Development and Demonstration of Redox Flow Battery System

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High expectations have been placed on rechargeable batteries as a key technology to power system reliability associated with introduction of an increasing volume of renewable energy, as well as efficient power supply and successful business continuity planning. We have developed a redox flow battery system that is safe with a long service life. A demonstration proved its applicability to multiple requirements from electric power companies and other businesses. This paper describes the system, demonstration results, and our effort to reduce the price.

Keywords: redox flow battery, energy storage, renewable energy, demand response, BCP

1. Introduction

In recent years, an increasing volume of renewable energy sources, such as solar and wind power, has been connected to electrical grids. One of the motivations for this is the inauguration of feed-in-tariff program for renewable energy. In particular, the extent of interconnection is large in Hokkaido because of the suitability of the region for the use of renewable energy. Accordingly, concerns exist over the impact of the integration of renewable energy into the electrical grid due to the output fluctuations induced by them. Against this backdrop, the world's largest redox flow (RF) battery system rated at 60 MWh (15 MW for 4 h) was installed in the Minami-Hayakita substation of Hokkaido Electric Power Co., Inc. (HEPCO) by Sumitomo Electric Industries, Ltd. In December 2015, a demonstration project, subsidized by the Ministry of Economy, Trade and Industry, has been initiated to evaluate the performance of the rechargeable battery and to develop a control technology with the aim of stabilizing the electrical power grid.

However, end users are encountering various challenges, such as peak shaving, which requires them to reduce the maximum demand for utility power and power grid blackout caused by natural disasters. Therefore, these end users are increasingly interested in business continuity planning (BCP), which enables them to continue their operations at least at the minimum required level even in the instance of any power incident. Moreover, in contrast to the traditional practice of power being supplied unilaterally by power companies, a new scheme known as the demand response*[1] (DR) scheme is emerging, using which electricity can be efficiently used by integrating the distributed power systems and power savings of end users. In order to fulfill these complex requirements of businesses, Sumitomo Electric installed a 3 MWh (500 kW for 6 h) RF battery system at the Technical Research Institute of Obayashi Corporation. The system commenced its operation in February 2015. This paper describes the features of the RF batteries and provides examples of operation of the installed RF battery systems.

2. Operating Principle and Features of Redox Flow Battery

Figure 1 illustrates the configuration of an RF battery. Its components include electrolyte flow cells where the cell reaction occurs, positive and negative electrolyte tanks, pumps used to circulate the electrolytes between the tanks and cells, and a piping system. Sumitomo Electric's RF batteries use aqueous solutions of vanadium sulfate as both positive and negative electrolytes. Charging and discharging processes of the RF battery are expressed by the following reactions:

(Positive side)

$$2VOSO_4 + 2H_2O \leftrightarrow (VO_2)_2SO_4 + H_2SO_4 + 2e^- + 2H^+ \quad (1)$$

(Negative side)

$$V_2(SO_4)_3 + 2e^- + 2H^+ \leftrightarrow 2VSO_4 + H_2SO_4 \quad (2)$$

While the battery is being charged or discharged, these reactions involve changes only in the valence of vanadium ions in the electrolytes. Since there is no phase change involved in the reaction, the electrolytes are free from degradation in principle and can be used semi-permanently. In addition, the RF battery has the following distinct

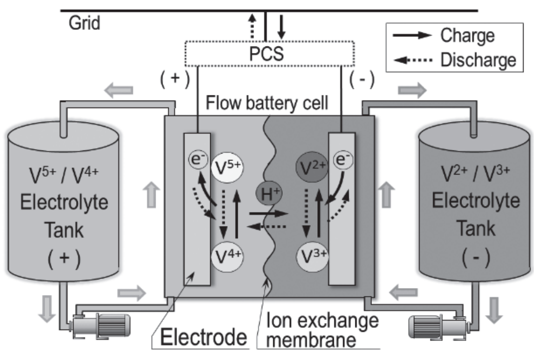


Fig. 1. RF battery operating principle

features: (1) The power output section (cells) is independent from the energy section (tanks), allowing for highly flexible output power and energy designs to meet specific application requirements; (2) Each cell is naturally in the uniform state of charge (SOC) because electrolytes of the same SOC are fed from the same tanks; (3) By passing the electrolytes through a dedicated single cell and measuring its voltage (open-circuit voltage), it is possible to measure the SOC of the cells accurately, even during the charging or discharging process; (4) Due to its fast responses in the order of milliseconds, the RF battery, for a short period of time, can be charged or discharged at twice the output power rating.[(1),(2)]

Figure 2 provides an example of the results of a long-term reliability test conducted on the in-house demonstration equipment. This figure shows changes in the cell performance of an RF battery over a period of time. The current efficiency represents the degradation of the membrane, which is a functional component. The cell resistance indicates the degradation of the electrodes. The test results revealed no noticeable degradation in these features, proving that the equipment has high performance as expected from the design. This test is still in progress.

