# ESTABLISING OPTIMAL HEAT PUMP SYSTEM WITH WATER THERMAL STORAGE - SIMULATION ALGORITHM OF TES_ECO AND PERIPHERAL TOOLS -

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**Abstract:** Optimized heat pump system will be defined by minimum energy consumption and minimum CO2 generation within reasonable cost in life-cycle basis. Either with or without thermal storage system is one of the factors to be evaluated as well as combination of kind of heat pumps. The cost as well as the indoor environment shall be the constraint at optimization process. Combination of the dynamic simulations for annual heating and cooling load estimation and thermal storage behavior with static parameter analyses for heat pumps and auxiliary equipments included in HVAC system, the performance of which are affected by varying outside-air conditions and variable flow-rate and temperature difference, will give satisfactorily correct results for decision making. TES_ECO that is provided by Heat Pump & Thermal Storage Technology Center of Japan is based on this philosophy and developed as an optimal system selection tool of heat pump with thermal storage system. Excluding the multi-split type air conditioning system, TES_ECO can calculate the performance of variable HVAC systems. The present paper introduces outline of the program and user-friendly interface.

**Key Words: simulation, thermal storage system, heat pumps**

## 1 INTRODUCTION

In recent years, global warming is becoming serious more and more and reducing emission of carbon dioxide has become an urgent issue. The HVAC is a principal energy consuming system in buildings, while such technologies as heat pumps and water thermal storage are very effective to reduce energy consumption. However, it is not easy to choose an optimized system among options, which minimizes energy consumption. In this situation, simulation programs have been developed to study how to select optimized heat generating systems by HPTCJ, Heat Pump & Thermal Storage Technology Center of Japan. The HPTCJ is actively engaged in the promotion, survey, research and investigation of heat pumps, thermal storage and other technologies on which they are based, and it also participate actively in international projects, in the role of Japan's only national center devoted to heat pumps and thermal storage systems. The present paper describes the outline of the program and results of example calculation.

## 2 THE NEED FOR SIMULATION SOFTWARE

There are a number of air conditioning systems and also various energy choices such as electricity, gas and oil. The capital cost, operating cost, carbon dioxide emissions, etc. are used as evaluation indices of air conditioning systems, because of which selection of the most proper energy plant and HVAC system to satisfy the requirements of the owner as well as the social needs is very difficult. An optimal system design will be effectively established using some proper simulation programs. In order to respond the needs of the industry, a series of simulation programs were developed by the authors as the committee woks in HPTCJ, which are to be explained in the following chapters.

## 3 THE CONSTRUCTION OF SIMULATION PROGRAMS

In the beginning respective roles of each program and relationship among them are described. Table 1 shows the name and role of each developed program. There are three kinds of programs which are used for planning, design and evaluation for HVAC systems, focusing on the energy generating plant. As the table1 indicates, the purpose of these three programs is different; however, they are used in cooperation with each other at the planning and design phases of the HVAC plant design, as shown in Figure1. These programs are particularly useful tools to design optimal HVAC plant with water thermal storage system. It is of course that they can be also effectively used for studying conventional plant without thermal storage and/or with cogeneration systems. However, multi-split type of air-conditioning system, or VRV system, is not supported.

**Table 1: Name and role of the developed program**

| Name | Role of the program |
|---|---|
| MicroHASP/TES | To calculate the annual heating and cooling load |
| TESEP-W | Optimal design of water thermal storage systems |
| TES_ECO | Calculation of the annual energy consumption, CO2 emission and economic efficiency of air conditioning systems |

