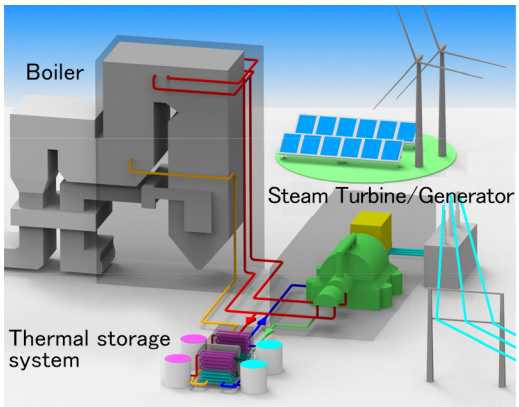
Thermal Storage System to Provide Highly-efficient Electric Power Resilience in the Era of Renewable Energy



KENJIRO YAMAMOTO*1 KAZUHIRO DOMOTO*2
MAKOTO TOBO*3 TSUTOMU KAWAMIZU*4
TAKAHIRO YAMANA*5 YUJI OTA*6

To enhance electric power resilience (robustness to endure a significant and sudden unbalance between supply and demand while regulating reserve capabilities) in line with the increasing use of renewable energy, thermal storage systems are incorporated into the turbine bypass system, etc., of thermal power plant systems so that waste heat during startup or the mismatched heat between boiler and turbine/generator outputs under extremely low load conditions can be stored. This stored heat can generate electricity by releasing its energy to the pre-boiler and/or boiler during high-load operation, which results in energy savings of around 2% or more. By utilizing the significant amount of latent heat of phase change materials (PCMs : applying melting/solidification processes) or by increasing the temperature difference of sensible heat storage materials such as molten salts and water, thermal energy storage equipment can be made compact, thereby making it possible to be installed on the premises of a power plant.

We are currently working on the development of such a system to realize its practical application at a price per electric capacity comparable to battery storage systems.

1. Introduction

According to the prediction based on published data such as the Japan's Energy Statistics by the Japanese Agency for Natural Resources and Energy, Japan's power generation breakdown by energy source in 2030 is considered to be as follows: 22-24% for renewable energy, 26% for coal, 27% for LNG, 3% for oil and 20-22% for nuclear energy. Renewable energy will become one of the major power sources, as its share is expected to increase from 17% in 2017. In addition, most renewable energy power generation systems are either photovoltaic (PV) or wind power. Their electricity supply to the power grid fluctuates considerably depending on the natural environment (e.g., insolation or wind conditions). Under such circumstances, increasing/decreasing the power supply from thermal power plants or water pumping/releasing from pumped-storage hydroelectric power plants are now key to balancing the supply and demand of electricity. This is also the case with European countries, despite their being advanced in terms of introducing renewable energy applications(1). **Figure 1** gives a balancing example by Kyushu Electric Power Co., Inc., which has the highest renewable energy application rate in Japan(2). This power company operates a coal-fired power generation unit at the minimum output level, and allows the GTCC (LNG) to run with the minimum number of axis. In spite of making full use of the regulating capability of all the thermal power plants, there was a case of a company limiting the connection of PV output to the power grid

*1 Authority of Technology, Boiler Business Strategy Planning Department, Boiler Technology Integration Division, Mitsubishi Hitachi Power Systems,Ltd.
*2 Deputy Director, Boiler Business Strategy Planning Department, Boiler Technology Integration Division, Mitsubishi Hitachi Power Systems,Ltd.
*3 Engineering Manager, Nagasaki Plant Engineering Department, Project Management Division, Mitsubishi Hitachi Power Systems,Ltd.
*4 Research Manager, Heat Transfer Research Department, Research & Innovation Center
*5 Heat Transfer Research Department, Research & Innovation Center
*6 Engineering Manager, CIS Department, ICT Solution Headquarters

when the amount of power it generated reached 60% of the demand in their supply area[3].

If the renewable electricity supply continues to increase, thermal power plants need to reduce the output likelihood in daytime by (1) increasing the number of shutdowns, (2) operating the unit at a lower output level than the current minimum level and (3) preferably improving the ramp rate to respond to sudden changes in insolation or wind conditions.

Under such circumstances, in accordance with Japan's 5th Strategic Energy Plan in 2018, in which renewable energy is expected to become a major power source in the future, national research and development agency (NEDO : the New Energy and Industrial Technology Development Organization) considers "heat energy storage (thermal energy storage)" to be a critical technology and is promoting its social implementation.

This report presents the feasibility of the function to provide electric power resilience with high efficiency by applying thermal energy storage systems at thermal power plants. Utilizing the high heat capacity of the latent heat of PCMs or increasing the temperature difference of sensible heat storage materials such as molten salts and water can make such a system compact. This report also introduces the current situation regarding the development of this system applying metallic PCMs and molten salts as thermal energy storage media, the former of which can further improve the responsiveness to output changes owing to its quick heat charging/discharging capability.

