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Theoretical analysis of the optimal configuration of co-generation systems and competitiveness of heating/cooling technologies

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ABSTRACT

This study aims at exploiting optimal configurations of technologies combined with co-generation theoretically based on a linear optimization model. With the objective function defining primary energy consumption to be minimized, optimal solutions are derived analytically. They describe the technological configurations as well as associated conditions depending on their final energy demand. An interesting finding is that the essential parameters to determine the configurations are heat, cooling and steam demands normalized by power demand. The optimal solutions are also applied to investigate the competitiveness of co-generation related technologies. The optimal solutions yield critical conditions theoretically, which is useful to understand the priority of the technologies. A sensitivity analysis numerically indicates that absorption chillers can be superior to compression chillers even though the former has lower COP than the latter. Actual data of various types of co-generation are also examined to show the practical competitiveness.

1. Introduction

Co-generation systems are well known technology nowadays to enhance the efficient use of primary fuels. Because it produces electric power as well as heat simultaneously, it can achieve as high energy efficiency as more than 70%. The installation of co-generation systems in Japan is growing from 1980s and get the capacity of 9.2 GW (7.4 GW for industrial use; 1.8 GW for residential and commercial use) in 2008 according to Japan co-generation Center [1], which is 3% of total power generation capacity in Japan. Although co-generation potentially provides higher efficiency than conventional systems, the attainable efficiency depends on the configuration of heating or cooling supply technologies combined with co-generation plants. Final energy demand also effects the performance of the systems. Furthermore, recent advanced natural gas combined cycles attain quite high energy conversion efficiency of more than 50%. It is not clear that total efficiency of 70% of co-generation is still superior to the efficiency of the conventional systems with such combined cycles.

Many studies have been conducted to investigate the performance of co-generation systems based on mathematical programming methods with given final energy demand profiles. Salgado [2] surveyed studies related to co-generation operation especially from the scope of short-term planning. Various kinds of solving techniques such as linear programming, mixed integer programming and non-linear programming are involved to find optimal co-generation system configurations or optimal operation of each technology. The objective functions also present variety. A typical formulation is maximizing benefit (Wille-Houssmann [3], Thorin [4]) or minimizing system cost (Seo [5], Wu [6], Yokoyama [7] and Yoshida [8]). Other mathematical techniques are also used for co-generation system optimization. For example, Sahoo [9] and Cerri [10] applied evolutionary programming or neural networks for the analyses. Another important aspect is to consider not only economical factors but also environmental factors in finding optimal picture of co-generation systems. Tsay [11] and Sayyaadi [12] proposed multi-objective approach from this point of view.

Even though such analyses are effective to know the optimal performance and the behavior of the systems in detail taking many energy technologies into account, they cannot clarify critical conditions where one technology is superior to the others. For example, there exist two kinds of heat pump technologies to supply cooling, that is, compression chillers and absorption chillers. While compression chillers have high COP (Coefficient Of Performance indicating the ratio of output to input energy) of 4, for instance, the COP of absorption chillers is around 1. However, once absorption

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Nomenclature

C	cooling demand [kW]
COP	coefficient of performance
E	electric power demand [kW]
H	heating demand [kW]
S	steam demand [kW]
X	output of technologies [kW]
η	efficiency
η_0	total efficiency of co-generation
λ	Lagrange multiplier for power supply
μ	Lagrange multiplier for steam supply
θ	Lagrange multiplier for heating supply
ρ	heat-to-power ratio of co-generation
σ	Lagrange multiplier for cooling supply

Subscripts

A	absorption chiller
B	boiler
C	co-generation
G	grid power
H	heat pump
S	steam assistance to supply heat
T	compression chiller

chillers are driven by discharged heat from co-generation, the efficiency of the chillers should incorporate the effect of co-generation. It is not so simple to evaluate the contribution because of multi-production process of co-generation.

Exergetic analysis is often attempted to compare the priority of such systems with conventional one because the concept of exergy can measure different types of energy such as electric power and heat at different temperature. Cortés [13] investigated a co-generation system in pulp and paper industry from an exergoeconomic viewpoint. Yilmaz [14] theoretically analyzed co-generation system as an engine and showed that there existed optimal settings to maximize total exergy rate of the system. Although exergy is a physical index to describe thermal energy, it is not always connected to social aspect of energy use, for example, to reduce fossil fuel consumption or CO_2 emission. To understand the effect of technologies on such aspects, the physical index of exergy is not necessarily easy to be interpreted.

