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Multi-criteria assessment of combined cooling, heating and power systems located in different regions in Japan

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HIGHLIGHTS

- Influences of building type and climate condition on the performances of CCHP systems are examined.
- The CCHP systems enjoy satisfied energy and environmental performances for commercial buildings.
- Hotels and hospitals are popular customers of the CCHP system from an integrated viewpoint.
- CCHP systems in Kagoshima achieve the most benefits for stores and offices.
- CCHP systems in Sapporo are more preferred for hotels and hospitals.

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ABSTRACT

As an efficient measure for rational use of energy, the combined cooling, heating and power (CCHP) system plays an increasingly important role in commercial buildings in Japan. In this study, aiming at examining the influences of building type and climate condition on the introduction of CCHP systems, four representative commercial building categories (hotel, hospital, store and office) located in six major climate zones in Japan are compared and evaluated. In order to have a comprehensive understanding about the performances of the assumed CCHP systems, besides simple assessment from energy, economic and environmental aspects, a multi-criteria evaluation method has been employed for the final determination. According to the assessment results, the CCHP systems in hotels and hospitals enjoy better overall performances than those in stores and offices. On the other hand, the potentials of energy-saving and CO_2 emission reduction of the CCHP systems in the mild climate zones are smaller than that in other climate zones. In addition, the performances of CCHP systems in stores and offices located in Kagoshima are superior to those in other cities; while, CCHP systems in hospitals and hotels located in Sapporo illustrate better overall performance.

1. Introduction

The investigation of national energy consumption trends showed that the consumption of energy in Japan had grown from 11.1 EJ in 1973 to 14.5 EJ in 2011. The commercial building takes the main responsibility for the high increase, followed by the residential and transport sectors. In Japan, since the 1970s oil crisis, energy-saving regulation in the industry sector has achieved great success, and reduces total industry energy consumption by 14% with increased output (32%) in 2011 compared with that of 1973 [1]. On the contrary, the commercial building sector illustrates an opposite trend, thus, energy-savings received in the industry sector may be offset by the increased consumption in commercial buildings. This situation is due, on the one hand, to the construction of new commercial buildings, and on the other hand, to the search of higher comfort levels. Therefore, energy conservation in commercial buildings is strongly required in Japan.

In addition, at the UN Climate Change Conference (COP 15), Japan had announced an ambitious goal (25% reduction from the 1990 level) to curb the emissions of greenhouse gas (GHG), with 2020 as the target year. However, in the year 2011, total GHG emissions amounted to about 1.3 billion tons of carbon, which increased by about 3.7% in comparison with that of 1990. Among which, along with reduced emissions from the industry sector, the

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GHG emissions from commercial buildings increased by 11.8% (93 million tons) [2]. Facing such a grim reality, the distributed energy resources (DER), which have been recognized as an important innovation to the conventional energy supply system, are paid more and more attention. Generally, DER means small-scale energy generation units, and is mainly composed of thermal technologies and renewable ones [3,4]. While recognizing the high initial cost and low utilization efficiency of the renewable technologies (e.g., solar, wind energy), the currently feasible DER option is the combined cooling, heating and power (CCHP) system which can acquire three different forms of energy, namely, cooling, heating and power, from a single primary energy source [5].

In Japan, the CCHP system has experienced rapid development during the last decades. The number of CCHP plants had increased from 67 in 1986 to 9350 in 2013, and the total generation capacity had increased from 200 kW in 1986 to 9852 MW as of March 2013. According to the investigation of Advanced Cogeneration and Energy Utilization Center of Japan (ACEJ), the largest emerging market for CCHP system is the commercial building, which shares more than 75% of existing CCHP applications [6]. However, while considering the vast number of commercial buildings, the share of CCHP systems is far from enough. In order to promote the penetration of CCHP systems in commercial buildings, for a specific case of demand, a comprehensive evaluation of potential benefits with CCHP system adoption is of vital importance. Gamou et al. [7] proposed an optimal unit sizing method for CCHP systems while taking into consideration the uncertainty of energy demands. Yoshida et al. [8] executed a sensitivity analysis of the system structure of the CCHP system for a hospital, while considering feasible technical improvement and cost down. Ruan et al. [9] examined the performances of the CCHP systems for commercial buildings located in Kyushu, from energy, economic and environmental viewpoints. Zhou et al. [10] discussed the economically optimal CCHP systems for five commercial buildings located in Tokyo.

