How Can "Solar PV + Battery System" Be Economically Competitive and Reliable Power Generation?
- Strategies for Post-FIT -

Yoshiaki Shibata*

Summary

This study, from the perspective of "post FIT," revealed the conditions required for the solar PV + battery system to be deployed with financial independence from FIT. A battery operation simulator was developed to identify battery storage capacity required for mitigating impact on the grid and the LCOE (Levelized Cost of Electricity) of the system was estimated.

In order to mitigate impact on the grid, the operation pattern of the residential solar PV + battery system was designed so as to raise the self-consumption ratio. Regarding mega solar PV + battery system, two operation patterns were proposed. One of the operation patterns is a "curtailment avoidance type" that charges and discharges the surplus electricity subject to curtailment. The other one is a "load following type" that shapes by battery the solar PV power generation output curve in accordance with electric load curve components (base, middle and peak), which means to alleviate the impact on the grid to an extreme extent by providing the system with a function of base load power generation or with ramping capability.

According to the analysis results, the LCOE of the residential solar PV + battery system is JPY60-80/kWh based on the current price and lifespan of solar PV and battery on the Japanese market, which is far away from parity with the residential electricity retail price (JPY 25/kWh). The LCOE of the mega solar PV + battery is JPY40-90/kWh that is also far beyond parity with the commercial & industrial electricity retail price (JPY 20/kWh). However, if the prices of solar PV and battery reach the current international levels, each system will be able to attain respective parity.

The study found a turning point between the curtailment avoidance type and the load following type. When the surplus ratio exceeds 9%, the necessary battery storage capacity for the curtailment avoidance type exceeds 3.2kWh/kW that is required for the load following type. This means that when mega solar PV is deployed to a scale that the surplus ratio is more than 9%, battery operation to avoid curtailment becomes irrational and choosing the load following type is more cost effective and advisable. In the near term when the surplus ratio is limited, it is reasonable to choose the curtailment avoidance type, however, in the longer perspective when the surplus ratio rises, it is of great significance to make the mega solar PV + battery play a role as load following.

* Senior Economist, New and Renewable Energy Group, The Institute of Energy Economics, Japan

If the price of solar PV is reduced to JPY100,000/kW (IRENA's 2025 outlook) and the price of battery is reduced to $125/kWh (the US 2022 target), the LCOE of the solar PV + battery system for either residential or mega solar can achieve as low as JPY10/kWh. Then, the solar PV + battery system can be competitive against any other power generation, while being able to meet a variety of electric load patterns. In Japan, strong needs for high quality products and lack of a competitive market due to excess financial support (such as FIT) allegedly keep the price level of solar PV and battery substantially higher than the world level. Therefore, it will presumably take time to reach the international price level. However, it is not until the early 2030s that solar PVs will meet the full-scale post-FIT era. Towards 2030, reinforcement of R&D aiming at extension of the lifespan of the system and market expansion are the challenging issues along with strengthening institutional activities to fill the price gap between Japan and the world.

Introduction

Five years have passed since the Feed-in Tariff scheme (FIT) was introduced in 2012 in Japan. Because of the issue raised by a high tariff level that increases consumer burden through surcharge, the tariff lowering target for 3 years (2017-2019) was set for small-scale solar photovoltaics (PV) and an auction scheme will be introduced for large scale solar PV from 2017. These measures are expected to curb an increase in consumer burden. On the other hand, one of the most important challenges with renewables is how to achieve financial independence of renewable deployment in the longer perspective.

Some residential solar PV will reach the end of the FIT purchase term from 2019. If the expired renewable power generation facilities do not continue their operation or are not reinvested, the cumulative installed capacity might decrease. However, continuous reliance on the FIT system to encourage reinvestment does not guarantee a sustainable manner to deploy renewables. Therefore, in order to realize sustainable deployment of renewables, the renewable should be economically feasible without FIT. In fact, the world trend shows that the price of solar PV is drastically decreasing and many of the mega solar PV projects prove their profitability even under lower bidding prices. Regarding the grid stability challenge, battery prices have also been dramatically decreasing recently. Due to the price-down trend of renewables and batteries, systems composed of renewables and batteries are drawing much attention for sustainable deployment of renewables.

However, it has not yet been revealed how the renewable + battery system could be a realistic option for sustainable and grid-stable deployment of renewables. This study identifies through battery operation simulation the conditions and requirements for the “Solar PV + battery” system to be feasible and competitive against other power generation.

1. Background; Price trend of Solar PV and Battery

Fig.1-1 shows the price trend of solar PV modules and residential solar PV systems in the major IEA member countries. The module price and the system price have decreased by 70% and 75%, respectively, for the last 9 years. IRENA[1] anticipates that the world average price of large-scale solar PV will be reduced to reach as low as $800/kW in 2025 from $2,000/kW in 2014. However, the prices in the Japanese market stay twice as high as the European level (Fig.1-2).

The world average price of lithium-ion batteries (Fig.1-3) in 2014 was $400/kWh, substantially decreasing from $1,300/kWh in 2006. The DOE of the US[2] sets a target for electric vehicle lithium-ion batteries of $125/kWh in 2022 from the current $270/kWh (Fig.1-4). In Japan, the current price of the residential battery is JPY220,000/kWh ($2,000/kWh at $1=JPY110) and the target is set at JPY90,000/kWh in 2020[3]. The large-scale battery has a target of JPY23,000/kWh in 2020, which is equivalent to the pumped-hydro level [4]. Though the US target is for electric vehicle batteries and Japan is for stationary batteries, the target of Japan does not seem to be ambitious, taking into account that electric vehicle batteries require anti-vibration conditions and that it is easier to reduce cost for stationary batteries than for electric vehicle batteries.

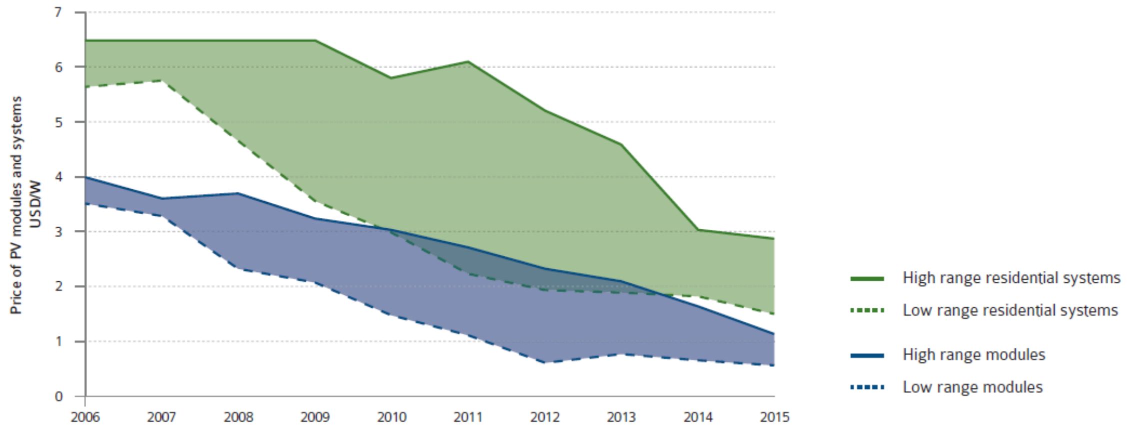


Fig. 1-1 Price trend of Solar PV module and Residential Solar PV system (IEA member countries)

Source: "PVPS TRENDS 2016 in Photovoltaic Applications," IEA PVPS

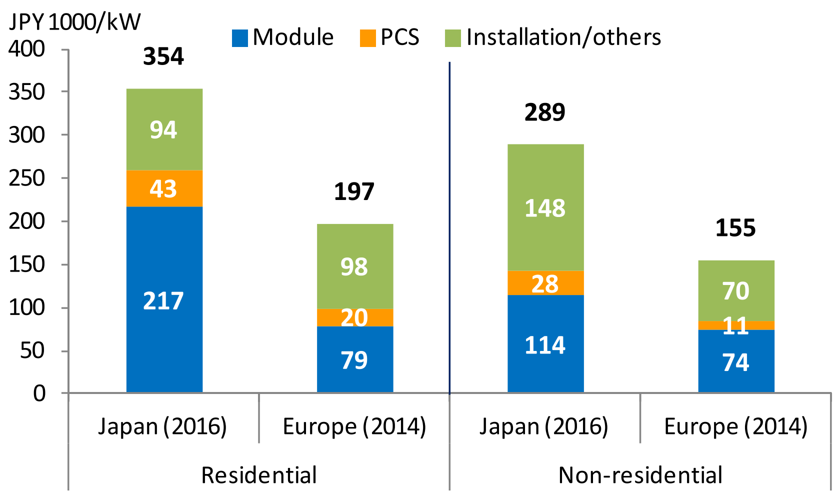


Fig. 1-2 Comparison of Solar PV system prices

Source: "Strengthening Competitiveness of Solar PV," Study group on strengthening competitiveness of solar PV, October 2016.

