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Multi criteria dynamic design optimization of a small scale distributed energy system

Andreas Rieder [a,*], Andreas Christidis [b], George Tsatsaronis [b]

[a] *Institute for Technology Assessment and Systems Analysis, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany*
[b] *Institute for Energy Engineering, Technische Universität Berlin, Marchstr. 18, D-10587 Berlin, Germany*

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ABSTRACT

The aim of this paper is to analyze the mutual interdependencies and trade-offs between heat storage and district heating network considering economic and ecological aspects. Therefore, a MILP (mixed integer linear programming) problem of a distributed energy system is formulated with a weighted multi-criteria objective function including profit and operational CO_2 emissions. The considered components include CHP (combined heat and power) units of three different types, a thermal storage facility, a boiler, and district heating pipelines. In a single optimization step placement, quantity and capacity of all components as well as their operation is determined. The computed designs as well as the operation of the energy system are compared under varying weightings and different technology scenarios. We also conduct a sensitivity analysis of the investment costs associated with heat storage and of the piping costs for the district heating network. The results favor the construction of heat storage devices over a district heating network. This applies to both environmental impact and cost of energy supply and can be well explained by the decoupling of heat demand and electricity production, which is shown in a correlation analysis.

1. Introduction

The energy concept of the German Federal Government seeks to expand the share of renewable energy to 50% of the gross electrical power consumption by 2030 (20% in 2011). By 2050, this proportion shall be further increased to 80%. Simultaneously, the use of primary energy shall be reduced by 50% until 2050, compared to the one in 2008. In order to achieve this goal, a significantly more efficient and flexible energy system must be established. Flexibility is vital because the majority of renewable energy production is driven by the supply of volatile factors, such as wind for wind turbines or solar radiation for solar panels, and is fed into the grid independently of the electrical energy demand. One way to achieve this integration, while maintaining high fuel efficiency, is the development of small, and therefore more flexible, CHP (Combined Heat and Power) plants.

The need for a temporal decoupling of heat demand and electricity production in CHP plants is emphasized by the results of various renewable energy development studies in Germany. In Ref. [1] for example, it is stated that the share of combined heat and power generation must account for 21% of the gross electricity production in the year 2050, while only 4% will be provided by conventional power plants in contrast to 67% provided by volatile renewable energies. This underlines the need for CHP units with a complete control of electrical power output.

A flexible, strongly decoupled electricity and heat supply by CHP plants can be achieved with thermal storage facilities. The advantage of heating networks is a higher overall thermal load for the CHP system: this allows for larger energy conversion units to be used, which have lower specific capital costs and a higher electrical efficiency compared to smaller units, due to the effect of scale.

These boundary conditions raise several questions:

- Are heat accumulators and district heating networks competing or collaborating components?
- How does a district heating network and heat storage affect the optimal design of the energy system and the unit commitment of the CHP plants? What are its implications for a future power system with a large share of renewable energy sources?
- How much does an optimal system design with respect to profitability differ from one where the focus is to keep CO_2 emissions low?

* Corresponding author. Tel.: +49 721 60826016.
E-mail addresses: andreas-g.rieder@kit.edu (A. Rieder), christidis@iet.tu-berlin.de (A. Christidis), tsatsaronis@iet.tu-berlin.de (G. Tsatsaronis).

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To answer these questions, we used a mathematical optimization approach where the design and structure of the energy system as well as the operation of each component are optimized. For this task, a MILP (mixed integer linear programming) problem of a distributed energy system was formulated, consisting of cogeneration units, (heat only) boilers, hot water accumulators, heat pipelines, and heat consumers. By implementing a weighted multi criteria objective function, we were able to consider both profit and operational CO_2 emissions.

1.1. Literature

A comprehensive review of different energy system models is given by Connolly et al. [2] and Keirstead et al. [3]. Whereas Connolly et al. are focusing on the integration of renewable energies, Keirstead et al. give a broad review in diverse areas, i.e. technology design, building design, urban climate, systems design, and policy assessment. The following publications were not mentioned in the reviews, though they have a special focus on combined optimization of district heating networks and distributed energy conversion units:

