# Energy Simulation Technologies for Optimization of Social Infrastructure

Yasushi Tomita
Tatsuki Inuzuka
Tsutomu Kawamura, Dr. Eng.
Michiki Nakano

*OVERVIEW: The need for energy infrastructure that has low carbon emissions, is economical, and provides security of supply is increasingly evident. This has created a demand for energy infrastructure with system-wide optimization achieved through the coordination of district heating and cooling systems and wide-area power systems from consumer utility systems. Hitachi is implementing multi-utility energy infrastructure with system-wide optimization through the lifecycle of the infrastructure by fusing various different energy analysis and control techniques for energy efficiency and power system control aimed at districts or factories and other buildings.*

## INTRODUCTION

THROUGHOUT the world, energy infrastructure faces demands for lower carbon emissions through the greater adoption of renewable energy, electric vehicles (EVs), and other new technologies; for economic performance in the face of rising fuel prices and the increasing cost of complying with carbon emission reduction measures; and for security of supply in the event of large power outages or earthquakes.

Energy infrastructure is built through the interconnection of different systems. These include power systems that supply consumers over a wide area with electric power from centralized power plants, district heating and cooling systems that supply the consumers in a community with hot or cold water from a centralized heat source, and utility systems at consumer sites that produce hot and chilled water, steam, and other utilities from primary energy sources. Recent years have seen increasing moves aimed at creating energy infrastructure in which these systems are coordinated to optimize overall operation.

Hitachi has been implementing multi-utility energy infrastructure with system-wide optimization throughout the lifecycle of the infrastructure by enhancing and fusing measures that it has built up over time, such as energy analysis and control techniques for power system control and energy efficiency at the district level or at factories and other buildings (see Fig. 1).

Simulation technologies essential to the development of these total solutions include a smart grid simulator that can perform flexible analyses of the interactions with consumers, particularly in regard to power systems, a district energy system simulator for the optimum control of multi-utility networks for district heat and electric power, and a simulator for analyzing the energy efficiency of utility systems for use in the energy-efficient design of multi-utility systems for consumers.

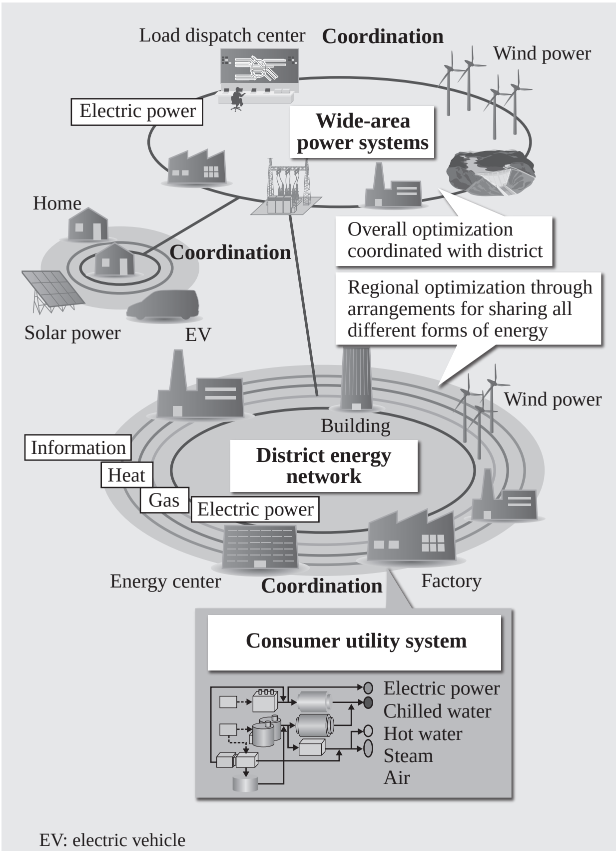


*Fig. 1—Energy Infrastructure.*
*The energy infrastructure is built from the interconnection of wide-area power systems, district energy networks, and consumer utility systems.*

This article describes simulation technologies that support the design, control, diagnosis, maintenance, and repair lifecycle of energy infrastructure, with a scope that extends from consumers to districts and power systems.