In Japan, strong needs for high quality products and lack of a competitive market due to excess financial support (such as FIT) allegedly keep the price level of Solar PV and battery substantially higher than the world level. However, pricing down is expected in the world. In particular, though batteries have remained expensive for grid stabilization technology for the last few years, recent EV market expansion is strongly driving down the price of lithium-ion batteries, which potentially opens up the economic use of stationary batteries as grid stabilization technology.

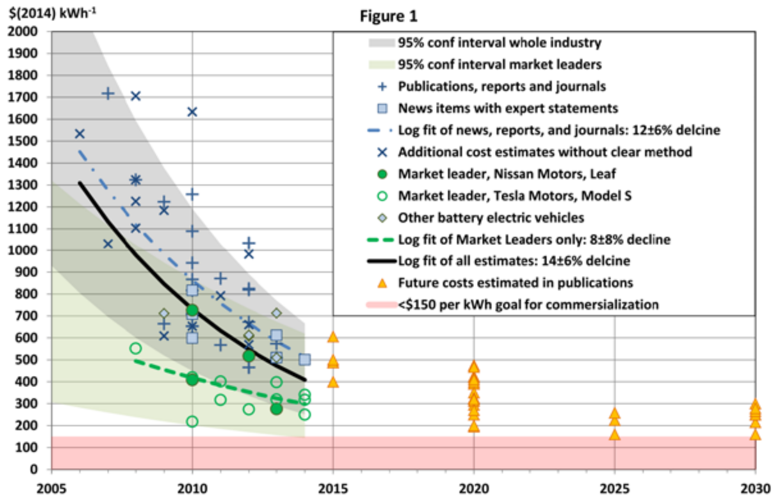


Fig. 1-3 Price Trend of Lithium-ion Batteries

Source: Björn Nykvist and Måns Nilsson, "Rapidly falling costs of battery packs for electric vehicles," 2015

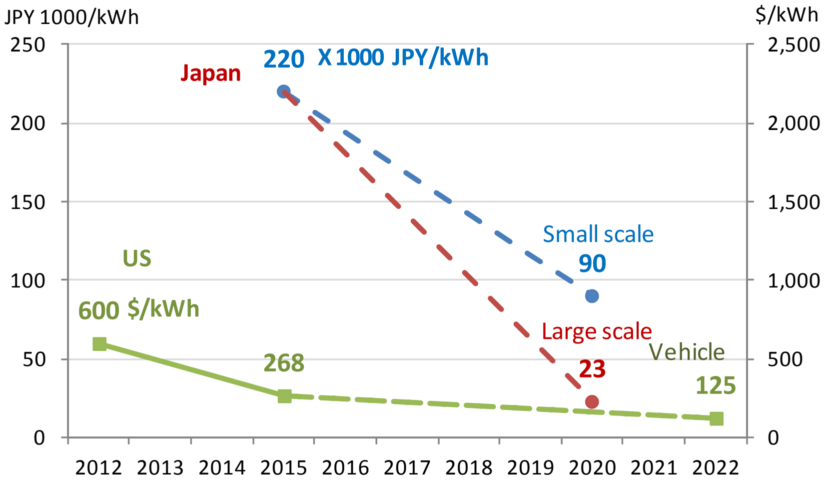


Fig. 1-4 Price Targets of Batteries

Source: Study group of energy resource aggregation business (Ministry of Economy, Trade and Industry; March 2017), "Strategies of Battery" (July 2012, Project team on Strategies of Battery, Ministry of Economy, Trade and Industry), "Overview of the DOE VTO Advanced Battery R&D Program" (Vehicle Technologies Office, DOE, June 6, 2016)

Note: The target of the US is for vehicle lithium-ion batteries. Japan's target is for stationary and does not specify the type of battery. Lifespan of the target battery in Japan is set at 15 years.

Energy storage technologies suffering from poorer round-trip efficiency of necessarily less than 1.0 do not in principle bring about any advantages in terms of economics. However, if sufficient cost reduction that can offset this disadvantage is realized, the situation may change. In the following chapters, how the "Solar PV + battery" system can be competitive against either a gas-fired power plant as ramping power generation or a nuclear/coal power plant as base load power generation will be discussed.

2. Analysis Framework

Based on the background presented above, the solar PV + battery system is expected to be economically affordable and also to contribute to grid stabilization. This chapter discusses possible operation patterns of the system and describes the analysis methodology of the economics of the system.

2-1 How to measure the impact on the grid

It is considerably difficult to quantify the contribution of the solar PV + battery system to grid stabilization, as there are a variety of factors that affect grid stability, such as power generation mix and transmission lines availability. For the sake of simplicity, this study focusing on the solar PV + battery system requires the system to take the operation pattern presented in Table 2-1.

Table 2-1 Operation Pattern of the Solar PV + Battery System

System/Type		Operation Pattern
Residential Solar PV + Battery		Increases self-consumption of solar PV power generation by battery
Non-residential Solar PV (mega-solar) + Battery	Curtailment Avoidance type	Charges curtailed (surplus) solar PV electricity and discharges at different time
	Load Following type	Shapes system power generation pattern following electric load curve component* (* base, middle, peak load)

For residential solar PV, when the reverse power flow increases, voltage in the distribution network rises, which could exceed the range (107V) stipulated in the Electric Utility Industry Law. Increasing the self-consumption of solar PV power generation by installing batteries brings about an advantage to curb the reverse power flow.

Most non-residential solar PV especially mega solar PV feed all of the generated electricity into the high voltage line. This study assumes two operation patterns. The first one is the battery operation pattern that charges the surplus electricity[1] supposed to be curtailed (curtailment avoidance type). This is currently a general operation pattern to cope with curtailment. On the other hand, the operation pattern that provides the solar PV + battery system with functions as a base load power generation and ramping capability (shaping the system power generation pattern to the electric load curve component; base, middle and peak load) is also assumed in order to evaluate minimization of the impact on the grid (load following type; See detail in 2.3).

2-2 Analysis Flow

A battery operation simulator was developed. As for the residential solar PV + battery system, inputting the residential electric load curve and solar PV power generation pattern into the

[1] It should be noted that surplus electricity of mega solar PV is different from that of residential solar PV. The surplus electricity from residential solar PV means the difference between the power generation and that self-consumed by household. The surplus electricity of mega solar PV occurs when the sum of base load power generation and renewable power exceeds the power demand.

simulator, the battery operation pattern is identified. The simulation reveals self-consumption of the solar PV, charged and discharged electricity, battery power loss, feed-in electricity and purchased electricity, and also ascertains the relation between self-consumption and necessary battery storage capacity.

As for the non-residential solar PV + battery system of the curtailment avoidance type, inputting the electric load curve and mega solar PV power generation pattern into the simulator, the necessary battery storage capacity is identified depending on the surplus electricity ratio. For the load following type, the battery storage capacity required for shaping the power generation pattern is identified.

2-3 Assumptions

(1) Solar PV power generation pattern

The hourly solar PV power generation is estimated from the insolation data in Tokyo in 2012. The capacity factor is 13%, which is equivalent to the level commonly observed in Japan [5].

(2) Residential solar PV + battery system

The residential electric load curve refers to [6] with adjustments below;

- Based on the existing statistic [7], most of the households that install solar PV are detached houses and the average number of family members is three. The annual electricity consumption for a detached house with three family members is estimated.
- The residential load curve is adjusted so that the annual electricity consumption calculated from the residential load curve equals the annual electricity consumption estimated from the statistic.
- At the same time, the load curve is adjusted so that the surplus ratio of 5kW of solar PV is equivalent to 70% (self-consumption ratio is 30%) that is commonly observed in Japan [5].

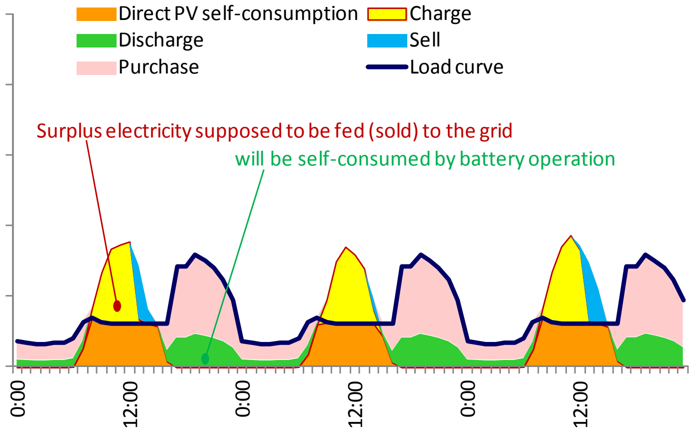


Fig. 2-1 Increase in Self-consumption of Residential Solar PV Power Generation by Battery

The battery operation pattern is set as below (Fig.2-1);

- Surplus electricity is charged in the battery. If the battery is full, solar PV power generation is fed into the grid.

