THE INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME ON HYDROPOWER

IEA Hydropower

Role and Challenges of Pumped Storage Hydropower Under Mass Integration of Variable Renewable Energy

Information gathered from PSH facilities in Europe and USA

October 2021

IEA Hydro Annex IX

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Contents

Acknowledgements

The main theme of Annex IX Phase II covers the value of hydropower, with each participating country contributing to the study on providing hydropower flexibility under mass integration of variable renewable energy, since 2018.

Pumped Storage Hydropower (PSH) has the function of providing storage capability that can absorb surplus power from variable renewable energy, in addition to the balancing function that can be provided by normal hydropower. It is an especially important facility to complement hydropower from the point of view of flexibility.

On the other hand, it is difficult to forecast revenue by arbitraged transaction in a deregulated electricity wholesale market on a long term basis. It is found here and there by region that a PSHP entity faces severe challenges to maintain its facility, in the case that PSHP is often overlooked from the point of view of business.

Based on such background, Japan has studied the improvement of power adjustment by PSHP in Europe and the USA, the current status of PSHP business, good practices of PSHP development, and the role of PSHP under mass integration of variable renewable energy in Japan, naming the title of this study as "Role and Challenges of Pumped Storage Hydropower Under Mass Integration of Variable Renewable Energy". This Report summarizes this information, and we hope it contributes to PSHP entities, network operators, regulating organizations, and etc. as a meaningful document.

We would like to take this opportunity to express our thanks for cooperation with our interview on PSHP to those concerned with Kyushu Electric Power Co. in Japan, Avce PSHP, Goldisthal PSHP, Gaildorf PSHP, Wehr PSHP, Reisach PSHP, Kops II PSHP, and Malta PSHP in Europe, Raccoon Mountain PSHP, Helms PSHP, Blenheim Gilboa PSHP, and Olivenhain Hodges PSHP in the USA, EDP in Portugal, and Niels Nielsen who created opportunities of interview to utilities in each country for our study team. We also express our thanks to Koichi Ota, Kansai Electric Power Co. for contribution to this study as a member of Expert Meeting of Annex IX, IEA Hydro and Dr. Miyanaga, Central Research Institute of Electric Power Industry, for giving guidance to us through the domestic committee for IEA Hydro in Japan.

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Japan Electric Power Information Center

Summary

PSH has been integrated for the purpose of power storage, by which water is pumped up using the power system when demand is low and power is generated using that water when demand is high. PSH has conventionally been used for supply and demand adjustment not only as a peak power source to assist the base load power sources in response to fluctuations in demand, but also as demand that can be adjusted directly by the TSO. In recent years, in addition to fluctuations in demand, fluctuations of variable renewable energy have had a greater impact on the supply–demand balance. PSH has been attracting attention, as it is operated also for the purpose of absorbing such fluctuations.

The balancing capability (down) is provided by thermal power plants, Demand Response and variable speed PSH that can provide larger scale capability, which has developed actively to participate in the balancing market.

In the United States, many PSH plants were constructed between the 1960s and 1980s, with an installed capacity of about 23 GW, the third largest in the world after China and Japan. Although the liberalization of electricity market has been promoted from an early stage, the form of wholesale electricity transactions differs by region, and the integration of variable renewable energy such as solar and wind is not consistent, depending on the policy of each state. By focusing on the United States, where the business environment for PSH varies from region to region as seen above, its operational status will be explained here.

As of 2018, PSH plants with a total capacity of approximately 160 GW were in operation worldwide. China, Japan and the United States account for about half of the total, followed by European countries. Many of these plants were constructed before the liberalization of electricity market, and their concept is pumping surplus power from base load supply such as nuclear and coal-fired thermal power during low-demand hours at night and generating during peak hours in the daytime. In recent years, the integration of variable renewable energy has been advancing, and opportunities for the use of PSH have increased to absorb its fluctuations. However, in the liberalized electricity market, it is difficult to forecast long-term profitability obtained from arbitrage transactions in the wholesale electricity market and through the provision of balancing capability in balancing market, and the situation for the development of new PSH remains severe, as it requires considerable construction costs and time. Against this background, approximately 17 GW of PSH plants have started operations worldwide in the recent 5 years (2014 to 2018), and the development in Asia and Europe account for most of them.

Japan has been experiencing rapid deployment of solar PV, since a Feed-in Tariff program was launched in 2012. Kyushu, the southernmost island among the main islands of Japan, has been the most significantly affected area in terms of solar PV penetration. According to the IEA definition (IEA 2018), Kyushu is regarded to be in Phase 3 of VRE integration (i.e. VRE generation determines the operation pattern of the system) due to limited interconnection capacity. To keep the balance between supply and demand in case of VRE generation surplus, all transmission system operators in Japan have launched the so-called “Priority dispatching rule” as of 2016. The priority dispatching rule determines in what order power generation is dispatched down, or curtailed, in order to balance supply and demand.

1. Introduction

As each country takes the initiative to integrate variable renewable energy, there is an increasing need for power storage and balancing capability to eliminate the supply and demand imbalance. PSH is capable of large-scale power storage and of providing balancing capability over a wide range of time scales, but its operation may be forced to be difficult depending on the market design and power generation mix. Therefore, the following survey was conducted with the purpose of clarifying the role of PSH and the challenges it faces, namely:

- Improvement in balancing capability of PSH
- PSH business
- PSH development

PSH has been integrated for the purpose of power storage, by which water is pumped up using the power system when demand is low and power is generated using that water when demand is high. PSH has conventionally been used for supply and demand adjustment not only as a peak power source to assist the base load power sources in response to fluctuations in demand, but also as demand that can be adjusted directly by TSO.

In recent years, in addition to fluctuations in demand, fluctuations of variable renewable energy have had a greater impact on the supply–demand balance. PSH has been attracting attention, as it is operated also for the purpose of absorbing such fluctuations.

In a vertically integrated system, power system operators are in charge of supply–demand balancing, and they instruct power plants to supply power in order to maintain a balance against fluctuations in demand. Therefore, under this system, PSH plants are operated, in principle, on the basis of load dispatching instructions from power system operators.

2. PSH in European Markets

2.1 Wholesale Electricity Market

In Europe, liberalization of the electricity market and the unbundling have been promoted in a stepwise manner since 1997, and full liberalization of retail sales and the unbundling of the power generation/supply and the transmission/distribution sectors has been completed up to now. In addition, power exchanges for domestic and international wholesale power transactions have opened, and wholesale power transactions are actively carried out.

Under this liberalized electricity market, the supply and demand balancing are realized by the market principles of the wholesale electricity market. In other words, if the supply capacity is insufficient for the demand, the market price will rise, and if the supply capacity is excessive, the market price will fall. It is a mechanism where the supply side adjusts the amount of power generation with a motivation to earn profits from the price fluctuation.

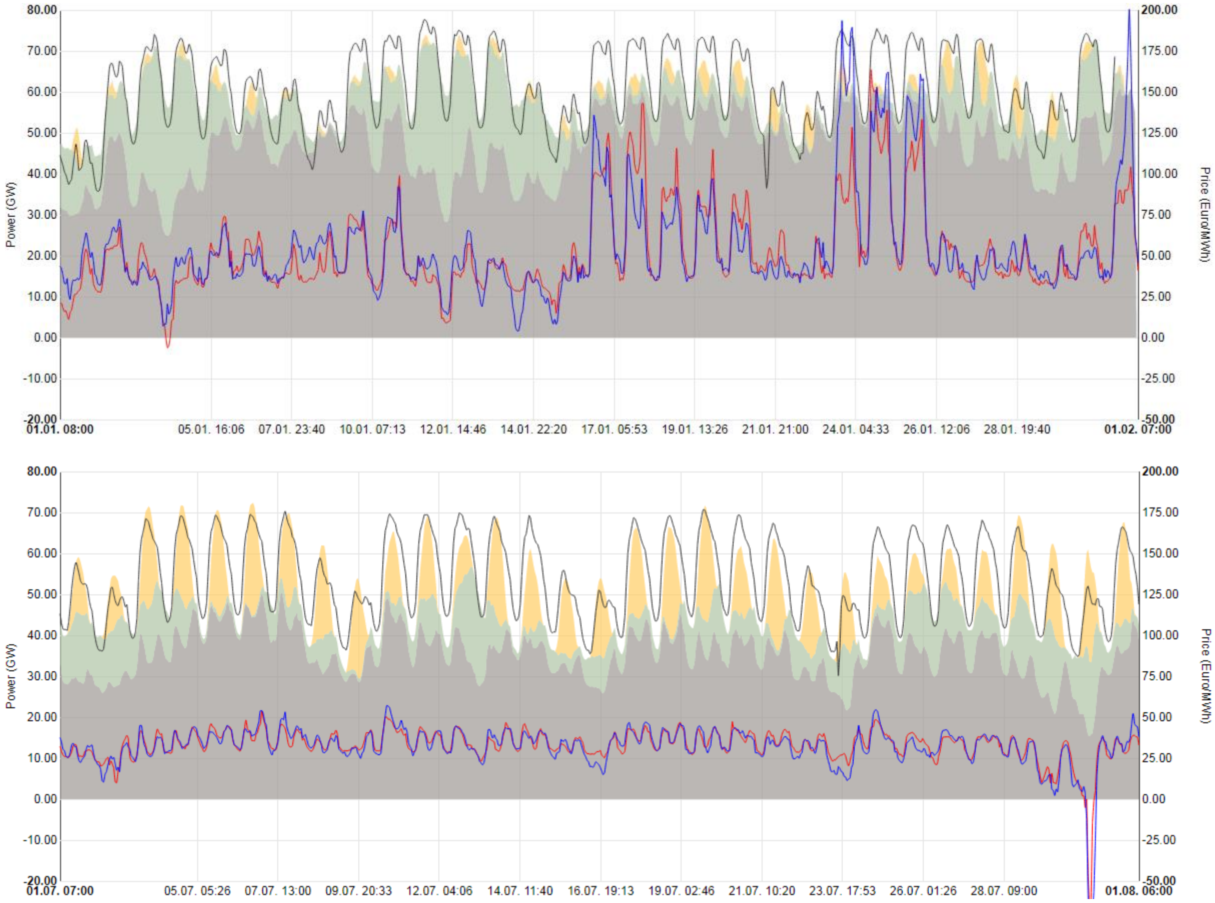
In European spot power exchanges, much of the required electric energy is first traded on the day-ahead market based on the supply and demand plan of the previous day. Thereafter, a more accurate forecast is made immediately before the market opening by taking into account the weather of the day, and a difference from the previous day's forecast is traded on the intra-day market. The difference (imbalance) between the forecasted and actual amount of actual supply and demand operations is ultimately adjusted using the balancing capability that power system operators secure in advance.

On the intra-day market, initiatives are taken to enhance the liquidity of the market, such as the introduction of a 15-minute call auction in Germany, and its transaction volume has been increasing year by year. Therefore, the imbalance in the actual demand and supply tends to be reduced, together with the improvement in the forecasting power generation of variable renewable energy such as solar and wind power.

In Europe, the power generation amount of renewable energy has been increasing year by year, and in 2017, it exceeded that of coal-fired power generation. Among these large amounts of renewable energy, variable renewable energy receive subsidies such as a feed-in premium scheme and receive priority treatment for power supply, in addition to the zero cost. Therefore, even if the market price is low, most of variable renewable energy is directly bid on the electricity market. For this reason, fluctuation of variable renewable energy due to weather conditions and seasons, as well as the correction of the output forecast, are largely reflected in electricity market prices.

When looking at the power generation amount of variable renewable energy and the wholesale electricity price trends on the day-ahead market and the intra-day market (Figure 1) by taking Germany as an example, the amount of wind power generation increases in winter with good wind conditions, whereas in summer, the amount of solar power generation increases with an increasing amount of solar radiation. Since solar power generation increases during the day when the demand increases, the price difference between day-time and night-time becomes small in summer. Moreover, since the forecasting accuracy of solar power generation is high in fine weather, it has little effect on the price difference between the day-ahead market and the intra-day market in summer associated with the forecast correction.

Figure 1. Power generation amount and wholesale electricity price of variable renewable energy in Germany (above: winter, below: summer)



Note: Excess and shortage of supply for demand are adjusted by import and export and adjustable renewable energy (such as biomass).

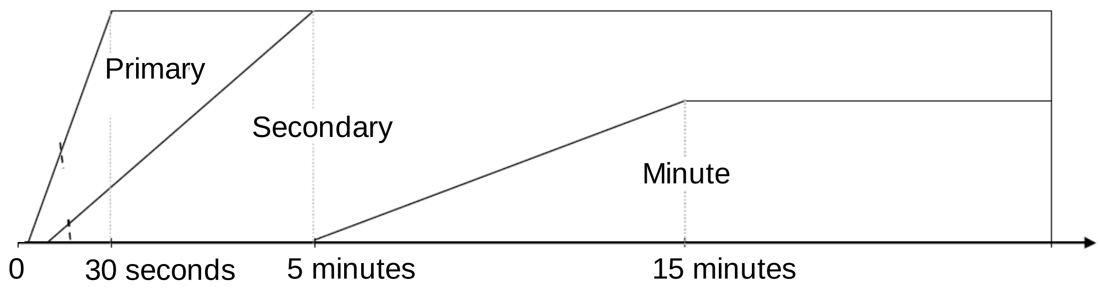
Source: Fraunhofer Institute website

The operation of PSH plants under the unbundling is based on the wholesale electricity price, rather than on load dispatching instructions from system operators. In this case, the basic operation in which pumped during times with low electricity prices and generated during times with high prices, profits are obtained by arbitrage. However, it is difficult to make a profit in a situation where the price difference in a day becomes small such as summer in Germany. Nonetheless, in recent years, in addition to the conventional price difference associated with the demand fluctuation of day and night, the price difference between the day-ahead market and the intra-day market has become large due to the correction of the power generation forecast of variable renewable energy, and thus the operation aiming at this price difference has been also carried out. Moreover, although it is rare, excessive bidding of variable renewable energy causes a negative price, and the pumped-storage operation at this timing becomes desirable.

2.2 Balancing Market

In Germany, for securing balancing capability efficiently, it is procured through auctions in the balancing market operated by TSO, divided into three categories (Figure 2).

Figure 2. Reserve classification in German balancing market



Source: University of Duisburg-Essen, “The German Market for System Reserve Capacity and Balancing Energy”

Compared with thermal power generation, PSH has advantages, fast start/stop and power control, as well as excellent balancing capability such as efficient partial load. However, the response requirement of less than 30 seconds for the primary reserve is intended for power control during operation. Even if PSH units start up quickly, it is difficult to satisfy the requirement of the primary reserve from the standstill state, and the output is basically modified from the state of generating with partial load in order to provide ΔkW.

In contrast, the secondary reserve is mainly provided by power control as in the case of the primary reserve, but a PSH unit that starts up quickly also provide the balancing capability from the standstill state. The secondary reserve is further divided into “up (increase power)” and “down (reduce power),” and since “down” can be easily realized by temporary output reduction of thermal power plants in operation with full load, it results in a large number of bidders, making successful bid prices tend to be low. However, thermal power generation needs to be operated with partial load in order to provide “up” and sending out power sources with low partial load efficiency tends to be refrained from bid.

The secondary reserve and the tertiary reserve (Minute) is also paid for kWh not only for ΔkW. Although this transaction volume is small compared with wholesale electricity transactions, the successful bid price may be more than double wholesale electricity transactions, making it a highly profitable for power sources, such as PSH, that can participate in balancing market.

