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# Sensitivity analysis in structure optimization of energy supply systems for a hospital

Shu Yoshida [a,*], Koichi Ito [b], Ryohei Yokoyama [c]

[a] *Research and Development Department, Kansai Electric Power Co., Inc., 3-11-20 Nakoji, Amagasaki, Hyogo, 661-0974, Japan*
[b] *Advanced Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Sinjyuku-ku, Tokyo, 169-8555, Japan*
[c] *Department of Mechanical Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Sakai, Osaka, 599-8351, Japan*

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**Abstract**

In this paper, the method of rationally determining the system structure and operational strategies is proposed for the energy supply system for a hospital based on the optimization approach. First, energy demands are estimated hourly, daily, and seasonally through one year for the hospital with total floor area of 25,000 m$^2$. Second, miscellaneous kinds of equipment are listed up such as refrigerators, heat pumps, gas engine cogeneration unit, steam boiler, thermal storage tank, and other similar things and 25 structures of alternative energy supply systems are composed by combining these kinds of equipment. By the mathematical optimization method, the following results have been obtained; that is, the optimal system is the hybrid-system that consists of electricity-driven and natural gas-fired equipment together with cogeneration equipment, which is difficult to get by intuition and experience of the designer. Sensitivity analysis is also carried out by changing parametric values related to initial capital cost and upgrading performance of each equipment in addition to energy charges, and as the obtained result the optimal energy supply system for the hospital is proposed from comprehensive viewpoints.


*Keywords:* Energy supply system; Hospital; Economic evaluation; Optimization; Sensitivity analysis

## 1. Introduction

For the purpose of saving cost, distributed energy supply systems have been installed in commercial and public buildings. In general, the distributed energy supply system is composed of many kinds of equipment, for example, cogeneration units, refrigerators, heat pumps, thermal storage tanks, boilers and so on. In order to realize the high economical system, it is necessary to determine its structure rationally by selecting some kinds of equipment from many alternative ones so that they match energy demand requirements for an objective building. It is also important rationally to determine the number and capacities of each kind of equipment selected, and maximum contract demands of utilities such as electricity and natural gas in consideration of the system's annual operational strategies corresponding to seasonal and hourly variations in energy demands [1–3].

The purpose of this paper is to investigate what system structure is suitable for a hospital by taking account of the aforementioned design and operation items based on an optimization method. First, the mathematical formulation of the optimal planning problem is presented. Then, the numerical study is carried out for a hospital building, which has 10 floors with 2500 m$^2$ per floor. The optimal system structure is affected by the performance characteristics and capital costs of equipment as well as the rates of utilities. Therefore, the optimal system structure is investigated under standard values of these conditions. In addition, the sensitivity analysis is carried out to investigate the influence of these conditions on the optimal system structure.

* Corresponding author. Tel.: +81 50 7104 2664; fax: +81 50 7104 2588.
*E-mail address:* yoshida@ese.me.osakafu-u.ac.jp (S. Yoshida).

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**Nomenclature**

| | |
|---|---|
| $D$ | maximum number of representative day |
| $H$ | maximum number of sampling time |
| $T_{dh}$ | operational hour for the *h*th sampling time on the *d*th representative day |
| $\boldsymbol{x}$ | vector composed of continuous variables for equipment capacities |
| $\boldsymbol{y}$ | vector composed of continuous variables for utility maximum contract demands |
| $z_{dh}$ | vector composed of continuous variables for utility maximum contract demands |
| $\boldsymbol{\delta}$ | vector composed of binary variables expressing the selection of utility rates |
| $\boldsymbol{\lambda}$ | vector composed of integer variables for numbers of equipment |
| BS | steam boiler |
| BW | boiler |
| CH | chilling unit (water cooling type) |
| CT | cooling tower |
| GE | gas engine (hot water type) |
| GES | gas engine (hot water and steam type) |
| GL | steam absorption refrigerator for GES |
| HB | brine electric heat pump |
| HEB | heat exchanger from brine to water |
| HEH | heat exchanger from water to water |
| HES | heat exchanger from steam to water |
| HP | electric heat pump |
| HPW | electric heat pump for hot water |
| IB | ice storage tank |
| IHB | ice and hot water storage tank |
| RB | electric compression refrigerator for ice storage |
| RE | electric compression refrigerator |
| RG-L | gas-fired absorption refrigerator (large scale) |
| RG-M | gas-fired absorption refrigerator (middle scale) |
| RS | steam absorption refrigerator |
| RW | hot water absorption refrigerator for GE |
| TW | hot water tank |
| THW | hot water tank for HPW |

## 2. Optimal planning of energy supply system

### 2.1. Concept of systems planning

In this paper, the optimization approach is adopted in order to perform the aforementioned planning rationally. First, a super structure composed of all the kinds of equipments considered as candidates for selection is created to match energy demand requirements. For the super structure, the selection of the kinds of equipments and utility rates, each number and capacities of the former, and the utility maximum contract demands are determined together with the system's annual operational strategies so as to minimize the annual total cost subject to the satisfaction of seasonal and hourly energy demand requirements. In this optimization, various parametric values such as input energy, output energy, equipment characteristics affect the optimal solution as shown in Fig. 1.

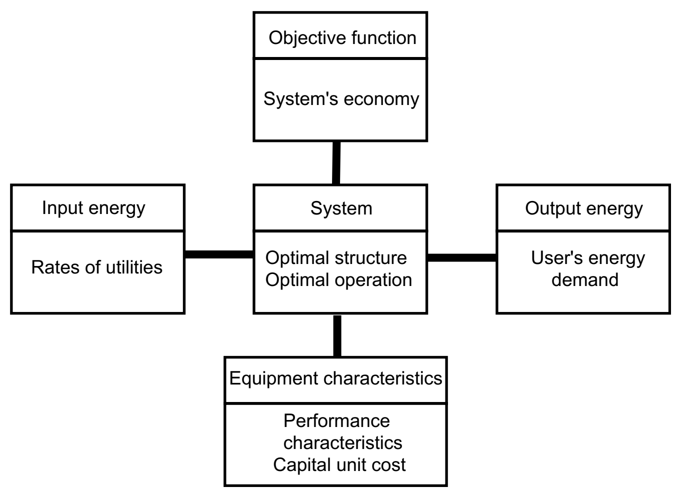


Fig. 1. Concept of systems planning.

### 2.2. Mathematical formulation

In formulating the optimal planning problem, the annual operational hours in a year are discretized by setting $D$ representative days and by dividing each day into $H$ sampling times, and the annual operational hour for the *h*th sampling time on the *d*th representative day is designated by $T_{dh}$. For each sampling time, average energy demands are estimated. In addition, peak energy demands are estimated for winter and summer peak demand days.

Decision variables are composed of design and operational ones. The design variable vectors are the selection of utility rates $\boldsymbol{\delta}$, the utility maximum contract demands $\boldsymbol{y}$, the numbers $\boldsymbol{\lambda}$ and capacities $\boldsymbol{x}$ of equipment. The operational ones are the energy flow rates at the *h*th sampling time on the *d*th representative day, which is expressed by a continuous variable vector $z_{dh}$.

The objective function to be minimized is the annual total cost from the long-term economic viewpoint. It is evaluated as the sum of the annual capital, construction, operational and maintenance costs based on the annualized costs method. The annual capital cost of each kind of equipment is considered as a function of its number and capacity by taking its scale merit into account. The annual construction cost is to be proportional to the annual capital cost. The annual operational cost is the sum of the customer, demand and energy charges of the utilities. The customer and demand charges are considered as functions of the utility maximum contract demands, and the hourly