- In order to avoid an increase in self-discharging loss caused by long-period storage, stored electricity is discharged according to the electricity demand when discharging is acceptable (other than charging time and when electricity is sufficient).
- Electricity is purchased from the grid to fill in the gap between electricity demand and the sum of the self-consumption of solar PV power generation and discharged electricity from the battery.
- Efficiency of charging and discharging is 95%, respectively. The self-discharge rate is 0.02%/h.

(3) Mega solar PV + battery system

1) Curtailment avoidance type

In the near term where solar PV penetration scale is limited, the battery operation pattern to charge the surplus electricity supposed to be curtailed is reasonable and realistic. The operation pattern is similar to that of residential batteries (Fig.2-2). As this operation pattern depends on the scale of surplus electricity that is affected by a variety of factors such as power generation mix and availability of transmission lines, the surplus electricity should be preferably identified by power generation mix simulation model under numerous scenarios. For the sake of simplicity, this study setting aside these factors focuses only on the mega-solar PV + battery system and ascertains the required battery storage capacity according to the surplus ratio assumed.

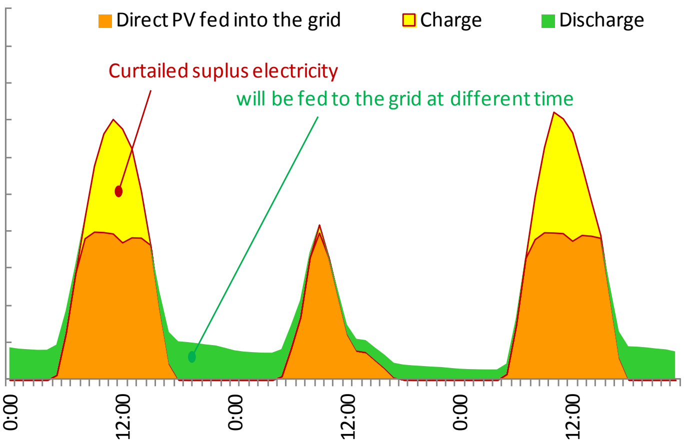


Fig. 2-2 Avoiding Curtailment by Mega Solar PV + Battery System

2) Load following type

On the other hand, in expectation of a price decline of solar PV and batteries from a long-term perspective, it is worthwhile to analyze mega solar PV + battery systems that are actively capable to minimize the impact on the grid. For this objective, this study purposely imposes stringent conditions on the systems, which means performing a stress test on the system.

The most severe operation pattern for the mega solar PV + battery system would presumably be a base load pattern that keeps constant through the year the power generation output after shaping. It is however necessary on the first day of a year to forecast daily solar PV power generation over a year in order to realize this operation pattern. This forecast is definitely not realistic. Meanwhile, the existing weather forecast proves that it is not difficult to make a daily forecast of the solar PV power generation of the next day. It is thus assumed that it is possible to make a daily power generation plan that shapes the mega solar PV power output flat.

The different possible patterns include operation following the electric load variation. As the power generation operation of the present utility companies is based on accurate forecast of hourly electric demand, it is also assumed that the power output from the mega solar PV + battery system is able to follow the hourly electric load daily. This operation pattern includes two cases where the power output is shaped into a pattern similar to the whole electric load and similar to the sum of middle and peak load. The electric load curve refers to the Tokyo metropolitan area [8].

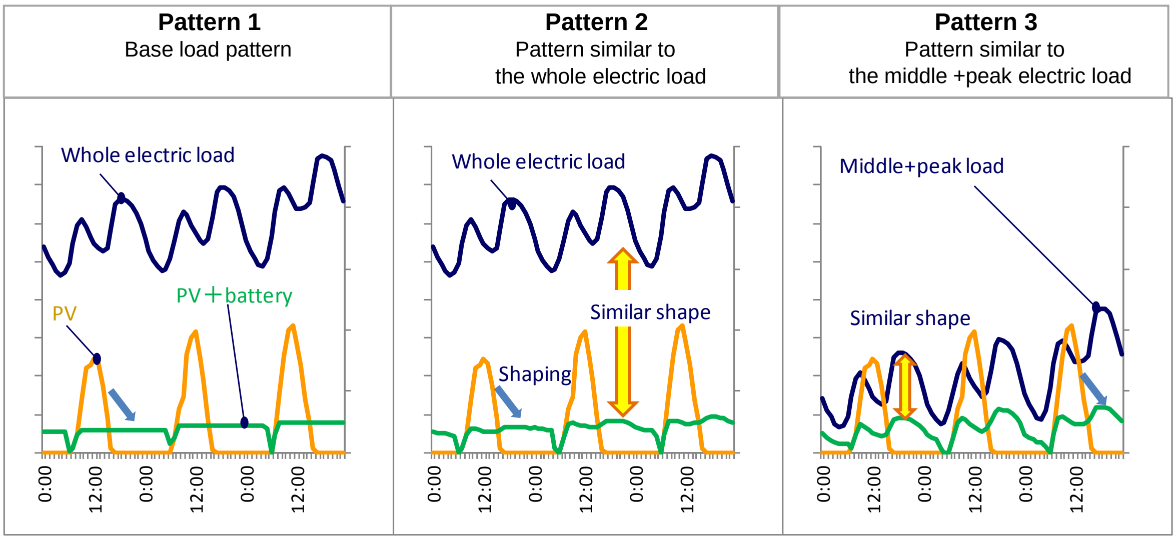


Fig. 2-3 Three Shaping Patterns in Load Following Type of Mega Solar PV + Battery

- Pattern 1: Daily base load
- Pattern 2: Similar to the daily whole electric load
- Pattern 3: Similar to the daily middle + peak electric load

Although each of the three operation patterns (Fig.2-3) represents an extremely stringent condition for the system, batteries can provide mega solar with functions of ramping capability corresponding to a variety of electric load variation, which can minimize the impact on the grid. Rather, from a different point of view, this means high-value added to the mega solar PV + battery system through multifunction. This operation pattern endows the mega solar PV + battery system with roles of base load power generation like nuclear and coal-fired power generation and also ramping capability that LNG/oil-fired power generation bears. This means to position the mega solar PV + battery system as power generation that actively contributes to stable power supply, instead of the conventional operation pattern that regards batteries as a passive role to avoid instability of the grid (curtailment avoidance type).

2-4 Evaluation of Economics

LCOE (Levelized Cost of Electricity) [9] is used as an index for economics of the solar PV + battery system with definitions below:

- Total cost = CAPEX of solar PV + battery and OPEX
- Annual power generation = Net power generation
  - ✓ Residential PV : Net power generation = Direct self consumption of PV + Self consumption of PV via battery + power selling
  - ✓ Mage solar PV : Net power generation = Direct PV power selling + PV power selling via battery

As the solar PV power generation going through a battery increases, the net power generation decreases due to charging and discharging loss. The lifespan of the battery is assumed to be 15 years as the present level and 30 years for the future level[2]. If the lifespan of the battery is 15 years, reinvestment is required to be consistent with 30 years lifespan of solar PV.

Below are the electricity retail price and LCOE of the power generation as references for the target of LCOE of solar PV + battery system.

- Electricity retail price for residential customers : JPY 25/kWh [3]
- Electricity retail price for commercial and industrial customers : JPY 20/kWh [3]
- LCOE of nuclear, coal-fired, LNG-fired :JPY 10-13/kWh [9]

3. Analysis Results

3-1 Residential solar PV + Battery System

(1) Target self-consumption ratio and required battery storage capacity

Fig.3-1 shows simulated representative weekly operation patterns of residential solar PV and battery for three seasons (winter, spring/autumn and summer). The left figures present 4kW of solar PV + 4kWh of battery and the right figures present 4kW of solar PV + 10kWh of battery. When the battery storage capacity is 4kWh, much of solar PV power generation is sold to the grid due to limited chargeable capacity. At the same time, power purchasing happens frequently. If battery storage capacity increases to 10kWh, power selling and purchasing decrease due to large storage capacity.

As this study set the objective of constraining impact on the grid, the self-consumption ratio is used as an evaluation index for the solar PV + battery system, which is defined below;

---

[2] The current battery lifespan is 10-15 years. According to NEDO's technology roadmap [10], the target at 2030 is 20 years.

[3] According to "Handbook of Energy and Economic Statistics in Japan 2017" (IEEJ), the electricity retail price in 2015 was JPY26.2/kWh for residential customers and JPY19.1/kWh for commercial and industrial customers.