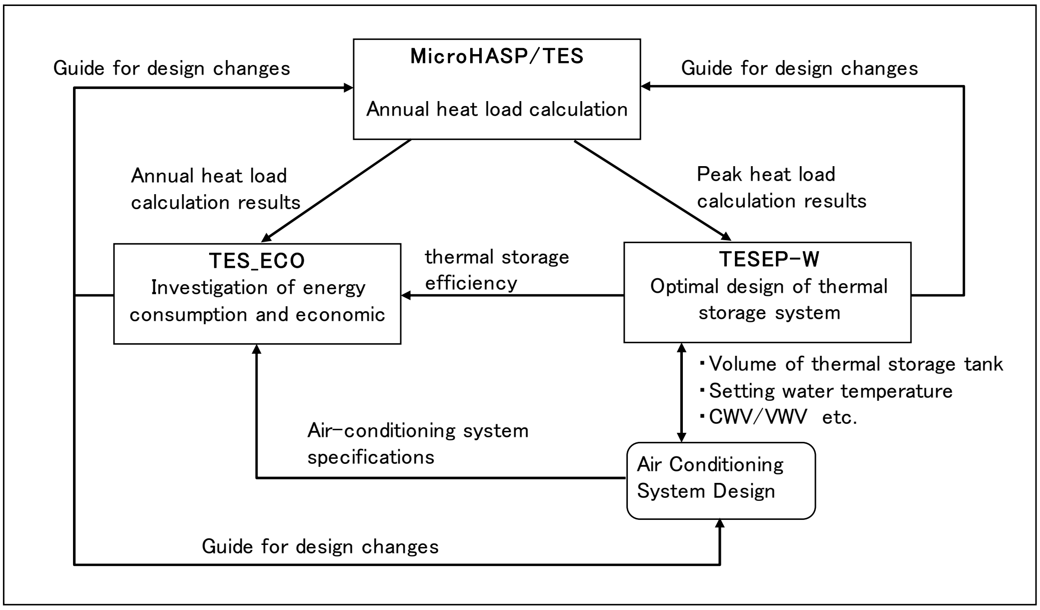


**Figure 1: Relationship among three programs in HVAC plant system design**

## 4 EXPLANATION OF SIMULATION PROGRAM

The contents of the three programs are described here indicating typical windows. Unfortunately, English versions of these programs are not available for the present, so that excuse us for just showing Japanese screens.

### 4.1 Micro HASP/TES

The MICRO-HASP, the annual dynamic cooing and heating load calculation program that had been developed in MS-DOS environment using N88 Basic was transferred into Windows version using Visual Basic, which has a user-friendly GUI. Figure2 shows an example of input screen. The program also made the following improvements.
(1) Enabled to utilize optional weather data based on the newest meteorological measurement system, AMeDAS.
(2) Enabled to adjust the partial internal activities to compute annual energy demand as precisely as possible
(3) Peak cooling and heating loads are also determined based on the annual calculations with scheduled internal conditions for peak demand and then selected applying environmental TAC method, which is based on the risk percent excessive loads during designated interval of summer and winter seasons in day and time basis.
(4) Integration effect on room temperature variations between perimeter and interior zones during the nighttime is considered.
(5) The device, i.e. the heating and cooling coil, capacity at the peak demand day and the time at the non-peak days are optimized to determine minimum available capacity and preparation time length for energy conservation as well as economical design.
(6) Energy saving effect of outside-air intake control, including economizer, is estimated at the phase of load calculations, which could assist determining HVAC control systems.
(7) Calculation results are displayed in tables and graphs using Microsoft Excel tool.
(8) Output load data which can be used by TESEP-W and TES_ECO


**Figure 2: Example of input screen specifying room properties**

## 4.2 TESEP-W

TESEP-W (Thermal Energy Storage Estimation Program-Water) was developed to simulate water thermal storage HVAC systems originally developed by the author (Nakahara) with Basic language based on his study (Nakahara et al.1982, 1988). This program can be utilized for the three prototypes of water thermal storage tanks, which are multi-connected complete mixing tanks, single or multi-connected temperature-stratified tanks, and self-balanced temperature-stratified tanks. It helps operators/designers improve efficiency of water thermal storage systems.

Figure3 shows an example of input screen. The primary input items are cooling or heating peak load, type of thermal storage tank, HVAC and plant system control, water temperature condition, schedule of heat source operation and heat loss through corresponding tank.

Figure4 shows an example of the transient output screen. The variables shown are the thermal storage tank volume and heat source capacity as supposed condition for the present calculation cycle, and water temperature in the tank, outlet temperature variation to the HVAC secondary circuit, temperature profile and heat balance in transient calculations. The advantage of this program is useful not only for design but also for understanding the property of the thermal storage tank system and methods of maximing tank efficiency in volumetric sense, because the temperature profiles are shown at every time step in computation, operators are able to understand the dynamic state of temperature variations in the tank. However, it should be noted that the user of this program should prepare cooling and/or heating load of a peak day using proper load calculation program such as Micro HASP /TES as described in the previous chapter.  Calculation of energy consumption is not this program's role, either.