In the project VoFEN (Vision of Future Energy Networks) the concept of so-called Energy Hubs is developed [4]. With this model, the coupling between different energy carriers (such as electricity, natural gas, and district heating) was analyzed by energy conversion plants and the optimal mass flows of the different energy carriers were determined. Many different plants can be modeled by coupling multiple energy carriers in a matrix. The coupling matrix is determined in a static optimization. Niemi et al. [5] used a similar approach, but incorporated features of a smart grid, i.e. control functions and network intelligence, among others. Zelmer [6] concentrates on the mathematical difficulties of modeling the transmission losses for the energy carrier gas, electricity and hot water with a high physical accuracy. Due to the resulting complexity, no unit commitment is conducted. Voll et al. [7] present an automated method to synthetize superstructures of decentralized energy supply systems with a sophisticated optimization method, but until now no storage systems were included. In contrast to the study mentioned before, Mehleri et al. [8] conduct a combined optimization of district heating layout and CHP units. A detailed pipeline model has been established, but without the implementation of storage options since Mehleri et al. did not apply it to a continuous calendar year but to characteristic periods. In Ref. [9], the so-called TURN (Technology Urban Resource Network) Model calculates the energy supply system at optimal cost for a whole city. The significant difference to the Energy Hub concept is the modeling of the city through an idealized grid layout, with each cell measuring 400 m × 400 m. In the publications [10–12] multi-criteria objective functions are included to analyze economic and environmental aspects of distributed energy systems. Buoro et al. are investigating a distributed energy supply system featuring a solar power plant in Ref. [10]. In Bin Shi et al. [11] and Motevasel et al. [12] different approaches are used to determine an optimal dispatch of cogeneration power plants, minimizing both fuel consumption and operational emissions of SO_x, NO_x and CO_2.

The approach presented in this paper is unique due to the combination of the following aspects:

- Consideration of a full year period and time intervals of 4 h
- Combined optimization of the design and the operation of all system components
- Multi-criteria optimization with respect to economic and ecological aspects and thus determination of Pareto optimal solutions
- More accurate modeling of cogeneration unit and storage characteristics than i.e. in Refs. [4–6,8,9].

In Section 2, the applied methodology is presented: Section 2.1 introduces the multi-criteria objective function, Section 2.2 presents two approaches to capture capacity-dependent characteristics whereas Section 2.3 and 2.4 describe detailed model formulation of the technologies employed in this work. In Section 3, the computed system designs for different scenarios are evaluated. Finally, conclusions and outlooks are given in Section 4.

2. Methods – generic model formulation

The presented model seeks to determine the best possible way to satisfy the time-varying heat demand of distributed sites. Therefore a single optimization program is formulated considering both the choice of technologies and their operation. The supply area is defined by a grid of nodes $(k, kn \in [1..n])$, where coordinates and heat consumption for each node are specified by the user. The developed model will determine how to satisfy these heat demands with the available equipment shown in Fig. 1, i.e. cogeneration units of three different types, a thermal storage facility, a (heat only) boiler and district heating pipelines, latter able to connect two nodes. Investments into capacities of each component and their operation are decision variables to the model. Cost functions and further numerical data is given in the appendix.

The heat demand must be covered by the optimization in every time interval (τ), which has a length of $\Delta\tau = 4$ h (a compromise between computational costs and operating characteristics of thermal storages, see also [13]). A further constraint is that the feed flow temperature is adjusted as a function of ambient temperature. As we assume a grid connection is available, the consumers' electrical power consumption is not modeled. Therefore, the incentives for electrical power production are modeled by both a financial benefit, by the power sale in the German energy exchange EEX (real hourly values of the year 2009) as well as an environmental benefit, by effectively reducing greenhouse gas emissions.

2.1. Objective function

The best possible solution to meet the given heat demand is calculated by maximizing the annual profit and minimizing the annual CO_2 emissions (M^{CO_2}). Therefore the objective function Eq. (1) is formulated following the weighted sum model, cf. [14], so that the weighting factor α can be interpreted as the importance of each criterion. By subtracting the CO_2 emissions these are minimized, while the overall objective function (O) has been maximized. For an easier comprehension of the weighting factor's influence, it is advisable to express both terms in the same magnitude; otherwise it is equivalent to "adding apples and oranges". Therefore the absolute values of profit and emission are divided by a respective reference value. Reference state refers to the system with $\alpha = 1$, i.e. a pure economic optimization. The objective function is constrained by a set of equalities and inequalities describing the technical and economical characteristics of the energy system.

$$\max O = \alpha \frac{p}{p^{\mathrm{ref}}} - (1-\alpha)\frac{M^{CO_2}}{M^{CO_2,\mathrm{ref}}} \tag{1}$$

$$p = R^{tot} + S^{tot} - OMC^{tot} - A^{tot} \tag{2}$$

$$R^{tot} + S^{tot} = \sum_{\tau}\sum_{k}\sum_{type} \mathbf{r}^{\mathbf{el}}_{\tau} \cdot \boldsymbol{P}^{\boldsymbol{CHP}}_{\tau,\mathrm{k,type}} \cdot \Delta\tau + \sum_{k} S^{CHP}_{k}\left(\boldsymbol{P}^{\boldsymbol{CHP}}_{\tau,\mathrm{k,type}}, \boldsymbol{P}^{\boldsymbol{CHP,max}}_{\mathrm{k,type}}\right) \tag{3}$$