## SMART GRID SIMULATOR

### Overview

Smart grids are seen as representing the next generation of electric power distribution systems for supporting the creation of a low-carbon society and the highly efficient supply of electric power while also maintaining security of supply. For example, the greater diversity of power sources and loads, such as the increasing connection of renewable energy to the grid or the growing use of EVs, demands a reliable and economic supply of electric power. Before actually implementing such systems, however, it is necessary to study the methods available, taking account of a variety of constraints. To deal with this situation and offer timely solutions, Hitachi has developed a smart grid simulator that it can use as an engineering environment for analyzing the effectiveness of installing various control equipment and systems.

### Configuration

While performing analysis and evaluation prior to implementation is essential to achieving the reliable and planned operation of a power system, running experiments on a live grid in the early stages is difficult. Instead, what are needed are simulators that can model the actual grid, perform numerical calculations of the supply and demand for electric power under given conditions, and then present the results in an intelligible format. While simulators of this type have been developed in the past, they have not been able to cope adequately with large grid configurations while also providing flexible equipment configuration.

The new smart grid simulator uses a distributed agent architecture and consists of a power flow computation engine and a data visualization function for displaying the calculation results.

(1) Power flow calculation engine

This calculates the flow of power through the power system. The engine has a distributed agent architecture made up of separate modules that model the distribution grid, voltage control equipment, consumer equipment (such as electric water heaters and EVs), photovoltaic power plants, consumers, and various control systems. These modules execute independently and concurrently when performing a power flow calculation, and pass messages between themselves to coordinate their operation (see Fig. 2). The calculation engine has a single master module, with all other modules being slave modules. The modules are coordinated by passing messages. The master module performs overall management of the simulation, including timing control.

This configuration provides flexibility in the modeling of the systems being analyzed, and allows prototypes to be implemented quickly. Examples include simulations for analyzing the impact of renewable energy on a power system, voltage stabilization control, and demand-side management. It also simplifies maintenance tasks such as adding or removing functions, and facilitates expansion of the simulation through the use of distributed modules[1].

The simulator models time-axis changes in power flow across the grid by executing the power flow calculation cyclically to represent the passage of time. Specifically, it alternates between the power flow computation that calculates the grid power flow and the calculation of equipment states. These equipment states refer to values such as consumer loads, the power produced by distributed generation, and the output of control equipment. The master module performs the power flow calculation and the slave modules calculate the equipment states. That is, the slave modules use the results of the power flow calculation from the previous cycle to calculate the equipment states for the current timing, and then the master module uses these results to perform the next cycle of the power flow calculation.

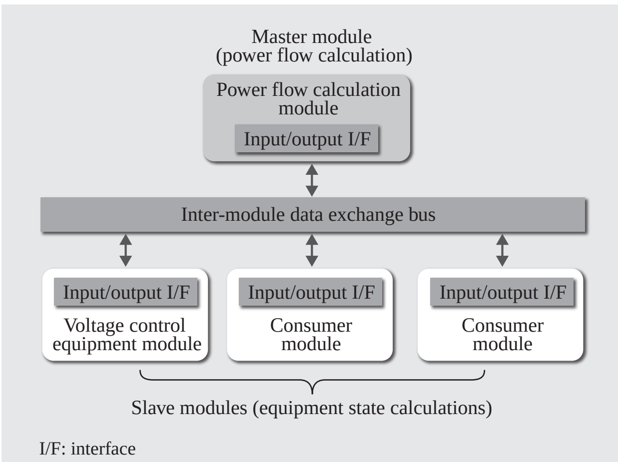


*Fig. 2—Distributed Agent Architecture.*
*Control systems and other equipment are implemented as independent modules.*

One type of control device is the voltage control equipment used to adjust the voltage of the distribution grid (see Table 1). This equipment is simulated by a slave module that calculates the equipment states from the past grid power flow and equipment state information. When using distributed control in which each voltage control device operates autonomously, the results of each calculation are then sent as messages to make the information available to other modules. Other control techniques include centralized control and coordinated control. In centralized control, equipment state information is managed centrally and control signals are issued based on a top-down configuration. Coordinated control, in contrast, is performed by adjacent control devices communicating with each other. A feature of the simulator is that it has the flexibility to support a wide range of different control techniques.

