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Economic valuation of heat pumps and electric boilers in the Danish energy system

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HIGHLIGHTS

- We assess the economic value of heat pumps and electric boilers in Denmark.
- The daily operation of a heat and power system is modeled by stochastic programming.
- Deterministic models overestimate the value of heat pumps and electric boilers.
- Heat pumps and electric boilers can reduce the cost of operating the Danish system.
- Falling power prices may boost the future value of heat pumps and electric boilers.

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ABSTRACT

Heat pumps (HP) and electric immersion boilers (EB) have great potential to increase flexibility in energy systems. In parallel, decreasing taxes on electricity-based heat production are creating a more favorable economic environment for the deployment of these units in Denmark. In this paper, the economic value of heat pumps and electric boilers is assessed by simulating their day-to-day market performance using a novel operational strategy based on two-stage stochastic programming. This stochastic model is employed to optimize jointly the daily operation of HPs and EBs along with the Combined Heat and Power (CHP) units in the system. Uncertainty in the heat demand and power price is modeled via scenarios representing different plausible paths for their future evolution. A series of case-studies are performed using real-world data for the heat and power systems in the Copenhagen area during four representative weeks of 2013. We show that the use of stochastic operational models is critical, as standard deterministic models provide an overestimation of the added benefits from the installation of HPs and EBs, thus leading to over-investment in capacity. Furthermore, we perform sensitivity studies to investigate the effect on market performance of varying capacity and efficiency for these units, as well as of different levels of prices in the electricity market. We find that these parameters substantially affect the profitability of heat pumps and electric boilers, hence, they must be carefully assessed by potential investors.

1. Introduction

Denmark has committed to pursue a 100%-renewable energy supply by 2050 [1]. Furthermore, half of the electricity consumption is to be provided by wind power by 2020. In view of these ambitious targets, integration across different energy systems is seen as fundamental, as it can improve the exploitation of the flexibility of heat and transport systems to support the growth of intermittent renewable power sources [2,3]. Non-renewable fuels, such as oil and coal, are currently used to produce a significant share of the Danish heat and power [4]. Traditionally, these have been widely used for generating heat and power through the use of highly efficient Combined Heat and Power (CHP) plants. However, the reconciliation of the large-scale integration of wind power production along with the wide use of CHP units for heat and power production (cogeneration) will be a challenge for future energy systems. Indeed, the profitability of cogeneration can be dramatically reduced in periods of large wind power production as wholesale power prices drop [5].

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A partial solution to this problem consists in an efficient joint management of the available heat and power units that takes into account the future evolution of heat demand and power prices. These are in turn driven by renewable power output, among other factors [2]. Furthermore, heat pumps (HP) and electric immersion boilers (EB) can be installed to increase the flexibility of the system (see, e.g., [6], where equipping CHP plants with heat pumps is suggested with a view to effectively increasing the penetration of wind power in the Danish power system).

Both HPs and EBs use electricity to generate heat. In general, units of this type may enhance the power system flexibility as electricity is used as fuel. Indeed, with an increasing share of fluctuating renewable power production in the power system, the number of events in which renewable power generation cannot be reliably accommodated in the grid or even exceeds the demand grows. During these events, the market price for electricity becomes close to zero, zero or even negative. Therefore, during these events, it may be beneficial, both from the standpoint of a single company and for the system as a whole, to utilize electricity to produce heat by means of HPs and/or EBs. From a purely thermodynamic point of view, transforming electrical energy into heat in an EB is considerable less efficient than doing it through a HP.[1] In contrast, EBs have lower investment costs and fast-regulation capabilities (with no start-up cost or ramping constraints), which makes them very suitable for the provision of grid ancillary services. All together, the conversion of electricity into heat via EBs and HPs may become economically attractive in energy systems with a high penetration of fluctuating renewable energy sources. A more thorough introduction to heat pumps and electric boilers can be found in [7,8].

The deployment of HPs and EBs in the Danish district heating systems began during the last decade. However, the extent of this trend has been rather limited as high taxation has constrained the profitability of these units. In 2013 a significant tax reduction was decided for this specific type of production technology, favoring especially the HP [9]. Even though the deployment of HPs and EBs is a relatively new phenomenon, previous research on the optimization and economic assessment of combined heat and power production systems including these units is abundant, some dating back several decades (see, e.g., [10] and references therein). However, to the best of our knowledge, all these studies were conducted under a deterministic framework.

