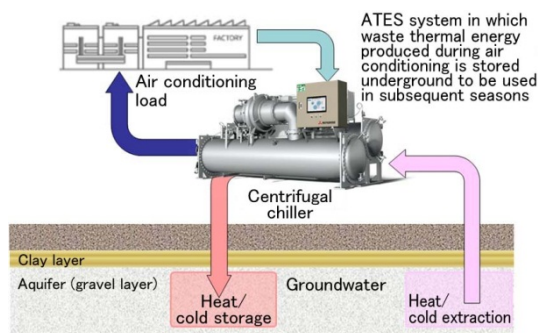


# Centrifugal Chiller System Using ATES (Aquifer Thermal Energy Storage) of Renewable Energy



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*This report introduces Aquifer Thermal Energy Storage (ATES) systems, which utilize renewable geothermal energy. Beneath our feet lies plenty of groundwater stored unused. When compared with the outside air temperature, groundwater is warmer in the winter and cooler in the summer, and therefore is of high value as a heat source or heat sink (cold source). Mitsubishi Heavy Industries Thermal Systems, Ltd. has constructed a heat/cold source system for heating/cooling by using a centrifugal chiller and aquifers with a very low flow of groundwater. The system is comprised of (1) the centrifugal chiller, (2) pumping wells, (3) cold/hot water pumps, and (4) the heat exchanger. Currently in test operation at the time of report publication (April 2017), the system has achieved a coefficient of performance (COP) of 4.77 while heating in the winter with an average outside air wet-bulb temperature (WBT) of 0.15°C.*

## 1. Introduction

This report introduces ATES systems, which use renewable geothermal energy. There is plenty of groundwater retained beneath our feet. When compared with the outside air temperature, groundwater is warmer in the winter and cooler in the summer, and therefore is of high value as a heat/cold source because of this difference in temperature. Thermal energy can be effectively utilized when using aquifers as if they were large heat/cold storage tanks. In the summer, waste heat produced during cooling operations is stored in aquifers and can be used for heating in the winter. Likewise, waste cold during heating operations in the winter is stored in aquifers and can be used for cooling in the summer. In the Netherlands, where the use of groundwater is progressing, ATES systems have been rapidly introduced since 2000, and more than 2,000 ATES plants are currently in operation. On the other hand, such practical applications are scarcely seen in Japan and the technology for the construction of such systems has yet to be established. This report provides an outline of the ATES system that we developed and presents the operating data of the demonstration test facility that we have constructed on the premises of our company.

The results were obtained as part of the Low Carbon Technology Research, Development and Demonstration Program by the Ministry of Environment of Japan.

## 2. What is an aquifer?

**Figure 1** is a diagram of the water cycle and shows how an aquifer forms part of it. Aquifers are underground geological formations in which groundwater is retained. They often refer to porous, permeable layers of sand and gravel, sandwiched between layers of impermeable materials such as clay. In these aquifers, the permeability is sufficient to secure the necessary supply of water in the well. In addition, when the flow of groundwater is slow, it can be used as a medium to store thermal energy.