(2) Data visualization functions

The new simulator includes data visualization functions to present its calculation results in an intelligible format (see Fig. 3). These include map mode for displaying the power system geographically and grid mode for highlighting its structure. By switching between screens, the user can view the variation in photovoltaic power generation output with changing weather conditions, the consequent fluctuations in the grid voltage, and the results of stabilization control by the voltage stabilization equipment. The system combines intelligible displays and easy operation, with functions available at the click of a mouse. Examples include a profile display of the grid voltage along power lines and the day-by-day voltage at a particular node. It also includes alarm functions, including the use of color coding to highlight instances where the grid voltage is high or low. These functions are implemented using hypertext markup language 5 (HTML 5).

Table 1. Voltage Control Equipment

*The table lists the main types of voltage control equipment and their functions.*

| Voltage control equipment | Function |
|---|---|
| LRT | Switching between transformer taps at distribution substations to adjust voltage |
| SVR | Switching between transformer taps on distribution grid power lines to adjust voltage (similar to LRT) |
| SVC | Adjustment of reactive power output on distribution grid power lines (similar to SVR) |

LRT: load ratio control transformer SVR: step voltage regulator
SVC: static var compensator

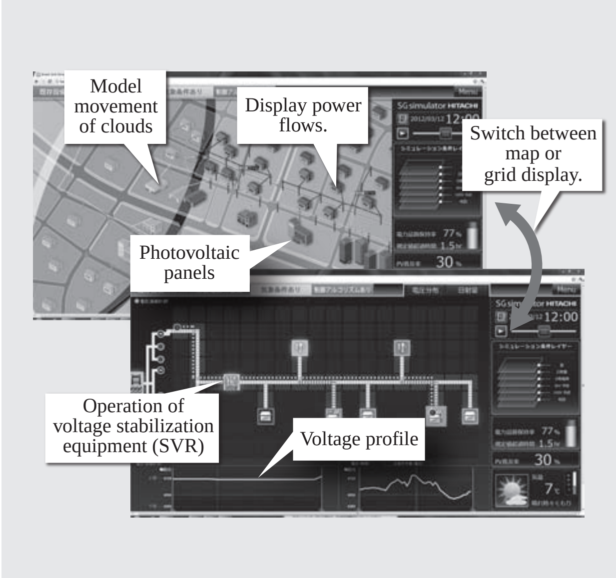


*Fig. 3—Example Data Visualization Screens.*
*The results of the power flow calculations are displayed in an intelligible format.*

## Example Application

This section describes the use of the smart grid simulator in the development of a prototype system for the local production and consumption of photovoltaic power. There are concerns about the impact that excess power and reverse power flows will have on power systems if greater use is made of photovoltaic power generation. Accordingly, this prototype system is designed to absorb mismatches between supply and demand by using excess power from local photovoltaic power generation to operate electric water heaters and store heat. A feature of the system is that it maximizes overall efficiency and the ability to absorb fluctuations by controlling the number of electric water heaters in operation (multiple unit control) based on factors such as the demand for hot water and the efficiency characteristics of the water heaters in each home.

Table 2 lists the modules used in the prototype simulation. The power flow calculation module collects demand data modeled by the consumer module and uses it to determine states across the entire distribution grid. Similarly, the consumer module obtains the voltages at grid connection points modeled by the power flow calculation module and calculates the power output limits set by the function for preventing over-voltage on the photovoltaic power generation plant. In this way, the modules interoperate to perform the simulation (see Fig. 4).

This prototype was then used for a case study of ordinary households that found that performing

TABLE 2. Modules and Functions
*The table lists the main modules and their functions.*

| Module | Functions |
|---|---|
| Power flow calculation module | Calculates voltage, current, and other state information for each node of the distribution grid. |
| Consumer module | Models the output of photovoltaic power plants, power consumption and heat output of electric water heaters, power and hot water consumption by consumers, and so on. |
| Weather module | Generates random weather scenario data. |
| Control server module | Demand-side management, including the generation of operating schedules for heat storage by electric water heaters in a number of homes |
| Main module | Supervisory control of other modules |

coordinated control of three houses together improved the ability to absorb excess power by 1.6 times compared to controlling each house independently.

Hitachi has also developed prototypes for a battery charging control system(2) that reduces the impact on the power system of increasing numbers of EVs, and demand response control that uses incentives to encourage consumers to hit a target level of power consumption. These prototypes could be implemented quickly using the available modules, including the power flow calculation and consumer modules.