In Germany, the auction-based system to procure balancing capability was introduced for the purpose of properly assessing balancing capability based on market principles. But in some cases, speculative bidding unfairly raises prices, this goes against the original purpose, and the German Federal Network Agency (BNetzA) is pursuing discussions regarding a review of the system.

In the recent balancing market in Germany, the required amount of balancing capability has been decreasing because of the narrowing of imbalances associated with an increase in the transaction volume on the intra-day market and because of the interchanged balancing capability among power system operators, in addition to the fact that the transaction prices have been falling due to the competition caused by an increased number of participants in balancing market. This has resulted in the market size tending to shrink. However, the primary and secondary reserve, which has stringent requirements, are highly profitable, and bidding in more profitable markets with mainly these two types of balancing capability is the basic policy for the operation of PSH.

3. Improving Balancing Capability of PSH in Europe

The balancing capability (down) is provided by thermal power plants, Demand Response and variable speed PSH that can provide larger scale capability, which has developed actively to participate in balancing market.

3.1 Variable speed PSH with secondary exciter system

PSHs are generally capable of easily control power output generation, but they cannot control power at pumping. This is because the rotating speed of reversible pump turbine is constantly in synchronization with the system frequency even though the amount of water pumped up is proportional to the cube of the rotating speed; the amount of water pumped up is also constant, and the power that increases or decreases in proportion to the amount of water is constant as well. Therefore, at pumping, it is not possible to participate in balancing market as the demand side of electric power such as DR.

A technology capable of solving this issue is variable speed PSH system. This system can increase or decrease the rotating speed of generators with frequency converter to change the electrical frequency of generators. Among the variable speed PSH systems, adopted mainly for large scale units is secondary exciter system, in which a frequency converter is installed in excitation system. The frequency converter can be made smaller than installed in the main circuit.

This secondary excitation type variable speed PSH is a world-leading technology developed in Japan. Although many of the systems currently operated in the world are already installed in Japan, also several cases in Europe. The following are examples in Slovenia and Germany.

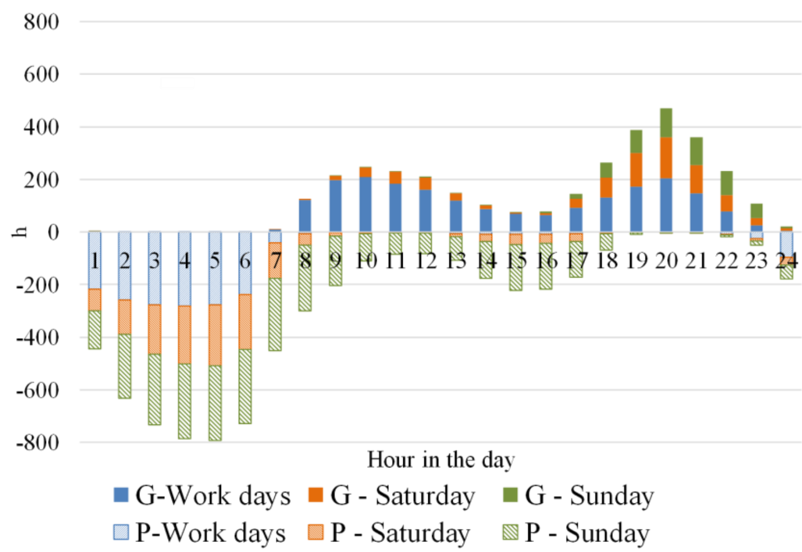
3.1.1 Avce PSH Plant in Slovenia

Avce PSH plant in Slovenia, with an installed capacity of 185 MW (1 unit), is the only PSH plant in this country, which commenced in 2010 with a purpose of providing peak power supply. This power plant, located near the border with Italy, plays a valuable role in regulating the power flow in Slovenia and as balancing capability in synchronizing the Slovenian and Italian power systems.

This power plant can control pumping power in range 140 to 180 MW with secondary excitation type variable speed system. This system is utilized as balancing capability at night-time when there are few available reserve, also plays a role in mitigating power system oscillation at the start and stop of pumping in relatively small 110 kV system. In addition, this plant can provide condenser mode operation which is superior with respect to the system voltage control, but it is not used, as there is no contract signed with a power system operator concerning condenser mode operation.

As the reservoir capacity of this PSH plant is relatively large and capable of generating for 14 hours with full output, the plant is operated on a weekly cycle by pumping at night-time or on weekends when the demand is low and by generating during the day-time on weekdays when the demand is high (Figure 3). Out of the electric energy generated, 93% is traded in the wholesale electricity market.

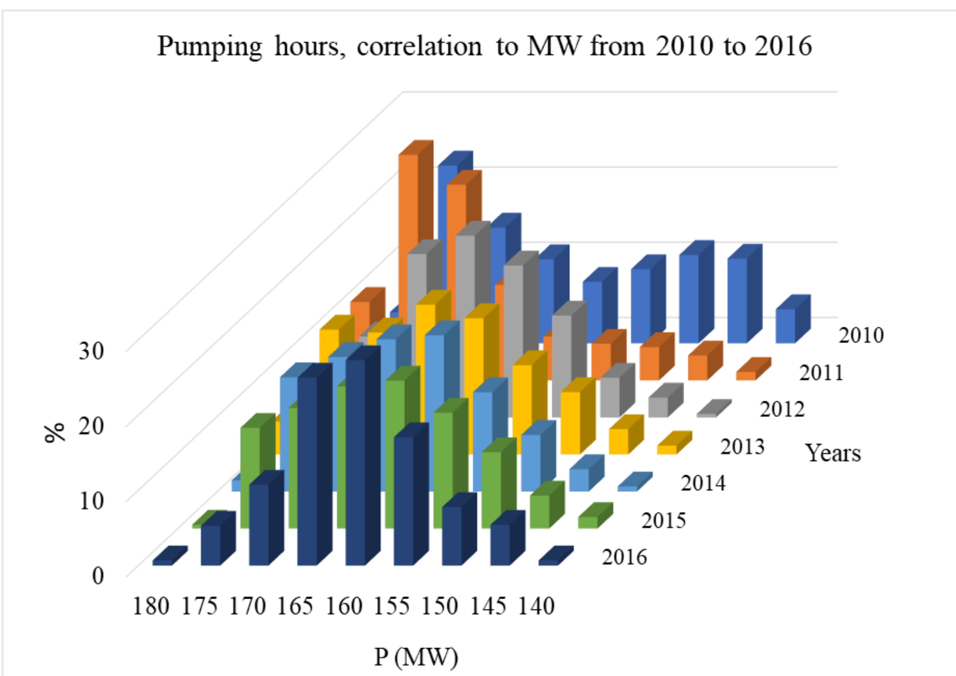
Figure 3. Generating and Pumping ratio of Avce PSH plant (one week)



Source: Documents from the HYDRO 2017 conference

Although this basic operation cycle has not changed since the commencement of its commercial operation to the present, the power range at of pumping has changed significantly from 2010 to 2016. In 2010, it was often operated at the full power of 180 MW in order to pump in a short period during a low electricity price as much as possible, but in 2016, there were more opportunities to operate at intermediate power of 160 MW (Figure 4).

Figure 4. Power range during pumping operation at Avce PSH plant (2010 to 2016)

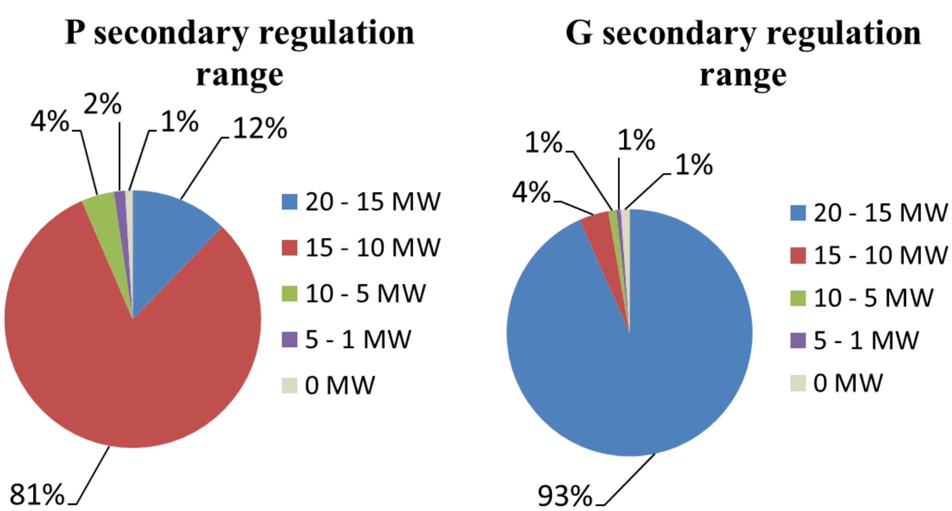


Source: Documents from the HYDRO 2017 conference

The reason the operating power range has been changing as seen above is that the opportunity to participate balancing market has increased as the volatility of wholesale electricity prices has decreased along with the increase in renewable energy. Slovenia has traditionally introduced a large amount of renewable energy, mainly hydroelectric power, but the government has set an even higher target, and the amount introduced, mainly variable renewable energy, has been increasing recently. In addition, inexpensive renewable energy procured from the European Energy Exchange (EEX) has also increased, and the average prices and the volatility of prices in the wholesale electricity market have declined, making it difficult for Avce PSH plant to make a profit in the wholesale electricity market.

The purpose of operating at the intermediate power of 160 MW is the operation to provide balancing capability. At Avce PSH plant, in order to make the best use of the power range of 90–185 MW at generating and 140–180 MW at pumping, the operation in the intermediate power range is set as the basis, and the secondary reserve is provided to make a profit (Figure 5).

Figure 5. Secondary regulation range of pumping and generating at Avce PSH plant



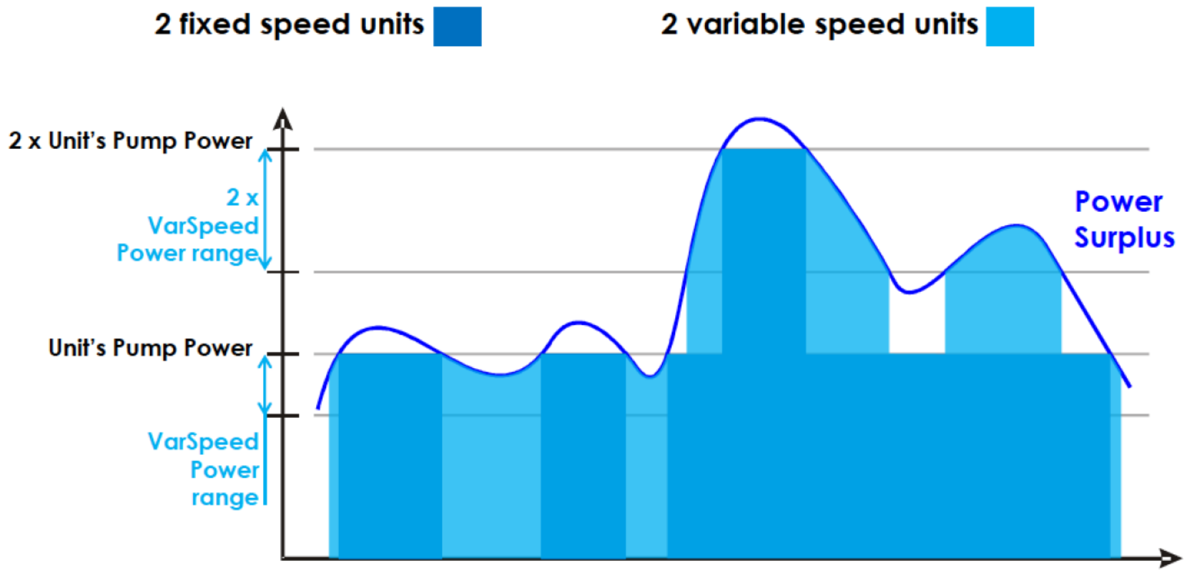
Source: Documents from the HYDRO 2017 conference

In Slovenia, there is a system whereby primary regulation is automatically provided by a generator in operation, however not remunerated for the primary regulation.

3.1.2 Goldisthal PSH plant in Germany

Goldisthal PSH plant in Germany, with an installed capacity of 1,060 MW (2 units of variable-speed and 2 units of fixed-speed), which commenced in 2003, is the first variable-speed PSH system in Europe. The reason the variable-speed and the fixed-speed units are each composed of two units is to reduce the installation space and cost of the frequency convertor required for variable-speed units, in addition to equipping the fixed-speed units with a black-start function, which is difficult to be equipped in variable-speed units. Even with such a structure, a power plant as a whole can meet the needs of power system operators by appropriately combining the operation of the variable-speed and fixed-speed units (Figure 6).

Figure 6. Combination of variable-speed and fixed-speed units



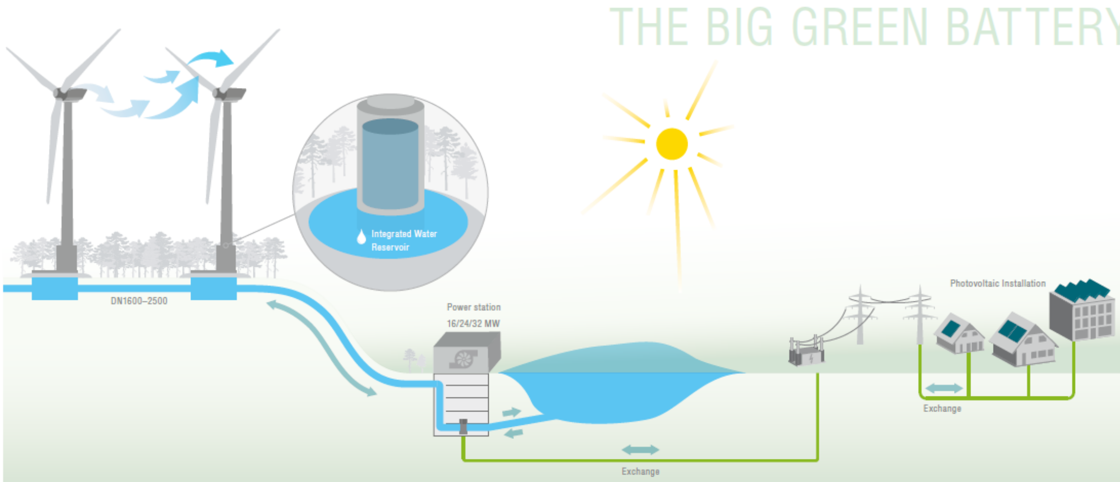
Source: NTMU, "Pump Storage Hydropower for delivering Balancing Power and Ancillary Services"

The reservoir capacity of this PSH plant is large, and can generate power for eight hours with full power; therefore, a basic operation is to make a profit by arbitrage in the wholesale electricity market on a weekly basis. In recent years, however, the opportunity to bid in balancing market has been increasing as the price volatility in the wholesale electricity market has decreased. In particular, the operating frequency of variable-speed units with high balancing capability has increased by about 30% compared with fixed-speed units. In this PSH plant, in order to avoid too much reliance on the operation of variable-speed units, the operational sequence of the unit has been devised such that it is set out as "the first unit of variable-speed → the first unit of fixed-speed → the second unit of fixed-speed → the second unit of variable-speed".