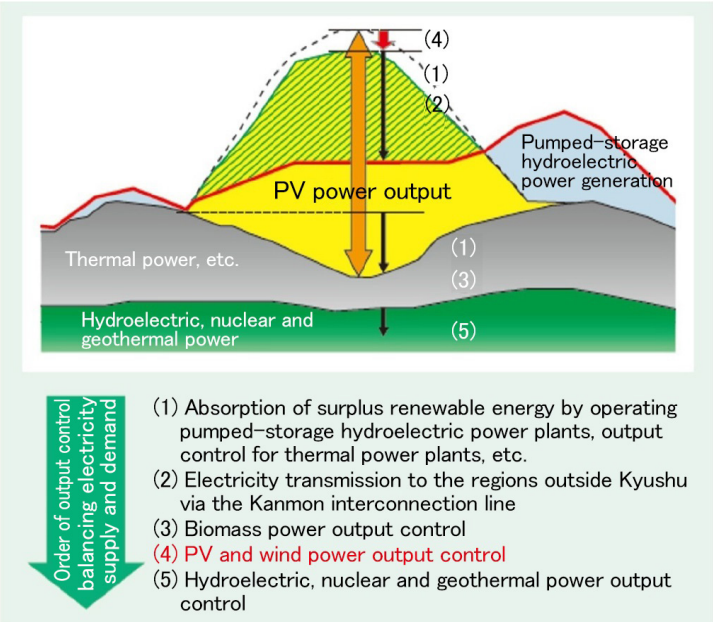


Figure 1 Electricity supply and demand balancing with increasing use of renewable energy (example of Kyushu Electric Power Co., Inc.)

2. Thermal storage system to enhance electric power resilience when renewable energy supply is significant

2.1 Thermal storage system concept

Thermal power plants normally operate boilers that feed heat corresponding to the electric generation output at the generator terminal, which is the sum of the sending-end output (electricity for supply) and auxiliary consumption (equal to roughly 5% of the rated generator capacity). When electric power demand and supply are balanced by shutdown/startup or extremely low-load operation in which the turbine/generator output is lower than the minimum boiler output, heat loss during startup or that caused by an output mismatch between the minimum output of boiler and turbine/generator output is released as waste heat to the condenser from the turbine bypass system, etc., and finally it is disposed of in the sea or atmosphere. This mismatch happens because, in coal-fired power generation units, it is necessary to keep the boiler output at around 15% or higher to realize a stable coal pulverization process in the mills and stable combustion in the boiler combustion furnace.

Figure 2 shows schematic diagram of a thermal power plant system in which the thermal storage system is incorporated into the turbine bypass system, etc., and also illustrates the concept

how to utilize it. To make maximum use of waste heat without causing loss, it is important for the thermal storage system to have the capability of storing the latent heat of steam as well as low-temperature sensible heat of water. As indicated by the h-s diagram in **Figure 3**(a), it is very desirable to use thermal energy storage equipment that can store nearly as much heat as the heat drops utilized by turbine cycle power generation. By utilizing the stored heat for electric generation under high-load operating conditions, where turbine efficiency is high, a substantial energy-saving effect can be obtained compared with low-load power generation (Figure 3(b)).

The thermal storage system consists of heat exchangers containing thermal energy storage materials with different thermal energy storage temperatures, piping, valves and control units, as shown in Figure 2(a). In the process of heat charging, steam or water from the turbine bypass system and separator drain system are introduced to the heat exchanger, and disposed of in the condenser after the heat is stored. On the other hand, in the process of heat discharging, the fluid (steam or water) in the pre-boiler and boiler are heated in accordance with the subranges of the operable temperature range to minimize the impact on the steam cycle (patent pending).

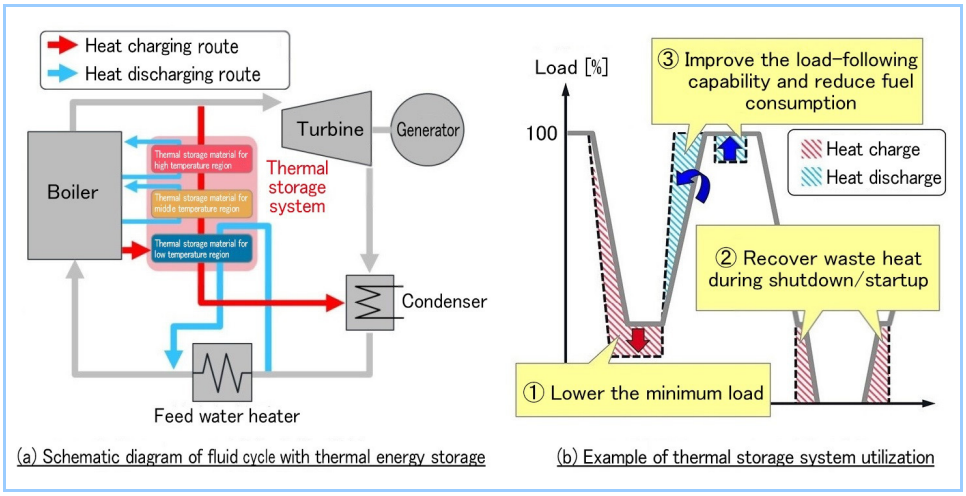


Figure 2 Schematic diagram of fluid system with thermal energy storage and conceptual diagram for utilization

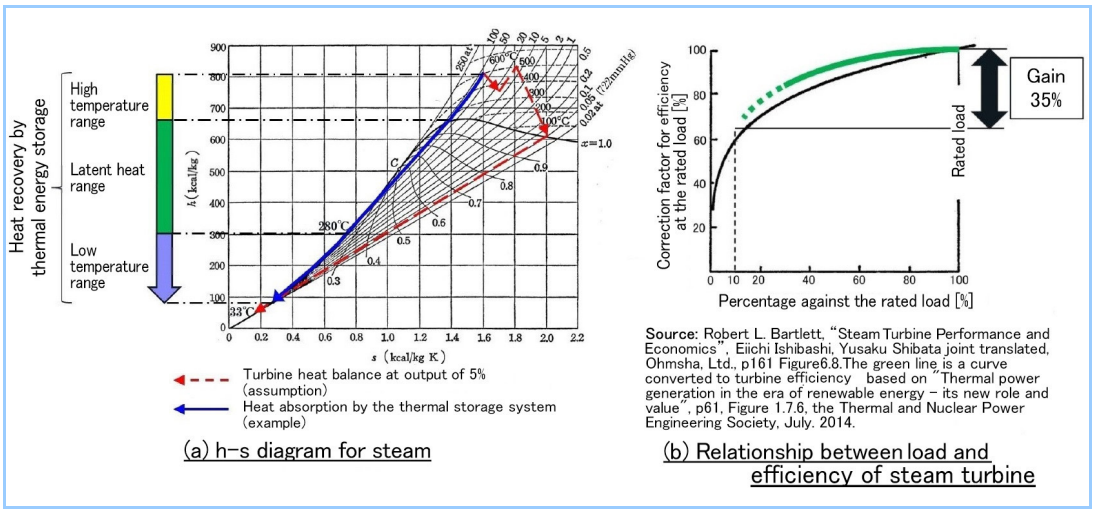


Figure 3 h-s diagram for steam water and relationship between turbine load and heat consumption rate