## DISTRICT ENERGY SYSTEM SIMULATOR

### District Energy Network System

Preventing global warming has become a pressing issue in recent years and has created a need to reduce the quantity of carbon dioxide ($CO_2$) emitted by the

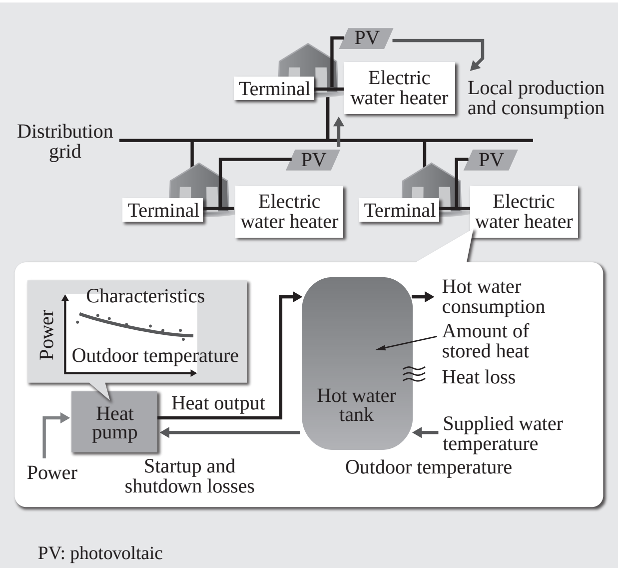


*Fig. 4—Control System for Local Production and Consumption of Photovoltaic Power.*
*The system balances supply and demand by the local consumption of any excess photovoltaic power.*

consumption of energy. To improve energy efficiency and reduce $CO_2$ emissions, it is necessary to build district energy network systems that establish an optimum supply-demand structure by networking local resources. These include sources of energy such as cogeneration, fuel cells, and refrigerators; renewable energy; and unused energy such as factory waste heat and groundwater. Also, the district energy network systems use information-communication and control technology to provide mutual interchange of energy.

### Simulation of Optimal Operation of Heat Interchange

District energy network systems provide mutual interchange of energy within the district through a "best mix" of electric power and heat. They use district heating pipelines to provide mutual interchange of thermal energy such as steam, hot water, and chilled water. Accordingly, improving energy efficiency and reducing $CO_2$ emissions within a district requires control technology that can optimize the operation of distributed heat source equipment with consideration for energy losses such as heat loss and pressure loss in the district heating pipeline.

Hitachi has been helping to improve energy efficiency and reduce $CO_2$ emissions at factories by developing energy management systems for manufacturing plants(3). Hitachi is now developing district energy management systems for industrial complexes or areas undergoing redevelopment.

As part of this work, Hitachi has developed technology for the simulation of optimal operation of heat interchange that couples the operation of heat source equipment with the use of pipe network analysis to estimate energy losses in district heating pipelines. This can reduce the energy consumption of heat source equipment through the preferential use of thermal energy such as waste heat from cogeneration, solar heat, or groundwater, and can supply consumers with thermal energy by coupling this with pipe network analysis to select district heating pipeline routes with low energy losses from heat source equipment with high operating efficiency (see Fig. 5).

The simulation was used to estimate the reduction in $CO_2$ emissions resulting from the use of heat interchange in two districts. It evaluated the supply of chilled water during summer for these two districts. One of these was a residential district where the demand for chilled water was highest at night, the other a commercial district with higher demand during the day. Each district had its own energy supply plant,

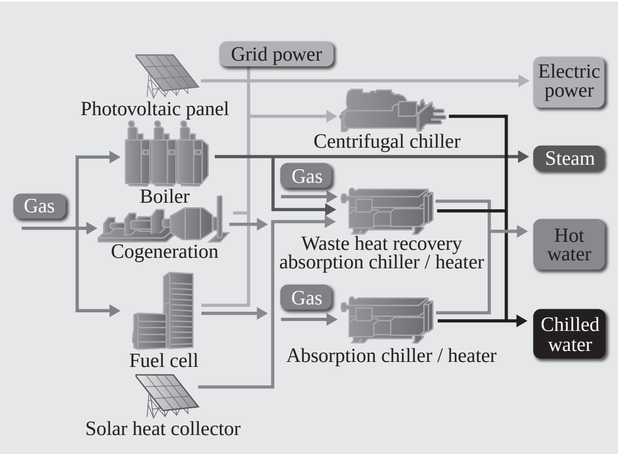


*Fig. 5—Optimum Operation of Heat Source Equipment.*
*The $CO_2$ emitted by a district can be reduced by making preferential use of renewable energy and waste heat, and by optimizing the operation of heat source equipment with consideration for energy losses in district heating pipelines.*