3.1.3 Gaildorf Water Battery Project in Germany

In the suburbs of Gaildorf in Germany, a project that combines PSH and wind power (PSH of 15.9 MW and wind power of 13.6 MW) has been underway since 2019 (Figure 7). The base of the wind turbine tower is made into a tank, which is utilized as an upper reservoir for PSH to reduce construction costs. Another feature of this project is that wind power can be directly used for pumping without using the power system. A full converter type variable-speed system is used for PSH, the scale of a frequency converter is large compared with the secondary exciter type variable-speed system, but the switching the mode between generating and pumping is fast, so that it can provide the primary regulation.

Figure 7. Gaildorf water battery project

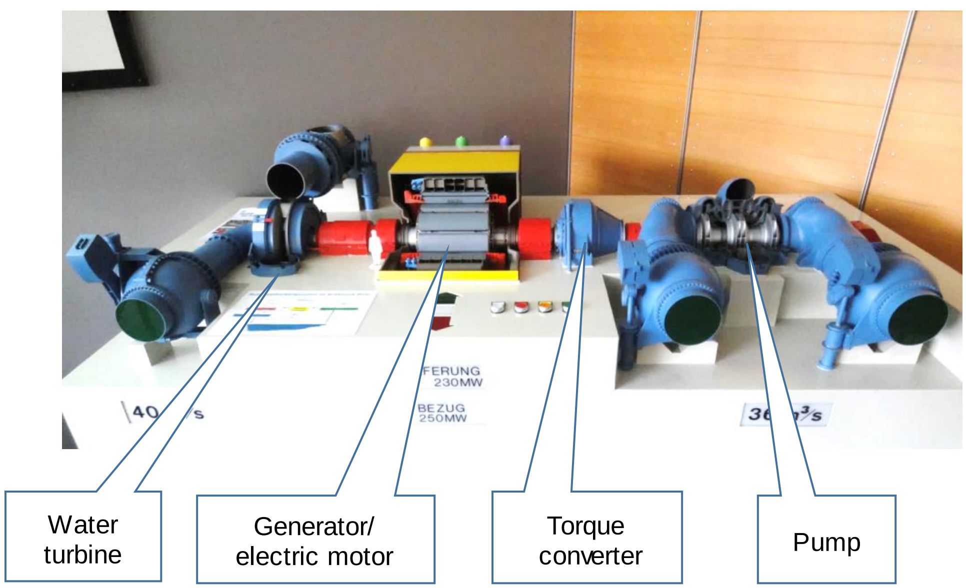


Source: Max Bogl

3.2 Ternary-type PSH

A ternary PSH system, which has been used in Europe for a long time, is also an effective method for participating the balancing market. Unlike the reversible PSH system in which water turbine and pump are integrated, which has been mainly adopted in recent years, the ternary system consists of water turbine, power generator/motor, and pump (Figure 8). It is a system with the purpose of optimizing the design of each of water turbine and pump.

Figure 8. Structure of ternary-type PSH



Source: Wehr PSH plant in Germany

One of the advantages of the ternary PSH system is the switching speed with the operating mode. In the reversible PSH system, since a generator and a motor rotate in opposite directions in generating mode and pumping mode, respectively, it is necessary to completely stop the unit for switching the operation mode. By contrast, in the ternary PSH system, since a generator and a motor rotate in the same direction in generating mode and pumping mode, the operation mode can be switched without stopping the unit. In addition, when the pump is initiated upon switching from generating mode to pumping mode, the torque of a water turbine is gradually transmitted to the pump via the torque converter to increase the rotational speed, so that pump start-up devices (pony motors and thyristor start-up devices) that are required for the reversible PSH system become unnecessary. The following is an example of an operator that participates in balancing market by taking advantage of the switching speed of operation modes in the ternary system.

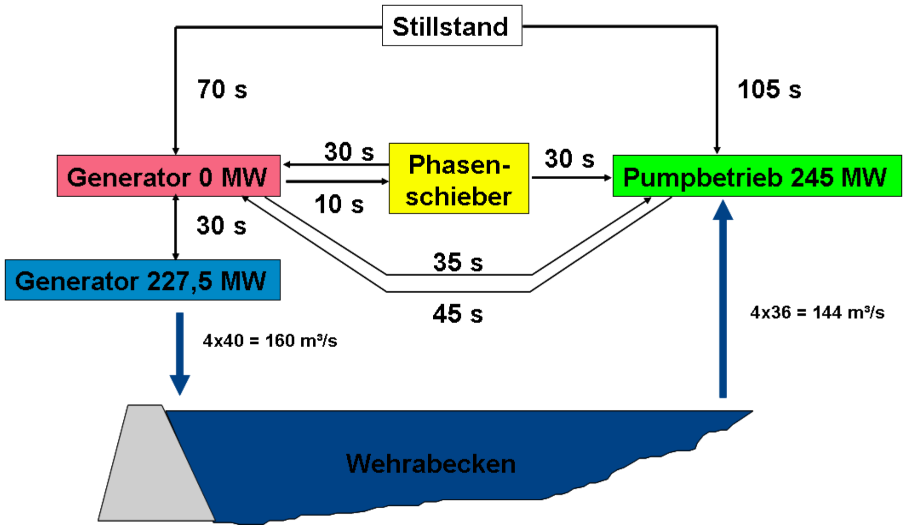
3.2.1 Wehr PSH plant in Germany

Wehr PSH plant in Germany, with an installed capacity of 910 MW (4 ternary units), is a plant which commenced in 1976, located near the border with Switzerland in southwestern Germany. Of the four units, two are owned by RWE and two by EnBW, and each of them are also operated under separate directives from two companies. In this plant, maintenance methods are devised to shorten the suspension period during inspection, such as conducting inspection by replacing the inlet valve with a spare part as well as separating a pump with a clutch during pump inspection to enable generating operation.

At Wehr PSH plant, a bid is flexibly made on the wholesale electricity market (day-ahead and intra-day) and balancing market (Figure 10), respectively, by taking advantage of the switching speed of the ternary system's operation mode (Figure 9). On the day-ahead market, pumping during times of low market prices, and generating during times of high market prices (orange frame in Figure 10). Moreover, in the intra-day market, in order to earn a profit from a large price difference with the day-ahead market price, generated in the case of a higher intra-day market price, and pumped in the case of a lower intra-day market price (purple frame in Figure 10). Furthermore, in the balancing market, even in the time when one unit is in pumping operation, another unit is made to stand by in generating operation with the partial load, and the balancing capability is provided by the instruction of the power system operator (green frame in Figure 10).

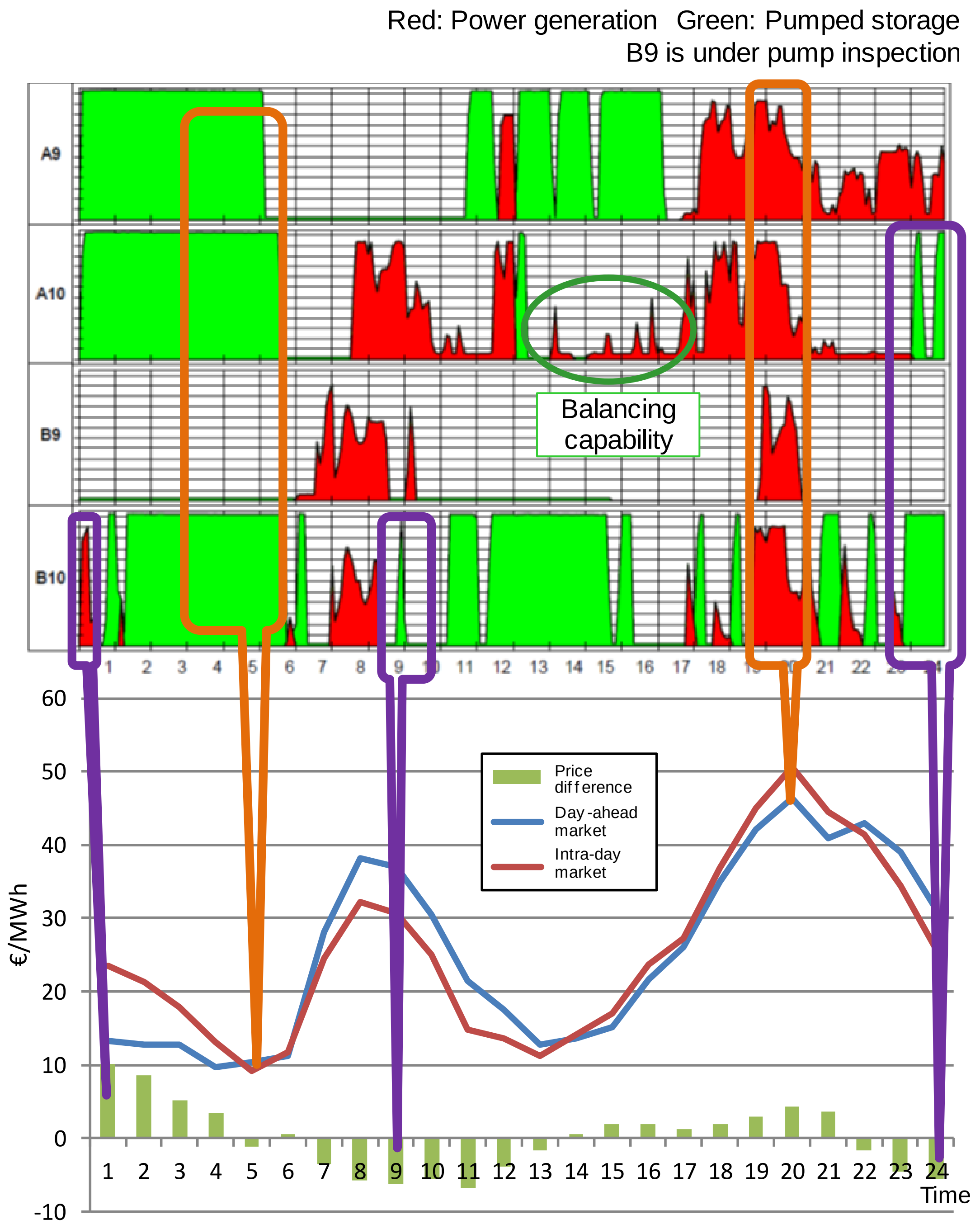
Unlike conventional operations, such as switching between generating mode and pumping mode many times a day, repeating frequent start/stop, and operating one unit for generating during the time when another unit is in pumping operation, are considered to bring an increase in mechanical stress. Moreover, since the revenue from the wholesale electricity market is also decreasing, the Wehr PSH plant is planning to introduce remote automatic supervisory using the SCADA system for efficient maintenance.

Figure 9. Operating mode switching of Wehr PSH plant



Source: Schluchseewerk

Figure 10. Wehr PSH plant operation

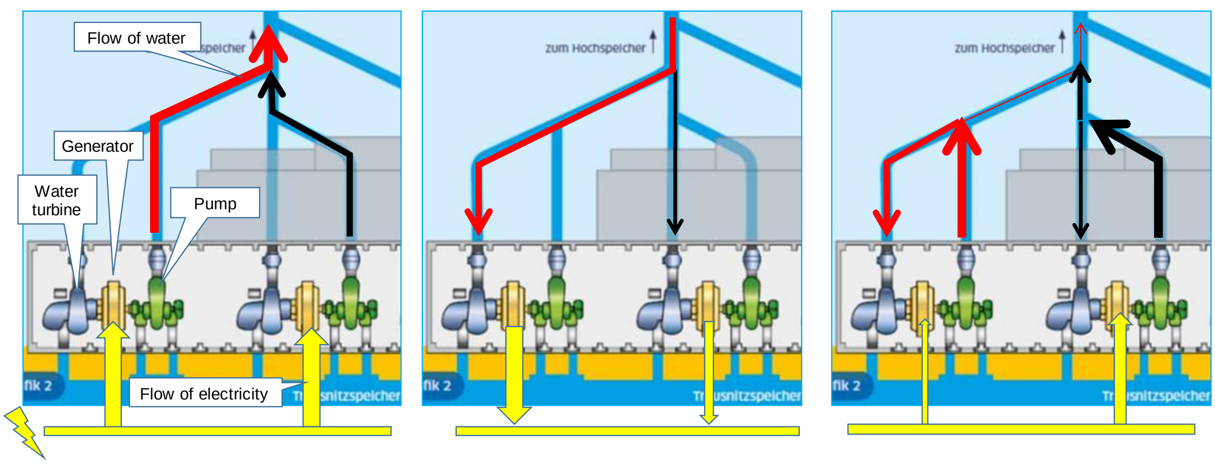


Source: Schluchseewerk

3.3 Hydraulic Short Circuit operation in ternary-type PSH

Since the ternary-type PSH is basically operated fixed-speed, it cannot adjust pumping power. However, it is possible by the HSC operation in which the pumping and generation operation are simultaneously performed in one unit. In the HSC operation, part of the water pumped up flows into the water turbine, so that electric power equivalent to the torque obtained by subtracting the torque of the water turbine from that of the pump is consumed in the generator/motor (Figure 11).

Figure 11. HSC operation of ternary-type PSH



(a) Conventional operation (pumped storage) | (b) Conventional operation (power generation) | (C) HSC operation

Source: Engie

As the pumping power can be adjusted by controlling the amount of inflow into the water turbine, the power control range is generally larger than variable-speed PSH. However, as the HSC operation uses not only a pump but also a water turbine, this causes water turbine losses and its efficiency is less than variable-speed pumping. The cases of Germany and Austria are described below.

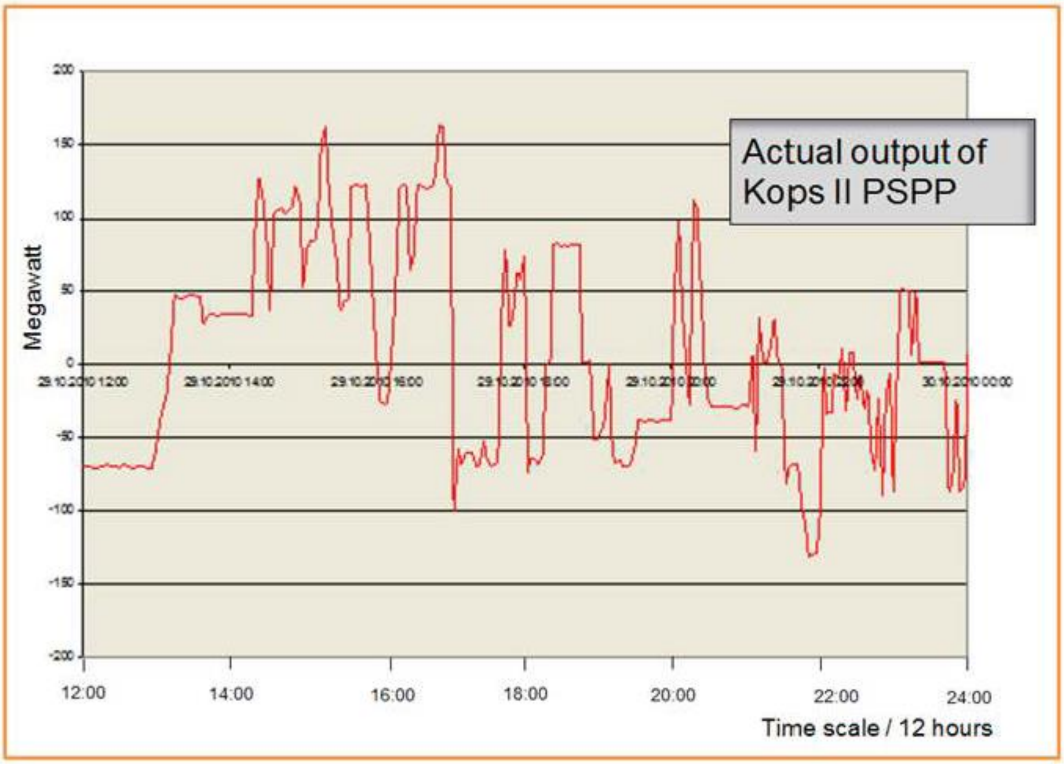
3.3.1 Reisach PSH plant in Germany

Reisach PSH plant in Germany, with an installed capacity of 106 MW (3 ternary units), commenced in 1955. HSC operation was not conducted conventionally, but with the aim of participating balancin market, the HSC operation was examined in 2015 by using Computational Fluid Dynamics (CFD) analysis, etc., confirmed the water flow at the point where penstock branch and reviewed the parameters of the governor system. It was determined that HSC operation was possible by using existing facilities, and the operation has been conducted since 2016. It should be noted that the balancing range per one unit is –26 to +6 MW, which is achieved through the combination of pump power (–27 MW) and water turbine output (+1 to +33 MW).