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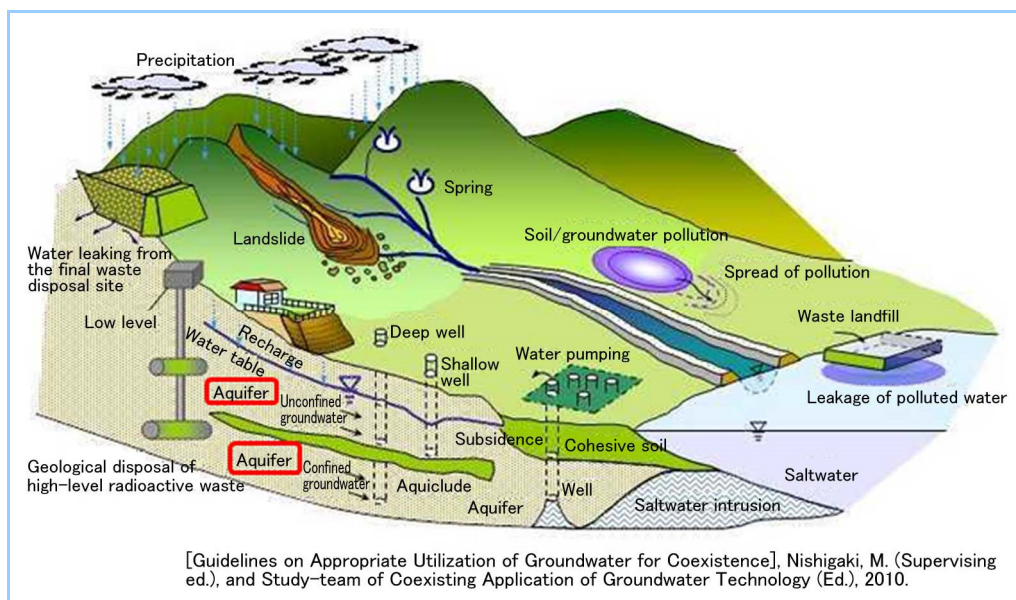


Figure 1 Diagram of the water cycle and the siting of aquifers

### 3. ATES system

#### 3.1 High-performance centrifugal chiller

The cooling/heating mechanism of the centrifugal chiller is shown in **Figure 2**. The operating mode can be switched between heating and cooling. In heating mode, the hot water temperature at the outlet of the condenser (i.e., the temperature supplied for heating) is kept constant. In cooling mode, on the other hand, the cold water temperature at the outlet of the evaporator (i.e., the temperature supplied for cooling) is kept constant.

**Figure 3** shows the exterior view of the centrifugal chiller (ETI-Z20), in which HFO (HFO-1233zd(E)) is used as the refrigerant. HFO has zero ozone depletion potential (ODP) and a GWP of 1 (i.e., equivalent to that of CO<sub>2</sub>, a natural refrigerant).