・ Self-consumption ratio = (Direct self-consumption of PV
+ Self-consumption of PV via battery) / PV power generation
= 1 － surplus ratio

The smaller the self-consumption ratio is, the less impact on the grid. Fig.3-2 shows the self-consumption ratio for a combination of solar PV power generation capacity and battery storage capacity. For example, in the case of 4-5kW of solar PV, the self-consumption ratio is around 30% without battery. As battery storage capacity increases, the self-consumption ratio rises and reduces the impact on the grid. However, the marginal improvement effect of the self-consumption ratio diminishes gradually with increase of battery storage capacity. For example, even if battery storage capacity increases from 20kWh to 50kWh, gain of self-consumption ratio is limited. This is because discharging opportunity is subject to electricity demand scale, though the charging amount grows along with battery storage capacity increase. So, it is not always possible to raise the self-consumption ratio to 100%, affected by solar PV capacity. The energy balance of the solar PV + battery system shown in Fig.3-3 describes that the self-consumption ratio cannot reach 90% in spite of an increase in storage capacity over 14kWh in the case of 5kW of solar PV capacity (“system is impossible”). It should, nevertheless, be noted that if the electricity consumption is larger than that of a 3-family-member household that this study addresses, the self-consumption ratio could be raised over 90%.

As shown in Fig.3-3, in the case of 3kW of solar PV, the self-consumption ratio is 46% without battery, and 1.8kWh and 5.2kWh of battery is required to elevate the self-consumption ratio, respectively to 60% and 80%. In the case of 4kW of solar PV, the self-consumption ratio is 36% without battery, and 4.0kWh and 8.7kWh of battery is required to elevate the self-consumption ratio, respectively, to 60% and 80%. In the case of 5kW of solar PV, the self-consumption ratio is 30% without battery, and 6.2kWh and 13.9kWh of battery is required to elevate the self-consumption ratio, respectively, to 60% and 80%.

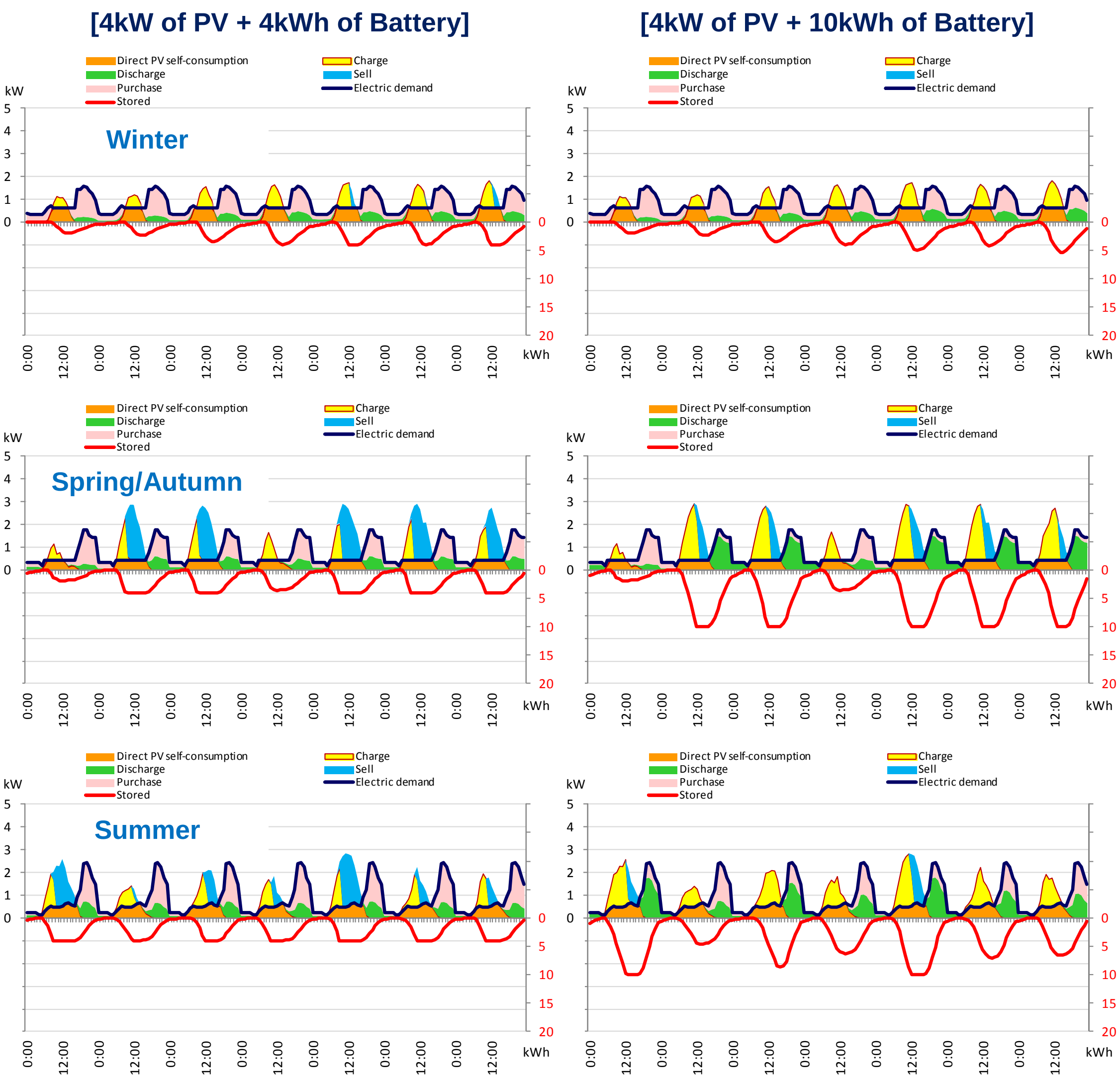


Fig. 3-1 Weekly Operation Pattern of Residential Solar PV + Battery by Season

Note: Stored electricity is expressed in negative range.