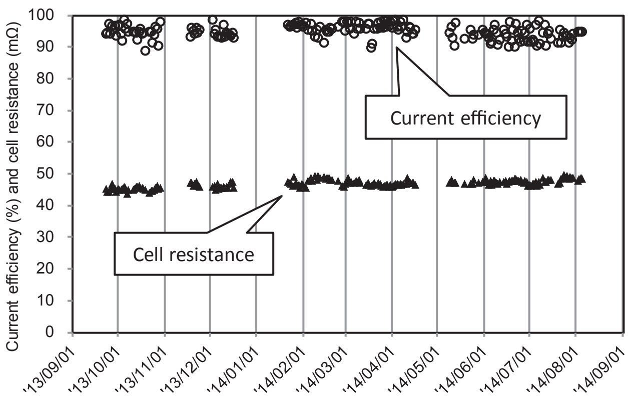


Fig. 2. Changes in cell performance over a period of time

3. Large Rechargeable Battery System for Electrical Grids

A rechargeable battery system rated at an output power of 15 MW (30 MW max.) with a discharge energy of 60 MWh[(3)-(6)] has been installed to the Minami-Hayakita substation of HEPCO by Sumitomo Electric. This system was placed in a dedicated two-story building since its installation took place in a cold region. Photo 1 depicts the equipment.

3-1 Objective of the demonstration project

Challenges associated with integrating a renewable energy source into an electrical grid include short- or long-period frequency fluctuations and surplus electricity. By developing a control methodology and by evaluating the performance of the large rechargeable battery system, the demonstration project is targeted to examine the functionality of the battery system to solve the aforementioned challenges. Figure 3 schematically illustrates the control system developed for the rechargeable battery systems. Power output information from the solar and wind farms in Hokkaido, information from the weather forecasting systems, and load conditions were used as fundamental information to operate the battery system. Based on these sets of information, the demonstration control unit at the load dispatching center has transmitted power charge and discharge command values to the rechargeable battery system. According to these commands, the battery system carried out charge and discharge operations.

2nd floor: Installed battery cubicles and BMSs

1st floor: Installed PCSs, tanks, and pumps

Photo 1. Large rechargeable battery system

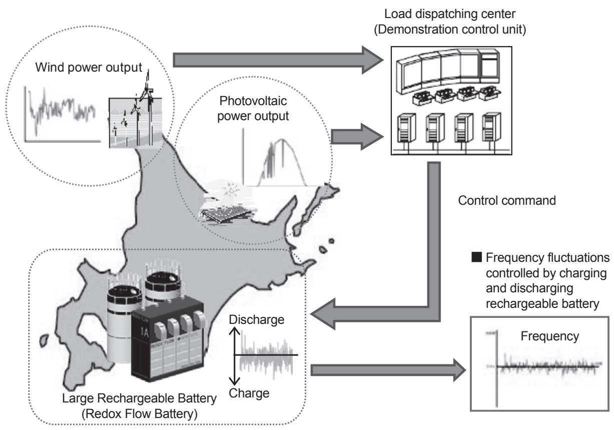
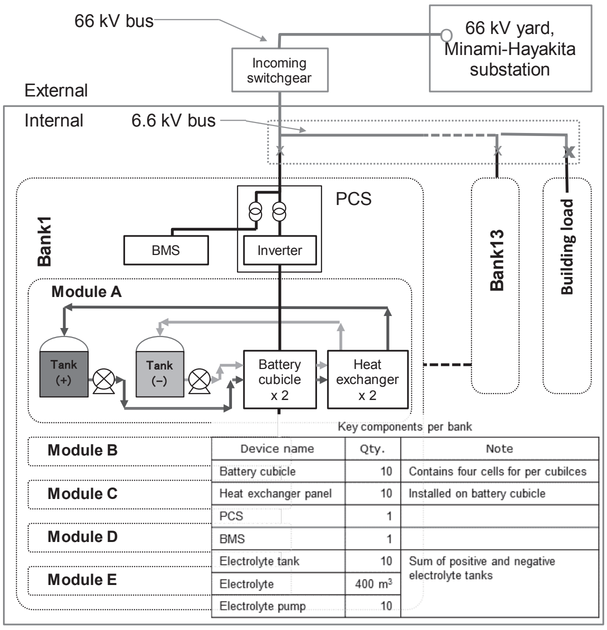