2.2 Operation of thermal storage system

Five operational patterns using the aforementioned thermal storage system are presented hereunder.

First pattern is a case in which the thermal power generation unit is shutdown during daytime when there is sufficient renewable electricity supply and the unit is started up in the evening to meet the demand until the morning when the renewable energy supply returns. The amount of mismatched heat between the boiler and turbine/generator outputs is usually disposed of as waste heat from the turbine bypass system (TB valve) and separator drain system (WDC, abbreviation of

water separator drain control, valve) to the condenser during startup. **Figure 4** is the heat balance chart of a 700-MW unit during startup (2 hours) after 8 hours shutdown. Waste heat to the condenser without being fed to the turbine accounts for 12.5% of the fuel heat input. As illustrated in Figure 5(a), this waste heat is stored (indicated by the red shaded areas) and the stored heat is discharged to be used for power generation (the blue shaded areas). This energy saving is not possible with a battery storage system or pumped-storage hydroelectric power generation, but is only enabled by employing a thermal storage system.

In Figure 5(b), the boiler output is reduced to the minimum level (15%), while the turbine/generator output is set at 10%, from which auxiliary consumption (5%) is subtracted, and the remaining 5% is transmitted to the grid. Waste heat equivalent in amount to the output mismatch of 5% is stored via the turbine bypass system. The stored heat is discharged in the same manner as in (a).

Figure 5(c) represents a thermal energy storage pattern in which, with the minimum boiler output of 15%, the turbine/generator output reduced to 5% is used for auxiliary consumption (5%) resulting in no electricity supply to the grid while the generator circuit breaker closed. The waste heat equivalent to the mismatch of 10% is stored via the turbine bypass system. As there is no power left to be transmitted to the grid, the renewable electricity supply can be increased.

Illustrated in Figure 5(d) is an operational pattern in which all the heat produced at the minimum boiler output of 15% is stored and power for auxiliary consumption (5%) is provided from the grid, while the turbine/generator are placed out of operation (i.e., boiler single operation) and the generator circuit breaker is open. As the boiler remains in a warmed-up condition, the synchronization of the turbine/generator and an increase in electricity output can be realized more rapidly than in the case of a plant shutdown. By receiving the power from the grid to the power plant, the renewable electricity supply can be further increased.

In Figure 5(e), in addition to (d), externally-provided power is also used for the electric heater that is used to heat thermal energy storage materials, and the renewable electricity supply can be further increased by this amount.

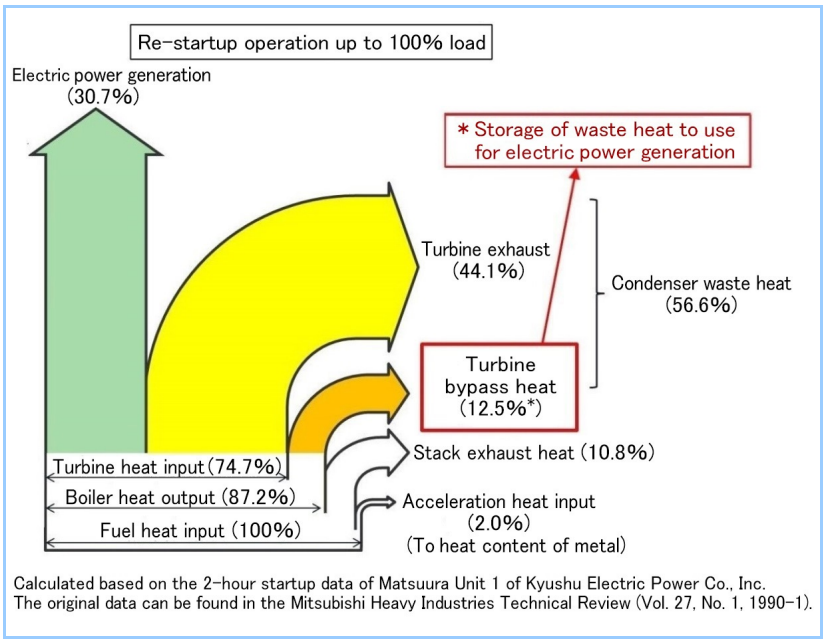


Figure 4 Heat balance chart of 700-MW unit during startup (2 hours) after 8 hours shutdown