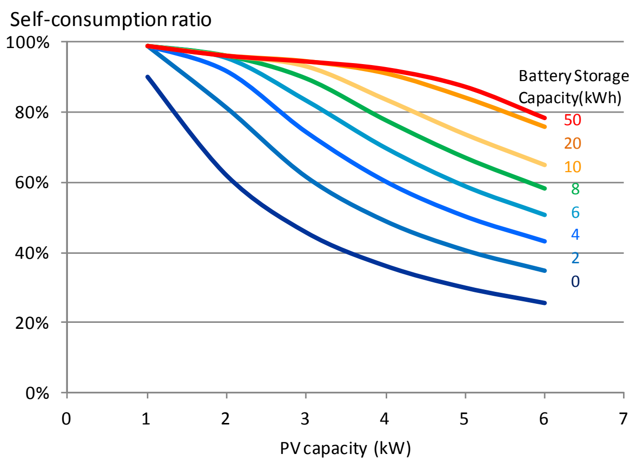


Fig. 3-2 Self-consumption Ratio

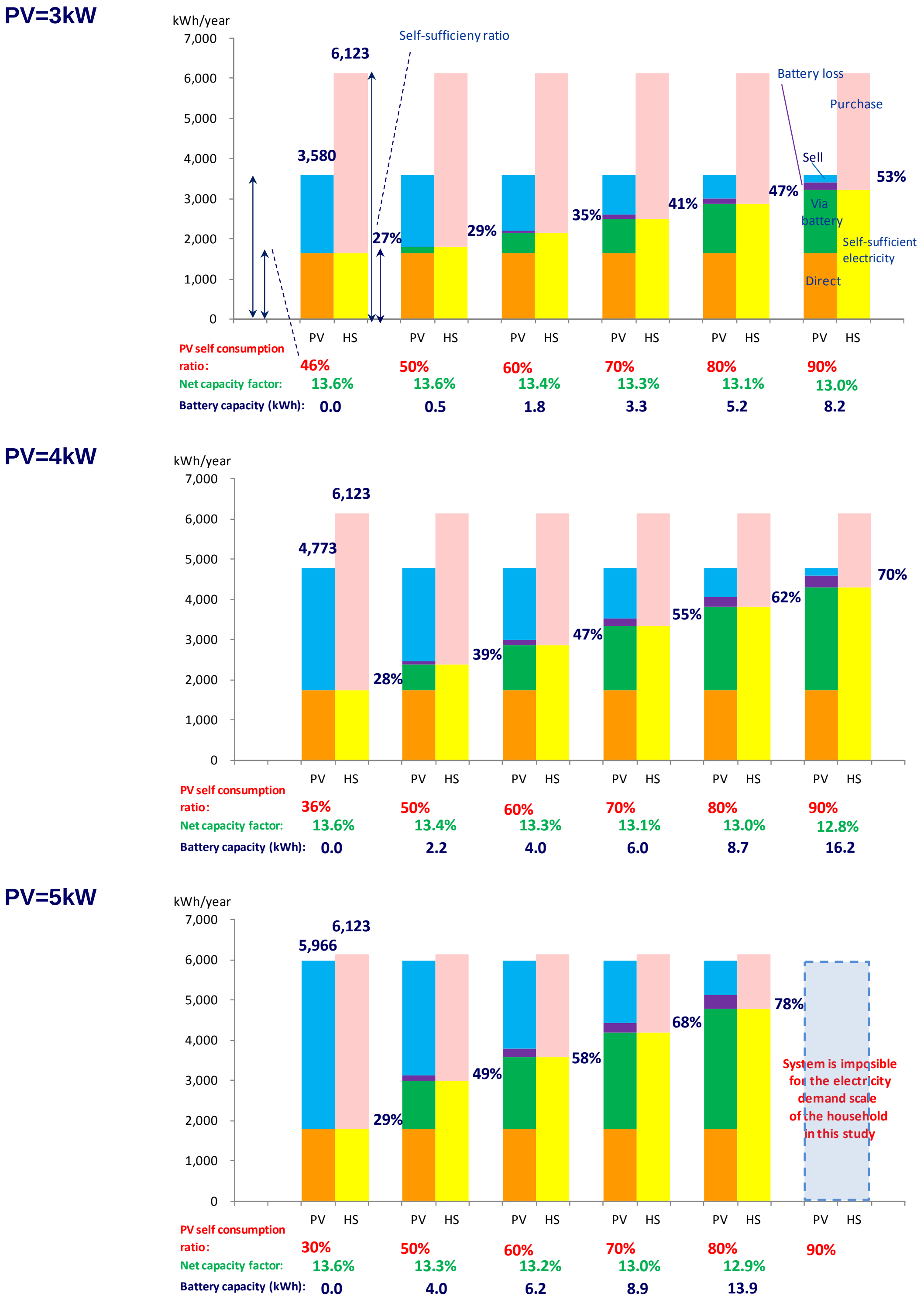


Fig. 3-3 Energy Balance of Residential Solar PV + Battery

Note: In the case of PV=5kW, the system is impossible to be established to achieve a 90% self-consumption ratio.

Note: Self sufficiency ratio = (Direct self-consumption of PV + Self-consumption of PV via battery)/Household electricity demand. Electricity selling is not included here.

Note: Net capacity factor = Net power generation/(PV designed output capacity x 8760hours). Net power generation = Direct self-consumption of PV + Self-consumption of PV via battery + Electricity sold

(2) LCOE

At first, the current status is ascertained. Table 3-1 shows LCOE of the residential solar PV + battery system based on the present cost of solar PV (JPY350,000/kW) and battery (JPY200,000/kWh) in Japan. As some solar PVs provide a 25-year guarantee though most presently provide a 15-20-year guarantee, the operation period is assumed to be 25 years. In the case of a 15–year battery lifespan, the LCOE is JPY30-50/kWh when the target is set at a 60% self-consumption ratio and the LCOE is JPY60-80/kWh when the target is set at an 80% self-consumption ratio. Even if battery lifespan expands to 30 years, the LCOE is no lower than JPY30/kWh and JPY40-50/kWh for a 60% and an 80% self-consumption ratio, respectively. From these results, we conclude that based on the current cost level of solar PV and battery in Japan, the LCOE of the residential solar PV + battery system is far from parity with the residential electricity retail price (JPY25/kWh).

Table 3-1 Current LCOE of Residential Solar PV + Battery System

PV output capacity (kW)	Self-consumption ratio		Battery capacity required (kWh)	Net capacity factor of the system	System cost (JPY/kW) PV=JPY350,000/kW Battery= JPY200,000/kWh		System LCOE (JPY/kWh)	
	Present status	Target			Battery lifespan =30years	Battery lifespan =15years	Battery lifespan =30years	Battery lifespan =15years
3	46%	60%	1.8	13.4%	47	59	26	32
		80%	5.2	13.1%	69	104	38	56
4	36%	60%	4.0	13.3%	55	75	30	40
		80%	8.7	13.0%	79	122	43	66
5	30%	60%	6.2	13.2%	60	85	33	46
		80%	13.9	12.9%	90	146	50	79

Note: The lifespan of PV is assumed to be 25 years.

Secondly, future LCOE based on the current international price of solar PV and battery and the expected price decline is calculated and the results are shown in Fig.3-4. The lifespan of solar PV is assumed to be 30 years. The left figures are LCOEs of the residential solar PV + battery system for a 60% self-consumption ratio and the right figures are LCOEs for an 80% self-consumption ratio. The reasons for choosing 60% and 80% are that there is a need to sufficiently raise the self-consumption ratio from the current 30%-40% with a view to improving grid stability and that a 100% self-consumption ratio might be unrealistic as described above. Battery lifespan is assumed to be 15 years (dotted line) and 30 years (solid line).

The smaller the solar PV capacity is, the larger the amount of solar PV power generation absorbed in the electricity demand and the smaller the battery storage capacity required, which leads to lower LCOE.

In the following, the results will be discussed for the case of an 80% self-consumption ratio. In the case of 3kW of solar PV, the required battery storage capacity is 5.2kWh. In order to achieve JPY25/kWh of LCOE (parity with the residential electricity retail price), battery lifespan should be

30 years if the battery price is JPY200,000/kWh (Japan's current level) and also the price of solar PV should be reduced to JPY200,000/kW equivalent to half of Japan's current level. If battery price is reduced to JPY90,000/kWh (Japan's 2020 target), the LCOE can reach JPY25/kWh in spite of a 15-year lifespan.

In the case of 4kW of solar PV, the required battery storage capacity is 8.7kWh. In order to achieve JPY25/kWh of LCOE, if the price of solar PV is JPY200,000/kW (Europe's current level), the required price and battery lifespan are JPY130,000/kWh and 30 years or JPY70,000/kWh and 15 years.

In the case of 5kW of solar PV, the required battery storage capacity is 13.9kWh. In order to achieve JPY25/kWh of LCOE, if the price of solar PV is JPY200,000/kW (Europe's current level), the required price and battery lifespan are JPY110,000/kWh and 30 years or JPY50,000/kWh and 15 years.

If the battery price decreases to as low as $125/kWh (the US 2022 target), the LCOE can reach lower than JPY20/kWh in spite of JPY300,000/kW of solar PV and regardless of battery lifespan. In addition, if solar PV price decreases to JPY100,000/kW, the LCOE can reach JPY10/kWh.

To summarize the results, for Japan's current price level (solar PV is JPY350,000/kW and battery is JPY200,000/kWh), when the target is set at an 80% self-consumption ratio of the residential solar PV + battery, the system LCOE is JPY60-80/kWh in the case of a 15-year battery lifespan and JPY40-50/kWh in the case of a 30-year battery lifespan. These LCOEs are far from parity with the residential electricity retail price (JPY25 /kWh). However, if the price of solar PV is reduced to JPY200,000/kW (Europe's current level) and battery price to JPY90,000/kWh (Japan's 2020 target), the LCOE can reach JPY25/kWh. If the battery price is reduced to JPY30,000/kWh (the US current level), the LCOE can reach JPY20/kWh. Moreover, if the solar PV price is reduced to JPY100,000/kW (IRENA's 2025 outlook) and the battery price is reduced to $125/kWh (the US 2022 target), the LCOE can reach as low as JPY10/kWh, equivalent to nuclear, LNG-fired and coal-fired power generation.