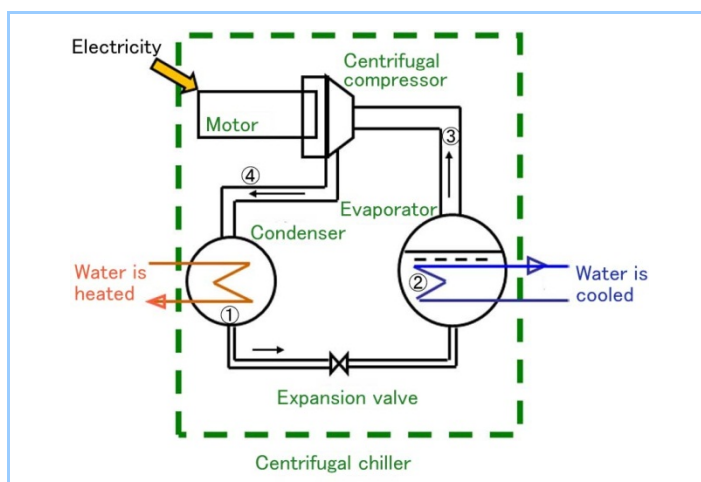


Figure 2 Cooling/heating mechanism of centrifugal chiller

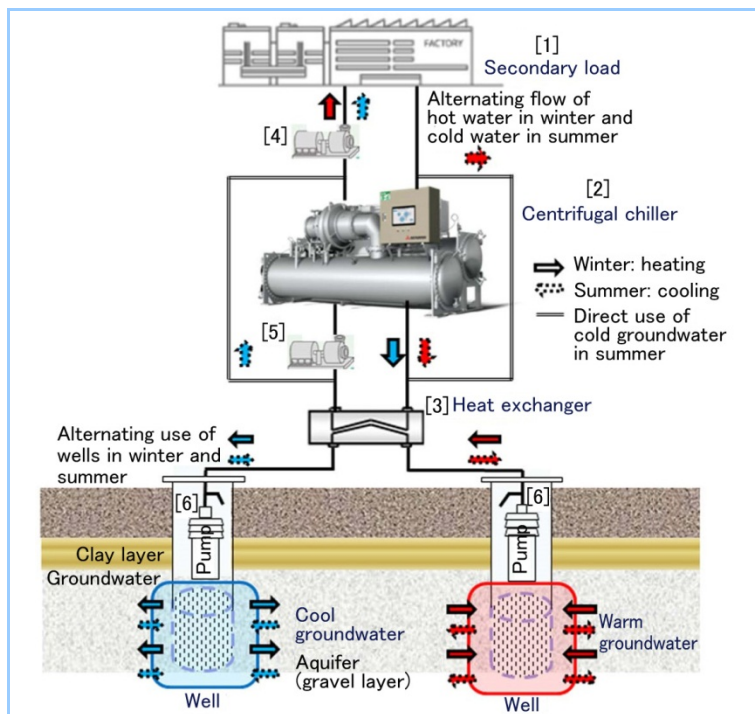


Figure 3 The centrifugal chiller used in our ATES system

### 3.2 ATES system

**Figure 4** shows the outline of our ATES system.

- The ATES system consists of [1] the secondary load (cooling/heating of air in the building), [2] the centrifugal chiller, [3] the well-water heat exchanger, [4] the cold/hot water pump for circulation between [1] and [2], [5] the water coolant pump for circulation between [2] and [3], [6] the well pump to extract or inject groundwater into the well and the electrical facilities for the compressor motor of the centrifugal chiller and pumping motors.
- In the winter, warm groundwater (e.g., 25°C) in which waste heat has been stored is pumped up from the aquifer. Using it as a heat source, the centrifugal chiller (operating in heating mode) produces hot water (45°C), which is then used for heating the building. Having provided heat, the temperature of the groundwater decreases and cool groundwater (15°C) is injected back into the aquifer, where cold thermal energy is stored.
- The cool groundwater in which cold thermal energy is stored stays without flowing away in the subsurface from winter until summer (when the flow of the groundwater in the aquifer is slow).
- In the summer, the flow of groundwater between the two wells is reversed. Groundwater is pumped up from the aquifer into which cool groundwater was injected in the winter. Using it as a cold source, the centrifugal chiller (operating in cooling mode) produces cold water (7°C), which is then used for cooling the building. Having received heat, the groundwater temperature increases and warm groundwater (25°C) is injected back into the aquifer, where heat is stored.
- If the temperature of the groundwater injected back into the aquifer as cold thermal energy storage in the winter can be lowered (to as low as 6°C), cold groundwater extracted from the aquifer in the summer can be directly used for cooling the building without operating the centrifugal chiller.
- The ATES system can be operated throughout the year, by alternating the operating mode between winter (heating and cold thermal energy storage) and summer (cooling and heat storage or the direct use of cold groundwater).



**Figure 4 Outline of the ATES system**

## 4. ATES systems are effective in mitigating the heat island effect and conserving water resources

In general air-conditioning systems, heat is released to the outside while cooling a room. Such heat in the summer is considered to be a cause of the heat island effect<sup>(Note)</sup>. The heat island effect increases cooling demand, which in turn increases the amount of waste heat released from