3.3.2 Kops II PSH plant in Austria

Kops II PSH plant in Austria, with an installed capacity of 525 MW (3 ternary units), was additionally constructed by using the existing dam of the Kops PSH plant and commenced in 2008. This plant mainly provides primary reserve through HSC operation. Generating and pumping mode are switched many times in a day, and control of generating and the pumping power is also frequently performed (Figure 12). The units are basically operated continuously without standstill in order to provide balancing capability at all times, and annual operating hours exceed 8,000 hours.

Figure 12. Operations of Kops II PSH plant



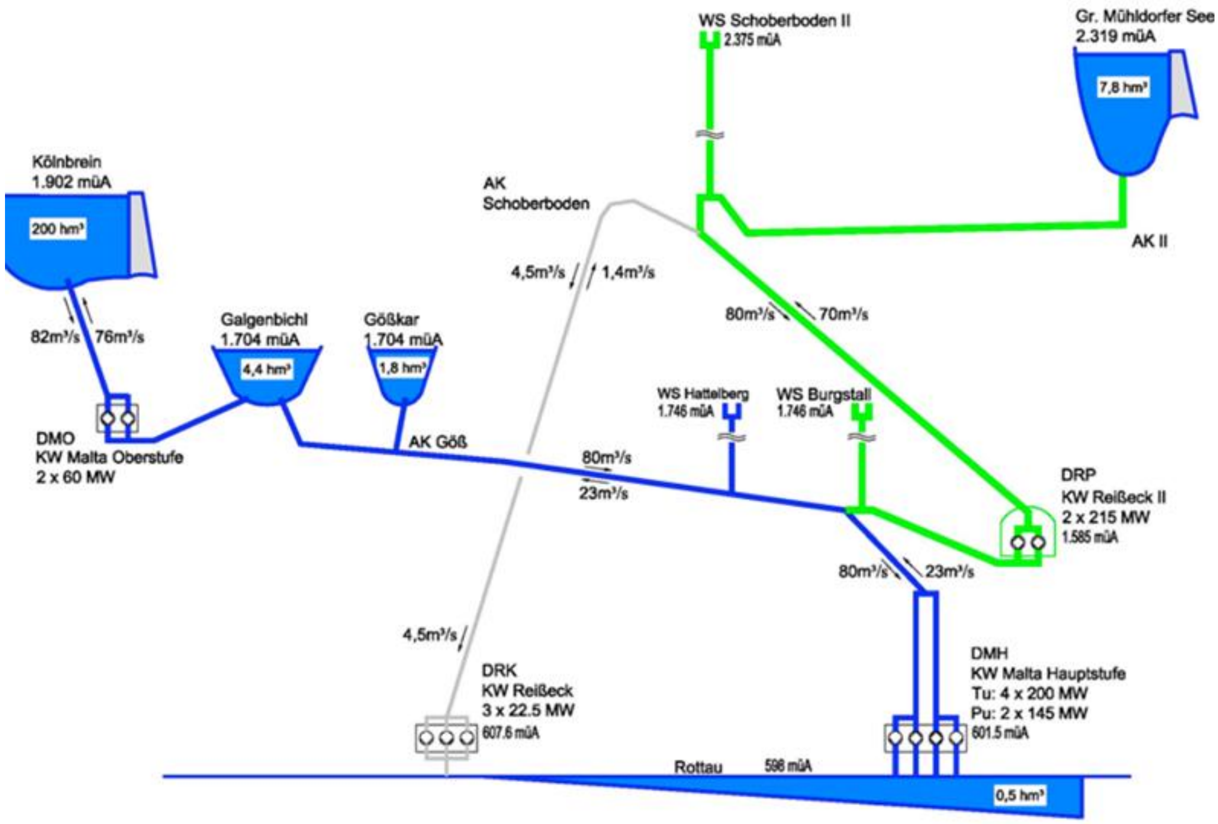
Source: Eurelectric, “Hydropower – supporting a power system in transition”

3.3.3 Malta Power Plant Group in Austria

Malta Power Plant Group in Austria, a cascade operation takes place at the Rottau PSH plant (installed capacity of 730 MW, with 2 ternary PSH units and 2 conventional hydropower units) which commenced in 1979, with the Reisseck II PSH plant (installed capacity of 430 MW, with 2 units of reversible and fixed-speed) which commenced in 2015 (Figure 13). The Reisseck II PSH plant uses the upper reservoir of the Reisseck PSH plant as well as part of the water channel of the plant, and was additionally constructed upstream of the Rottau PSH plant. The construction cost of the Reisseck II PSH plant is significantly reduced by leaving out the reservoir construction and adopting reversible, fixed-speed. A comparison of the Reisseck II PSH plant (reversible system) and the Rottau PSH plant (ternary system) shows that the reversible system has less equipment and can be made more compact in construction (Figure 14), although there is a difference in the commencement year, thus reducing both construction and maintenance costs.

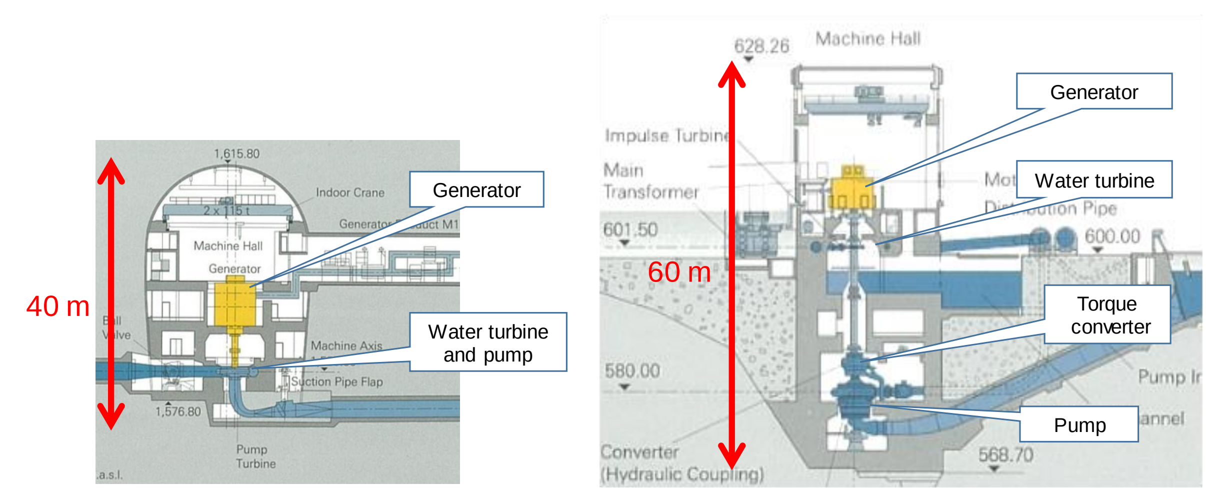
As described above, the fixed-speed unit cannot control pumping power; however, the additional construction of the Reisseck II PSH plant consequently increased the available amount of water at the Rottau PSH plant, which has excellent balancing capability for the HSC operation using a ternary system. As a result, the balancing capability of the power plant group has improved entirely.

Figure 13. Malta power plant group



Source: Documents from the HYDRO 2017 conference

Figure 14. Cross-sectional view of Reisseck PSH plant (reversible) and Rottau PSH plant (ternary)



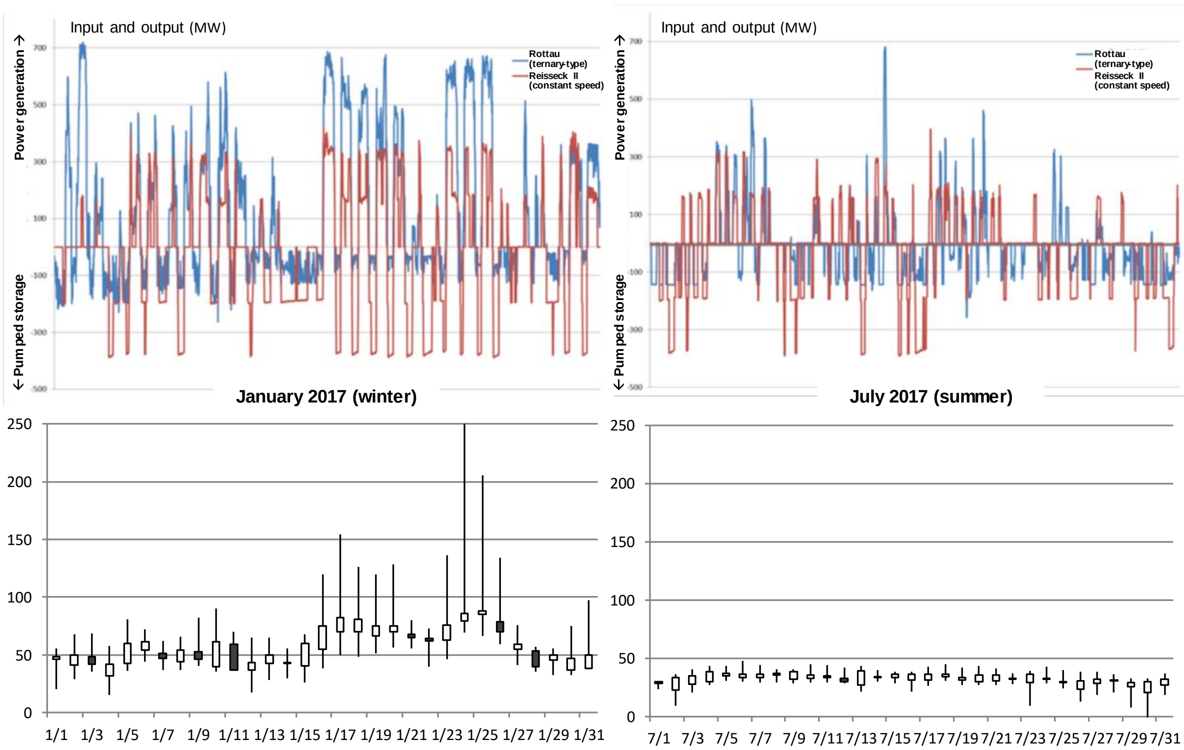
Reisseck II pumped-storage power plant
Reversible type: power generation of 215 MW, pumped storage of 215 MW

Rottau pumped-storage power plant
Ternary type: power generation of 180 MW, pumped storage of 145 MW

Source: Verbund

Malta power plant group participates in the wholesale electricity market and balancing market by combining the function of each power plant in the group, but their operation differs greatly in summer and winter. As the amount of solar power increases in summer, the volatility of wholesale electricity prices decreases as compared with winter. Therefore, transactions take place mainly in balancing market in summer and in wholesale electricity market in winter (Figure 15).

Figure 15. Operation pattern and wholesale electricity price of Malta power plant group for one month (winter and summer)



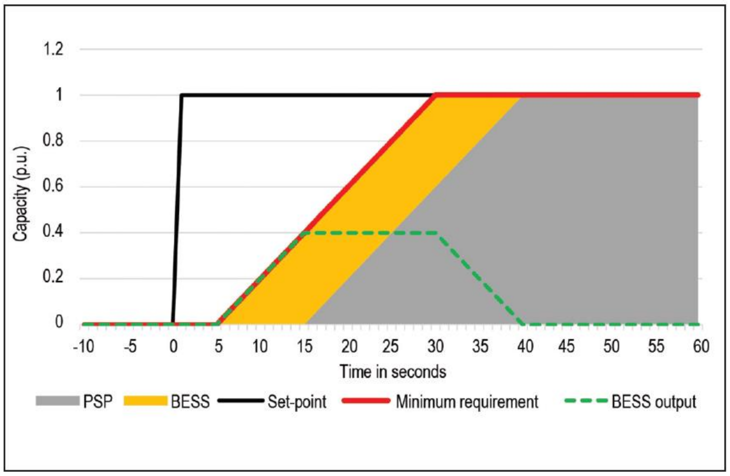
Source: Prepared based on documents from the HYDRO 2017 meeting

3.4 Hybrid operation of PSH and Battery Energy Storage System

BESS, smaller capacity but faster response compared with PSH, is suitable for providing primary reserve. Tanzmuhle PSH plant (installed capacity of 31 MW, with 1 ternary unit) in Germany has installed BESS (capacity of 13 MW/12.5 MWh) on its premises since 2018, and a verification test has been conducted combined with PSH.

It is necessary to secure in which the ΔkW can be provided whenever a bid has been successfully made as a primary reserve in balancing market. Although BESS have a limited capacity to be bid as balancing capability, the reserve capacity can be increased by charging and discharging through the power from PSH constructed alongside, and payment for transmission tariff will be unnecessary. Furthermore, in the provision of the primary reserve, the BESS output precedes the output of PSH, allowing a large amount of ΔkW to be provided seamlessly (Figure. 16).

Figure 16. Output of PSH combined with BESS



Source: Documents from the HYDRO 2017 conference

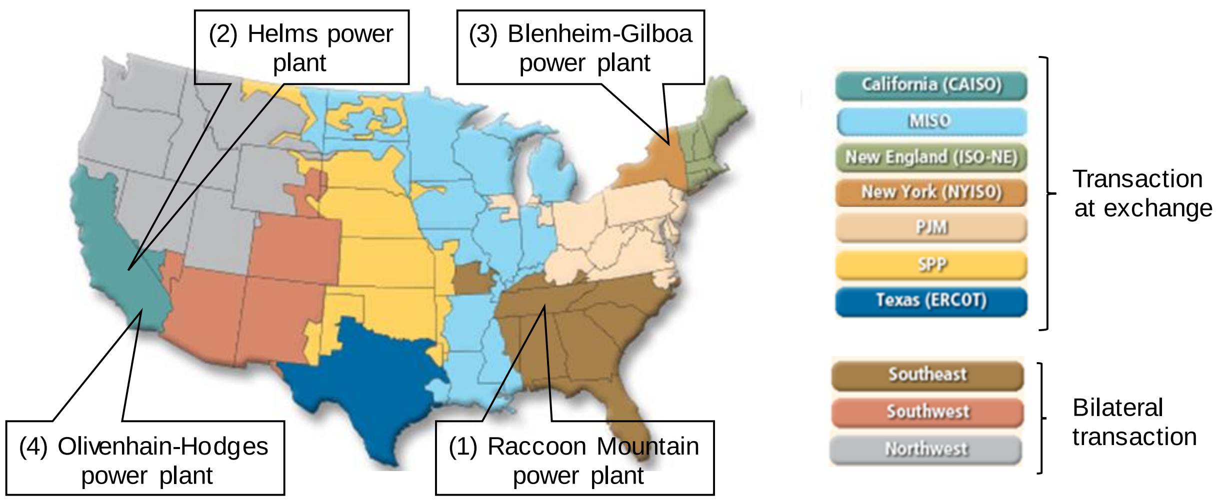
4. PSH Business in the United States

In the United States, many PSH plants were constructed between the 1960s and 1980s, with an installed capacity of about 23 GW, the third largest in the world after China and Japan. Although the liberalization of electricity market has been promoted from an early stage, the form of wholesale electricity transactions differs by region, and the integration of variable renewable energy such as solar and wind is not consistent, depending on the policy of each state. By focusing on the United States, where the business environment for PSH varies from region to region as seen above, its operational status will be explained here.