Fig. 3. Schematic image of rechargeable battery control

3-2 System configuration

Figure 4 shows the configuration of the battery system. One set of electrolyte circulation lines consisting of tanks, pumps, and cell stacks is called as a module. A group of modules connected to a PCS as a unit that enables independent charge and discharge control is called a bank. The entire system is comprised of 13 banks, with each bank (output rating: 1,250 kW; max. output: 2,500 kW) consisting of five modules. Accordingly, the battery system had a total of 520 cell stacks and a discharge energy of 60 MWh with 5,200 m^3 of electrolyte. These specifications made the system the largest RF battery system and the largest rechargeable battery system in the world.



Device name	Qty.	Note
Battery cubicle	10	Contains four cells for per cubilces
Heat exchanger panel	10	Installed on battery cubicle
PCS	1	
BMS	1	
Electrolyte tank	10	Sum of positive and negative electrolyte tanks
Electrolyte	400 m^3	
Electrolyte pump	10	

Fig. 4. System configuration diagram

3-3 Initial performance evaluation

After installation, the system was subjected to completion testing for initial performance evaluation. Shown below are the representative test results.(5),(6)

(1) Energy test

The energy test was intended to check whether the battery met the applicable discharge duration requirement when set to discharge at the rated output from fully charged state. The energy test examined the banks on a bank-by-bank basis and as an integrated unit. In both the tests, the system marked a discharge duration of at least 4 h, as specified. Figure 5 represents the test waveforms exhibited by the banks when they were integrated as a whole and operated at the fixed discharge rate. The upper graph indicates active power waveforms of all banks, whereas the lower graph shows the waveforms of a representative bank (DC voltage, DC current, and SOC). In total, the discharge energy of all banks reached approximately 75 MWh.

An efficiency test was conducted in an operation that simulated a short-period fluctuation control. The system efficiency reached 70.8% as an average of all the 13 banks.

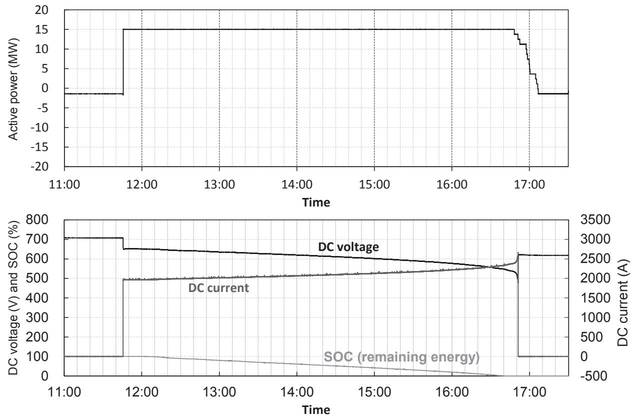


Fig. 5. Energy test

(2) High-power charge and discharge test

Cells can be charged and discharged to excess of the output rating for a short period of time. This feature is useful for the purpose of short-period fluctuation control (output fluctuation control in a relatively short time in the order of few milliseconds to seconds), making it possible to reduce the number of installed cell stacks. The battery system incorporated a PCS with twice the output rating of the rechargeable battery. Figure 6 shows an example of the test results. The battery was charged and discharged at 120% (1,500 kW), 160% (2,000 kW), and 200% (2,500 kW) of the battery output rating (continuous charging and discharging for 60 s). Under any of these conditions, the system proved itself to be capable of being charged and discharged at high power.