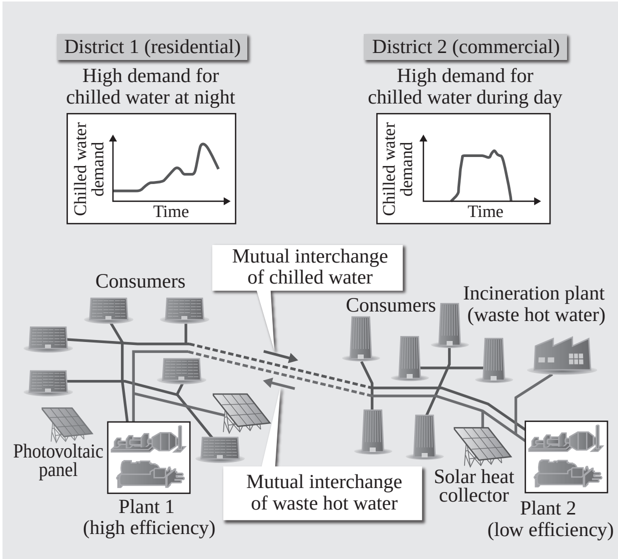


*Fig. 6—Calculation Conditions for Study of Heat Interchange Benefits.*
*The study calculated the reduction in $CO_2$ emissions that would result from the mutual interchange of heat between two districts with different thermal demand characteristics and plant operating efficiencies.*

with the commercial district also having a roughly constant, 24-hour-a-day supply of waste hot water from an incineration plant. Also, the energy supply plant in the residential district was assumed to have an efficiency 10% higher than that in the commercial district (see Fig. 6).

Whereas plant 2 in the commercial district only used the waste hot water from the incineration plant during the day if heat interchange was disabled, when heat interchange was enabled, the waste hot water was used effectively across the two districts 24 hours a day. Also, preferential use was made of the more efficient heat source equipment at plant 1 in the residential district. These results showed that, while using heat interchange resulted in extra $CO_2$ emissions due to the heat loss in the district heating pipeline and the energy consumed by pumps used for chilled water and waste hot water, total $CO_2$ emissions were still 32% lower than when heat interchange was not used (see Fig. 7).

## Optimization Simulation of Energy Consumed by Pumps Used for Hot and Chilled Water

District energy network systems use pumps to transfer thermal energy via district heating pipelines in the form of hot or chilled water. To provide a reliable supply of hot or chilled water to consumers, pump control in the past involved maintaining a constant pressure at the heat exchangers located at the consumer site and running pumps at their rated speed. This required a high water supply pressure and resulted in the energy consumed by pumps being higher than necessary. To reduce the energy consumed by pumps, it is necessary to optimize the pump speeds and the valve openness at each consumer site.

To simulate water distribution systems, Hitachi has already developed a water distribution simulator with a scope that extends from the reservoir to the consumer. When developing the optimization simulator for the energy consumed by pumps used for hot and chilled water, Hitachi developed a simulation technique that minimizes the energy consumed by pumps used for hot and chilled water by extending the functions of the water distribution simulator to include the pressure and flow rate balance of pipe networks as constraints, and to optimize the speed of each pump and the valve openness at each consumer site[(4)].

To confirm the energy saving produced by this method, Hitachi ran a calculation for an energy network consisting of two energy supply plants and three consumers (see Fig. 8). The calculation found that optimizing the pump speeds and the valve openness of the flow control valves at the consumer sites reduced the energy consumed by pumps by approximately 54% compared to the case when the pumps ran at rated speed (see Fig. 9).

By using a combined simulation of the above heat interchanges, it is possible to perform optimal operation planning of distributed heat sources to improve energy efficiency and reduce $CO_2$ emissions across the entire district.

