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Research Paper

Multicriteria evaluation of carbon-neutral heat-only production technologies for district heating

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HIGHLIGHTS

- Heat storages and electric boilers are best solutions for peak-load situations.
- CCS technology is too immature, unreliable, costly, and has too large space demand.
- Solar heat is unfavorable at Helsinki latitude due to bad coincidence with demand.
- Multicriteria method was developed for treating conflicting experts' preferences.

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ABSTRACT

Climate change mitigation requires reducing dependence on fossil fuels and transition to low carbon energy production technologies. Nearly half of the global final energy consumption is thermal energy produced from technologies with high carbon dioxide emission. As such, it is imperative to employ carbon-neutral heat production to achieve a sustainable energy system.

This paper presents a real-life case of applying multicriteria decision analysis for evaluating carbon-neutral heat-only production technologies in a major district heating system in Finland. A group of 10 experts from the energy company contributed in defining the alternative technologies and multiple economic, technological, and environmental evaluation criteria. The experts also provided the criteria measurements and preference information for different criteria. The alternatives were compared using Stochastic Multicriteria Acceptability Analysis (SMAA). SMAA is a simulation based method for decision problems where different kind of uncertain information is represented by probability distributions. Because the preferences of the experts were highly conflicting, the SMAA method was extended within this study to treat conflicting preferences.

The most preferred alternatives were short-term heat storages and electric boilers based on renewable power. These alternatives may be considered attractive future solutions particularly in balancing peak load heat consumption and production.

1. Introduction

1.1. Background

The design of future energy systems generally aims at reaching acceptable levels of carbon dioxide (CO_2) emission. The common approach is by increasing energy efficiency and integrating carbon-neutral or renewable energy sources in the energy system to a greater extent, as indicated in many studies [42]. Carbon-neutral means that the technology emits no or very little CO_2. A number of studies have aimed at the design of future 100 percent renewable energy systems [52]. However, these studies often focus on electricity production and overlook the role of thermal energy. A number of recent studies, including Heat Roadmap Europe [7], have recognised the role of thermal energy production in the efforts to reduce emissions of the energy sector. In fact, nearly half of the global final energy consumption is thermal energy.

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The demand for thermal energy, such as heating and cooling fluctuates greatly both within the day and between different seasons. For this reason the production capacity needs to be flexible enough to satisfy the demand. Many renewable energy sources, such as wind power, solar power, and solar heat are intermittent. Increasing the share of such energy sources is making it more challenging to balance the supply and demand for thermal energy.

District heating DH) has in several studies been considered the most energy efficient and environment friendly heating system in cities, as the heating network enables improvements in the overall energy efficiency with the use of any available heat source including waste and surplus heat from other industrial processes [43]. Besides, the DH network allows more cost-efficient integration of renewable energy into the energy system [11].

This study evaluates different carbon-neutral heat production technologies for the district heating and cooling (DHC) system of the city of Helsinki, capital of Finland. The DH system covers over 90% of the heat demand and operates with over 90% energy efficiency. Currently over 90% of the DH production is based on efficient combined heat and power (CHP) production, using different fuels, such as natural gas, coal, and biomass. In addition, large scale heat pumps are applied for co-production of DHC. The possible carbon-neutral heat production technologies for Helsinki include different types of biomass combustion, solar heat, geothermal heat, heat pumps, electric heating, and carbon capture and storage (CCS). The decision between the different technology options must consider many local conditions and objectives. Therefore, we applied multicriteria decision analysis (MCDA) in the selection process.

In this study the Stochastic Multicriteria Acceptability Analysis (SMAA) method was used for analyzing the suitability of different renewable and carbon-neutral heat-only production alternatives for DH. The case study considered the existing DH system of the city of Helsinki, which also aims to become carbon-neutral in the long term because of national and international climate policy. Therefore, the objective of this study was to identify the most suitable carbon-neutral heat-only production technologies for DH considering particularly the technical, economic and environmental points of view. In addition, significant aspects to consider were energy security and the supply during peak demand.

Both criteria measurements and preferences were provided by a group of experts. Because the experts provided partly conflicting information, as methodological novelty, a new way to treat such information in SMAA was developed in this study.