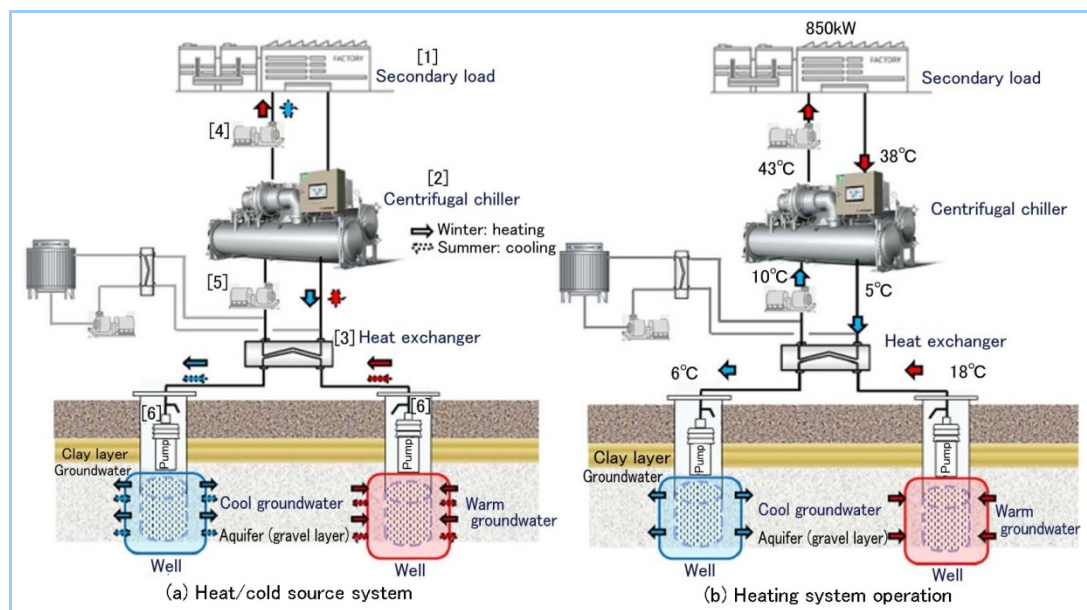
buildings, thus establishing a vicious circle. However, the ATES system introduced in this report, releases no waste heat in the summer or waste cold in the winter to the air. Instead, it uses groundwater to store heat/cold for several months, and the stored thermal energy can be collected when needed in a different season. Therefore, it can contribute to mitigating the heat island effect. For cooling in the summer, the cooling tower is incorporated as part of the cold source system. Because the water coolant evaporates to release heat to the air in the cooling tower, a certain amount of water has to be supplied during operation. However, no water is needed for the ATES system in operation, when the waste cold is extracted and can be used for this purpose.

(Note) A phenomenon of urban area warming due to waste heat generated by the massive consumption of energy by cars, buildings, etc., as well as reduced green space and natural surfaces.

## 5. Demonstration test

An ATES system was constructed at MHI's Takasago Machinery Works, with a 700 kW centrifugal chiller and a space of 4,000 m<sup>2</sup> to be heated or cooled. Conventionally, a single well is assigned for groundwater extraction, while a few wells are needed for groundwater injection. However, using only a single well for groundwater injection, we have made it possible to switch wells between extraction and injection. The well pumps have a rated capacity of 70 m<sup>3</sup>/h (max. 100 m<sup>3</sup>/h) for groundwater extraction/injection. Groundwater is continuously pumped up in large quantities and is then injected back immediately after being used as a heat/cold source. Although groundwater is conveyed around within a certain area, there will be no environmental issues such as subsidence. The flow diagram of the heat/cold source system is given in **Figure 5a**. **Figure 6** is a photo of the wells. The specifications of centrifugal chiller are shown in **Table 1**.

The demonstration test (for heating) in combination with the centrifugal chiller started in February 2017. Figure 5b is a diagram of the heating system operation. It is designed to keep the temperature of hot water to the factory at 43°C and the temperature of the groundwater injected back into the well at 6°C.