4.1 Form of wholesale electricity transactions and operation of PSH

Wholesale power transactions in the United States vary by region as they can be broadly divided into transactions conducted on an organized power exchange operated by independent system operators (ISO) and bilateral transactions conducted between operators (Figure 17). The form and operational status of wholesale electricity transactions are outlined below by covering the four PSH plants indicated in Figure 17.

Figure 17. Wholesale electricity transaction by region in the United States



Source: FERC, "Electric Power Markets: National Overview"

4.1.1 Bilateral transaction: Raccoon Mountain PSH plant

Raccoon Mountain PSH plant, with an installed capacity of 1,652 MW (4 units), is in Tennessee, which commenced in 1978. The plant is owned by the federal company, Tennessee Valley Authority (TVA), a vertically integrated electric utility that owns and operates hydro, thermal and nuclear power plants as well as transmission facilities. TVA belongs to the Southeast market that is based on bilateral transactions, and the wholesale electricity is basically sold to distribution and retail utility in its jurisdiction under the power purchase agreement (PPA) at regulated prices. It is also possible to indirectly participate in transactions at the exchange by selling electricity to electric utilities belonging to the adjacent markets such as PJM and MISO. However, TVA does not engage in transactions with other companies with regard to ancillary services such as frequency regulation and voltage regulation, and only utilizes the power plant for its own power system operations.

Operation of the Raccoon Mountain PSH plant is carried out by the economic dispatched by control center, and it mainly provides reserve during the peak demand period in the day-time. Pumping power is provided by surplus in night-time from TVA's nuclear power plants and inexpensive power from the neighboring PJM and MISO. Moreover, the company also provides ancillary services, including frequency and voltage regulation (reactive power control and condenser mode), in response to instructions from control center.

4.1.2 Transactions at exchange: Helms PSH plant

Helms PSH plant, with an installed capacity of 1,212 MW (3 units), is in California, which commenced in 1984. The owner of the power plant is PG&E, private utility that is responsible for electricity generation, transmission, distribution, and retail. CAISO, to which PG&E belongs, stipulates that all quantities should be supplied to the market in wholesale power transactions, requiring all power generated by PG&E and one procured through the PPA to be bid on the wholesale power exchanges. Therefore, all power plants cost must be recovered through wholesale power transactions in the market without some fixed costs, and pumping power sources must also be procured from wholesale power exchanges.

PSH plants are operated based on arbitrage transactions, whereby they procure electricity from the exchange and use it as a pumping power source during times with low demand for electricity and low wholesale electricity price, and generating electricity during times with high demand for electricity and high wholesale electricity price and supply electricity to the exchange, which consequently allowing to earn profits from the price difference. Moreover, the Helms PSH plant also provides frequency regulation and contingency reserve to the exchange as ancillary services, and approximately 70% of the plant's revenue comes from arbitrage transactions and 30% from the provision of ancillary services.

4.1.3 Transactions at exchange: Blenheim-Gilboa PSH plant

Blenheim-Gilboa PSH plant, with a capacity of 1,160 MW (4 units), is in New York State, commenced in 1973. This power plant is owned by the state company, New York Power Authority (NYPA), which has hydropower plants and transmission facilities. As the NYISO, to which the NYPA belongs, has no obligation to supply power to the market in wholesale power transactions, generating power is basically sold directly to large-scale consumers, etc., and surplus or deficit electricity is traded on the exchange.

As the main operation of the PSH plant is to balance the supply and demand, the plant provides the NYISO exchange with frequency regulation and contingency reserve as ancillary services. Ancillary services such as voltage regulation and black start are based on a bilateral contract, as transactions of such services on the market are not organized.

4.1.4 Bilateral transactions within the jurisdiction of an exchange: Olivenhain-Hodges PSH

Olivenhain-Hodges PSH plant, with an installed capacity of 40 MW (2 units), is in California, commenced in 2012. Although its capacity is small, it is the newest PSH plant in the United States, owned by the public utility, San Diego County Water Authority (SDCWA). The upper reservoir of this PSH plant plays an important role in supplying tap water in emergency, and PSH is required to be operated within a range that does not affect the operation of the tap water supply.

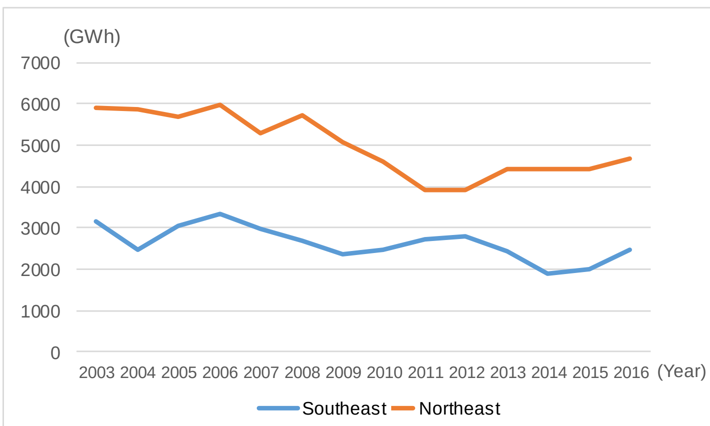
Although Olivenhain-Hodges PSH plant is located within the jurisdiction of the CAISO, the SDCWA does not trade directly at the exchange and has 25-year PPA contract with SDG&E, a private utility whose supply area includes the location of the power plant. Regarding operation of the power plant, the

SDCWA submits the operation plan for generating and pumping, which is prepared with consideration of water supply operation, to SDG&E by 6 a.m. of the previous day, and SDG&E submits bids to the CAISO exchange market based on this plan. In addition, the PPA contract does not permit bidding on real-time markets or ancillary services, and generating and pumping operations are limited to twice a day, respectively. This operational restriction appears to be a disadvantageous contract for SDG&E in a way that does not take full advantage of the balancing capability of PSH. However, the PPA contract also has advantages, as it allows for the obtainment of the supply capacity (with no assets), rather than through capital investment, in the electricity market where it is difficult to predict long-term profits.

4.2 Integration of variable renewable energy and operation of PSH

As mentioned above, in areas where wholesale power exchanges are located, PSH plants basically earn profits through arbitrage transactions. In the United States, there are significant differences in the operation and profitability of PSH, depending on the power supply mix and the state of integration of variable renewable energy in the region where an exchange is located. In particular, the amount of electric energy generated by PSH plants is decreasing remarkably in the northeastern United States (NYISO and PJM) compared with the southwestern United States (CAISO) (Figure 18). The following section outlines the PSH business by focusing on NYISO and CAISO.

Figure 18. Amount of PSH generation in the northeast and southwest of the United States

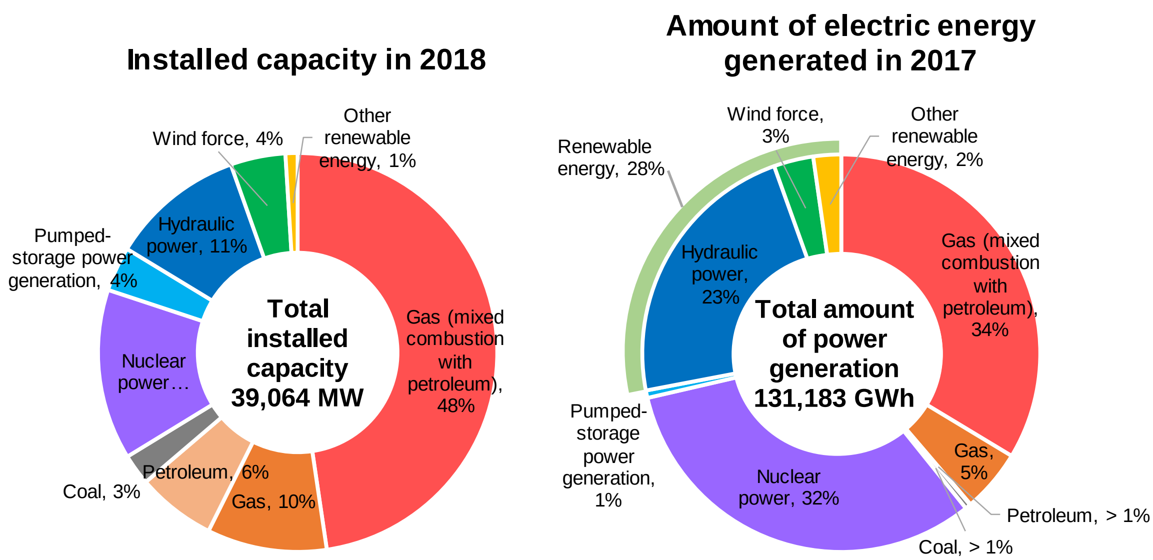


Source: “2018 Hydro Power Market Report”

4.2.1 PSH business within the jurisdiction of NYISO

Within the jurisdiction of NYISO, the installed capacity of gas-fired thermal power plants has increased since 2000, while coal-fired thermal power plants are being phased out. As a result, there is a power supply configuration in which base load power generated by nuclear and hydroelectric power plants is supported by the balancing capability generated by gas-fired thermal power plants (Figure 19).

Figure 19. Power supply mix within the jurisdiction of NYISO

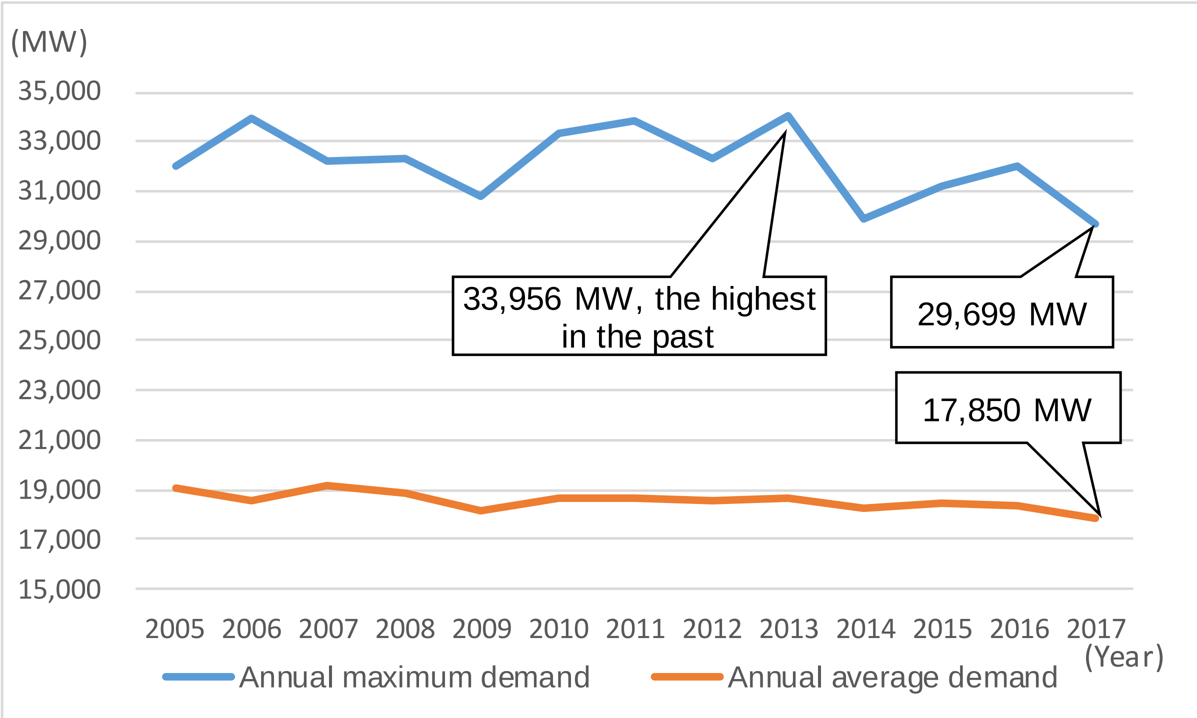


Source: NYISO, "2018 POWER TREND" report

On the demand side, New York State is one of the regions in the United States where industrial power consumption is low and commercial power consumption is high, with peak demand often generated by cooling demand in the daytime in summer; however, in recent years, both the annual average demand and the peak demand have been decreasing (Figure 20). This is due to the progress in integrating solar power to the demand side in addition to energy efficiency initiatives. In New York State, the net metering system and other support measures have led to a steady increase in the integration of solar power to the demand side (Figure 21). Since the solar power generation that increases during the daytime in summer with large amount of solar radiation matches the cooling demand, an increase in the installed capacity of solar power of the demand side contributes to a decrease in the demand for electricity. Such decline in the peak demand during the daytime lowers the volatility of wholesale electricity prices and reduces the profitability of PSH, which is pumping during the night and generating during the daytime. In general, it is said that the needs for reserve capacity such as PSH will increase as the variable renewable energy increases. However, the share of variable renewable energy is still about 5% on the basis of electricity supply mix, and the effect of variable renewable energy on the power system is marginal (Figure 19). Furthermore, since the amount of reserve to be procured at exchanges as an ancillary service is determined based on the maximum demand, an increase in variable renewable energy does not lead to an increase in procurement amount. In addition, the business environment for PSH is also harsh, because competitors, who supply reserve such as gas-fired thermal power, BESS and demand response, are increasing. Against this background, Blenheim-Gilboa PSH plant mentioned above has had a continuous budget deficit in recent years.

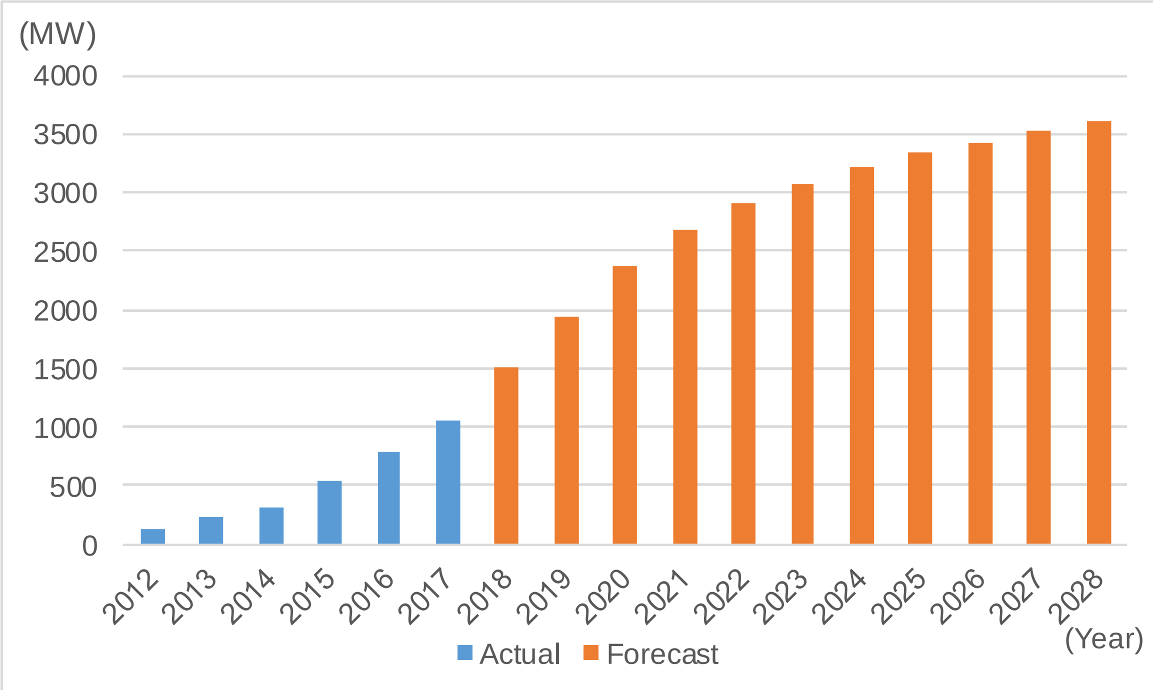
New York State has set a target of renewable portfolio standard (RPS) of 50% by 2030, and it is expected that variable renewable energy, mainly wind power, will increase in the future; therefore, how the PSH business will change is gaining attention.

