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Investigating influential techno-economic factors for combined heat and power production using optimization and metamodeling

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HIGHLIGHTS

- Metamodel is used to study influential factors for combined heat and power production.
- Combined heat and power production is investigated with 6 techno-economic factors.
- Estimated variations in energy system cost are caused by main and interaction effects.
- Optimal factor setting maximizes electricity production and provides extra benefits.

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ABSTRACT

This paper investigates the interaction of a wide range of electricity and fuel prices and technical factors of combined heat and power production in a district heating system. A linear programming-based optimization model with the objective to minimize system cost was used to study the energy systems in the cities of Gävle and Sandviken in Sweden. The comprehensive outcomes from optimization and parametric studies have been analyzed using a polynomial-based metamodel. System costs include variable costs for the production and revenues for sale of heat and electricity. The metamodel is used as an analytical and explanatory tool to interpret input-output relationships. Municipal district heating systems of Gävle and Sandviken in Sweden are studied as an interconnected regional system with improved and new combined heat and power plants. The results show that effects from electricity and fuel prices are important, but that variations in energy system cost may also be caused by many cross-factor interactions with technical factors. A comparative system performance analysis with defined cases and optimal factor setting shows a substantial increase in the electricity production, here by up to 650 GWh annually. The profitability of investing in a new plant depends highly on the considered investment risk and electricity and fuel market prices. CO_2 emission savings by up to 466 kton annually can be accomplished if marginal electricity production from coal-condensing power plants is avoided and biofuel is released at the same time.

1. Introduction

District heating (DH) is a well-recognized concept to utilize recovered excess heat from combined heat and power (CHP) plants [1,2]. Joint production of heat and electricity in CHP plants enhances energy supply efficiency by saving primary energy and making it cheaper to provide heat and electricity than to produce them separately. A network of pipes provides the distribution of produced heat to satisfy heat demands, e.g., for space heating and hot water use. Most favorable conditions for DH appear in urban areas with many buildings, residential areas, and industrial complexes through high heat density and lower distribution costs [3]. Through effective resource use and the potential to reduce CO_2 emissions, DH systems and cogeneration of heat and electricity in CHP plants are promoted to reach short and long-term energy and emission targets [4,5].

To study energy systems, including DH and CHP, optimization models based on linear programming are widely used. Optimization models make it possible to identify optimal solutions for a combination of energy supplies by fulfilling the objective of, for instance, minimized total cost by satisfying energy demand during specified time steps. Several studies concern the optimal use of energy supplies and the integration of heat and fuel supplies in DH systems. Åberg [6] used

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typical system models to study changes in DH production by stepwise heat demand reductions. Gebremedhin [7] studied impacts of different levels of biomass prices and emission allowances on the choice of fuels and production technologies by considering new plant investments. Djuric Ilic et al. [8] investigated the cooperation between the transport and DH sectors by introducing a large-scale biofuel polygeneration production with new CHP plant installations. Amiri et al. [9] analyzed conditions for connecting CHP plants to a biogas system with the objective to present the model for biogas production systems. A number of studies used multi-integer linear programming models to study plant operations, design and operation strategy. Ommen et al. [10] considered lowering DH temperatures to study operation of power and heat production in utility plants based on network characteristics and presented by performance curves of typical CHP plant technologies. Romanchenko et al. [11] investigated the interplay between DH systems and electricity system to study optimal operating strategies for DH systems based on electricity price curves. Studies by Morvaj et al. [12] and Buoro et al. [13] used multi-objective models to reduce costs and CO_2 emissions simultaneously and investigated optimal design and operation of distributed energy systems in urban and industrial areas, respectively.

However, optimization modeling of DH systems with CHP plants depends on many factors. DH systems operate locally, and the heat production is adapted to variations in local heat demand, while a CHP production directly links the DH system to the electricity market. Uncertainties through the evolution and variation of energy prices in, for instance, a deregulated electricity market introduce difficulties in defining system conditions leading to additional approaches. Considering cogeneration system planning and by including probabilistic and simulation models, incorporating uncertainties of electricity, bio and natural gas prices with different time frames of electrical and thermal loads can be used for optimal operation of the cogeneration plant [14]. Using cases of electricity price profiles based on recent price variations and reasonable expectations on the price development enables testing of a system's sensitivity to diurnal and seasonal price variations [15]. Shadow prices (incremental cost of generating one extra unit of electricity) from a power system as input data for electricity pricing provide more exact system conditions than assumed electricity price data [7]. Considering variations in fuel and electricity prices, a statistical factorial design can be used to analyze the sensitivity of different plant capacities to evaluate the profitability and financial risk of CHP investments [16,17]. The studies also highlight the importance of considering interaction effects between techno-economic factors. Most of the mentioned energy system studies used scenarios, some sensitivity analysis or parametric studies to analyze system sensitivity and uncertainties in input data. Only a few consider interactions between economic and technical factors. With an expected increase in the complexity of operating DH systems with CHP plants, there is a need to achieve a better understanding of influential factors for CHP production.