**Figure 5** Flow diagram of the heat/cold source system and heating system operation



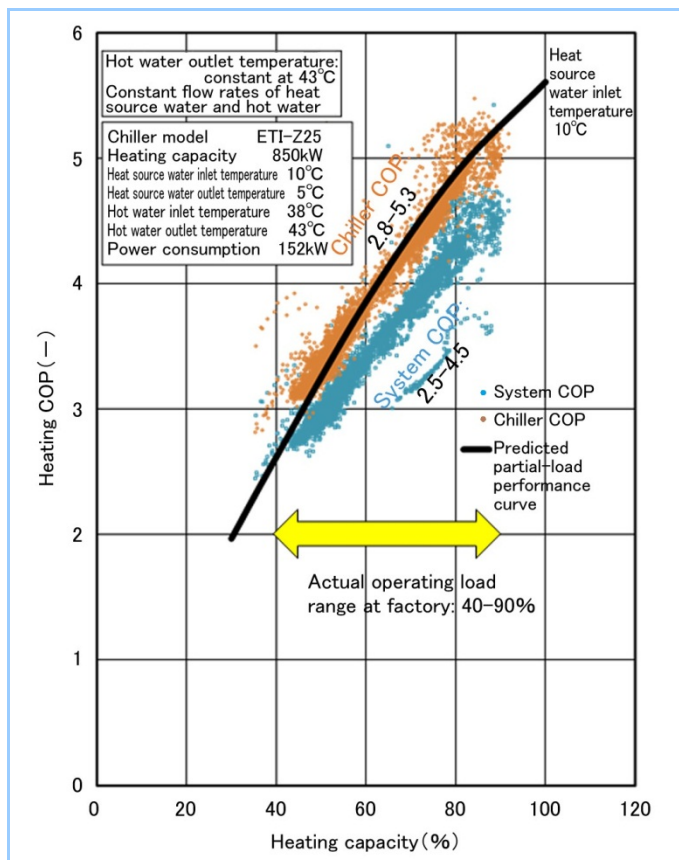
**Figure 6** Photo of the well

**Table 1 Specifications of centrifugal chiller**

Centrifugal chiller model: ETI-Z25

Specifications	Cooling	Heating	Unit
Capacity	703.3	850	kW
Condition for supply	10→5	38→43	°C
Supply flow rate	120.9	146.2	m <sup>3</sup> /h
Heat/cold source water condition	32→37	10→5	°C
Flow rate of heat/cold source water	141.3	120.5	m <sup>3</sup> /h
Power supply voltage	3φ/400		V
Power consumption	122	152	kW

The COP of the heat source equipment and of the whole system after reaching the desired temperatures ( $43^{\circ}\text{C} \pm 1^{\circ}\text{C}$  for supplied hot water and  $6^{\circ}\text{C} \pm 3^{\circ}\text{C}$  for injected groundwater) in heating are shown in **Figure 7**. The thermal load ranges from 40% to 90%. The system COP fluctuated in the range between 2.5 and 4.5. With regard to the heat pump COP, the difference between the predicted partial-load curve and the measured values roughly fell within 10%.

**Figure 7 Heating operation data (February 3-21, 2017)**

**Figure 8** shows the change in outside air WBT during the period of heating operation. The lowest outside air WBT in the daytime was observed on 11 February ( $2.4^{\circ}\text{C}$  WBT at 13:38). The operating data is given in **Figure 9**. The average outside air WBT of this day was  $0.05^{\circ}\text{C}$ .

Unlike multi-split building air conditioners or air source heat pumps, water is the heat source of our ATEs system, which is warm enough not to freeze. Therefore, the temperature inside the factory increased sufficiently in about an hour after start-up and the hot water reached the rated temperature of  $43^{\circ}\text{C}$ . The supply of hot water remained stable until the time of shutdown. The hourly-averaged system COP achieved the maximum value of 4.77 after reaching the rated temperature of  $43^{\circ}\text{C}$  (load factor: 81%, 10:00 a.m.,  $0.15^{\circ}\text{C}$  WBT).

To prepare for the test on the direct use of cold groundwater in the coming summer, the temperature of the groundwater injected back into the well is set at  $6^{\circ}\text{C}$ . We will examine how much cold thermal energy stored in  $6^{\circ}\text{C}$  groundwater can be recovered in the summer, and how the efficiency can change with the varying temperature of the groundwater in the aquifer.

