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Optimization of combined heat and power production with heat storage based on sliding time window method

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HIGHLIGHTS

- New sliding time window method for optimizing CHP with storages.
- The method benefits both design and operation of CHP systems.
- Simulation of the benefit of the method in practice.
- Optimization can lead to significantly larger revenue from power sales.
- The method can be used to optimize the size of new heat storage.

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ABSTRACT

A combined heat and power (CHP) optimization model with heat storage is proposed to minimize the production cost and to maximize the revenue from power sales based on a sliding time window method. The model can be applied both for operating heat storage optimally and supporting investment planning for a new storage. Heat demand is forecasted based on a weather forecast. Each day the heat demand and power price forecasts are input to a generic CHP optimization model for a several-day time window to obtain a heat storage operation plan. Then only the first day of the plan is implemented with actual power price and heat demand using a single-day optimization model to compute the actual production amount, fuel costs and revenue from power sales. After that, the time window is slid one day forward, and the above-mentioned process is repeated. In the test runs, forecasts for power price and temperature are simulated by disturbing actual (historical) data by the Wiener process (random walk). To evaluate the benefit and validate the proposed method, the results are compared with the no-storage case and the theoretical optimum assuming perfect demand and price forecasts. The results show that the revenue from power sales can be significantly improved. The method is used to evaluate the benefit of different sized storages for the CHP system. Also the effect of the width of the time windows on the performance of the method is evaluated. The model was tested using real-life heat demand data for the city of Espoo in Finland, and NordPool spot market data for power price for a one year time horizon. The results indicate that considering the forecasting uncertainty, 5-day sliding time window method can obtain 90% of the theoretically possible cost savings that can be derived based on perfect forecasts.

1. Introduction

Combined heat and power (CHP) is a booming technology which simultaneously produces heat and power by recovering heat that would otherwise be wasted in conventional condensing generation of electric power. Since 2007, the European Council has targeted to tackle several serious climate change and energy related issues. In details: 20% CO_2 emissions reduction comparing to 1990; 20% improvement in energy efficiency; 20% share of renewable energy sources in the end-use, which is called 20–20–20 goals, should be acquired by 2020 [1]. CHP is considered a sustainable and economic technology to fulfill those abovementioned goals for its significant performance in fuel demand reduction, greenhouse gas reduction and fossil fuel independency [2]. For instance, biomass-fired CHP plants are technically and economically advantageous for carbon emission reduction given the proper system efficiencies, fuel costs, incentives, thermal energy usage, etc. For small scale CHP, Micro-CHP units are considered to replace

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Nomenclature

Indices and index sets

J	the set of extreme points of the operating region of CHP plant
j	index of extreme point in characteristic
t	time index (h) within time horizon

Variables

x_j^t	to encode the operating region of the CHP plant as a convex combination
s_q^t	the heat storage content at hour t (MW h)
q_{s+}^t	the amount of charged heat at hour t (MW h)
q_{s-}^t	the amount of discharged heat at hour t (MW h)
q_{hob}^t	The heat production by heat only boiler at hour t (MW h)

Parameters

c_p^t	the spot price of power at hour t (€/MW h)
c_{hob}^t	the fuel cost for heat only boiler at hour t (€/MW h)
c_j	fuel cost at the CHP characteristic point $j \in J$ (€/MW h)
p_j	power production at the CHP characteristic point $j \in J$ (MW h)
q_j	heat production at the CHP characteristic point $j \in J$ (MW h)
Q^t	heat demand at hour t (MW h)
s_q^{max}	heat storage capacity (MW h)
s_{q+}^{max}	maximum heat storage charging power (MW h)
s_{q-}^{max}	maximum heat storage discharging power (MW h)
T	the last time step
η_{s-}	efficiency ratio for heat charge–discharge cycle
η_s	efficiency ratio heat storage per hour