Response surface models enable graphical solutions and are widely used to provide the understanding of input-output relationships between design factors (input variables) and response (output). Response surface models include polynomial regression models, associated with traditional response surface method and advanced Design of Experiment [18], and so-called metamodels when applied to approximate computer-based model outcomes. A detailed background to metamodeling and response surface method with applications can be found in [19]. The approach used in this study is illustrated in Fig. 1. To the best of the author's knowledge, this is the first time the approach of energy system (including DH and CHP), optimization model and metamodel is used. Principally, an energy system with supply and delivery is described by an optimization model. Specific model input data in the form of design factor level combinations ($x_1, \dots, x_k$), also referred to as factor setting, are used to generate a limited set of model runs (scenarios) and output data (y), which in turn are used to fit a metamodel that approximates the model's input-output transformation.

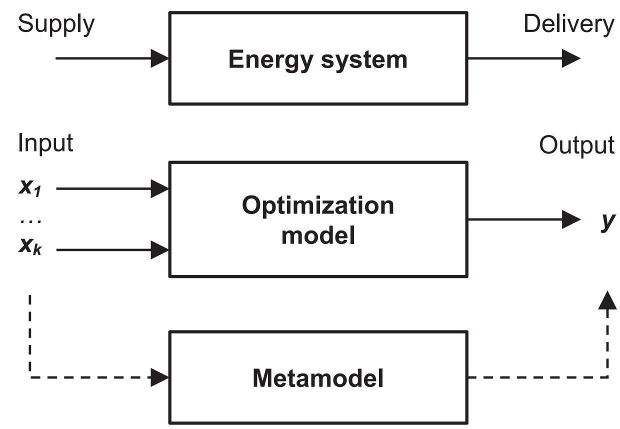

Fig. 1. Illustrated method approach with energy system (including district heating and CHP), optimization model, and metamodel.

The aim of the study was to investigate influential factors for CHP production by using an optimization tool and metamodeling. The linear program MODEST was used for optimizations. Metamodeling includes a polynomial-based metamodel to approximate cost-minimized model outputs, and Box-Behnken experimental design to generate the limited set of scenarios. Municipal DH systems were connected into a larger regional system and studied with improved and new CHP plant installations. A comparative system performance analysis with defined cases based on optimal factor setting was used to show impacts on heat and electricity production, industrial heat use, energy system cost, and CO_2 emissions. CO_2 emissions were accounted for using a Nordic electricity system perspective with models for marginal electricity, limited biofuel, and electricity production mix. Different discount rates were used to evaluate the investment opportunity of improved and new plants.

The paper is organized as follows. Section 2 includes a background of studied cases with local and regional DH systems and description of energy supplies. Section 3 describes the linear program MODEST and the modeling of the studied energy system with input data. Metamodeling also includes generated scenarios and design factors. Differences to separate systems and models are highlighted as well as model validation, CO_2 emission accounting and calculation of investment opportunity. Section 4 shows the metamodel for energy system cost, graphical solutions and changes in system performance. Section 5 includes further considerations to develop the study and findings and conclusions are presented in Section 6.

2. Energy system description and defined cases

The studied energy systems deliver heat for DH in the cities of Gävle and Sandviken with a combined population of about 130,000 inhabitants. The systems are located close to each other in Gävleborg County in east-central Sweden (Fig. 2). Both systems are owned and operated by a municipal energy company, Gävle Energi AB (GEAB) and Sandviken Energi AB (SEAB) respectively. Each system currently uses heat supplies from its own biofuel CHP plant, mainly from November to March. Heat-only plants and boilers (HOBs) are used during summer (Sandviken) and for increased DH demand. Industrial heat is used in Gävle for base heat loads throughout the year. Heat supplies come from a pulp and paperboard mill, mainly as excess and evaporator heat, and a jointly owned CHP plant (GEAB, mill). The biofuel-fired industrial CHP plant produces steam and electricity for the mill, while heat from the flue-gas condensation (FGC) is supplied for DH, but also from a (steam) condenser to cover peak heat loads. A fossil fuel-based HOB is also used for peak demand from both pulp and paperboard mill and DH. Industrial stand-by electric boilers are not considered here. The energy