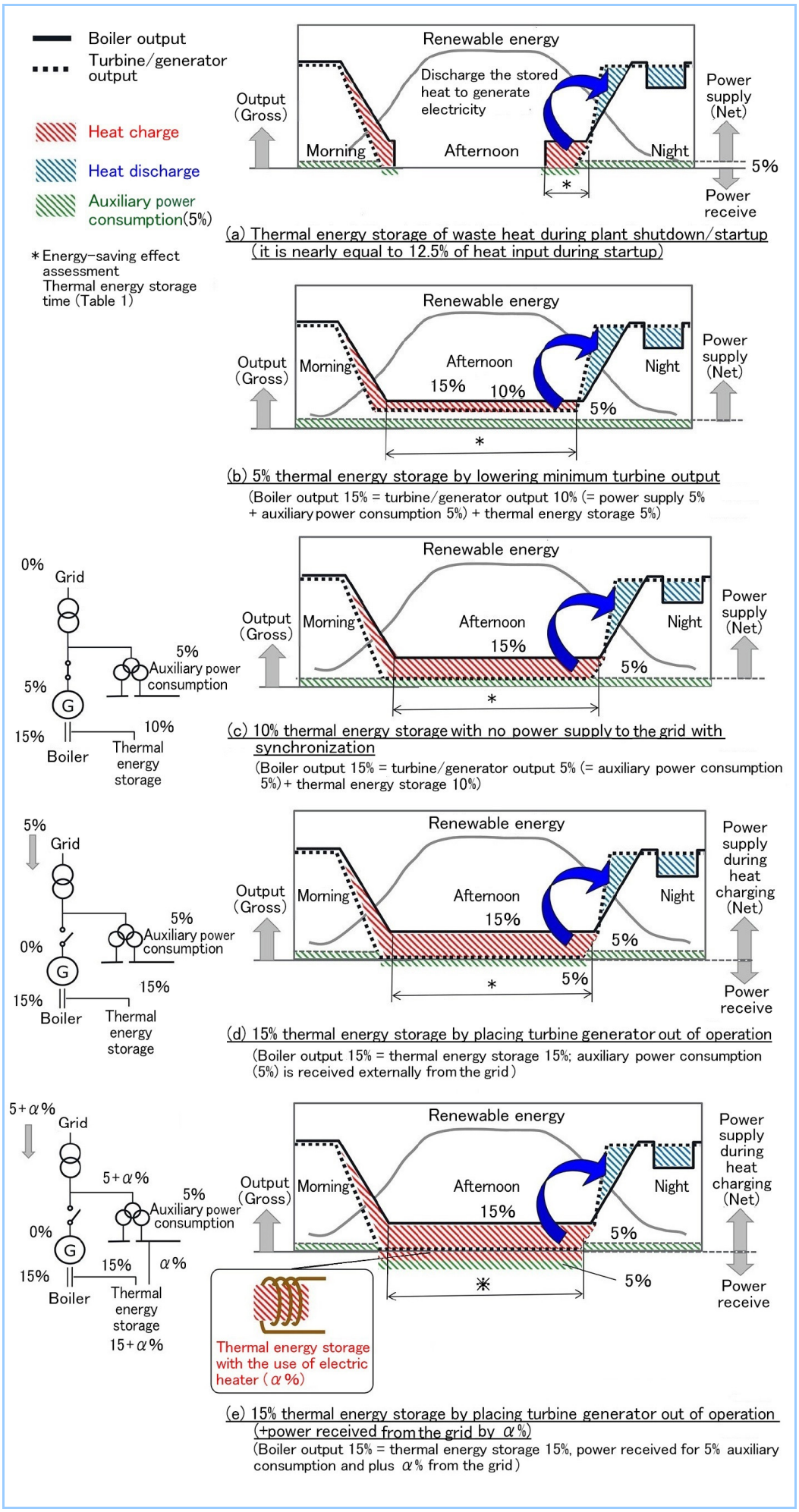


Figure 5 Operational patterns of thermal power plant with use of thermal storage system

2.3 Estimation of energy-saving effect and economic efficiency

Table 1 summarizes the energy-saving effects of the aforementioned five operational patterns. When controlling the amount of power supplied from the thermal power plant by shutting down the plant for 8 hours, lowering the electricity output to the grid or receiving electricity from the grid during daytime while utilizing thermal energy storage as in the case of Figures 4(a) to 4(e), an additional energy-saving effect of 2-6% can be achieved in comparison with a battery storage system or pumped-storage hydroelectric power plant. As mentioned in Figure 3(b), this is because the stored heat can be used under high-load conditions with a high turbine efficiency. From the perspective of energy usage, the efficiencies of conversion to electric power in a thermal energy storage system, battery storage system and pumped hydroelectric storage system are estimated to be 90%, 85% and 70%, respectively. These values correspond to the approximate ratio among heat charging and discharging efficiency, power charging and discharging efficiency and pumped-storage efficiency. With the increase of renewable energy, thermal power plants will often be operated under low-load conditions with the low turbine efficiency. Therefore, the thermal energy storage system can be an effective method to offset the deviation from the target efficiency of thermal power generation provided as the benchmark by the Energy Conservation Act of Japan. Furthermore, from the perspective of utilizing energy of waste heat for power generation, which is otherwise released into the sea or atmosphere from the condenser, the benchmark index will be improved by as much waste heat as is used based on the calculation formula as defined by the Agency.

Table 1 Energy-saving effect estimation

Thermal energy storage pattern	Evaluation index	Stored thermal energy	In the case of storing as electricity by transmitting it instead of storing as thermal energy	
			Battery storage*3	Pumped hydroelectric storage*4
Figure 5(a) Thermal energy storage of waste heat during plant shutdown/startup (it is nearly equal to 12.5% of heat input during startup)*1	Fuel heat input	1.9%	Applicable only to thermal heat storage	
Figure 5(b) 5% thermal energy storage by lowering the minimum turbine output*2		2.9% (1.8%)	1.1% (Baseline)	Baseline
Figure 5(c) 10% thermal energy storage with no power supply to grid with synchronization *2		6.2% (3.9%)	2.3% (Baseline)	Baseline
Figure 5(d) 15% thermal energy storage by placing turbine generator out of operation *2		10.0% (6.2%)	3.8% (Baseline)	Baseline
Figure 5(e) 15% thermal energy storage by placing turbine generator out of operation (+power received from girdexternally by α%)*2		10.0%+α (6.2%+α)	3.8%+α (Baseline)	Baseline

*(In general) With regard to the numerical values given in the table above, the stored energy reduction due to aging degradation is not considered in any storage methods.