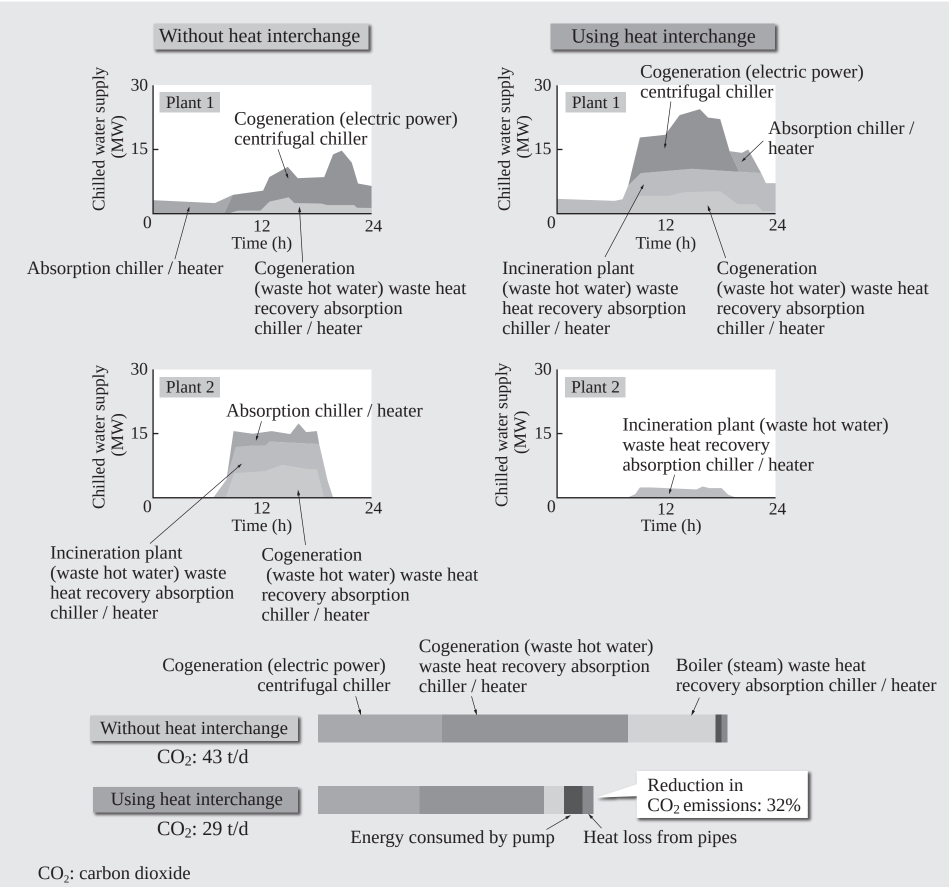


*Fig. 7—Results of Calculating Heat Interchange Benefits.*
*The study demonstrated the benefits of the preferential use of waste hot water and more efficient heat source equipment in terms of lower $CO_2$ emissions.*

## SIMULATOR FOR ANALYZING ENERGY EFFICIENCY OF UTILITY SYSTEMS

For factories and other buildings that use large amounts of electric power or heat, saving energy not only cuts costs, it is also an important social responsibility in relation to environmental problems. This section describes energy analysis simulation techniques for designing energy-efficient consumer utility systems (see Fig. 10).

### Energy Efficiency for Consumer Utility Systems

Consumers use a variety of utilities for purposes such as production processes, air conditioning systems, lighting, and office automation equipment. These include electric power, chilled water, hot water, steam, and compressed air. Utility systems obtain primary forms of energy, such as electric power, gas, or fuel oil, and convert them into the required utility. Utility systems are complex, consisting of refrigerators, air compressors, fans, pumps, boilers, cogeneration, and other components connected together by piping, and in some cases including mechanisms for sharing resources between different utilities. System configurations are also designed to suit the consumer’s level of demand for utilities.

