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Feasibility of CHP-plants with thermal stores in the German spot market

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ABSTRACT

The European Energy Exchange (EEX) day ahead spot market for electricity in Germany shows significant variations in prices between peak and off-peak hours. Being able to shift electricity production from off-peak hours to peak hours improves the profit from CHP-plant operation significantly. Installing a big thermal store at a CHP-plant makes it possible to shift production of electricity and heat to hours where electricity prices are highest especially on days with low heat demand. Consequently, these conditions will have to influence the design of new CHP-plants. In this paper, the optimal size of a CHP-plant with thermal store under German spot market conditions is analyzed. As an example the possibility to install small size CHP-plant instead of only boilers at a Stadtwerke delivering 30,000 MW h-heat for district heating per year is examined using the software energyPRO. It is shown that, given the economic and technical assumptions made, a CHP-plant of 4 MW-el with a thermal store participating in the spot market will be the most feasible plant to build. A sensitivity analysis shows to which extent the optimal solution will vary by changing the key economic assumptions.

1. Introduction

An increasing energy demand, depletion of fossil energy resources and the emission of green house gases provide incentives to develop and fully utilize highly efficient energy technologies. Cogeneration (combined heat and power, CHP) is a well known and highly efficient approach to produce electricity and heat in a single thermodynamic process [1,2]. By cogenerating the electricity and heat, CHP-plants have the possibility to decrease fuel consumption by 20–30% as compared to decoupled production in conventional power plants and boilers [3,4]. This technology reduces overall fossil fuel consumption and thus the energy is generated in a more environmentally friendly way [1,5,6]. Promotion of high-efficiency cogeneration based on a useful heat demand is also required under the EU Directive 2004/8/EC [5].

Denmark is one of the countries in Europe that has been able to develop a comparatively high share of CHP production, a significant part of it being decentralized plants with an electrical output of less than 20 MW. This has been achieved mostly by granting feed-in tariffs. However, the biggest achievement is not merely the high share of CHP production, but also that those plants have been incentivized to operate flexibly by the tariff structure which has been higher during the day than during the night time and even higher during peak hours in the middle of the day. Plants could be designed for flexible operation by installing significant thermal stores. This way decentralized CHP-plants in Denmark have been rewarded when matching their production better with the electricity demand and are now well prepared for being an active participant in the power market. Having a thermal store also makes it possible to operate the production units at the most fuel efficient load and to store the surplus heat. If the prime movers are gas turbines or spark-ignited gas engines the most fuel-efficient operation is full load [7].

The advantage of the Danish operating strategy becomes even more obvious when acting under market conditions with hourly prices. The larger the difference between peak and off-peak prices the more attractive it becomes for flexible plants.

In Germany, one of the largest energy markets in Europe, high-efficiency cogeneration especially in combination with district heating/cooling is regarded as strategic technology to support the government's energy and climate policy goals. However, targets set in the CHP act of 2002 have not been achieved. In June 2008 German Parliament has approved a new CHP law, which aims at doubling the total share of CHP electricity to 25% by 2020. The estimated economic potential for CHP electricity production in Germany is lying between 300 and 350 TW h-el per year. This translates into about 35 GW-el of CHP capacity [8].

CHP electricity is promoted by bonus payments for the produced electricity paid on top of the achieved electricity sales price. Besides the bonus and the commodity price CHP operators will receive a compensation for avoided grid use if connected at a lower

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voltage grid. The setup results in the CHP-plant being exposed to the electricity market. Electricity spot prices in Germany show a distinct daily pattern with very high peak prices, thus the application of a flexible operating strategy can be expected to be highly attractive in the German market. Also, Germany is one of the EU leaders in renewable energies. Especially wind and solar power production is fluctuating, hence increasing the demand for flexible response from other producers.

Two aspects of the German CHP market are conspicuous though: despite the support scheme decentralized CHP electricity production is still rather low, and interestingly, only few decentralized CHP-plants in Germany are designed to operate in a flexible, market oriented way. Thermal storage tanks are rarely built or relatively small.

This paper shows that the German power market is highly attractive for decentralized CHP development if the plants are designed and operated as flexible units that take advantage of the fact that electricity is priced differently at different times of the day and week. This method proposes a plant design that differs significantly from common practice in Germany.

2. Optimized operation of a CHP-plant with thermal store

To optimize the operation of CHP-plants with thermal stores is far from being a new problem. It has been analyzed in a vast number of studies and programmes [1,2,9–19]. However, the focuses in these analyses are very different.