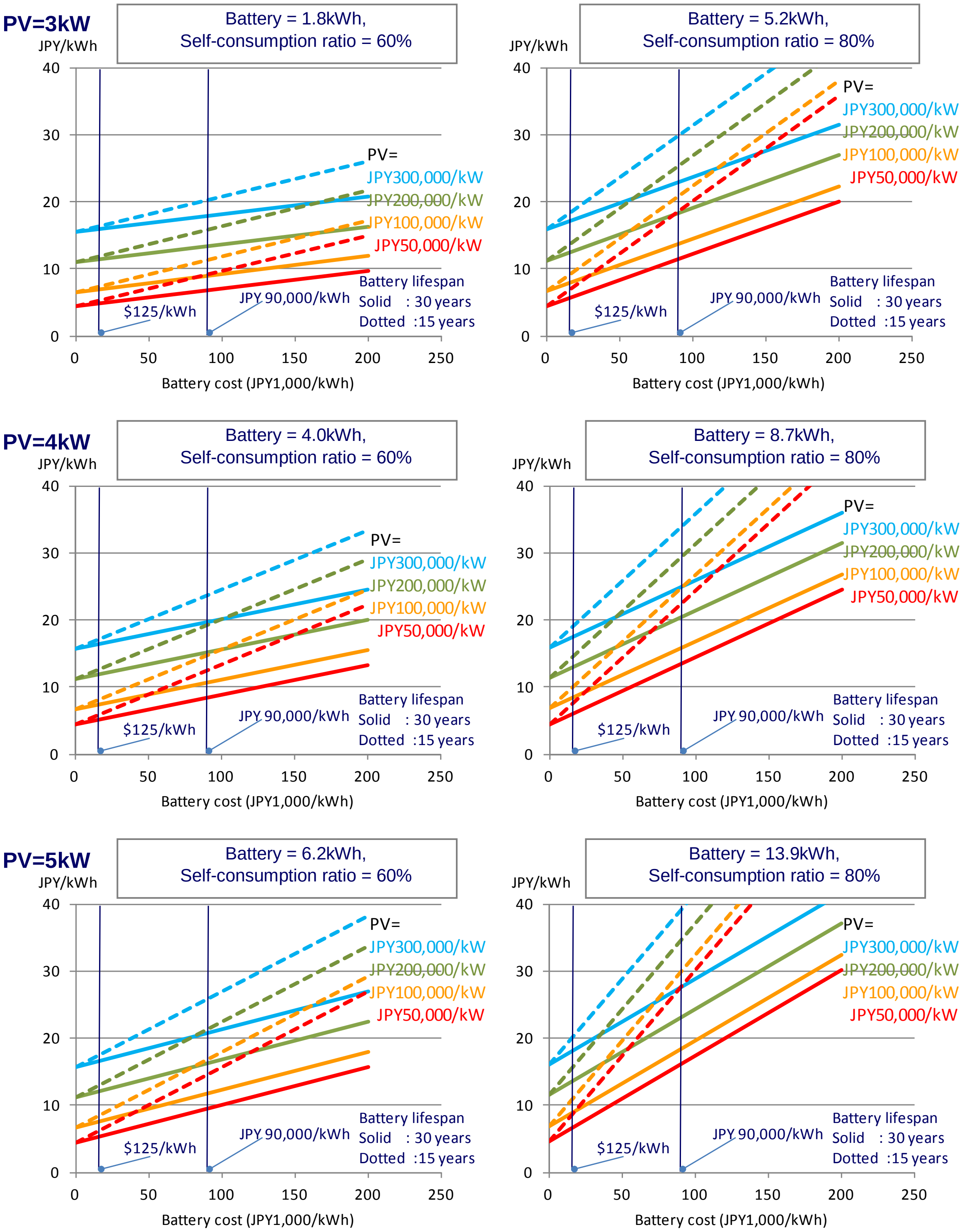


Fig. 3-4 Future LCOE of Residential Solar PV + Battery System

Note: The lifespan of solar PV is assumed to be 30 years.

Note: JPY90,000/kWh of battery is the 2020 target of Japan and $125/kWh is the US 2022 target.

3-2 Mega Solar PV + Battery System

(1) Battery Storage Capacity

1) Curtailment avoidance type

Fig.3-5 illustrates weekly operation patterns of the curtailment avoidance type in the case of 1% and 5% surplus ratio. In the spring/autumn when solar radiation is strong, it is observed that the surplus electricity is charged, then discharged at a different time.

Fig.3-6 shows the relation between the surplus ratio and required battery storage capacity. When the surplus ratio is 1% or 2%, the required battery storage capacity per 1kW of solar PV is 1.2kWh or 2.4kWh, respectively. And the required capacity exceeds 3kWh when the surplus ratio is more than 8%.

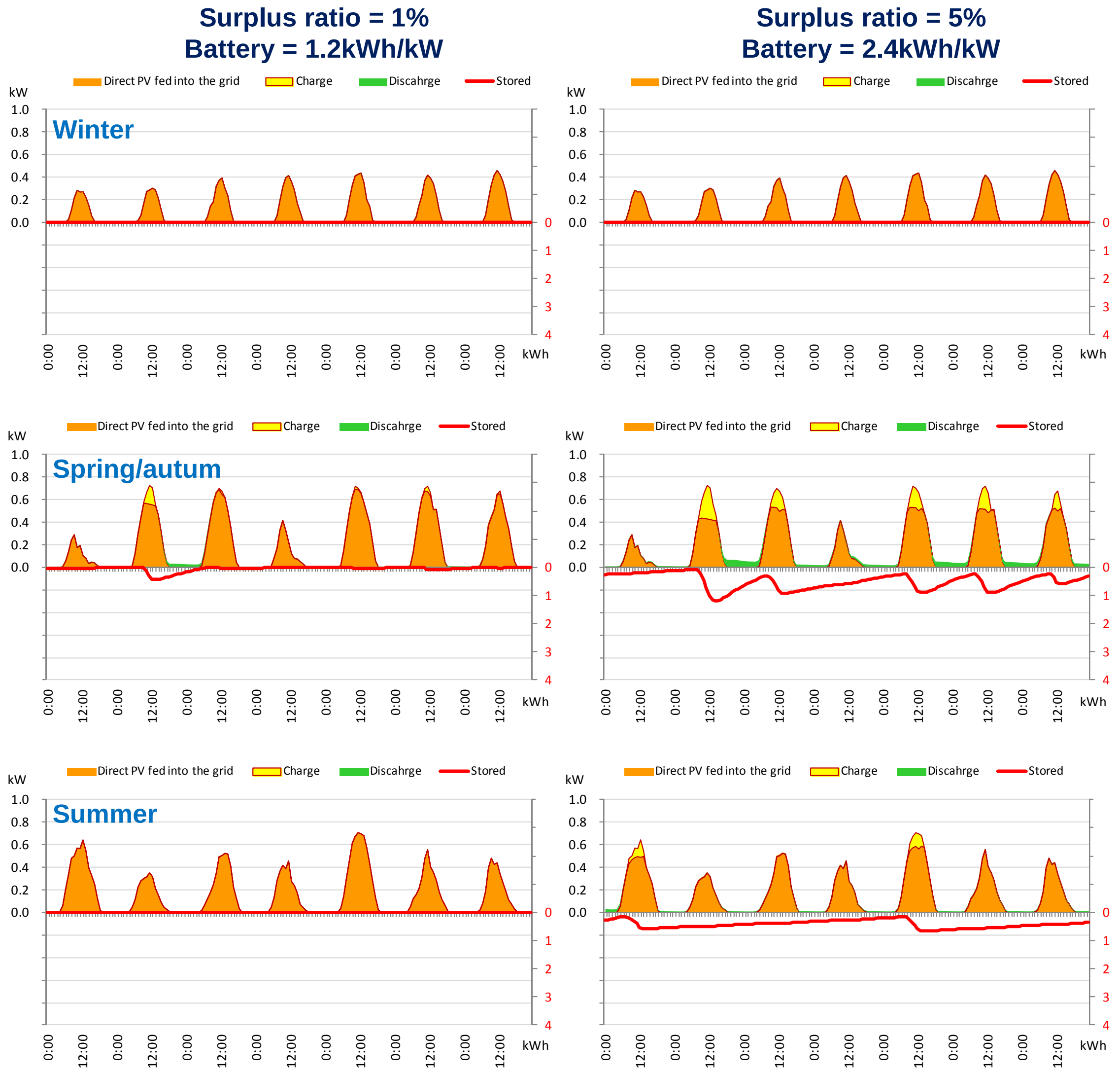


Fig. 3-5 Operation Pattern of Mega Solar PV + Battery (Curtailment Avoidance Type)

Note: Stored electricity is expressed in negative range.

Note: Surplus ratio = Surplus electricity/Total amount of power generation of solar PV

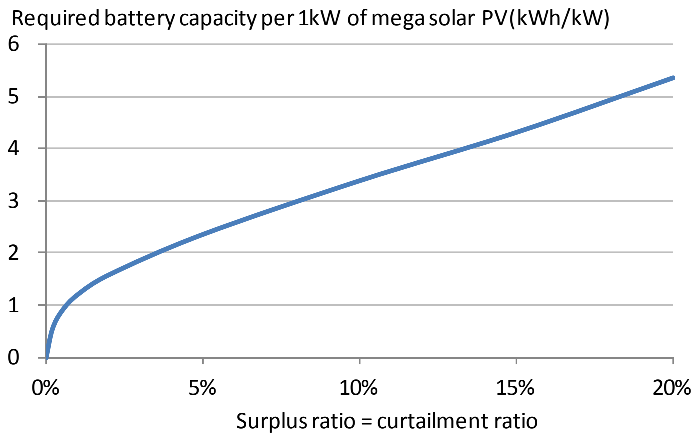


Fig. 3-6 Surplus Ratio and Required Battery Storage Capacity for Curtailment Avoidance Type of Mega Solar PV + Battery System

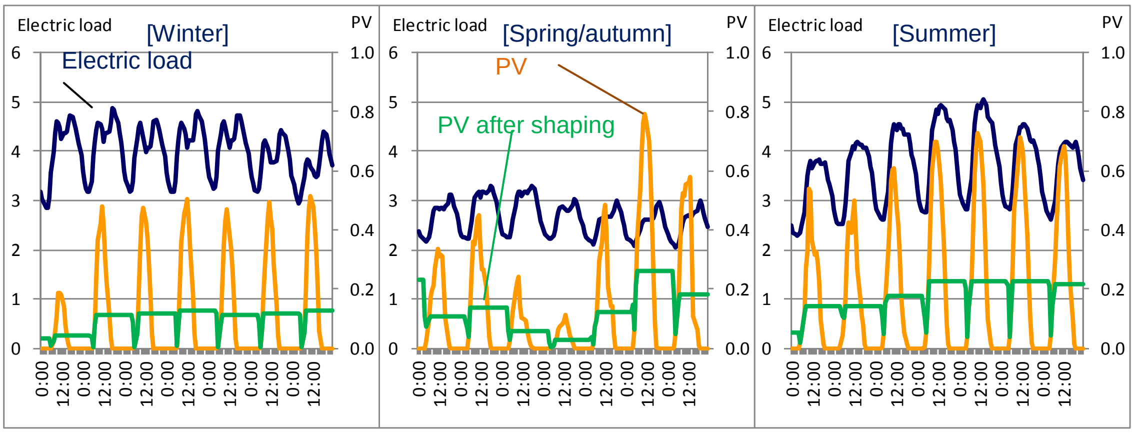
2) Load following type

Fig.3-7 illustrates representative weekly operation patterns of the load following type for pattern 1 (daily base load), pattern 2 (similar to the whole electric load) and pattern 3 (similar to the middle + peak electric load). Though charging and discharging are not shown in the figures, it is observed that the daily solar PV power generation output pattern is shaped in accordance with the electric load patterns. The simulation analysis found that 3.2kWh of battery storage capacity is needed per 1kW of solar PV for any load following pattern. This is presumably because the maximum level of stored electricity that occurs in May which receives the strongest insolation in a year is almost identical among the three patterns.