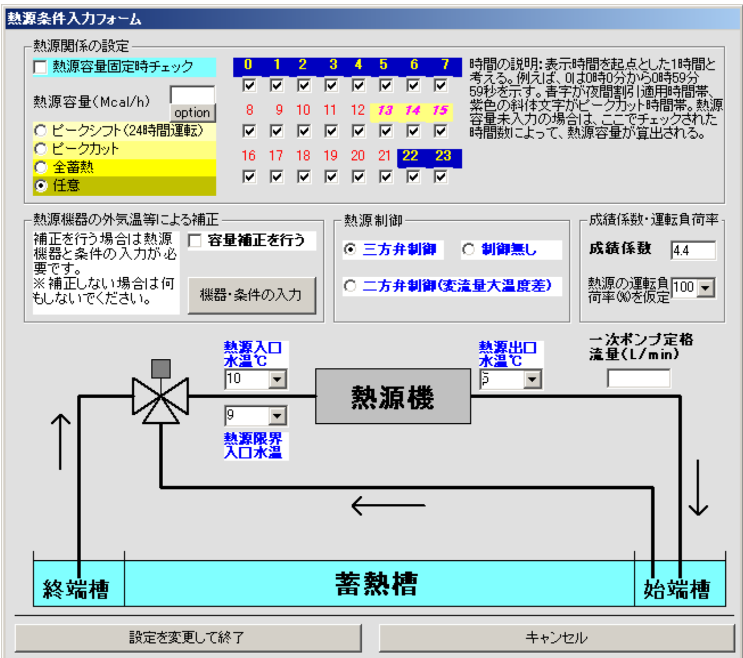


**Figure 3: Example of input screen for temperature condition and schedule of heat source**

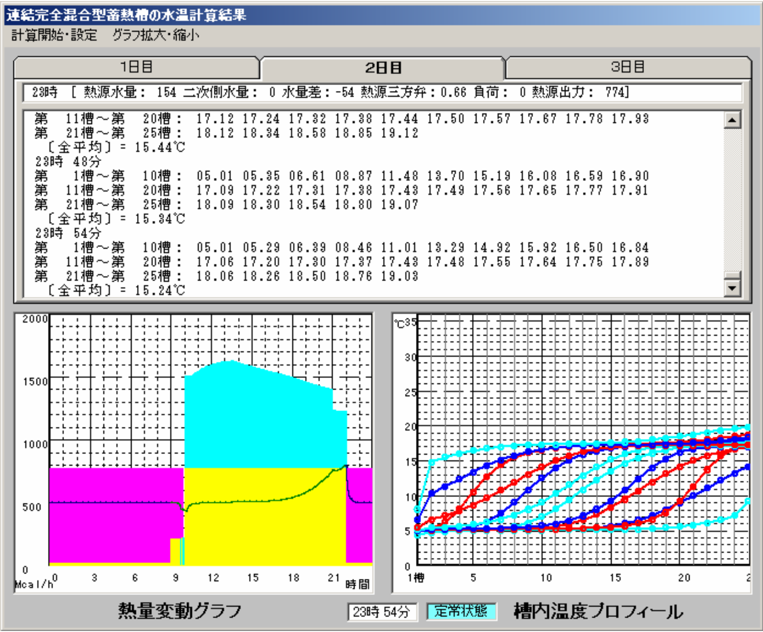


**Figure 4: Example of transient output screen for water temperature profile in the tank**

## 4.3 TES_ECO

Calculation of annual energy consumption of HVAC energy plant is very important to judge the cost and environmental performance. However, it is not easy to compute it when we wish to introduce several performance factors and parameters specific to each assemble and the system. TES_ECO was developed to solve the problem and it calculates annual energy consumption, CO2 generation, annual cost and system COP and so on. Basically calculations are performed in static but cooling and heating load as well as the water thermal storage tank was optimized by dynamic simulation beforehand as described in the previous chapter.