Some studies focus mainly on the modelling approach, others more on the effects of changing the design of the CHP system. Those focussing more on the system design differ especially in the way they make use of a thermal store. In this context it makes sense to differentiate between storages that enable more steady and extended operation of CHP-units (operational storage utilization) and storages that are aimed at shifting operation to the commercially most viable points in time (commercial storage utilization). While the first ones are aimed mostly at allowing extended full load operation of small-scale CHP-units, the latter ones are meant to improve economic feasibility especially for bigger units facing variable electricity prices.

Marchand et al. [9] presented a static linear programming model of a district heating system with a cogeneration station. The model was applied to a medium-sized city. It was shown that operations research models could be used to answer the key issues raised by the introduction of cogeneration.

Gustafsson and Karlsson [10] showed that thermal stores might be of interest for CHP networks. They showed that sources of fuels could have influence on the attractiveness of the thermal store, especially if waste heat was utilized and it covered the base load. Ito et al. [11] analyzed a diesel engine cogeneration plant with thermal store using a dynamic programming method with mixed-integer programming. They showed that the installation of the thermal store and the adaptation of the optimal operation policy reduced the daily and the annual operation costs of the total plant.

Dotzauer and Holmström [12] showed that finding the optimal production of both heat and electricity and the optimal use of the thermal storage was a complex optimization problem. They solved the short-term production-planning problem using a combination of dynamic programming, general-purpose solvers and the Lagrangian relaxation method. Electricity prices play an important role in their solution. Lee et al. [13] analyzed a daily operation scheduling method for industrial CHP systems with thermal storages, electricity chargers and auxiliary boilers. The authors proposed an operation scheduling scheme for cogeneration systems using fuzzy linear programming. They showed that scheduling of buying and selling of electricity influences the calculation of total operation cost.

Khan et al. [14] carried out a feasibility study of cogeneration using a double-effect absorption chiller and cogeneration coupled with a thermal energy storage of chilled water. They showed that on-site cogeneration using the double-effect absorption chiller provides a potential of about 13% peak-demand reduction and savings in energy consumption of about 16%. Khan et al. concluded also that thermal store coupled with cogeneration was more economic compared to cogeneration only. Rolfsman [15] made a study of district heating supplied via boilers and CHP-plants. It presented an optimization model for short-term planning of the operation of thermal store together with CHP-plants. It was shown that variations in the electricity prices can influence the investment potential. The commercially operated store is the driver behind that. Siddiqui et al. [16] found that for a specific site with a small heating load, there was no incentive to use a thermal store at all. On the other hand, a customer with a medium ratio of heating to electricity loads used thermal store to meet 30% of the heating loads. Again commercial store utilization is not applicable in this case. However, every particular case needs detailed analysis.

Schaumburg-Müller [17] presented a model that created day-ahead production schedules for a CHP-plant using CPLEX 10.0.1 under GAMS. The CHP-unit was divided into several segments to allow taking into account varying efficiency and production costs at different load levels. Such segmentation concepts may be used for the modelling of CHP-plants at partial load. Obara [18] analyzed a residential CHP system consisting of a methanol-steam-reforming fuel cell, a geothermal heat pump, both electrical and thermal store. The complex energy system was analyzed using a genetic algorithm. The thermal store was connected to the heat pump and the stored heat was supplied to the heat load during the day time. The analysis showed that thermal storage capacity must be chosen according to the available technologies for heat and power production. Bogdan and Kopjar [2] assessed the influence of a district thermal store on a big-scale CHP-plant using an optimization code ACOM, which has been specially developed for simulating and optimizing the EL-TO plant in Zagreb. They could show that the introduction of a district thermal store may substantially improve the economic performance of the CHP-plant when electricity prices are governed by the dual-time tariff system, with significant differences between day- and night-time tariffs. Here the thermal store is used commercially, though in a rather simple tariff system.

Onovwiona et al. [19] presented a model for a residential CHP with internal combustion engine. The chosen thermal store of 300 kg hot water was too small for a 6 kW capacity engine because the CHP system did not utilize its full potential. Having a large CHP-unit with a small thermal store may lead to excess heat output which is dumped. A 2 kW-el CHP-unit reduces heat dump and is more efficient as compared to a 6 kW-el CHP-unit. These results indicate that it is important to make a proper selection of the capacity of both thermal and electrical devices in the CHP system. However, the system is optimized under operational rather than commercial aspects.

Hongbo et al. [1] developed a mixed integer nonlinear programming model, using a commercial software package LINGO for a residential CHP system with thermal store. That analysis was conducted to find the economically optimal CHP investment for a prototypical residential building. It was found that an optimal storage tank can extend the operating time of the CHP-plant; however, an oversized tank leads to less economic merits because of increased energy losses. Also in this case the thermal store is used operationally rather than commercially.

The number of studies shows that finding the optimal configuration of a CHP-plant is a frequently addressed topic. In general most of the previous works focus on modelling and optimization.