Figure 20. Electricity demand within the jurisdiction of NYISO



Source: NYISO, "2018 POWER TREND" report

Figure 21. Integration of solar power on demand side within the jurisdiction of NYISO (actual and forecast)

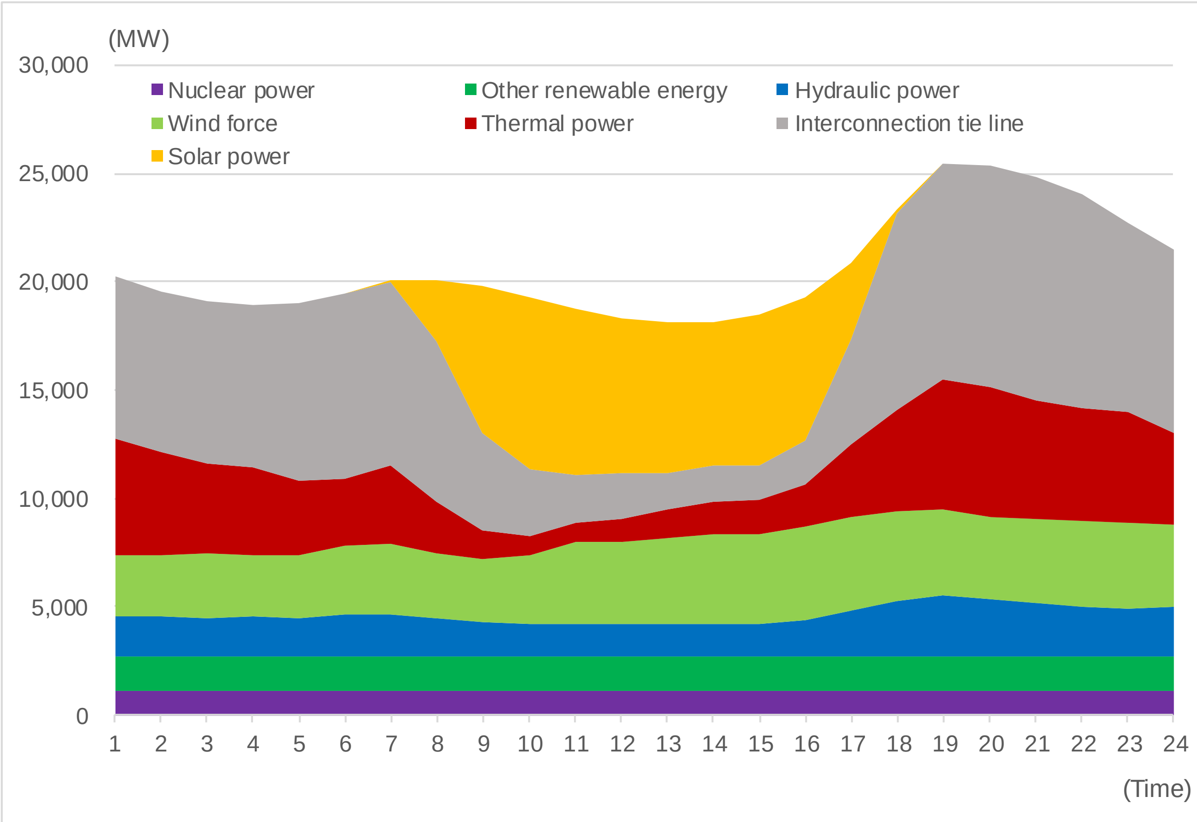


Source: NYISO, "2018 POWER TREND" report

4.2.2 PSH business within the jurisdiction of CAISO

Within the jurisdiction of CAISO, the integration of solar power has rapidly progressed since around 2012, and as of 2018, the capacity of large-scale solar power facilities operated by utilities was approximately 12 GW, accounting for approximately 17% of the total power installed capacity in CAISO. In addition, support measures such as net metering have resulted in the integration of approximately 6 GW of household solar power generation. As a result, a so-called duck curve phenomenon, in which demand during the daytime declines due to household solar power generation, has been advancing, and solar power generation by utilities may account for nearly 40% of demand at times (Figure 22).

Figure 22. Daily load curve of CAISO (February 18, 2018)

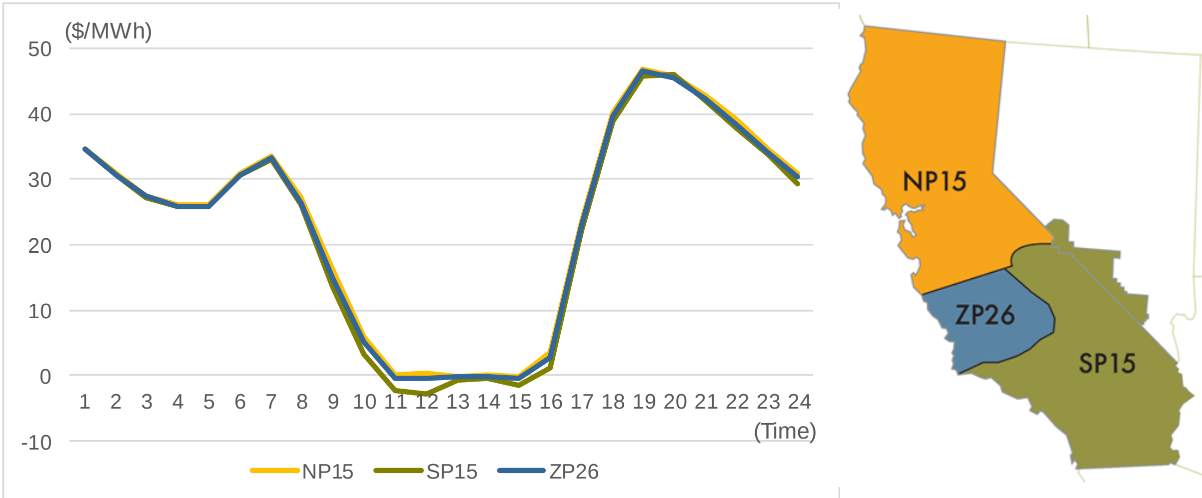


Note: Solar power does not include solar power of the consumer side (amount of solar power generation by customers is a decrease in demand).

Source: CAISO website

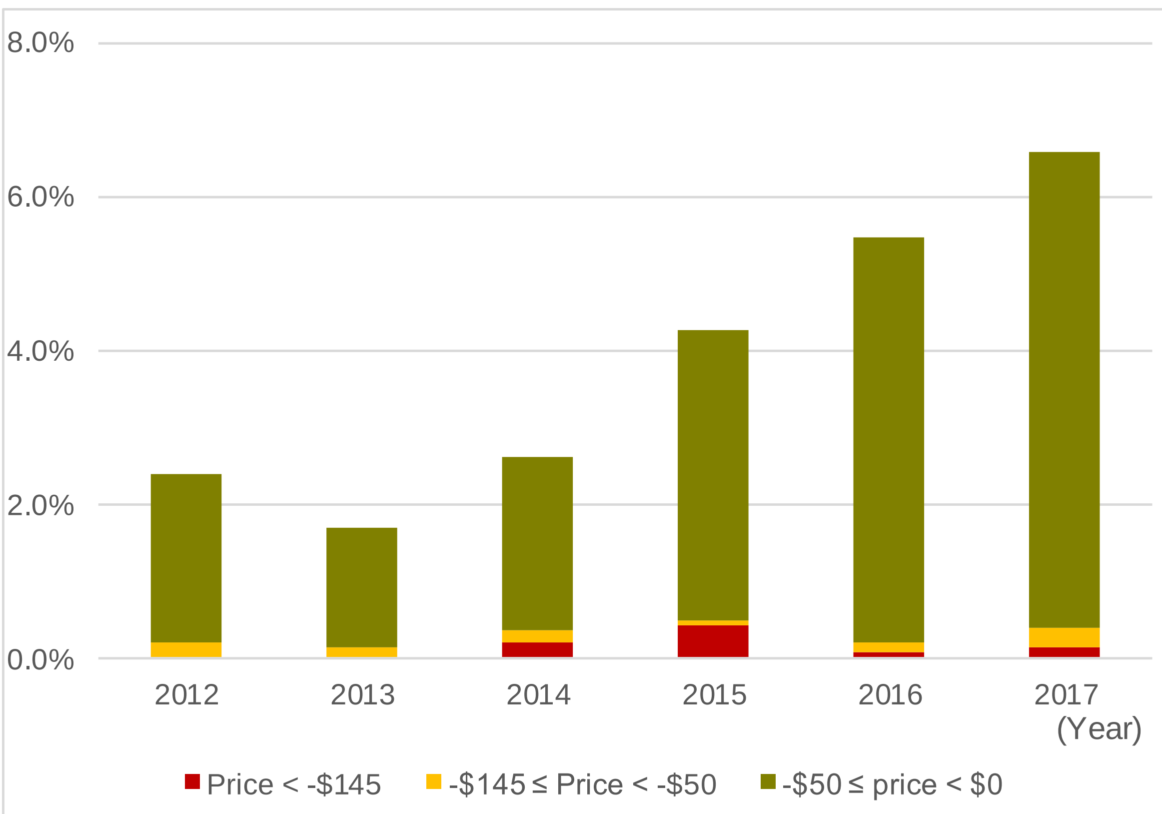
In the United States, variable renewable energy such as solar and wind power are subject to the Production Tax Credit (PTC) and the Renewable Energy Certificate (REC). Since these are schemes that provide incentives according to the amount of electricity generation, the full amount of renewable energy is contracted even if the wholesale electricity price is low. Therefore, the wholesale electricity price drops significantly in the daytime when solar power increases, which may result in a negative price (Figure 23), and the frequency of negative price occurrence increases year by year (Figure 24). A negative price indicates a surplus of electricity, which then requires curtailment of variable renewable energy or electricity storage. For PSH, a negative price refers to a situation where PSH can be profitable, but the California Public Utilities Commission (CPUC) recognizes that the situation itself, in which generated power even paying, is distorted and is proceeding with examination for improvement of the situation.

Figure 23. Wholesale electricity price in CAISO (February 18, 2018)



Source: CAISO OASIS (Open Access Same-time Information System)

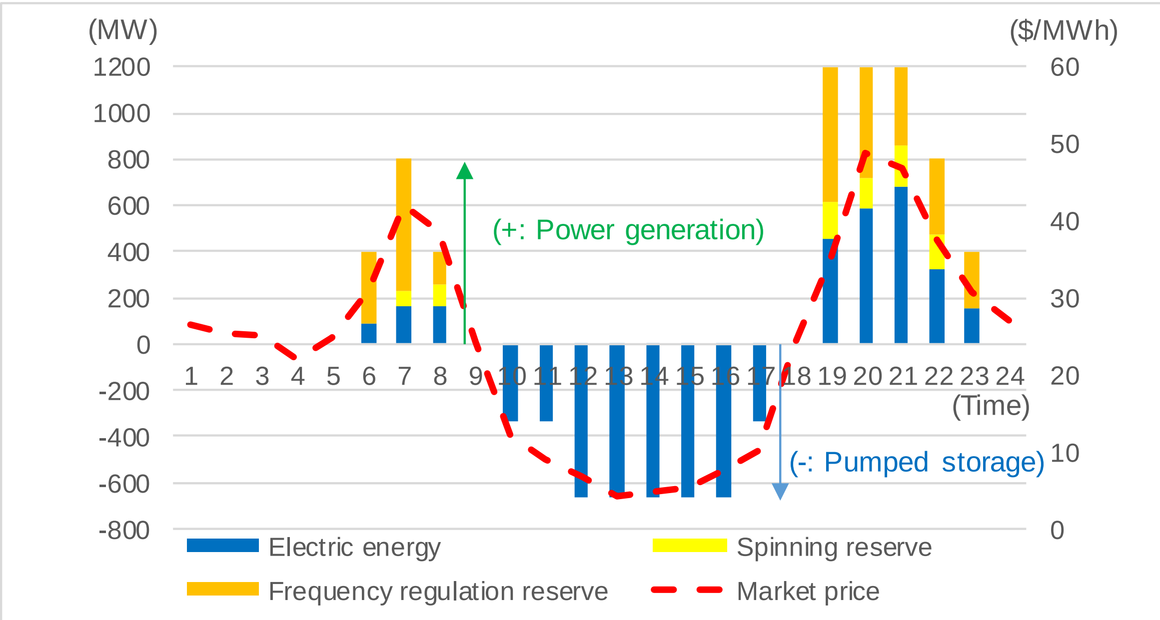
Figure 24. Frequency of negative price occurrence in the CAISO



Source: CAISO, "2017 Annual Report on Market Issues & Performance"

Helms PSH plant trades all of its generating and pumping power in the wholesale electricity market, and operates in a pattern whereby pumping during the daytime when wholesale electricity prices decrease and generating during peak hours in the morning and evening when wholesale electricity prices increase (Figure 25). Other than the above, the power plant also provides the market with frequency regulation reserve and spinning reserve as ancillary services during power generation.