TES_ECO can calculate variety of HVAC energy plant systems except for multi-split type air conditioning system, or VRV, and HVAC energy saving methods such as VWV and VAV can be selected. Due to availability of TES_ECO that can evaluate wide range of system variations users/designers can compute and evaluate annual performance of energy consumption, CO2 generation, cost and system COP among various options, i.e., capacity combination of electricity- and gas- driven heat pumps, either constant or variable speed of high performance heat pumps with or without thermal storage and the effects of variable water pump and fan speed control for chilled water, cooling water and cooling tower. The calculation results gives a informative guidance of decision making for system selection at the program phase of construction process on what factors should be taken into account for the given project that has peculiar project requirement according to the building use as well as the building or site scale.

Figure5 shows an example of input screen for planning HVAC. Energy plant Items on the screen are generators for co-generation, boilers, chillers, heat pumps, thermal storage tank, pumps, heat exchangers and headers. Users/designers can choose any items constituting the energy plant he wants to include. Figure6 shows an example of output screen of heat balance between cooling load and chiller output. Since calculations are running 24 hours, 365days, it is possible to confirm whether each unit was operated as expected or not. Energy consumption calculation is done every hour for a whole year.

Detailed data, such as input and output, COP or efficiency and partial load characteristics, concerning determining actual capacity and efficiency for corresponding system parameters and weather conditions shall be inputted in order to meet variations of annual conditions.
In the calculation of the water thermal storage system, the optimum operating time zones of heat source are to be determined to increase the power consumption of nighttime in order to maximize the use of cheap electric rate during the night-time by shifting the daytime peak electric demand to the night-time.