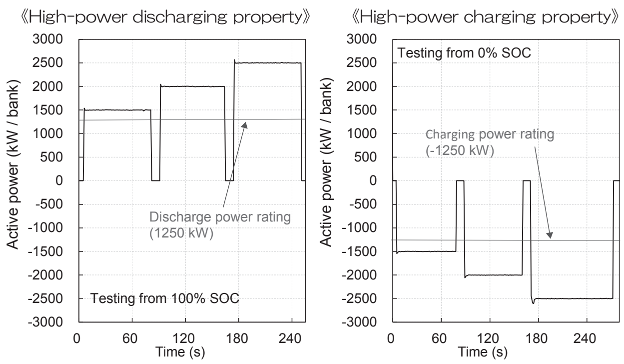


Fig. 6. High-power charge and discharge test

(3) Response time test

The response time of the battery system from the instant it receives a power charge or discharge command from the demonstration control unit and till it reaches the specified output power has been measured. The test results are shown in Fig. 7. The system required a duration of approximately 60 ms (time required to reach 98% of the command value) for a transition from +2,500 kW or twice the output power rating to −2,500 kW, and vice versa. Its response was noticed to be suitably high for short-period fluctuation control operation.

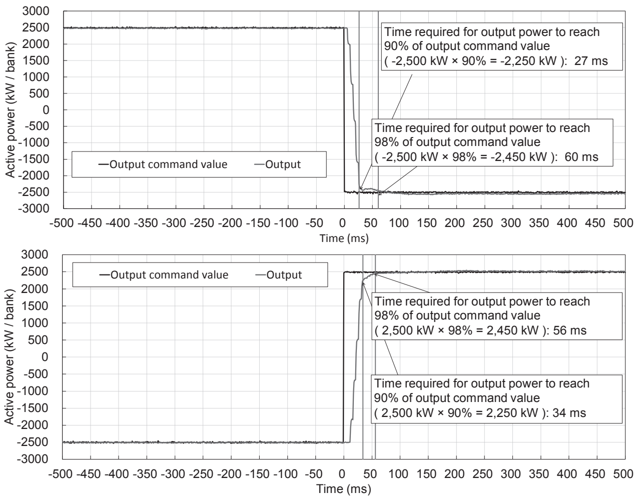


Fig. 7. Response time test

3-4 Results of governor-free mode equivalent control test

As an example of the demonstration test results, this section presents the test results of governor-free mode equivalent control.*2 This islanding control allows the rechargeable battery system to detect the frequency, computes required power accordingly, and subsequently charge or discharge the battery. This control provides fast responses because it does not involve the time required to transmit command signals from the demonstration control unit. In general, the grid frequency increases or decreases when an imbalance occurs between the supply (generated power) and the demand (load). One of the possible consequences for the grid frequency to go beyond certain limits is the stoppage of production lines to the end user. Therefore, rechargeable battery systems need to ensure fast responses in order to reduce frequency fluctuations. The test results showed that the system could follow frequency fluctuations without delay, as shown by the test waveforms in Fig. 8.

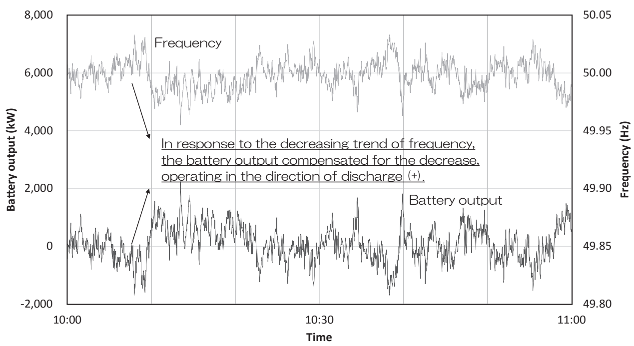


Fig. 8. Example results of testing governor-free mode equivalent control

4. Rechargeable Battery System for End Users

4-1 System objective

The battery system was installed at the Technical Research Institute of Obayashi Corporation to serve as a smart energy system. The purposes of this system were to make the maximal use of renewable energy in order to reduce CO_2 emissions, to reduce utility power demand peaks for a lowered base rate, to cut electricity demand for energy savings, and to improve BCP capabilities.

This paper reports the results of a DR test and an island operation*3 test. The DR test was conducted with an aim of reducing import from a utility. The purpose of the islanding operation test was to improve BCP capabilities.[7]

4-2 System configuration

In addition to the RF battery installed from Sumitomo Electric, which is rated at an output power of 500 kW and a discharge energy of 3 MWh, the system included photovoltaic power generation equipment (PV, 820 kW in total) and generators (445 kW in total), all of which were controlled and managed by an energy management system (EMS). Figure 9 presents the configuration of the system.