1.2. Literature review

MCDA methods have recently become more employed in sustainable energy planning problems. Several earlier MCDA studies have concerned different aspects of power systems. These include site selection for hydropower [51,73], solar power [44], [4], wind power [60], production technology evaluations [54], selection of prime mover for organic Rankine cycle [27], community level power solutions [5,12,56], and large scale power system analyses [58,46,47,61,65]. Mixed heat and power system analyses include definition of the general sustainability index to measure the sustainability of an urban energy system by Jovanovic et al. [21], MCDA model for evaluating renewable energy technologies for the island of Crete by Tsoutsos et al. [71], sustainability ranking of renewable power and heat generation technologies by Dombi et al. [9], MCDA evaluation of multi-source energy systems by Catalina et al. [3]. Combined heat and power CHP) systems analyses include evolutionary multicriteria optimization of fuel cell–gas turbine combined cycle by Burer et al. [2], evaluation of CHP technologies in terms of energy, economy and environmental points of view by Wang et al. [75], and selection of residential energy supply system by Alanne et al. [1].

MCDA for heating systems include both building level studies [6,74] and community level analyses [49,10,28]. Reviews about using MCDA methods for sustainable energy planning can be found in [55], Wang et al. [77], Si et al. [63], Kumar et al. [29] and Mardani et al. [45].

SMAA method was introduced by Lahdelma et al. [33] and developed further by [31], Lahdelma et al. [34], and [37]. SMAA was developed for decision problems where the criteria measurements and preference information can be uncertain, inaccurate or even partly missing. SMAA is a simulation based method, where different kinds of uncertain information are represented by probability distributions. SMAA computes statistically for each alternative the probabilities to obtain each rank. The computation is implemented by Monte-Carlo simulation, where values for the uncertain variables are sampled from their distributions and alternatives are evaluated by applying the decision model [67]. The recommended solution is typically the alternative with highest probability for the first rank. However, the probabilities for other possible solutions are also provided for the decision makers (DMs). This means that SMAA describes how robust the model is subject to different uncertainties in the input data [32,38]. For a survey on SMAA methods, see [66].

SMAA has been applied to many problems in the areas of municipal planning [18], harbor development [19], polluted soil remediation [20,40,35], waste treatment plant siting [39], forest management [22–24], waste storage area siting [36], risk-based classification of nanomaterials [68]; multimodal cargo hub development [48], strategic environmental assessment [59], rural electrification in developing countries [56], energy policy assessment [57], benefit-risk analysis of drugs [70,72,50], energy monitoring systems selection [53], dredged material management [62], peak heating plant siting in DH system [76], residential heating alternative evaluation [28], and public sector facility selection [25].

2. Decision problem

The studied case concerned the DH system in the city of Helsinki, the capital of Finland. The DHC system in Helsinki is operated by Helen Ltd (Helen), which is the former municipal energy company of Helsinki and now a limited company fully owned by the city of Helsinki. The city of Helsinki and Helen have a long-term objective to become carbon-neutral by the year of 2050 [13]. The current DH production system consists of 3 combined heating and power (CHP) plants fuelled with coal, natural gas, and biomass, 10 heat-only plants fuelled with natural gas and oil, and a large scale combined heating and cooling heat pump plant using municipal treated wastewater, passive solar heat, and seawater as heating and cooling sources. The DH network in Helsinki is presented in Fig. 1 [14].

Over 90 percent of the city building stock or about 132 million m^3 is heated by DH. The total length of the DH lines is over 1300 km. The annual demand of DH varies between 6000 and 7000 GWh. Depending on the yearly variations, approximately 90 percent of the DH is produced energy-efficient in CHP plants, which serve primarily as base-load plants [16]. However the DH capacity for the case of peak heat demand needs to be significantly larger, since the DH demand is strongly dependent on seasonal variations. Thus there is also a need for relatively large capacity of peak heat plants, which are rarely used. The City Council of Helsinki has decided to decommission one of the CHP plants, which is currently fuelled by coal and biomass, and to release the area for urban planning [17].

Accordingly, there is a need for new carbon-neutral energy production capacity that is technically, economically and environmentally feasible in the specific conditions of Helsinki. Helsinki has