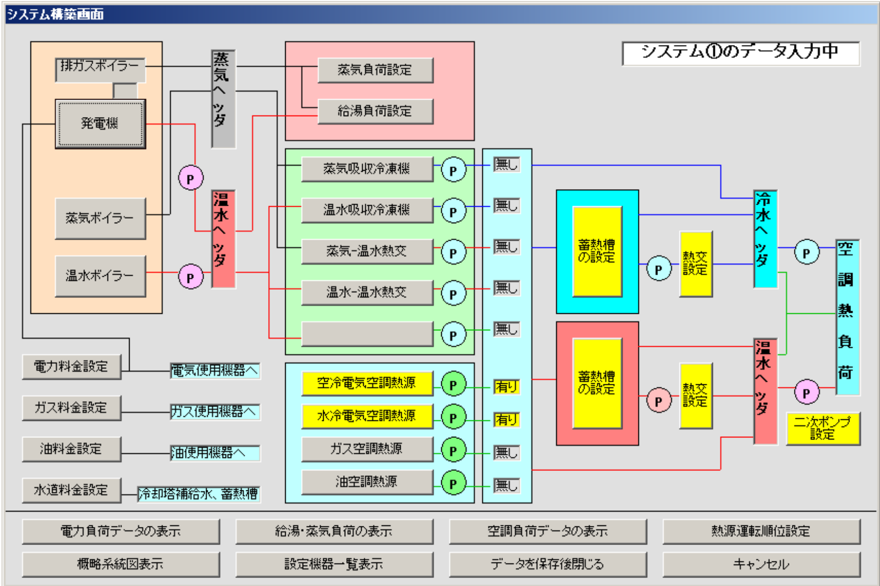


**Figure 5: Example of input screen for planning energy plant**

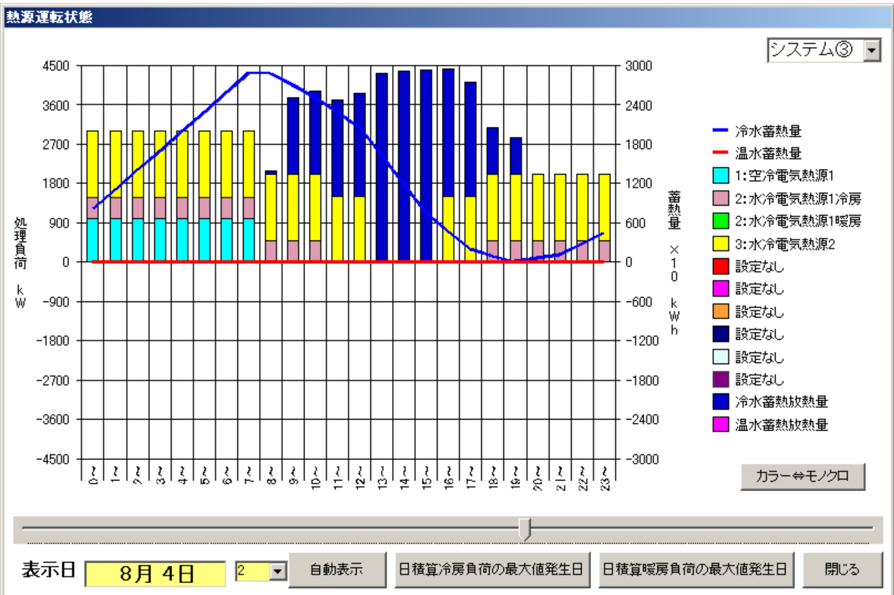


**Figure 6: Example of output screen of heat balance**

# 5 CALUCULATION EXAMPLE USING TES_ECO

## 5.1 Model Building and System Options

Calculation examples using these programs are described in the followings. The model building to be calculated is a large scaled office building located in Tokyo. The buildings has 30 stories above the ground, lower levels of floors are for the commercial establishment, and higher levels of floors are for the office usage. The total floor area of the building is 55,386m2. The annual load calculation was executed using Micro HASP/TES. The annual load profile proved existence of cooling demand throughout a year. Table2 shows the outline of cooling and heating energy plant options of the model building. Four systems without thermal storage and four other systems with water thermal storage were examined. The capacity of heat pumps and water tank are calculated using TESEP-W.

**Table 2: Outline of cooling and heating energy plant options of model building**

<table>
<tr><th></th><th>Sign</th><th>Energy plant system</th></tr>
<tr><td rowspan="4">Non thermal storage system</td><td>NS-1</td><td>Water cooled centrifugal refrigerating machine ,<br>Air source screw heat pump</td></tr>
<tr><td>NS-2</td><td>Variable frequency driven, water-cooled centrifugal refrigerating machine<br>Air source screw heat pump</td></tr>
<tr><td>NS-3</td><td>Gas direct-fired absorption water chiller</td></tr>
<tr><td>NS-4</td><td>Variable frequency driven, water-cooled centrifugal refrigerating machine<br>Gas direct-fired absorption water chiller</td></tr>
<tr><td rowspan="5">Water thermal storage system</td><td>S-1</td><td>Water-cooled centrifugal refrigerating machine ,<br>Air source screw heat pump<br>Chilled and heating water thermal storage tank</td></tr>
<tr><td>S-2</td><td>Variable frequency driven, water-cooled centrifugal refrigerating machine<br>Air source screw heat pump<br>Cold and hot water thermal storage</td></tr>
<tr><td>S-3</td><td>Variable frequency driven, water-cooled centrifugal refrigerating machine<br>Water source heat recovery heat pump<br>Chilled and heating water thermal storage tank</td></tr>
<tr><td>S-4</td><td>Variable frequency driven, water-cooled centrifugal refrigerating machine<br>Gas direct-fired absorption water chiller<br>Chilled water thermal storage tank</td></tr>
<tr><td colspan="2">Type of water thermal storage is temperature stratification model.<br>Summer : cold water tank : 435m3×6<br>Winter : Chilled water tank : 435m3×3 heating water tank : 435m3×2</td></tr>
</table>

## 5.2 Calculation Results of Energy Consumption

Figure7 shows the calculation results of annual energy consumption of each system. According to the calculation results, the annual energy consumption of S-2 system is the smallest, but differences among NS-2, S-1, S-2 and S-3 are so small that the order may be changeable according to the annual load profile, characteristic curves of machines and selection of peripheral machines such as pumps and cooling towers. Differentiating factors of energy consumption between S-1 and S-2 depends not only on the difference of heat source but also on the difference of lower limit of the allowable cooling water inlet temperature, because the value was set at 18℃for S-1 but at 13℃for S-2, which were specified by each manufacturer.