Potential ways of saving energy include adjusting the operational settings on equipment, upgrading machinery to more efficient models, use of more advanced system control techniques such as multiple

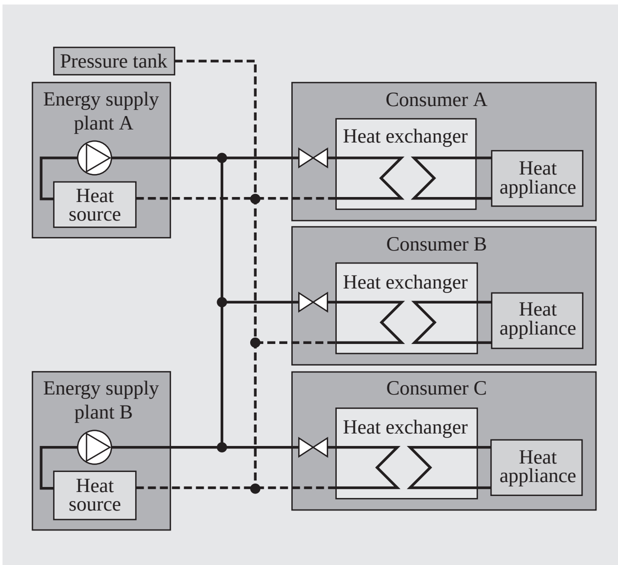


*Fig. 8—Calculation Conditions for Optimizing Energy Consumed by Pumps.*
*The calculation was performed for an energy network consisting of two energy supply plants and three consumers.*

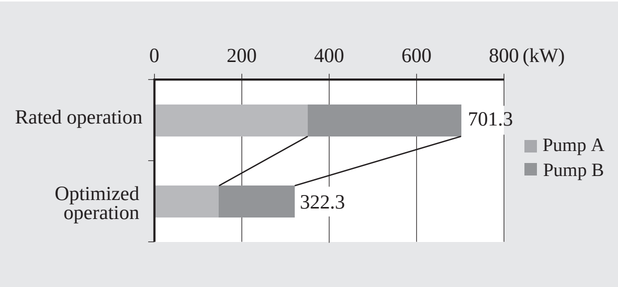


*Fig. 9—Results of Calculation Optimizing Energy Consumed by Pumps.*
*The calculation found that optimizing pump speeds and the valve openness of flow control valves at consumer sites reduced the energy consumed by pumps by approximately 54%.*

unit control, and improving the energy flow by using techniques such as waste heat recovery. Before proceeding with any of these, it is important to be able to analyze the energy savings in order to assess the cost-benefit ratios.

## Features of Simulator for Analyzing Energy Efficiency

To estimate energy savings, the simulator for analyzing the energy efficiency of utility systems calculates a comparison of the total annual consumptions of primary energy before and after the energy-saving measures are implemented. The core function of the simulator is to calculate primary energy consumption at one-hour time intervals for a typical week from each season of the year, for a given system configuration and using load data for each of these one-hour intervals, and then to collate the results into annual totals.

To provide a general-purpose method for automatically generating energy quantity formulas for a given system configuration, the simulator consists of a generalized data model with an object model architecture that characterizes the multi-utility energy conversion process in terms of the combination of equipment characteristics, energy flow connections, and system control, and a network state calculation model that handles all the interconnections between different utility systems, state values, and other variables. The user specifies the equipment and interconnections from a graphical user interface (GUI), using drag and drop to build a system configuration block by block from a tool box containing the different equipment, control devices, piping, and other components.

The simulator also provides various support functions, including an equipment database (DB), a function that provides guidance on measures for improving energy efficiency, and functions for outputting the simulation results. The equipment DB contains the characteristics of each model for different types of equipment and allows the user to try different models by selecting from a list. The energy efficiency guidance function provides a menu