*1 Based on the hypothetical operating conditions of startup (2 hours) in DSS mode (8 hours of shutdown time during daytime), followed by operations at 50% load for 2 hours and at 20% load for about 12 hours (average daily load percentage: approx. 15%).

*2 Based on the hypothetical operating conditions of 8 hours of thermal energy storage time, followed by operations at 50% load for 6 hours and at 20% load for about 10 hours (average daily load percentage: approx. 20%).

*3 The battery energy conversion efficiency of 85.7% is taken into consideration (with the assumption of AC-to-DC conversion 95% × charge/discharge 95% × DC-to-AC conversion 95%).

*4 The general efficiency of pumped-storage hydroelectric power generation of 70% is taken into consideration.

3. Development of thermal energy storage equipment

3.1 Thermal energy storage materials

The first example of a successfully-applied thermal energy storage material in the field of power generation was water used in the Ruths accumulator(4) to cope with peak load in Europe in 1916. Since then, various studies have been conducted, and PCM application technologies are also under development(5)-(9). In order to have variation of the range of the dischargeable temperature as described in Section 2.1, from the perspective of minimizing the impact on the steam/water cycle during heat discharge, it is desirable that the temperature range of the thermal energy storage equipment can be set for multiple conditions by employing several types of PCMs with different

melting points. **Figure 6**(a) is a schematic diagram that shows the principle of the PCM heat charging/discharging process. The use of metallic PCMs enables quick charging/discharging of heat and reduction in the equipment size by taking advantage of their high heat capacities and conductivities. Size reduction can also be achieved using liquid sensible heat storage materials such as molten salts, oils and water, because the difference in temperatures between pre- and post-storage is increased. With these liquid sensible heat storage materials, heat charging/discharging processes can also be accelerated by increasing the flow rate in the heat exchanger. Figure 6(b) compares the sizes of metallic PCMs, molten salt and concrete (sensible heat storage). The degree of size reduction is determined by the reciprocal of heat capacity. **Figure 7**(a) presents an example of a thermal storage system with a PCM, while Figure 7(b) is an example of a thermal storage system in which a liquid sensible heat storage material is used. **Table 2** lists some of the thermal energy storage material candidates for each of the temperature subranges. Since some materials are highly susceptible to corrosion, if this is the case, anti-corrosion measures for equipment in the thermal storage system are required.

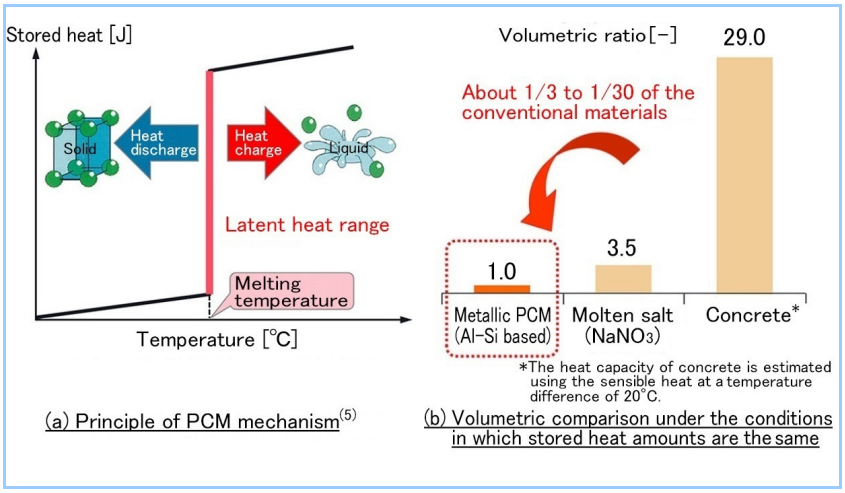


Figure 6 Principle of PCM mechanism and volumetric comparison under the conditions in which stored heat amounts are the same

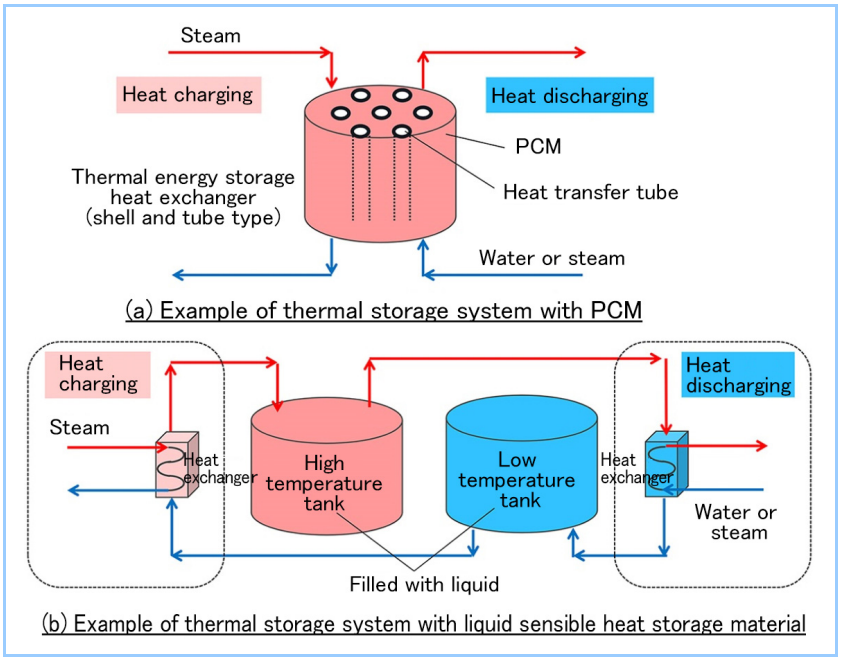


Figure 7 Thermal storage system examples

Table 2 Examples of thermal energy storage materials, physical properties and thermal indices (Values are approximate)