conventional boilers in home installations. The production of electricity simultaneously with the generation of heat yields an economic benefit for the user. Also, the fossil fuel consumption and CO_2-emissions are effectively lowered. These good performances for micro-CHP are evaluated in [3,4]. CHP has been widely utilized due to the liberalization of the power market, the rise in fuel prices, the improvements in CHP technology, tax exemptions when CHP is adopted, the introduction of environmental restrictions from both municipal and central governments [5]. The thermal and electrical efficiency depend on the operating point (loading conditions), unit capacity and technology [6]. The economic benefits of CHP systems depend on the specific conditions under different operation strategies, as the performance varies when operating in partial load [6,7]. When all the thermal energy of a CHP system can be utilized, it can reach much higher efficiency than conventional separate heat and power production [8]. CHP fits well in applications like industries, which have constant thermal demands. CHP has also been applied successfully for applications which have time-varying demand of thermal energy, such as municipal district heating and cooling systems, and even small scale applications for residential buildings, office buildings, hospitals, supermarkets, etc. [3]. Finland is one of the leading countries in CHP production due to its cold climate and energy-intensive metal and forest industries. CHP generates around 34% of the power in Finland [9]. Optimization of CHP production can result in a considerable savings. The target of the optimization is to satisfy customers' demand of heat while minimizing the production costs and maximizing the revenue from selling power. The time horizon of an optimization model can vary from a few hours up to several years.

Heat storage which collects heat for later use can be integrated into a CHP system to further improve the energy efficiency [10]. On one hand, the storage can be charged when the heat demand is low and discharged during high demand; on the other hand the storage allows increasing the power production by CHP to the power market when the spot price is high and producing less power when the spot price is low. Thus, the heat storage can be charged or discharged when either one is beneficial. The flexibility of the heat demand allows developing algorithm to optimally control the coupling between decentralized energy resources and heat storage in order to achieve economical and practical benefits for the CHP system [11]. Without storage the operation of CHP plants mainly depends on the current heat demand and thus determines the range of power production. Heat storage can decouple the heat production and allow for price-driven power production. To decrease the operational fallibility of the CHP plants, heat storage is used to maximize the operation of CHP units when heat demand is even smaller or larger than operational capacity of the CHP plants.

The cost efficient solutions about CHP system with heat storage have been discussed in many recent studies. Christidis et al. [12] optimized the design of heat storage devices together with the operation of a power plant supplying a large district heating network by formulating a mixed integer linear programming (MILP) problem in GAMS and solving it in CPLEX. Fragaki et al. [13] analyzed the economics and optimum size of a CHP system operating with gas engines and thermal stores in British market conditions using energyPRO software. Fragaki and Andersen [14] optimized the timing of power sale at the power exchange market for a CHP system with heat storage in the UK using energyPRO software and Excel spreadsheets. Chesi et al. [15] optimized the heat storage size using a TRNSYS unsteady model in the context of combined cooling, heating and power (CCHP) with renewable energy source. Ren et al. [16] optimized the size of CHP system with a heat storage using mixed integer non-linear programming model. Buoro et al. [17] explored the optimal operation strategy in order to minimize the total annual cost based on a mixed integer linear programming (MILP) model for a distributed energy supply system including a CHP plant, a DH network, a solar thermal plant and conventional components such as boilers and compression chillers. Taljan et al. [18] optimized the operation of biomass CHP plant and the heat storage subject to maximizing the economic index in form of modified internal rate of return (MIRR). Noussan et al. [19] searched the optimal configuration by simulating a biomass-fired CHP and heat storage system from economic and energetic point of view. Steen et al. [20] proposed a new Distributed Energy Resources Customer Adoption Model (DER-CAM) with thermal energy storage to minimize the energy cost or CO_2 emissions using mixed integer linear programming (MILP). Barbieri et al. [21] assessed the influence of the thermal energy storage on the energy and economic performance of a CHP system consisting of a prime mover, an auxiliary boiler and a storage unit. The effect of the size of the thermal energy storage is not linear and is heavier by increasing the thermal power of the prime mover. Smith et al. [22] investigated the performance of a CHP system with and without thermal energy storage for eight different commercial building types, the model evaluated which types of commercial buildings may show benefits from adding the heat storage to the CHP systems and which types are unlikely to benefit from the addition of heat storage. However, no studies were done to achieve the optimal operation plan for the CHP system with heat storage by