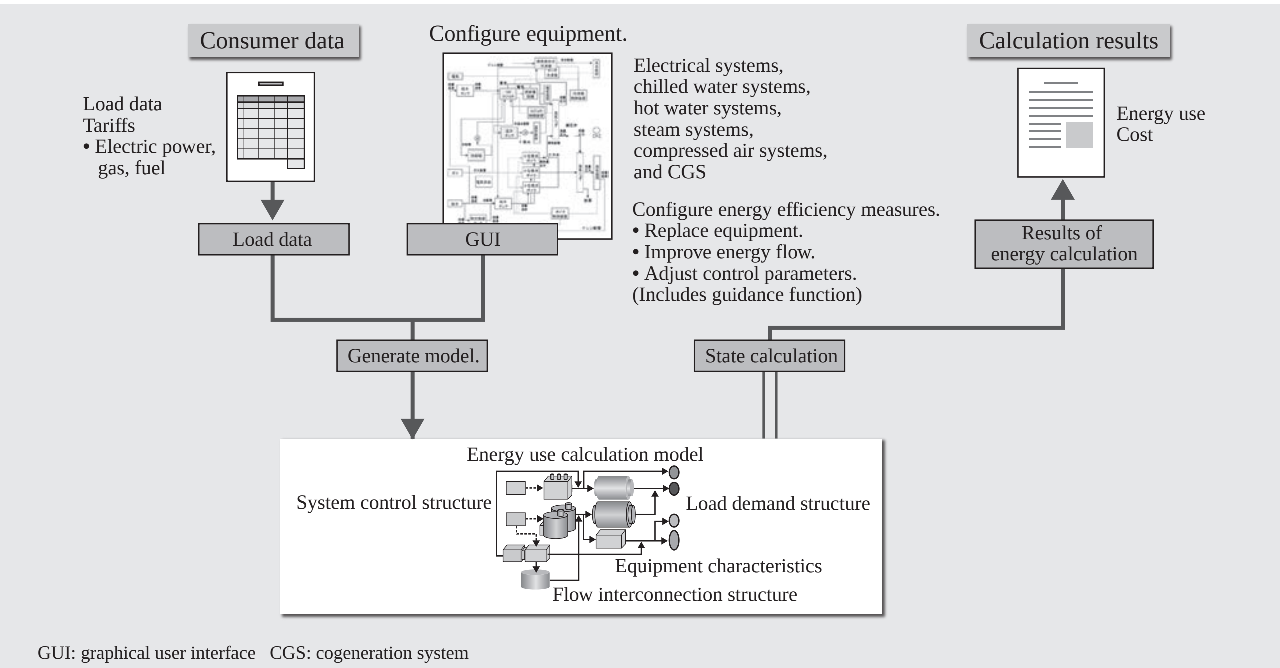


*Fig. 10—Overview of Simulator for Analyzing Energy Efficiency of Utility Systems.*
*The simulator estimates annual consumption of primary energy for a given utility system configuration.*

of energy efficiency measures. When the user selects one of these, the function searches the network for potential equipment in the specified utility system where the measure can be used and suggests what settings to use for the change. This helps share the knowledge of experts in energy efficiency.

In the future, Hitachi intends to add to these models of equipment and energy efficiency know-how to make the simulator more useful in practice and to expand its scope of application.

## CONCLUSIONS

This article has described simulation technologies that support the design, control, diagnosis, maintenance, and repair lifecycle of energy infrastructure, with a scope that extends from consumers to districts and power systems.

There is a need for the timely development and proposal of total solutions for energy infrastructure with system-wide optimization achieved through various forms of coordination such as multi-utility and the balancing of supply and demand. Hitachi intends to continue using the latest simulation technology to contribute to the implementation of efficient and reliable low-carbon energy systems.

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## ABOUT THE AUTHORS

Yasushi Tomita

*Joined Hitachi, Ltd. in 1990, and now works at the ES2 Unit, Department of Energy Management Systems, Hitachi Research Laboratory. He is currently engaged in the research and development of energy infrastructure systems. Mr. Tomita is a member of The Institute of Electrical Engineers of Japan (IEEJ) and IEEE.*

Tatsuki Inuzuka

*Joined Hitachi, Ltd. in 1981, and now works at the ES1 Unit, Department of Energy Management Systems, Hitachi Research Laboratory. He is currently engaged in the research and development of smart grids. Mr. Inuzuka is a member of The Institute of Electronics, Information and Communication Engineers (IEICE) and the IEEE.*

Tsutomu Kawamura, Dr. Eng.

*Joined Hitachi, Ltd. in 1989, and now works at the ES2 Unit, Department of Energy Management Systems, Hitachi Research Laboratory. He is currently engaged in the research and development of energy solutions.*

Michiki Nakano

*Joined Hitachi, Ltd. in 2006, and now works at the Social Infrastructure Systems Research Department, Yokohama Research Laboratory. He is currently engaged in the research and development for social infrastructure systems. Mr. Nakano is a member of the IEEJ.*