Thermal energy storage material		Melting point ℃	Density kg/m^3	Latent heat kJ/kg	Storable thermal energy (latent heat) MJ/m^3	Specific heat kJ/KgK	Storable thermal energy (sensible heat) MJ/m^{3}K	Heat conductivity W/mK	Storage method example
High temperature	Al based	From ≈560	≈2500	≈500	≈1300	≈1.0	≈2.5	≈160	Latent heat
	Zn based	From ≈380	≈6600	≈140	≈920	≈0.5	≈3.3	≈100	Latent heat
Medium temperature	$NaNO_3$	≈310	≈2000	≈180	≈360	≈1.7	≈3.4	≈0.5	Sensible heat Latent heat
	Mineral oil	—	≈770	—	—	≈2.6	≈2.0	≈0.1	Sensible heat
Low temperature	Water	—	≈1000	—	—	≈4.2	≈4.2	≈0.5	Sensible heat
	Erythritol	≈120	≈1500	≈340	≈510	≈1.0	≈1.5	≈0.7	Latent heat

3.2 Heat exchanger and heat transfer analysis

Figure 8 describes a heat transfer analysis model of the system in Figure 7(a) with a heat exchanger using a PCM. Supposing that an Al-based PCM with a latent heat range of 560°C to 580°C is used as the thermal energy storage material, the heat exchanger has a heat transfer tube of 20m in length. The dynamic behavior of the steam temperature at the tube outlet and the amount of heat charged/discharged were predicted. The typical analysis results are given in **Figure 9**. In the case of charging heat from steam at a temperature of 600°C (Figure 9(a)), the temperature of steam at the tube outlet falls down to approximately 570°C in the beginning, as the storage of thermal energy sequentially starts from upstream. As the temperature of the upstream PCM increases, the steam temperature at the tube outlet also increases. In about 2100 seconds (35 minutes), the two temperatures (i.e., PCM and steam at the tube outlet) will reach a level almost as high as the steam temperature at the tube inlet, which means the completion of heat charging process. At the time of completion, the PCM temperature at the outlet will be as high as or higher than the latent heat range, i.e., 560-580°C. To the contrary, when stored heat is discharged to steam at a temperature of 500°C (Figure 9(b)), the steam temperature at the tube outlet is elevated to approximately 565°C in the beginning. As the PCM temperature decreases as a result of heat discharge, the steam temperature at the tube outlet also decreases. In about 1200 seconds (20 minutes), the PCM temperature becomes almost as low as the beginning temperature level of the inlet steam (500°C), completing the heat discharging process. These results indicate that the use of a metallic PCM can realize the function of quick heat charge and discharge, which is equal or superior to systems using molten salts, etc.