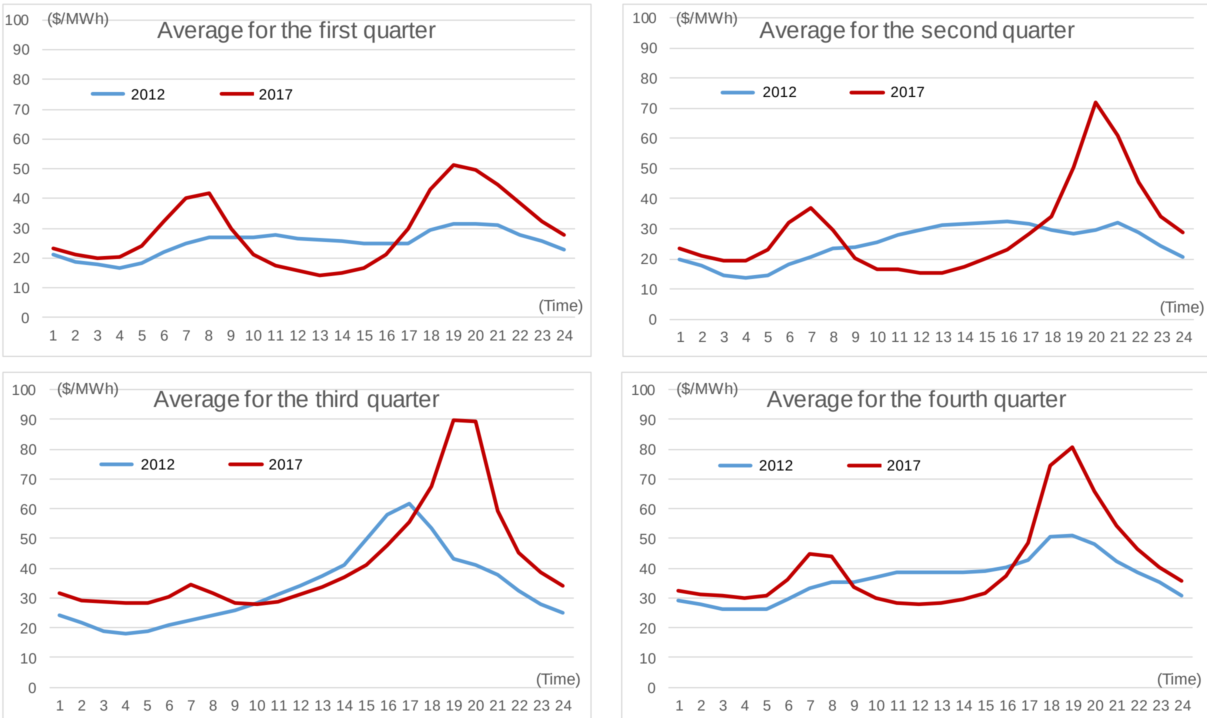
Figure 25. Operation pattern of Helms PSH plant



Source: PG&E

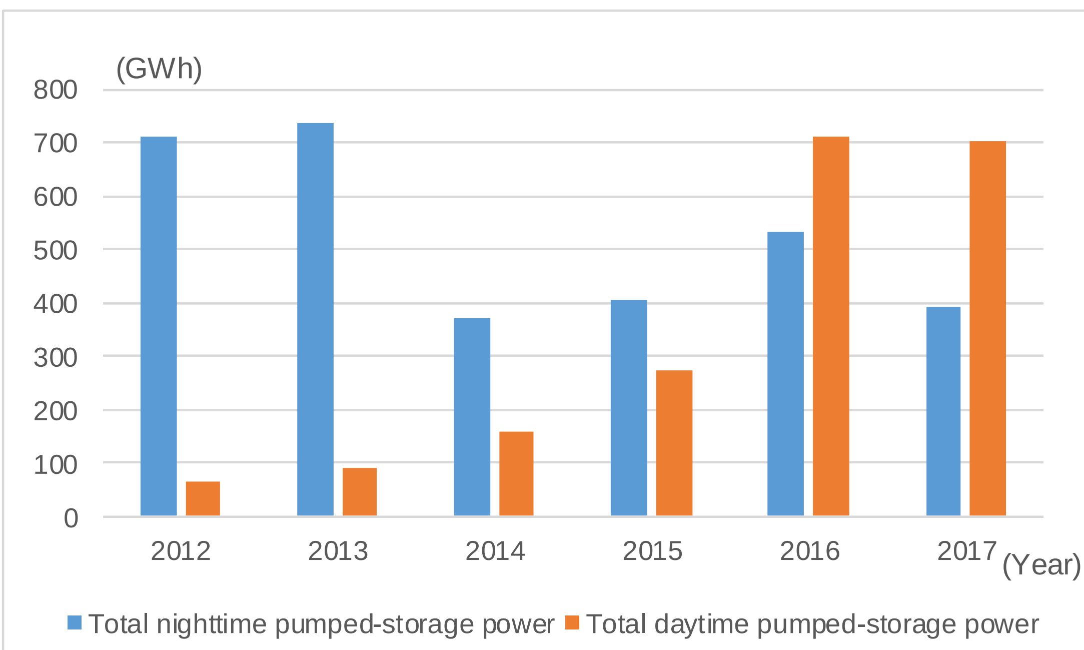
As described above, the duck curve phenomenon has advanced within CAISO, and it conventionally occurred only in the spring when demand was low and solar radiation was high. However, it can be seen throughout the year now (Figure 26), and the operation pattern whereby pumping in the daytime has become ordinary. Pumping operation of Helms PSH plant during the daytime had increased by about 10 times from 2012 to 2017 (Figure 27). Wholesale electricity prices during peak hours are on an upward trend, and as the difference between wholesale electricity prices during the daytime and peak hours is becoming large (Figure 26), it is considered that the profitability of arbitrage transactions for PSH has improved, leading to increased opportunities for the operation of PSH.

Figure 26. Wholesale electricity market price within CAISO
(comparison of 2012 and 2017)



Source: CAISO "Report on Market Issues & Performance"

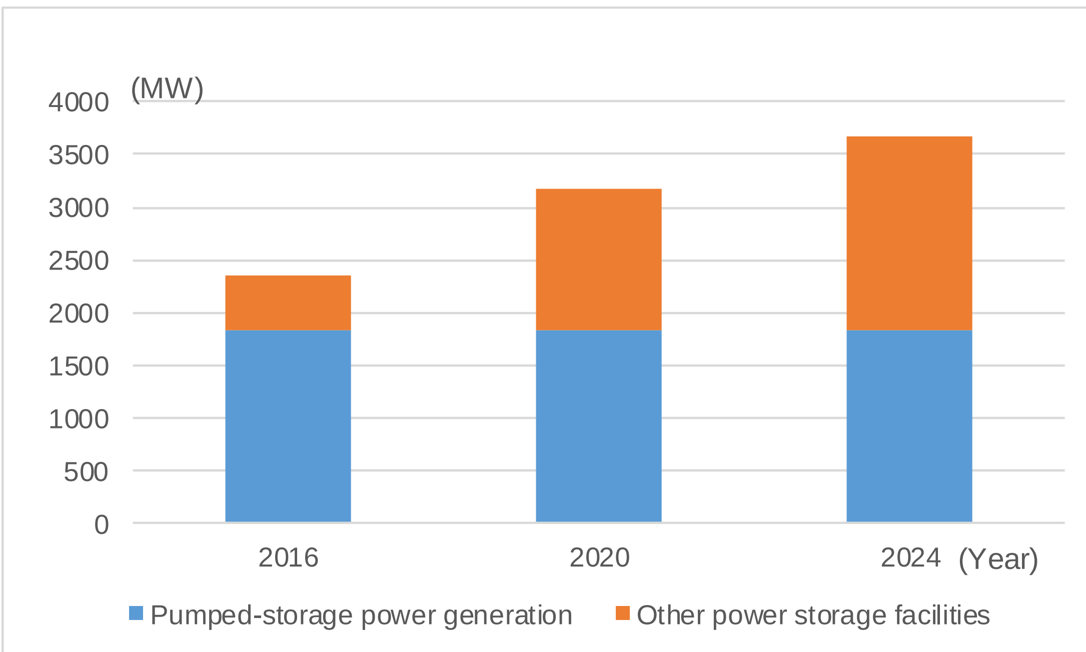
Figure 27. Pumped-storage power during nighttime and daytime at the Helms PSH plant



Source: PG&E

As mentioned above, needs for electricity storage have been emerging within CAISO for integrating a large amount of variable renewable energy, but there is no plan to develop a new PSH plant in California. By contrast, the integration of BESS is being promoted under a state law enforced in 2013 (AB 2514) and one enforced in 2016 (AB 2868). AB 2514 mandates the three major private utilities (PG&E, SCE, SDG&E) in the state to procure by 2020 a total of 1,325 MW of power storage facilities, while AB 2868 additionally mandates a total of 500 MW of distributed power storage facilities. Under AB 2514, PSH as well as BESS and flywheels are covered as power storage facilities, but as a measure to promote the introduction of new technology, large-scale PSH (over 50 MW) is excluded. According to these laws, the three major private utilities had installed approximately 500 MW of power storage facilities by 2016, and their capacity is expected to increase to 1,700 MW by 2024, which is about the same level as PSH facilities (Figure 28).

Figure 28. Power storage facilities of three major private utilities in California



Source: CPUC

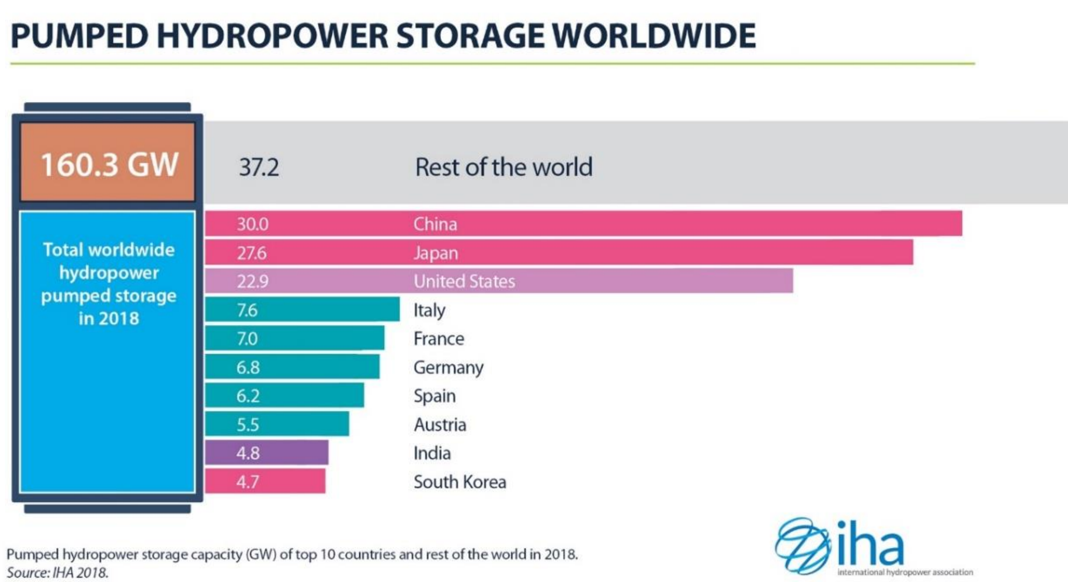
Because BESS are excellent in power control, the utilities also provide ancillary services such as frequency regulation reserve. Within CAISO, the secured reserve for frequency regulation is about 400 MW, has already been satisfied only by BESS. In addition, the capacity mechanism of CAISO (Resource Adequacy) stipulates a requirement of a continuous output time of four hours to meet the peak demand in the evening, which is an issue in the duck curve, and large-scale BESS within CAISO meet this requirement. Furthermore, the CAISO does not impose transmission charge for power used to charge BESS, while it imposes for pumping of PSH.

As described above, within CAISO, it is easy for PSH plants to make profits along with the large-scale integration of variable renewable energy, but the competition is expected to be severe in the future, since there is also a system advantageous for BESS that play a similar role.

5. PSH Development

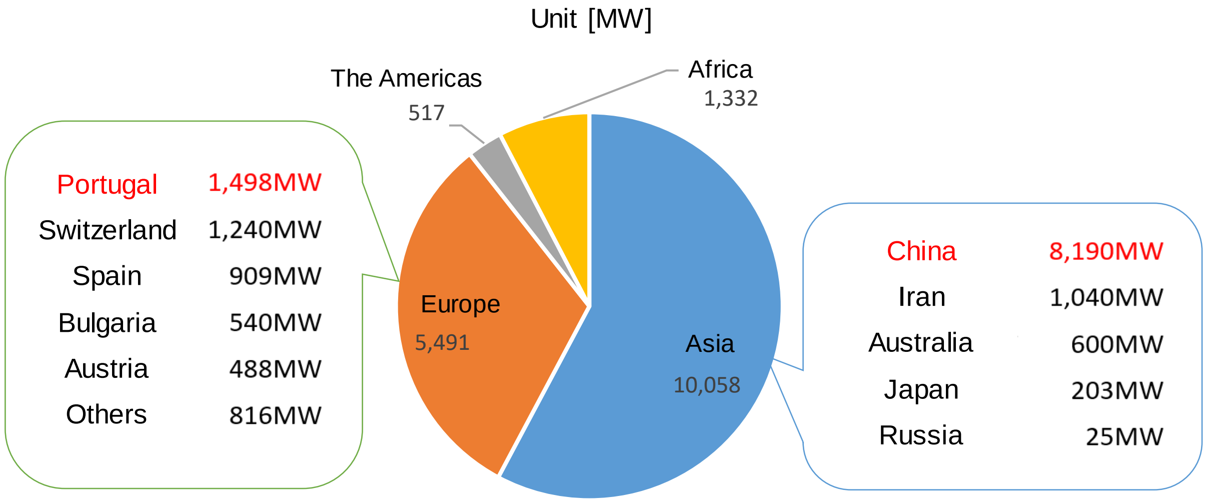
As of 2018, PSH plants with a total capacity of approximately 160 GW were in operation worldwide. China, Japan and the United States account for about half of the total, followed by European countries (Figure 29). Many of these plants were constructed before the liberalization of electricity market, and their concept is pumping surplus power from base load supply such as nuclear and coal-fired thermal power during low-demand hours at night and generating during peak hours in the daytime. In recent years, the integration of variable renewable energy has been advancing, and opportunities for the use of PSH have increased to absorb its fluctuations. However, in the liberalized electricity market, it is difficult to forecast long-term profitability obtained from arbitrage transactions in the wholesale electricity market and through the provision of balancing capability in balancing market, and the situation for the development of new PSH remains severe, as it requires considerable construction costs and time. Against this background, approximately 17 GW of PSH plants have started operations worldwide in the recent 5 years (2014 to 2018), and the development in Asia and Europe account for most of them (Figure 30). In Asia, China has the largest share of development, driven by a national development plan, and plans to increase the installed capacity of PSH to 100 GW by 2025. In Europe, Portugal established the PNBEPH in 2007 with the aim of increasing its energy self-sufficiency ratio, and set a target of increasing the installed capacity of hydropower from 5 GW to 7 GW by 2020. Moreover, in Portugal, since the integration of wind power, variable renewable energy, was underway, the development of PSH advanced with the expectation that it would provide power storage and balancing capability. The following is an overview of the development process in consideration of market design and other factors by focusing on Portugal, where the largest capacity of PSH were developed in recent years among countries in Europe and the United States in which the electric power market was liberalized from early on.

Figure 29. PSH installed capacity in the world (2018)



Source: iha

Figure 30. Development of PSH over the most recent five years (2014 to 2018)



Source: Prepared based on data of iha

Liberalization in Europe began with the first EU Power Directive in 1996, the privatization, unbundling, and electricity market development were sequentially carried out in Portugal as well. EDP, a vertically integrated national utility, was formerly in charge of the electric power business, but its transmission division was unbundled in 1994, which led to the establishment of REN, transmission system operator that became an independent system operator by the separation of ownership in 2000. In addition, the Portuguese government began selling EDP shares in 1997, and the privatization was completed in 2013. In 2007, balancing market operated by REN was also established, in addition to MIBEL, common wholesale electricity market with neighboring country Spain. Against this liberalization, Portugal also introduced a system to support investment in conventional power plants (Figure 31).

First, a PPA system called CAE came into force in 1995, and a long-term purchase agreement was signed between EDP and REN for all existing power plants (hydropower and thermal power, including those under construction) until the end of their licenses. However, in response to the second EU Power Directive in 2003, the abolition of CAE was requested in order to fully liberalize retailing, and a system called CMCE was introduced in 2004 as a compensation system alternative to the CAE. CMCE is a system that compensates for the difference between the contract price of CAE and the wholesale electricity market price in the case of lower market price, and it has been in effect in place of CAE since 2007 when the wholesale electricity market MIBEL was established. CAE and CMCE are support systems for investment in the transition period of electric power liberalization, and these are power sources developed before 2000.