The increasing focus on cogeneration, together with a greater awareness of the uncertainty in electricity prices and heat demand, has resulted in numerous papers jointly dealing with these aspects in the last decades. Deterministic optimization models to maximize the profit of heat and power production systems are proposed in [11,12] and are also available in software packages such as energyPRO [13]. The stochastic programming approach [14] to the same problem is followed in [15,16]. Finally, a model based on robust optimization is proposed in [17]. Furthermore, Zapata et al. [18] developed a deterministic optimization scheme to assess the potential of coordinated real-time market operation of micro-CHP and PV units. None of these works, however, include HPs and EBs. Furthermore, the focus in this paper is on assessing the value created by these heat production units rather than evaluating operational strategies.

Existing literature on economic valuation and investment analysis in heat and power systems has relied on deterministic operational models so far. For example, the deterministic analysis tool, Balmorel, models the entire Greater Copenhagen district heating system, including the Nordic power market, and provides long-term information on an aggregated level [19]. The profitability of different CHP technologies in a smart energy system is assessed in [20] using the deterministic model Energyplan. Furthermore, Blarke and Dotzauer [21] assess the economic value of a HP utilizing flue gas from a CHP. Hendriksen [22] analyzes the economic potential for a HP to utilize waste heat from industrial facilities, but not in the context of combined heat and power production. In [23], a stochastic programming model is used to evaluate the value of HPs and EBs in a system including wind power. In contrast to the work in this paper, only wind power is considered stochastic. Furthermore, the analysis is only carried out for a short period in February, where wind power production usually fluctuates much and thus a high benefit is to be expected from introducing HPs and EBs.

Although the use of stochastic programming in the operation of systems of power production facilities is well established, see [24,25] and references therein, the economic assessment of the value of HPs and EBs using daily operational models for heat and power systems based on this state-of-the-art stochastic approach remains not studied. Therefore, the contributions of this paper are threefold. Firstly, we propose a stochastic programming model for the joint daily operation of heat and power systems that exploits probabilistic forecasts of heat demand and power prices. This model represents the decision-making process that utilities conduct in an uncertain market environment. Secondly, we use this model to assess the yearly return of potential investments in heat pumps and electrical boilers in an already existing energy system. These two contributions together lead to a methodological and modeling framework for the economic valuation of heat and power systems that can be easily tailored to the specific market and system conditions prevailing in the area, region or country of interest. In this line, our third and last contribution is the use of such a modeling framework to analyze a series of case studies based on real-world data for the Copenhagen area under the current conditions of the Danish heat and power markets and systems. We assess the sensitivity of our results to different technological and market parameters such as unit efficiencies and market-price level.

This paper has the following structure. The physical and market setups that serve as the basis for our model are presented in Sections 2 and 3, followed by the mathematical model in Section 4. The methods for forecasting the heat load and the power price are introduced in Section 5. Results from the proposed model and the conducted analyses are discussed in Section 6. Finally, conclusions are duly drawn in Section 7.

2. Physical setup

Fig. 1 shows a simple overview of the physical system considered in this paper. Two different CHP units are included, one coal-fired extraction unit (denoted in the remainder of this paper as “ex CHP”) and one biomass-fueled back-pressure unit (“bp CHP”). The extraction unit produces at a variable heat-to-power ratio with a variable efficiency, which is lowest when only power is produced. The back-pressure CHP plant produces at a constant heat-to-power ratio. More details on the operation of these plants can be found in [7]. Both units feed heat directly to the transmission network and to a large heat accumulator. The transmission network supplies several local distribution networks, only two of which are shown in the illustration. The HP is connected to a local distribution network and a small local heat accumulator. The HP operates as a negative load for the system, i.e., it is assumed that the size and heat demand of the distribution network is large enough for the HP to produce at any time. Both the HP and EB consume electricity and produce heat. Red dashed lines represent heat transfer, while black arrows represent electricity inputs or outputs.

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[1] A HP utilizes energy from a low-temperature heat source such as waste water, sea or air in the process of producing heat. This gives a HP a higher coefficient of performance (COP), which is the power-to-heat ratio, compared to an EB.

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