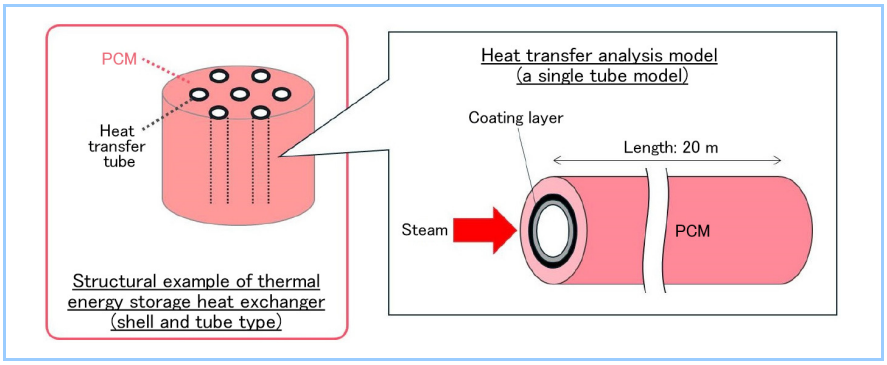


Figure 8 Thermal energy storage heat exchanger and heat transfer analysis model

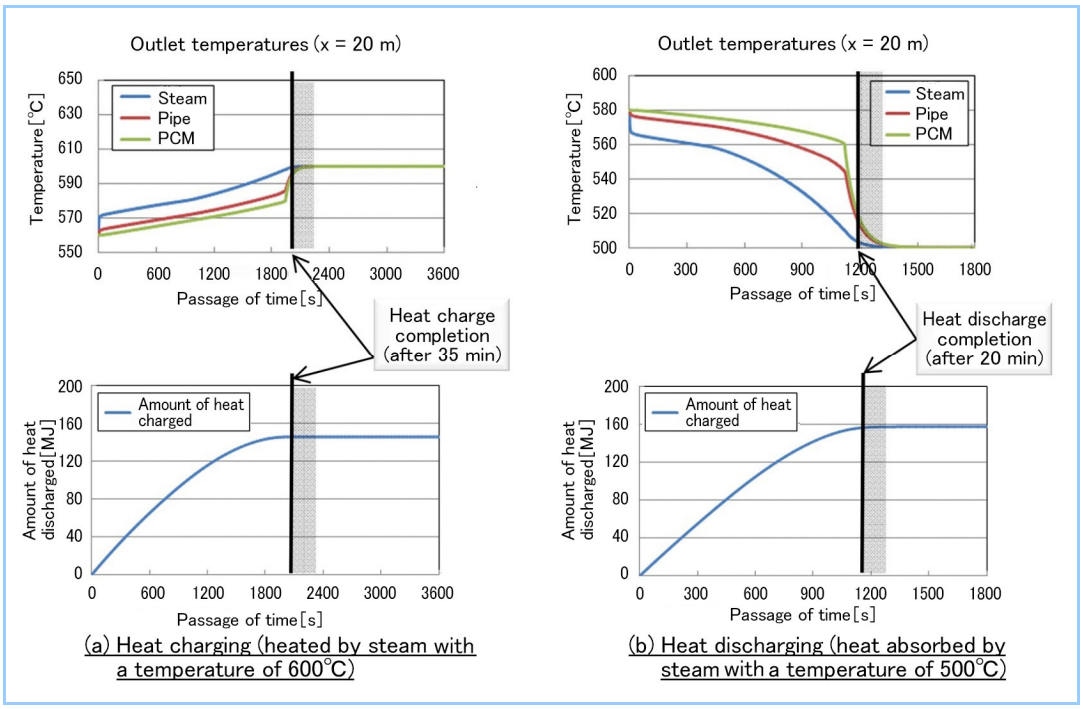


Figure 9 Example of heat transfer analysis using a thermal energy storage heat exchanger with a metallic PCM
(Dynamic behavior of outlet temperatures, etc.)

3.3 Evaluation of the impact on steam/water cycle during heat discharge

Transient response simulation of heat discharge to high-pressure feedwater heater system from heat storage equipment with a medium temperature range (300°C class) was conducted to confirm no occurrence of problems in the power plant steam/water cycle. **Figure 10** gives the results. The behaviors of the generator output, etc., were examined under the conditions in which 15% of the flow rate of high-pressure feedwater was bypassed to the thermal energy storage heat exchanger during the operation at 100% rated load. A transient change in plant behavior is observed soon after the start of heat discharge, which is, however, not problematic to the extent that all the process values remain in their respective permissible ranges. Further examination has also confirmed that after the completion of heat discharge (i.e., [PCM outlet temperature] < [feed water heater outlet temperature]), there is no significant impact on plant behavior even in the case of continued water flow, and the rated output can be maintained.

Simulation will also be planned to examine the transient response to heat discharge during operation in the high temperature range (400-600°C class) and determine the bypass ratio that causes no problematic behavior in terms of the temperature of the boiler heat transfer surface.

As for the heat charging process, operation is conducted according to the concepts that quick valve manipulation should be avoided at the start of heat charge and the steam that has passed through the thermal energy storage heat exchanger is damped to the condenser, so we have therefore concluded that the transient response of the thermal energy storage system has no impact on plant behavior.

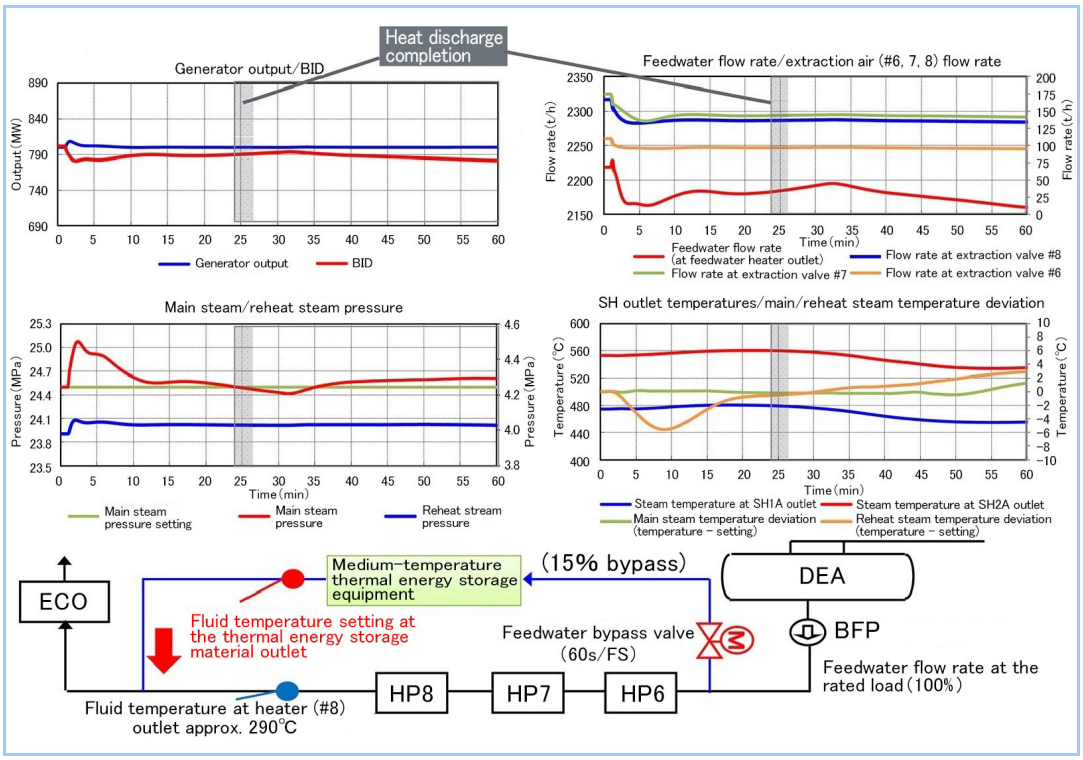


Figure 10 Transient response simulation results during heat discharge (discharge of heat to high-pressure feedwater heater system)

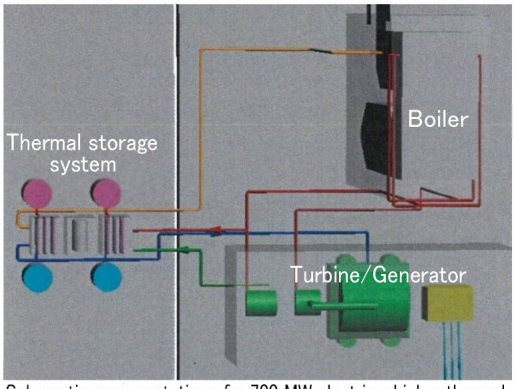
3.4 Development of thermal storage systems and their practical application

In selecting thermal energy storage materials, high heat capacity and high thermal conductivity are desirable properties. However, it is also necessary to ensure the feasibility of the entire system by considering the corrosion potential, corrosion prevention measures and prices.