It can be concluded that most of previous studies have focused on the single-criterion evaluation (e.g., annual energy cost) of the CCHP system for a specific customer within a particular location. However, as a demand-side dominated energy system, the performance of a CCHP system is greatly dependent upon the seasonal climate conditions which may determine local energy demands (especially, space heating and cooling loads). Actually, some previous studies have been reported on the influence of climate condition on the energy consumption in buildings in Japan [11–16]. However, further research is escaped. The influence of climate condition on the performance of energy systems (e.g., CCHP system) is uncertain, thus will be one of main topics of the current study.

On the other hand, as energy-saving and environmental issues are paid more and more attention, the conventional single-criterion analysis is unsatisfied and the decision problem becomes more challenging. This is because the best system from an economic viewpoint may have more environmental emissions; and contrarily, the promising system from an environmental viewpoint may cost more. Under these backgrounds, the multi-criteria decision making (MCDM) method has been proposed to handle a wide range of variables appraised from different viewpoints. Over the past few decades, it has been employed for the evaluation and determination of energy systems widely [17–20].

The purpose of this study is to assess and compare the performances of CCHP systems for various commercial buildings located in different climate zones in Japan, based on a multi-criteria analysis involving energy, economic and environmental issues. In detail, the paper is structured as follows. Section 2 presents the concept for the design and operation of the CCHP system, the evaluation criteria as well as the multi-criteria decision aid method. In Section 3, main assumptions used for the integrated assessment are presented. The assessment results and discussions are illustrated in Section 4. Section 5 draws a conclusion for the whole study.

2. Methodologies

In this study, a multi-criteria decision aid method has been employed, in order to have a comprehensive understanding about the benefits of introducing CCHP systems for commercial buildings located in different regions in Japan.

2.1. Outline of the assessment process

The whole assessment process can be divided into four phases, as shown in Fig. 1. Following the initial collection of building properties (e.g., energy demands) and technical information (e.g., efficiencies), the capacity of the CCHP system can be determined according to the method introduced in the following subsections. Based on the instantaneous fraction of the CCHP system (ratio of energy load and its nameplate capacity, θ), its running strategies can be determined. In detail, if the instantaneous fraction is lower than the critical coefficient (σ), the system is out of operation; if the value is larger than 100%, the system will operate at its nameplate capacity; otherwise, the system will operate following the energy (electricity or heat) load. Subsequently, based on the selected assessment criteria, all alternative CCHP systems for various building types located in different regions are evaluated, respectively. After achieving the single-criterion assessment results, the preference values including the scores and the weights can be determined. The scores reflect the preferences a decision-maker has for different achievement levels under each criterion considered, while the weights reflect the preferences for the different criteria. Following which, based on the selected MCDM method, the overall evaluation index can be obtained following the multi-criteria assessment procedure introduced in the following sub-sections. Finally, the ranking of all the CCHP systems can be reported.

2.2. Modeling of the CCHP system

To carry out a comparative analysis, a conventional energy supply system which generates electricity and heat separately, is assumed. Fig. 2 shows the energy flows of the conventional system and the proposed system based on CCHP plant. On the demand side, four types of energy forms (electricity for lights and equipments, space cooling, space heating and hot-water) have been considered.

As to the conventional system, the electrical demand is totally served by the utility grid. The space heating and cooling loads are supplied by the electric heat pump which is the dominant thermal equipment in commercial buildings. In the CCHP system, both utility grid and on-site CHP plant can be employed to satisfy the electrical demand, and the shares of them are determined according to the running schedules. Similarly, the thermal demand could come from either the recovered heat, or an auxiliary boiler, or a combination of both. In addition, because electricity buy-back from on-site CCHP systems is permitted in Japan, the surplus electricity out of the CCHP system can be sold back to the grid when the generated power exceeds local demands.