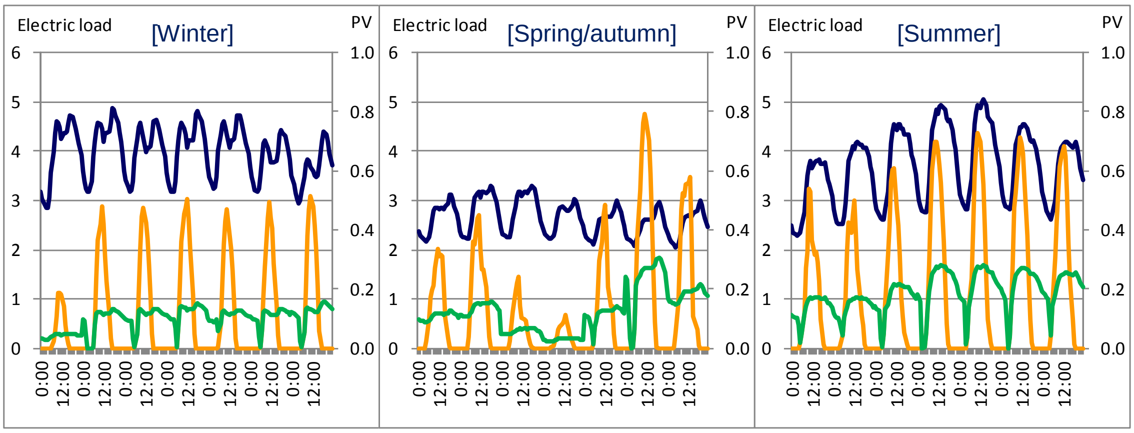
3) Turning point from curtailment avoidance type to load following type

It is obvious that necessary battery storage capacity for the curtailment avoidance type increases as the surplus ratio grows. According to Fig.3-6, when the surplus ratio is larger than 9%, the necessary battery storage capacity for the curtailment avoidance type exceeds 3.2kWh/kW that is required for the load following type. This means that when solar PV is deployed to a scale that the surplus ratio exceeds 9%, battery operation to avoid curtailment becomes irrational and choosing the load following type is more cost effective and advisable.

Pattern 1 (Daily base load): Required Battery Storage Capacity = 3.22kWh/kW



Pattern 2 (Similar to the Whole Electric Load): Required Battery Storage Capacity =3.21kWh/kW



Pattern 3 (Similar to the Middle + Peak Electric Load): Required Battery Storage Capacity =3.28kWh/kW

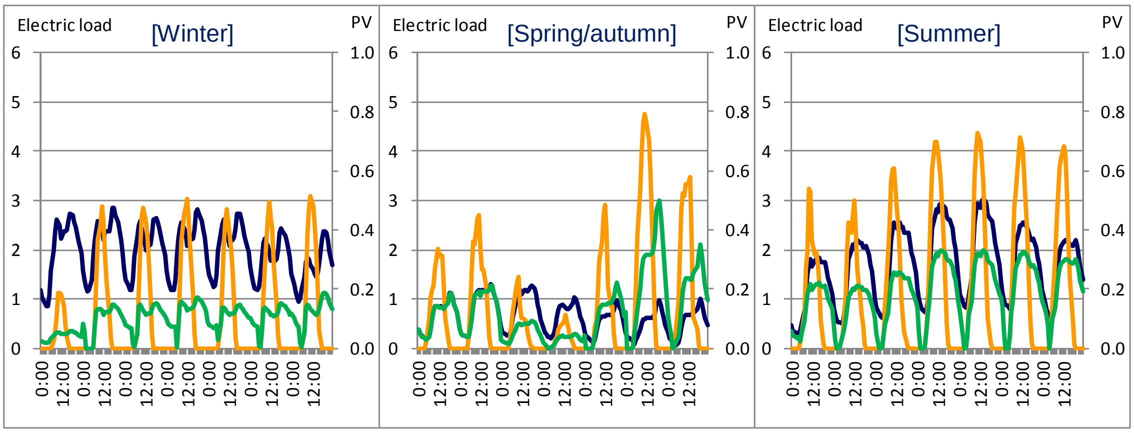


Fig. 3-7 Shaping Mega Solar Power Generation Pattern by Battery (Load Following Type)

Note: Electric load curve and solar PV power generation output are normalized individually.

(2) LCOE

First, the current status is ascertained. Table 3-2 shows LCOEs of the mega solar PV + battery system based on the present cost of mega solar PV (JPY290,000/kW) and battery (JPY200,000/kWh) in Japan. Since it is economically rational for the curtailment avoidance type to be equipped with a battery to the extent that the storage capacity does not exceed that of the load following type as mentioned above, the LCOE is calculated for the cases where the surplus ratio is 1% (required storage capacity is 1.2kWh per 1kW of mega solar) and 5% (2.4kWh/kW). The LCOE is JPY40-70/kWh for 15 years of battery lifespan and JPY30-40/kWh for 30 years. The load following type becomes extremely costly due to a requirement of as large as 3.2kWh of battery, and the LCOE is JPY92/kWh for 15 years of battery lifespan and JPY56/kWh even if the lifespan extends to 30 years. In any case, the current LCOE is far beyond parity with the commercial and industrial electricity retail price (JPY20/kWh).

Table 3-2 Current LCOE of Mega Solar PV + Battery System

	Surplus ratio	Battery capacity required per PV capacity (kWh/kW)	Net capacity factor of the system	System cost (JPY/kW) PV=JPY290,000/kW Battery= JPY200,000 /kWh		System LCOE (JPY/kWh)	
				Battery lifespan =30years	Battery lifespan =15years	Battery lifespan =30years	Battery lifespan =15years
Curtailment avoidance type	1%	1.2	13.6%	53	77	31	44
	5%	2.4	13.6%	76	123	44	69
Load following type	-	3.2	12.9%	93	158	56	92

Note: The lifespan of PV is assumed to be 25 years.

Secondly, future LCOE based on the current international price of solar PV and battery and an expected price decline is calculated and the results are shown in Fig.3-8. The lifespan of solar PV is assumed to be 30 years. For both the curtailment avoidance type and the load following type, if the solar PV price is the current level, the battery price should be no higher than JPY50,000/kWh in order to achieve JPY20/kWh of LCOE which is at parity with the commercial and industrial electricity retail price. Especially for the load following type, the battery price is required to be as low as JPY10,000/kWh. If the solar PV price is reduced to JPY200,000/kW, the requirement on battery price is mitigated to JPY50,000-100,000/kWh for the curtailment avoidance type and JPY30,000/kWh for the load following type. According to the current European solar PV price level (JPY160,000/kW) and the current US battery price level (JPY30,000/kWh), the conditions imposed to achieve parity with the commercial and industrial electricity retail price are not unrealistic.

If the price of solar PV decreases to JPY100,000/kW, equivalent to IRENA’s 2025 world average outlook, and the battery price decreases to JPY20,000/kWh, equivalent to the US 2022 target, the LCOE can reach as low as JPY10/kWh, which equals nuclear, coal-fired and LNG-fired power generation and this means that the mega solar PV + battery system becomes versatile power generation that is able to coordinate with a variety of electric load patterns and is also economically competitive with any power generation.