The reliability of corrosion resistance and coating material soundness (against cracking/ detachment and self-healing property, etc.) must be ensured for thermal energy storage equipment, particularly so if corrosion resistant materials such as metallic PCMs are used for the heat exchanger. With a view to pilot-scale demonstration test in the future, we have started conducting basic tests at our Research & Innovation Center to realize societal implementation in 2025.

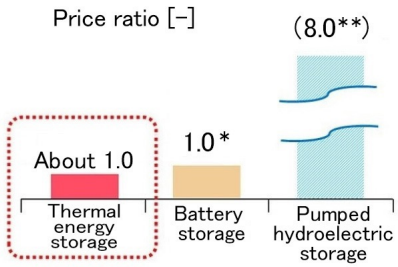
4. Prototype design and economic evaluation

The prototype design to incorporate the thermal storage system into an existing thermal power plant was made and its economic evaluation was roughly conducted. **Figure 11**(a) is a schematic representation with the assumption of using a thermal energy storage material with the same heat capacity as molten salt, which indicates that the system can be successfully installed on the premises of an existing plant. With the use of metallic PCM as a thermal energy storage material, the system can fit in even more compactly. Figure 11(b) compares the price per resultant electricity output of the thermal storage system with those of a battery storage system and a pumped-storage hydroelectric power plant (the value of pumped-storage was estimated very roughly based on a certain assumption about construction cost as a reference). The estimation results show that it is possible to set a price as low as or lower than a battery storage system if development is carried out regarding thermal energy storage systems. It is also worth evaluating whether the economic feasibility of thermal storage systems is further improved by integrating the energy-saving effect (about 2-6%) mentioned in Section 2.3. We will continue to work on the development and practical application to realize its social implementation.



Schematic representation of a 700 MW plant in which a thermal energy storage material with the same property as a molten salt is used for thermal energy storage equipment and it is used to store heat equivalent in amount to 10 % of the rated load for 2 hours (angled overhead view)

(a) Schematic representation of thermal storage system installation



*¥41,000/kWh, the price of a battery storage system with a capacity of 240 MWh (60 MW × 4 h) according to an NREL report: "2018 U.S. Utility-Scale Photovoltaics Plus-Energy Storage System Costs Benchmark." ¥70,000/kWh, the price of Tesla's 100-MWe battery storage system in South Australia in 2016.
**The value for the pumped hydroelectric storage was estimated very roughly based on a certain assumption about construction cost as a reference.

(b) Comparison of the system price ratio per stored energy

Figure 11 Thermal storage system price estimation

5. Conclusion

We reported the result of feasibility study when a thermal storage system is incorporated into a thermal power plant as a measure of providing electric power resilience in the era of the increasing use of renewable energy. This can be realized by installing thermal energy storage equipment in the turbine bypass system and separator drain system. Not only improving the plant's output regulating/reserve capabilities, but also energy-saving effect of about 2-6% can be produced. This energy-saving effect is superior to that of battery storage systems or pumped-storage hydroelectric power generation. With some development regarding thermal energy storage systems, it is feasible that the thermal energy storage system will be made compact enough to be installed on the premises of an existing thermal power plant. From the perspective of economic evaluation, setting a price as low as or lower than a battery storage system is considered possible.

References

(1) RWE, "Sector coupling – a key for the energy transition and security of supply", 12th VGB-TENPES Technical exchange meeting, 26th-29th February, 2019 Tokyo, Japan
(2) Kyushu Electric Power Co., Inc. Data book 2019
(3) VGB-TEPES Technology exchange meeting , Feb. 26. 2019, "Operation of Thermal Power Plants to Accommodate PV Output in Kyusyu"
(4) Müenzinger, Steam Power（Water Tube Boiler and Steam Power Plant）:Friedrich Müenzinger, Dampfkraft: Berechnung und Bau von Wasserrohrkesseln und ihre Stellung in der Energieerzeugung, 2 aufl, Berlin, Julius Springer, 1933）, Japanese translation published in 1938 by Corona Publishing Co., LTD., translator Kenichi Takase
(5) Takahiro Nomura et al., Microencapsulation of Metal-based Phase Change Material for High-temperature Thermal Energy Storage, Scientific Reports, 2015
(6) Hokkaido University, Development of advanced latent heat storage materials for high-temperature thermal energy storage, https://metec.messe-dus.co.jp/fileadmin/essj/uploads/essj_presentations_2017/1108-Tec-4-2-HOKKAIDO_UNIV_-_Mr_Nomura_-_JPN.pdf
(7) Ming Liu et al., Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage system, Renewable and Sustainable Energy Reviews 16, 2012, p.2118-2132
(8) E.Risueno et al., Zinc-rich eutectic alloys for high energy density latent heat storage applications, Journal of Alloys and Compounds, Volume 705, 25 May 2017, p714-721
(9) JikSu Yu, Research for Thermal Storage and Heat Dissipation behavior of Mixed Thermal Storage Material of Erythritol and Mannitol, Graduate School of Natural Science and Technology, Okayama University, 2012