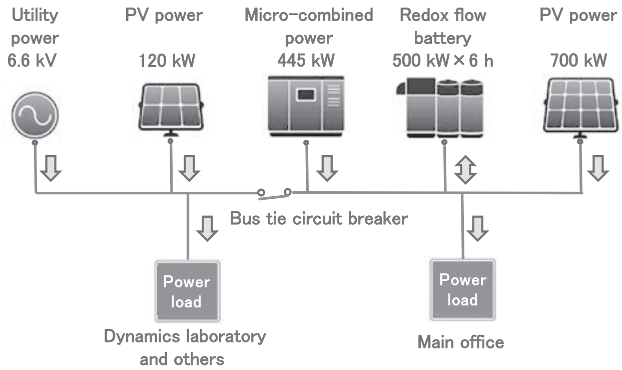


Fig. 9. System configuration

4-3 Demand response functionality test

(1) Test overview

In a DR scheme, in response to a request from a power company, the system computes the negawatt power (command value)*4 that the system could offer and responds to the request for reduced power demand. The test was run based on an assumption that Waseda University's EMS Shinjuku R&D Center, which held the only DR demonstration facility in Japan, was a power company and an aggregator*5 and the Technical Research Institute, which had the rechargeable battery system, was an end user.

(2) Test description

The testing can be categorized into two types: one with receiving a DR request with a one-day advance notice and the other with a one-hour advance notice. The DR with a one-day advance notice is described below. Demand response target hours were 2 h in the morning (9:00–11:00) and another 2 h in the evening (17:00–19:00). Table 1 provides the negawatt power required during these hours.

Table 1. DR requested hours and negawatt power

DR requested hour		Negawatt power
Morning	9:00 ~ 10:00	200 kW
	10:00 ~ 11:00	400 kW
Evening	17:00 ~ 18:00	200 kW
	18:00 ~ 19:00	200 kW → 400 kW

It was planned that for the morning hours, the required negawatt power will be supplied by discharging the RF battery. For the evening hours, the negawatt power was planned to be increased by 200 kW 1 h prior to the DR target hour (18:00–19:00) and to have generators operating in addition to the RF battery. These operations were examined in the test.

(3) Test results

Figure 10 presents the test results, which reveal that in the morning, the RF battery was discharged in order to reduce the demand for utility power and in the evening, the demand for utility power was reduced by using generators in addition to the RF battery, as originally planned. Throughout the testing, which included the DR with one-hour advance notice, the ratio of actual performance to the command value varied from 71.5% to 349.0%. Thus, the test using the RF battery is considered to be successful since success in DR is defined to be the ratio being at least 70%.

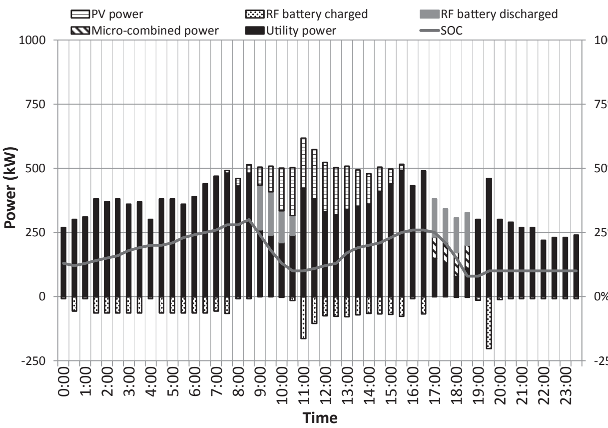


Fig. 10. Power log for DR operation day

4-4 Island operation test

(1) Test overview

Figure 11 shows the configuration of the tested islanding operation system. In many cases of islanding operation, generators serve as the voltage source. However, where PV accounts for a high percentage and provides power in excess of demand during high solar radiation hours, generators cannot accommodate for the surplus power. As a solution to this problem, the tested islanding operation system was configured to ensure balanced supply and demand during islanding operation without PV output control. This was achieved by using the RF battery as the voltage source, which was charged when PV generated surplus power and was discharged when demand exceeded the power supplied by PV and generators.