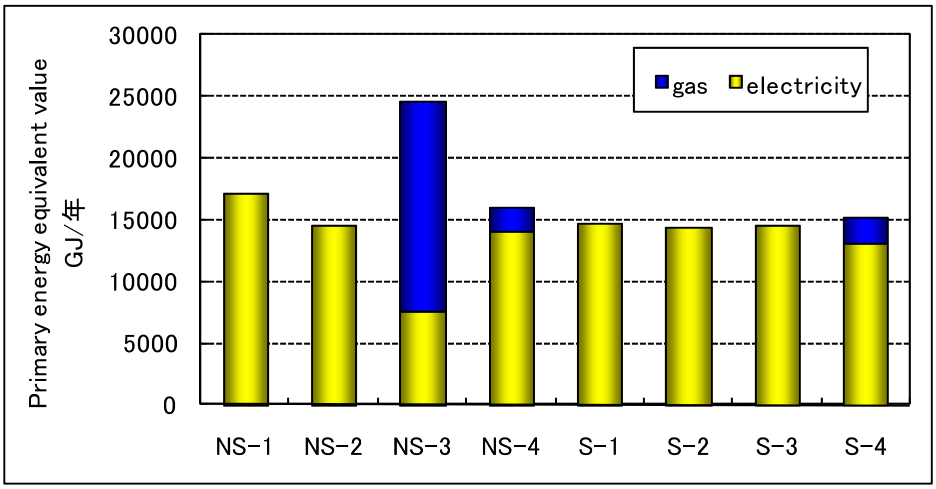


**Figure 7: Calculation results of energy consumption of each system**

### 5.3 Evaluation of Advantage of VFD Chillers for Thermal Storage System

Another examination is evaluation of the energy efficient effect of variable frequency driven centrifugal refrigerating machine applied to HVAC energy plant with water thermal storage. In the thermal storage system, the heat source usually drives at full capacity which is a method to achieve energy savings, as the conventional chiller efficiency is maximum at the full capacity, that operation hours are shortest that achieves minimum pump energy consumption and that it realize maximum power shift from daytime to night-time.

However, as the figure8 indicates, the coefficient of performance of inverter-motor driven centrifugal refrigerating machine, to be called shortened as VFD chiller, improves when it works at a partial load, if the cooling water temperature is sufficiently low in winter and intermediate season as well. This example is to verify if the full-capacity-operation principle for thermal storage system is still correct. Calculation conditions that the VFD chiller can drive at partial load are set as follows. It can only drive at the partial load on the day when;
(1) all the cooling load during the daytime, 8:00~22:00, can be treated only by thermal storage without any duplicated operation of chillers and cooling load.
(2) the chiller does not need to work over ten hours night operation mode
(3) total power consumption, the sum-of the chiller, chilled water pump, cooling water pump and cooling tower fans, at the partial load operation mode becomes less than that of the full load operation mode.

Figure9 shows different operation mode for a typical day of the intermediate season, i.e., the full load and three different partial load operations. As the figure indicates, when the chiller operation is prolonged by the partial load operation, the driving time is also prolonged so that the power consumption of pumps and cooling tower fans increase. Table3 shows results of the effect of VFD chiller applied to water thermal storage system. The effect of the reduction of annual power consumption was small, even though advantage of VFD is found. The reason may be that the operation mode when the condition (1) is fulfilled is not so many and that the power consumption increase by prolonged operation of pumps and fan is larger than decrease of chiller energy.

Also, it should be remembered that simulations suppose the ideal control where the partial load operation is only accomplished when the consumed energy is calculated less than that of full load operation, which needs precise load predicted optimal control. Therefore, in actual operation, little control misjudgement can easily lose the advantage of less energy of approximately two to four percent as shown in the table.

In conclusion, the full-load-operation principle in thermal storage operation still proves correct, even if highly efficient VFD chillers are available, considering the actual background of optimal control development to achieve the accuracy of the simulation level.

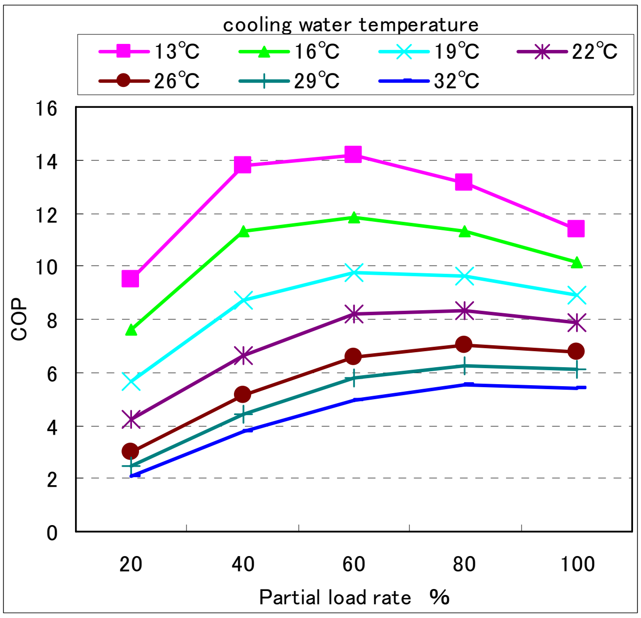


**Figure 8: Characteristic of the coefficient of performance of inverter-motor driven centrifugal refrigerating machine**