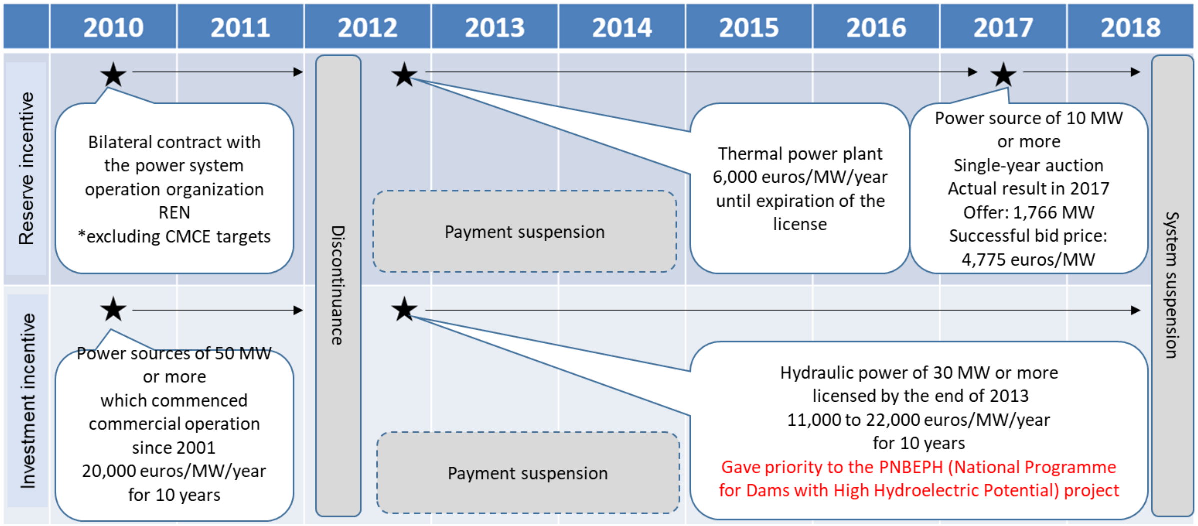
By contrast, in order to secure reserve capacity after the liberalization, the introduction of a capacity payment system was decided to be introduced in 2007, the same year as the market establishment. Capacity payment is divided into reserve incentive and investment incentive. Reserve incentive is a mechanism such that the necessary balancing capability is secured by the system operator REN from the existing power sources, whereas the investment incentive is a mechanism to secure the long-term supply capacity based on the energy policy (Figure 32). First of all, with respect to the implementation of the system in 2010, a fixed amount was determined to be paid for 10 years, covering the following for each type of incentive: a bilateral contract with the system operator REN as the reserve incentive; and new development projects, as well as conventional power plants (hydropower and thermal power) of 50 MW or more which commenced within the previous 10 years (from 2001 onward), as the investment incentive. Subsequently, the Portuguese government faced a financial crisis in 2011, and capacity payment was temporarily abolished in May 2012 as part of its economic reforms; however, it was decided that it would be resumed in August of the same year on a reduced scale. The reserve incentive was to guarantee the maintenance of thermal power plants that were operated infrequently, and with regard to the investment incentive, a fixed amount was to be paid for each facility, covering the hydropower plants that were licensed by the end of 2013 (Figure 33). This is to prioritize the development of hydropower in line with the PNBEPH established in 2007. Payment for capacity payment was suspended between 2012 and 2014 for the purpose of financial recovery. In addition, the system was changed in 2017 to one in which the reserve incentive is collected through auction every year, and it was determined in 2018 that the reserve capacity was sufficient based on the analysis by the system operator REN; therefore, capacity payment was been suspended thereafter, including both the reserve incentive and investment incentive applied in the past, and resumption has not been determined yet.

Figure 31. Electric power liberalization and investment support system in Portugal

Year	Progress of liberalization	Investment support system
up to 1994	Vertically integrated management by the state-run EDP	
1994	Establishment of power transmission company (REN)	
1995		Implementation of CAE (PPA system)
1996	First EU Power Directive	
1997	Listing of EDP shares	
2000	REN became independent as a power system operation organization	
2003	Second EU Power Directive	
2004		Decided to discontinue CAE and introduce CMCE (compensation system)
2007	Establishment of wholesale electricity market and supply–demand adjustment market	Decided to implement CMCE and introduce capacity payment
2010		Capacity payment implemented
2012		Capacity payment once discontinued and resumed with reduced compensation amount (payments stopped from 2012 to 2014)
2013	Government's sale of EDP shares completed	
2017		Capacity payment modified
2018		Capacity payment suspended

Source: Prepared based on each website

Figure 32. Overview of capacity payment



Source: Prepared based on each website

Figure 33. Overview of investment incentives in capacity payment (2012)

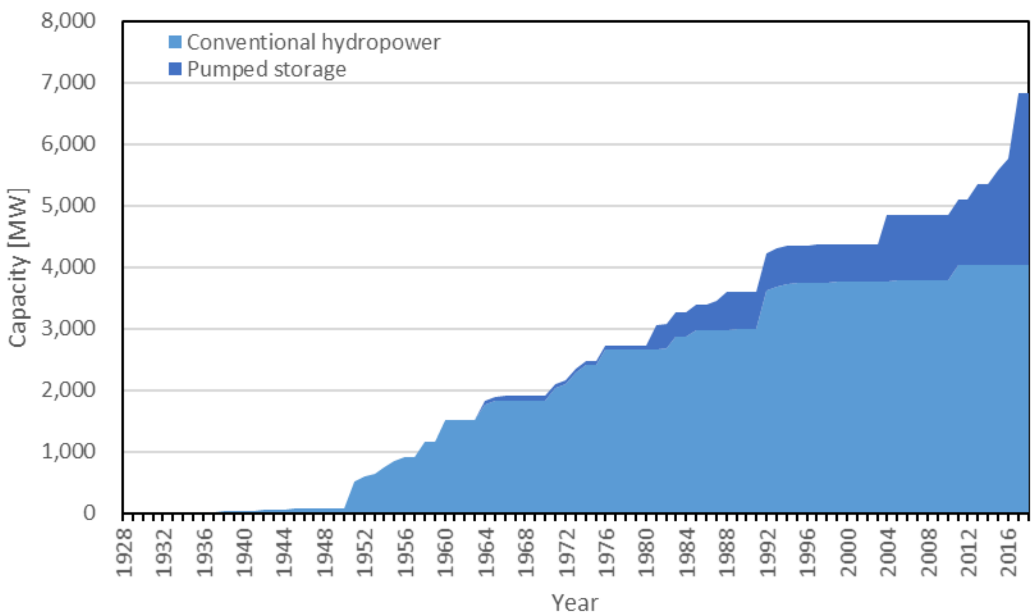
Power supply type	Power plant	Capacity	Amount of money (MW per year)	Commencement year of commercial operation	Business operator	Remarks
River pumped-storage scheme	Baixo Sabor	190 MW	22,000 euros	2016	EDP	
Reservoir type	Ribeiradio	147 MW	22,000 euros	2015	EDP	
River pumped-storage scheme	Foz Tua	270 MW	13,000 euros	2017	EDP	
River pumped-storage scheme	Girabolhos Bogueira	360 MW	13,000 euros 13,000 euros	Construction suspended *1	Endesa	
Reservoir type	Alto Tâmega	160 MW	11,000 euros	Planned in 2023	Iberdrola	
River pumped-storage scheme	Gouvães	880 MW	11,000 euros	Planned in 2021	Iberdrola	
Reservoir type	Daivões	118 MW	11,000 euros	Planned in 2021	Iberdrola	
River pumped-storage scheme	Fridão	256 MW	11,000 euros	Construction suspended *2	EDP	
River pumped-storage scheme	Alvito	136 MW	11,000 euros	Construction suspended *1	EDP	
River pumped-storage scheme	Alqueva II	256 MW	11,000 euros	2012	EDP	Add to existing plant
River pumped-storage scheme	Frades II	780 MW	11,000 euros	2017	EDP	Add to existing plant
River pumped-storage scheme	Salamonde II	224 MW	11,000 euros	2015	EDP	Add to existing plant

*(1) Construction suspended in April 2016 on the basis of environmental assessment process
*(2) Construction suspended in April 2019 on the basis of environmental assessment process

Source: Prepared based on 2012 Ordinance No. 251

The installed capacity of PSH in Portugal accounted for about 40% of installed capacity of hydropower as of 2018, has increased significantly in recent years compared with that of conventional hydropower and has doubled in the past 5 years in particular (Figure 34 and Figure 35). This was due to promotion of the development under the PNBEPH initiative, along with support from the investment incentives in capacity payment. In addition, since the developed PSH plants were open-loop PSH plants and have the aspect of conventional hydropower plants, it is not necessary to forecast long-term earning profits that strictly considers pumping losses and arbitrage transactions, and the fact that construction costs were reduced due to many projects of constructing additional facilities to the existing PSH plants is also considered to have contributed to the development.

Figure 34. Hydropower development in Portugal



Source: Based on REN data

Figure 35. List of PSH plants in Portugal (including under construction)

Power plant	Capacity [MW]	Commencement year of commercial operation	Business operator	Remarks
Alto Rabagão	68	1964	EDP	
Vilarinho das Furnas	125	1972	EDP	
Aguieira	336	1981	EDP	
Torrão	140	1988	EDP	
Alqueva I	260	2003	EDP	
Frades I (Venda Nova II)	192	2005	EDP	Add to existing plant
Alqueva II	256	2012	EDP	Add to existing plant *1
Salamonde II	224	2015	EDP	Add to existing plant *1
Baixo Sabor (including Feiticeiro)	190	2016	EDP	*1, *2
Foz Tua	270	2017	EDP	*1, *2
Frades II (Venda Nova III)	780	2017	EDP	Add to existing plant *1
Gouvães	880	Planned in 2021	Iberdrola	*1

*1 Subject to investment incentives in capacity payment
*2 To be sold to Engie by the end of 2020

Source: Prepared based on each website

6. VRE Integration and the Role of PSH in Japan

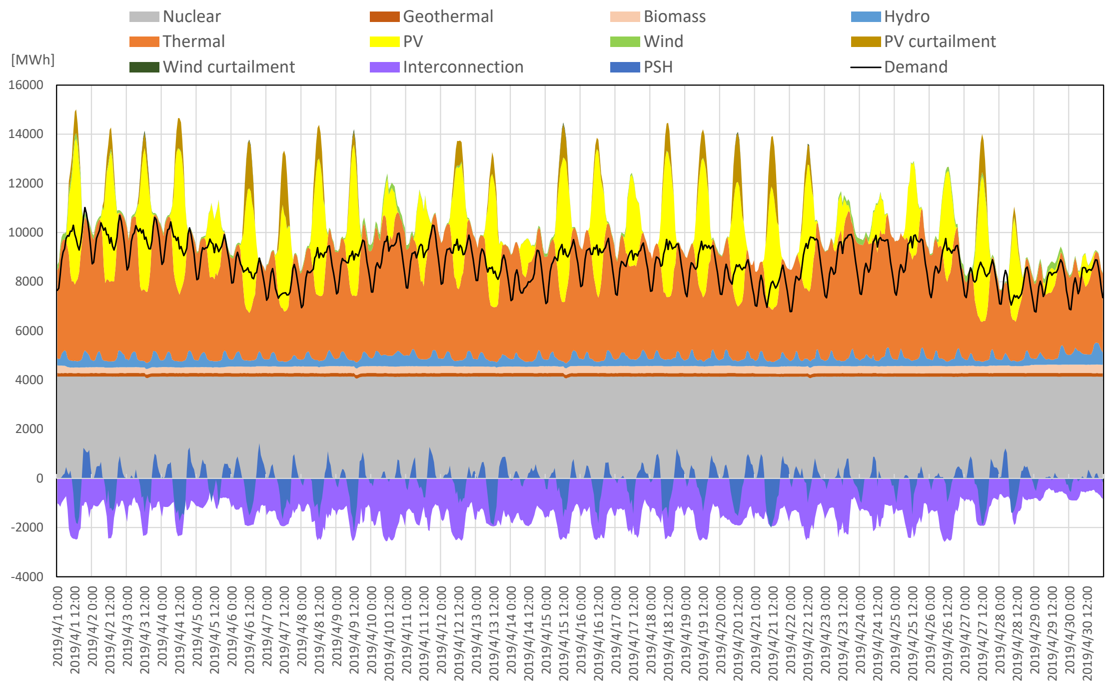
Japan has been experiencing rapid deployment of solar PV, since a Feed-in Tariff program was launched in 2012. Kyushu, the southernmost island among the main islands of Japan, has been the most significantly affected area in terms of solar PV penetration. According to the IEA definition (IEA 2018), Kyushu is regarded to be in Phase 3 of VRE integration (i.e. VRE generation determines the operation pattern of the system) due to limited interconnection capacity. To keep the balance between supply and demand in case of VRE generation surplus, all transmission system operators in Japan have launched the so-called “Priority dispatching rule” as of 2016. The priority dispatching rule determines in what order power generation is dispatched down, or curtailed, in order to balance supply and demand. The rule consists of the following steps:

(1) Curtailment of fossil-fired power generation (coal, oil, and gas) and absorption of surplus VRE generation by pumping in PSH plants
(2) Export of VRE generation surplus to other areas through interconnection
(3) Curtailment of biomass power generation
(4) Curtailment of VRE generation (PV and wind)
(5) Curtailment of nuclear, geothermal and hydropower generation

In Kyushu, PSH plants have been operated following the rule to avoid curtailment of VRE generation, especially in light-load seasons (spring and autumn); pumping during day-time to absorb surplus VRE generation, and generating in the evening to provide electricity for corresponding demand. This includes variable speed PSH units, which are more flexible than conventional fixed-speed PSH plants and therefore particularly suitable for VRE integration. Figure 36 shows supply and demand in Kyushu, including pumping and generation from PSH, for a month with light loads in 2019.

Since the TSO needs to secure an effective reservoir capacity for the next day-time period, PSH plants are required to generate during night-time regardless of electricity price. This situation threatens the optimal arbitrage opportunity and disrupt the maintenance schedules of PSH plants. Overall, PSH plants have played a crucial role in the power system by accommodating higher levels of VRE, and hence, it is important that these resources are remunerated and maintained appropriately.

Figure 36. Electricity supply and demand in light-load season, April 2019, Kyushu



Source: Kyushu Electric Power Transmission and Distribution

7. Conclusion

PSH has been playing an important to absorb surplus power from conventional baseload supply and variable renewable energy such as solar and wind, reduce supply and demand imbalance. This role for variable renewable energy also contribute to worldwide carbon neutrality. By contrast, revenue from PSH operation is required to earn through arbitrage transactions in the wholesale electricity market and from the provision of balancing capability in balancing market. PSH is likely to be profitable in regions, such as California in the United States, where a large amount of variable renewable energy has already been integrated. However, in regions where the integration of variable renewable energy has not yet advanced in spite of setting a goal of increasing variable renewable energy in the future, the operation of PSH may be in the red. For this reason, severe management conditions are expected until the point where the role of power storage becomes needed in the future. In order to maintain PSH against this background, it is necessary not only to entrust its operation to utilities, for purpose of minimizing social cost between utilities, system operators and consumers, but also to appropriately evaluate the potential of future power storage through forecasting power supply mix and power system planning, and to design a system that covers construction and maintenance costs.

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9. List of Figures