), the solar PV + battery system can even compete with conventional power generation technologies in most ASEAN countries. According to IRENA and Fraunhofer ISE, the system cost of solar PV can be reduced to as low as US$630/kW till 2025[7] and US$320/kW[8] till 2050.[9]

The IRENA also forecasted that the installation cost of Li-ion battery could be reduced to US$77–US$215/kWh until 2030.[10] Given that most components of solar PV systems and batteries have become internationally circulated commodities, a medium- to long-term drop in the cost to US$500/kW for solar PV and US$100/kWh for battery is supposed to be within reach in ASEAN countries.

If PSH is available, the solar PV + PSH system could have lower LCOE and the same output pattern as that of solar PV + battery. However, when the battery cost is further reduced to US$100/kWh, it can compete with PSH in terms of the cost.

The use of batteries for residential solar PV systems was also discussed in the study, taking Lao PDR as an example. The electricity demand pattern is derived from surveys from households in a suburban area near Vientiane. The peak load is around 3 kW. In such a household, the self-consumption rate is around 50% for a 4 kW solar PV without any energy storage system. The self-consumption rate could be improved to 85% using a 5 kWh battery.

From the perspective of the PV installer, his economic incentives to install a battery depend not only on the system cost of the battery but also on the electricity tariff and the net metering policy. For example, if net metering is allowed and if the excess solar PV can be sold at a higher price, there will be no need to install a battery. However, if the excess solar power is compensated at a lower price or, worse, has no compensation at all, the incentive to install a battery storage

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[5] IRENA (2018), ‘Renewable Power Generation cost in 2017’.

[6] IRENA (2017), ‘Electricity Storage and Renewables: Costs and Markets to 2030’.

[7] IRENA (2016), ‘The Power to Change: Solar and Wind Cost Reduction Potential to 2025’.

[8] Converted from euro to US$ based on exchange rate of €1=US$1.14.

[9] Fraunhofer ISE (2015),‘Current and Future Cost of Photovoltaics’. Presentation material at the IRENA Cost Competitiveness Workshop, Germany.

[10] IRENA (2017), ‘Electricity Storage and Renewables: Costs and Markets to 2030’.

system comes from the reduction in the electricity bill by using self-generated electricity.

When the solar PV + battery system can produce electricity at a cost lower than the electricity tariff (which is the retail price of buying electricity from the grid), the end-users will prefer to use more self-generated electricity, thus giving them incentives to install batteries. The example of Lao PDR shows that, for the household with a 4 kW solar PV and 5 kWh battery (at current prices of US$1,800/kW for solar PV and US$600/kWh for the battery), electricity produced by the system is much higher than the electricity tariff. The system starts to become competitive with grid electricity when the costs of the solar PV and battery are reduced to US$1,000/kW and US$300/kWh, respectively.

If net metering is not allowed, the excess solar PV will have to be curtailed. For the same household with a 4 kW solar PV, the self-consumption rate is only around 50% when there is no battery. This means that about half of the power generated by the solar PV has to be thrown away (i.e. curtailed). In this case, the installation of a battery can help increase the effective solar power and, thus, lower the generation cost. The LCOE results show that there is an optimal size for solar PV and battery that will minimise the system’s power generation cost. For a 4 kW solar PV system, the size of the battery that can bring the least generation cost is 5 kWh or 6 kWh, depending on the cost of the solar PV and battery.