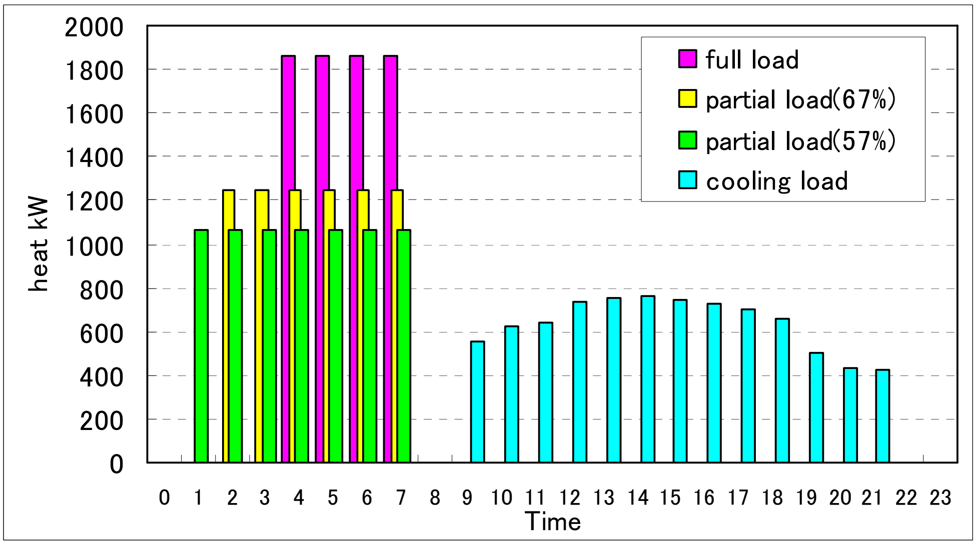


**Figure 9: Type of operation by the partial load driving of the inverter turbo**

## 6 CONCLUSION

Simulation programs for optimization of water thermal storage system with evaluation of energy, cost and global environment viewpoints were introduced. Some examples to demonstrate their usability were explained, through which advantage of thermal storage system as the HVAC energy plant was also introduced. The authors appreciate the contribution by HPTCJ committee members on developing the present simulation tools.

**Table 3: Results of effect of variable frequency driven turbo refrigerating machine applied to water thermal storage system**

| S-2(Standards) | | Partial load operation of variable frequency driven turbo refrigerating machine | | | |
|---|---|---|---|---|---|
| Chilled water pump | CWV | VWV | CWV | VWV | CWV |
| Cooling water pump | CWV | CWV | VWV | VWV | CWV |
| Unit | kWh | kWh | kWh | kWh | kWh |
| Air source heat pump | 226,966 | 226,966 | 227,047 | 226,966 | 226,966 |
| Chilled water pump | 31,201 | 31,201 | 31,230 | 31,201 | 31,201 |
| Variable frequency driven turbo refrigerating machine | 953,016 | 918,868 | 945,913 | 941,433 | 919,182 |
| Chilled water pump | 53,578 | 50,814 | 54,648 | 51,215 | 57,755 |
| Cooling water pump | 110,136 | 119,504 | 84,024 | 71,204 | 118,724 |
| Cooling tower | 34,454 | 37,385 | 35,142 | 37,085 | 37,140 |
| Cooling and hot water pump | 70,101 | 70,101 | 70,101 | 70,101 | 70,101 |
| Total(kWh) | 1,479,452 | 1,454,839 | 1,448,105 | 1,429,205 | 1,461,069 |
| Primary energy equivalent value (GJ) | 14,439 | 14,199 | 14,134 | 13,949 | 14,260 |
| Reduce rate (%) | 100 | 98.3 | 97.9 | 96.6 | 98.8 |

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