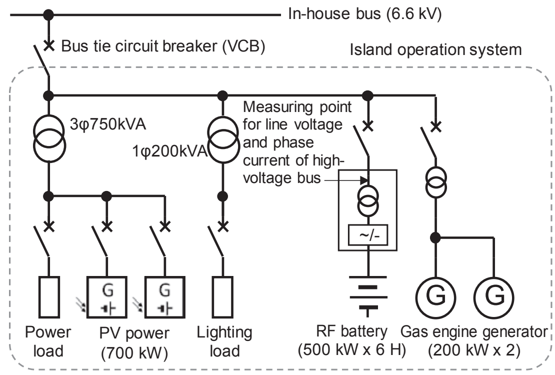


Fig. 11. System configuration (island operation system)

(2) Test description

During the island operation test, the bus tie circuit breaker was opened and the island operation system was subjected to a simulated power outage in the area defined by dashed lines, as shown in Fig. 11. Following the power outage, island operation was established by starting up the RF battery and using it as a voltage source, which was subsequently followed by a sequence of connections established between the RF battery and PV and the generators.

(3) Test results

The test induced changes in the operating status of the distributed power system by making in-house load adjustments and by varying control settings. Conditions that ensured stable operation and output power were examined in instances such as PV disconnection, reconnection, and generator startup and shutdown. In this paper, we explain the behaviors of the system at the time of PV disconnection. The test results are plotted in Fig. 12. Sequential disconnections of PV caused rapid changes in the output.

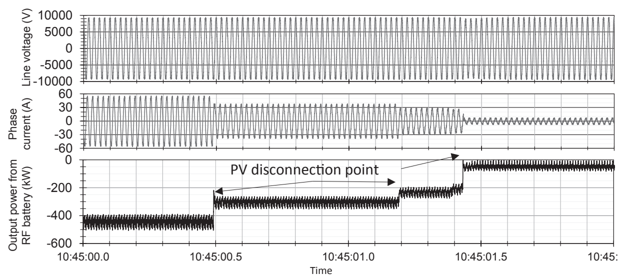


Fig. 12. Behaviors at PV disconnections

Despite these changes, the power used to charge the RF battery underwent instant change with the corresponding time, thus maintaining an appropriate balance between the supply and the demand. Even in the event of a rapid change in the generated power, the line voltage was observed to be stable, thus establishing the functionality of the RF battery as a voltage source to be satisfactory.

5. Cost Reduction Efforts

While the RF battery has proved itself to offer excellent functionality as explained above, the greatest challenge facing its widespread usage is its cost. In order to reduce the transportation and construction expenses of the RF battery, Sumitomo Electric is striving to improve the output power of cell stacks and build the system into a package, key design points of which are: i) output rating to be at least twice as high as the current system and ii) packaging of all principal devices including cell stacks, pumps, tanks, and piping entirely into a standard shipping container. A prototype system has been installed in-house for demonstration and testing purposes. Photo 2 shows the exterior of the container system.

Photo 2. Exterior of container system

6. Conclusion

Redox flow battery systems have been developed in order to stabilize the electric power grids against the integration of an increasing bulk of renewable energy and to meet the emerging electricity needs of the end users. These systems are safe and long lasting and fulfill their respective performance requirements. Future goals include improvement in the operating efficiency, further technology development, and cost reduction. Sumitomo Electric is committed to contributing to the wider introduction of renewable energy and the efforts towards building a society inclined to saving more energy.

Technical Terms

∗1 Demand response: Demand response is a change made by end users in their power consumption pattern as required by the utility. This is done in response to certain electricity rate settings or incentive payments at the instance of soaring market electricity prices or declining reliability of electric power grids.

∗2 Governor-free mode equivalent control: In the governor-free mode of operation, the governor (a device that maintains uniform speed and is used along with a water wheel or steam turbine) operates free of restrictions imposed by load controller and responds directly to the frequency fluctuations. Rechargeable batteries have no governor. However, they have a similar function (to detect and independently control the frequency); and hence the term "equivalent control."

∗3 Island operation: In this mode, when a blackout of a utility power grid occurs, the distributed power sources including rechargeable batteries serve as voltage sources to supply power to important loads connected.

∗4 Negawatt power: The power demand is reduced in the instance of tight supply of electricity. Reduced demand is viewed as negative power in contrast with usual positive power, and is termed as "negawatt power" (negative watt power).

∗5 Aggregator: It is an entity in charge of carrying out efficient energy management between power companies and end users. Aggregators buy and sell electricity, by collecting some negawatt power from end users.

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