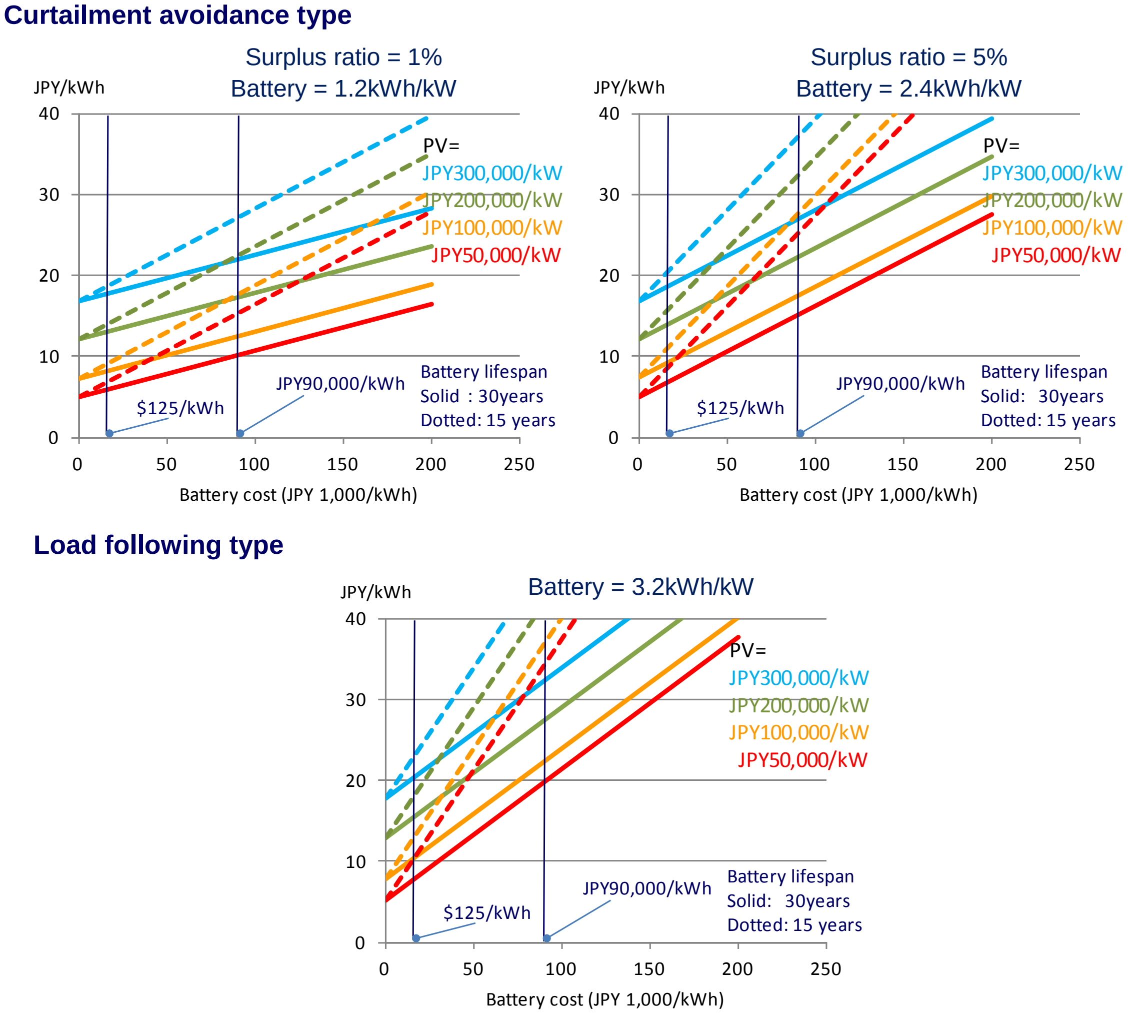


Fig. 3-8 Future LCOE of Mega Solar PV + Battery System

Note: The lifespan of PV is assumed to be 30 years.
Note: JPY90,000/kWh of battery is the 2020 target of Japan. $125/kWh is the US 2022 target.
Note: Battery capacity is expressed by required storage capacity per 1kW of mega solar PV.

4. Challenges towards Deploying Solar PV+ Battery System

Regarding the residential solar PV + battery system, this study addressed only a 3-family member household, which is the average household installing solar PV in Japan. In order to raise the self-consumption ratio of solar PV with a view to constraining the impact on the grid, it would be an option to install solar PV less than 4.5kW that is currently the average residential solar PV power generation capacity. Smaller solar PV capacity allows curbing the required battery storage capacity and as a result the LCOE can be reduced. The optimum design of the residential solar PV

+ battery system in accordance with household scale should be identified.

Since the implementation of FIT in July 2012 in Japan, curtailment has so far (as of end of April 2017) been issued and executed no more than about 50 times to the mega solar PVs installed on the smaller remote islands isolated from main transmission lines in the Kyushu region. However, it is likely that curtailment would be executed more frequently as renewable energy is increasingly deployed. It should be kept in mind that when the ratio of surplus electricity subject to be curtailed exceeds 9%, in terms of economics, the load following type rather than the curtailment avoidance type should be chosen for the mega sola PV + battery system.

It should not be forgotten that there are technological challenges in the solar PV + battery system. For reduction in LCOE of the system, extension of system lifespan is a crucial issue aside from reduction in the CAPEX of solar PV and battery. Although the lifespan of solar PV is presently as long as 25 years, further R&D is needed to extend the lifespan up to 30 years. The battery lifespan of currently 10-15 years should also be extended. However, extension of lifespan generally induces CAPEX increase. One of the challenges is to realize extension of lifespan and CAPEX reduction simultaneously. Nevertheless, as substantial decrease in CAPEX can mitigate the impact of reinvestment caused by short lifespan on the system price, there may be an R&D strategy that focuses only on CAPEX reduction at the expense of lifespan extension.

5. Concluding Remarks

This study, from the perspective of “post FIT,” revealed the conditions required for the solar PV + battery system to be deployed with financial independence from FIT. A battery operation simulator was developed to identify battery storage capacity required for mitigating impact on the grid and the LCOE (Levelized Cost of Electricity) of the system was estimated.

In order to mitigate impact on the grid, the operation pattern of residential solar PV + battery system was designed so as to raise the self-consumption ratio. Regarding the mega solar PV + battery system, two operation patterns were proposed. One of the operation patterns is the “curtailment avoidance type” that charges and discharges the surplus electricity subject to curtailment. The other one is the “load following type” that shapes by battery the solar PV power generation output curve in accordance with electric load curve components (base, middle and peak), which means to alleviate the impact on the grid to an extreme extent by providing the system with a function of base load power generation or with ramping capability.

According to the analysis results, the LCOE of the residential solar PV + battery system is JPY60-80/kWh based on the current price and lifespan of solar PV and battery on the Japanese market, which is far from parity with the residential electricity retail price (JPY 25/kWh). The LCOE of the mega solar PV + battery is JPY40-90/kWh which is also far from parity with the commercial & industrial electricity retail price (JPY 20/kWh). However, if the prices of solar PV and battery reach the current international levels, each system would be able to attain respective parity.

The study found a turning point between the curtailment avoidance type and the load following type. When the surplus ratio exceeds 9%, the necessary battery storage capacity for the curtailment avoidance type exceeds 3.2kWh/kW that is required for the load following type. This means that when mega solar PV is deployed to a scale that the surplus ratio is more than 9%, battery operation to avoid curtailment becomes irrational and choosing the load following type is more cost effective and advisable. In the near term when the surplus ratio limited, it will be reasonable to choose the curtailment avoidance type, however, in the longer perspective when the surplus ratio rises, it is of great significance to make the mega solar PV + battery play a role as load following.

If the price of solar PV is reduced to JPY100,000/kW (IRENA's 2025 outlook) and the price of battery is reduced to $125/kWh (the US 2022 target), the LCOE of the solar PV + battery system for either residential or mega solar can achieve as low as JPY10/kWh. Then, the solar PV + battery system can be competitive against any other power generation, while being able to meet a variety of electric load patterns. In Japan, strong needs for high quality products and lack of a competitive market due to excess financial support (such as FIT) allegedly keep the price level of solar PV and battery substantially higher than the world level. Therefore, it presumably will take time to reach the international price level. However, it is not until the early 2030s that the solar PVs will meet full-scale post-FIT era. Towards 2030, reinforcement of R&D aiming extension of lifespan of the system and market expansion are the challenging issues along with strengthening institutional activities to fill the price gap between Japan and the world.

References

[1] "THE POWER TO CHANGE: SOLAR AND WIND COST REDUCTION POTENTIAL TO 2025," IRENA

[2] "Overview of the DOE VTO Advanced Battery R&D Program," Vehicle Technologies Office, June 6, 2016

[3] Study group of energy resource aggregation business, Ministry of Economy, Trade and Industry, March 2017

[4] "Strategies of Battery," July 2012, Project team of Strategies of Battery, Ministry of Economy, Trade and Industry

[5] "Cost Trend of Solar PV and Wind," The 25th Committee on Estimation of Purchasing Price, November 2016

[6] Shibata, Y., "Analysis on the Cost Effectiveness of the Residential Distributed Energy System composed of Fuel Cell, Photovoltaics and Battery," IEEJ Energy Journal, September 2012

[7] Survey for Estimation of CO_2 Emission from Household Sector, Ministry of Environment, 2014 (http://www.env.go.jp/earth/ondanka/ghg/kateitokei.html)

[8] Shibata, Y., "Evaluation of Wind Power Integration Potential in Japan by Strengthening of Interregional Transmission Lines and by Power Curtailment," IEEJ Energy Journal Vol.8, No.3, 2013

[9] Working Group for Evaluation of Levelized Cost of Electricity, May 2015

[10] "Technology Development Roadmap of Rechargeable Battery," NEDO, August 2013