Some studies have tried to describe co-generation models in rather simplified ways with some parameters such as energy efficiencies for power and heat production. Verbruggen [15] analyzed co-generation performance to reduce CO_2 emission with a few essential parameters of co-generation and the share of fuels for grid power generation. The study provided graphical diagrams to distinguish the impact of co-generation to decrease or increase CO_2 emission. Meunier [16] also investigated the effect of co- or tri-generation on the reduction of CO_2. The relationship was formulated analytically with the efficiencies of the co-generation and the boiler and CO_2 emission coefficients of the fuels. Fumo [17] made a co-generation model representing energy balance equations and discussed the fuel consumption at co-generation site compared with that of conventional system. Ruan [18] studied co-generation performance for various buildings such as hotels, hospitals, stores and offices. Energy saving rate was expressed mathematically, which indicated the influence of heat-to-power ratio of the demand on the energy saving rate by engine types of the co-generation. Mancarella [19] formulated the efficiency of co-generation systems combined with a heat pump analytically, which shows relationship among parameters of the technologies. The study revealed the effect of electricity supply from the co-generation to the heat pump on the system performance. Mancarella [20] investigated a tri-generation system supplying electric power, heat and cooling. In the model, an absorption chiller driven by co-generated heat produces cooling. The analysis mathematically derived a break-even indicator at which the co-generation system and the conventional system are equivalent in terms of CO_2 emissions. It is interesting that the indicator is expressed based on the efficiencies of the involved technologies. The effect of various co-generation engine types was evaluated numerically. It should be noted that these studies assumed system configuration empirically and did not optimize the technological selection in a comprehensive way.

The objectives of this study are to derive the optimal configurations of co-generation systems for minimizing the primary energy consumption corresponding to their technological parameters and to apply the optimal solutions for assessing the competitiveness of co-generation versus related technologies of heating supply and cooling supply. The analysis provides not only critical conditions theoretically but also numerical case studies practically.

2. Modeling of co-generation system

Generally co-generation systems are installed with auxiliary boilers and chillers, and also connected to the power grid to satisfy excess power demand more than the co-generation capacity. To conduct theoretical analysis, the authors assume that a co-generation plant is accompanied by a boiler and a heat pump for heating supply as well as a compression chiller and an absorption chiller for cooling supply. Fig. 1 illustrates the technological configuration of the co-generation system. Here, the final energy demand is classified into four kinds, such as power, steam, heating (including hot water supply) and cooling. It should be noted that the grid power is implicitly assumed to be based on fuel-fired power stations. Co-generation plants are considered to substitute for the fuel-fired grid power.

Since the objective of the analysis is to understand the contribution of the technologies for reducing the primary energy consumption, the theoretical analysis has the criteria of the primary energy input to be minimized. The system operation is mathematically formulated as the following. Here, it is assumed that the technological parameters such as efficiency are constant

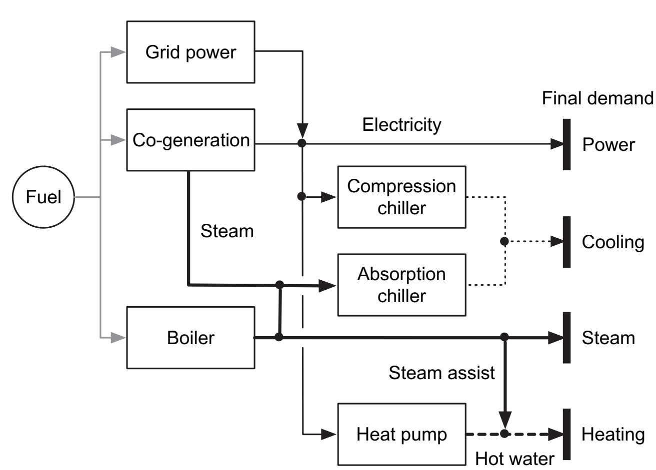

Fig. 1. Configuration of co-generation systems.