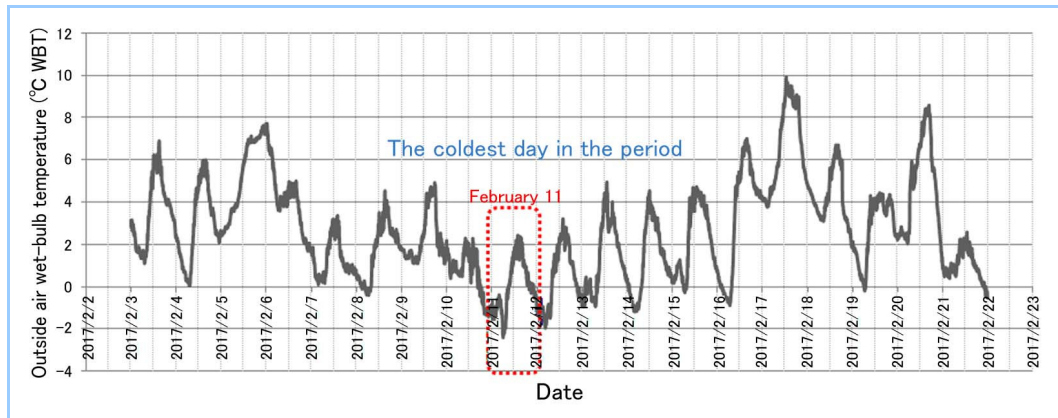


Figure 8 Outside air temperature change over time (February 3 to 21, 2017)

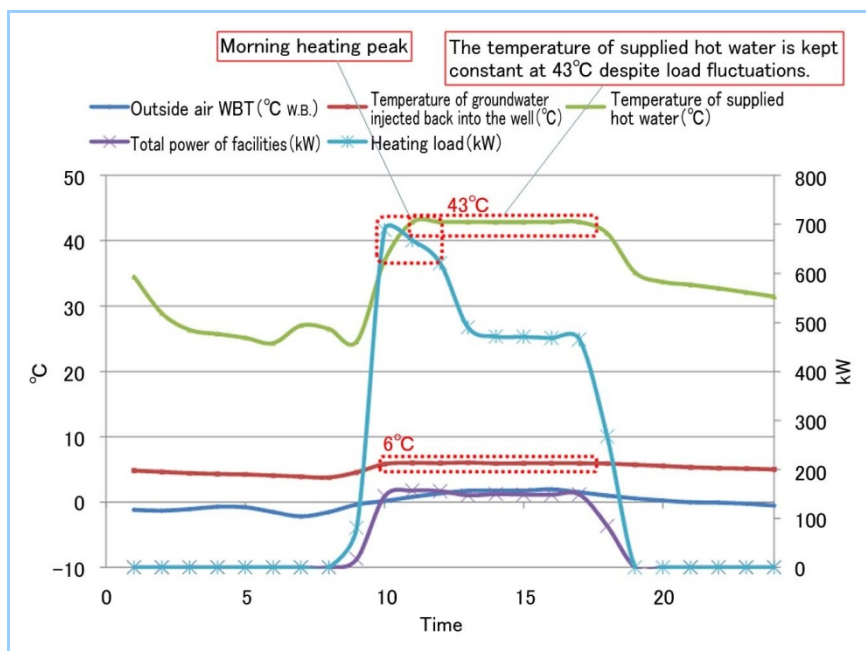


Figure 9 Heating operation data (February 11)

## 6. Conclusion

We have constructed an ATES system for cooling/heating operations, in combination with a high-performance inverter centrifugal chiller. Conventionally, the centrifugal chiller is used only in cooling for freeze protection of the cooling tower in the winter. However, the use of the centrifugal chiller for heating eliminates the need for boilers, realizing high efficiency and the conservation of energy and water throughout the year. Thus, it is very beneficial to use the centrifugal chiller for heating, in addition to its main use for cooling. We tested the ATES system in heating mode and, as expected, an hourly-averaged system COP of 4.77 was achieved under the rated operating conditions with the average outside air WBT of 0.15°C.

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