



The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system

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ABSTRACT

The coupling of the heating and the electricity sectors is of utmost importance when it comes to the achievement of the decarbonisation and the energy efficiency targets set for the 2020 and 2030 in the EU. Centralised cogeneration plants connected to district heat networks are fundamental element of this coupling.

Despite the efficiency benefits, the effects of introducing combined generation to the power system are sometimes adverse. Reduced flexibility caused by contractual obligations to deliver heat may not always facilitate the penetration of renewable energy in the energy system. Thermal storage is acknowledged as a solution to the above.

This work investigates the optimal operation of cogeneration plants combined with thermal storage. To do so, a combined heat and power (CHP) plant model is formulated and incorporated into Dispa-SET, a JRC in-house unit commitment and dispatch model. The cogeneration model sets technical feasible operational regions for different heat uses defined by temperature requirements.

Different energy system scenarios are used to assess the implications of the heating–electricity coupling to the flexibility of the power system and to the achievement of the decarbonisation goals in an existing non interconnected power system where CHP plants provide heating and electricity to nearby energy dense areas.

The analysis indicates that the utilisation of CHP plants contributes to improve the overall system efficiency and reduce total cost of the system. In addition, the incorporation of thermal storage increases the penetration of renewable energy in the system.

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1. Introduction

Renewable energy has experienced a rapid growth in the past years supported by energy policies that pursue the decarbonisation of the energy system and thus contributing to the climate change mitigation. The energy transition, from traditional fossil-fuel and nuclear based energy systems to sustainable energy systems, requires the integration of large-scale of intermittent renewable sources [1]. For this reason, future energy systems should rely on

the “smart energy system” concept based on the integration of multiple energy sectors [2].

In the particular case of the heating and cooling sector, its integration with the electricity sector enables the utilisation of available technologies such as heat pumps or combined heat and power (CHP) plants [3].

To achieve a large scale integration, the deployment of thermal networks, recognised as a cost effective way of decarbonising the energy system [4], becomes fundamental.

In the European context, the heating and cooling sector has been recently recognised as a priority to achieve decarbonisation targets. Accounting for half of the EU energy consumption, the sector is characterised by low efficiencies and large amounts of waste heat [5].

While there is room for energy efficiency improvements

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especially in the European residential and tertiary sectors, a holistic energy system approach is required, meaning the aforementioned integration of different sectors such as transport, electricity and heating sector itself [6]. This not only allows the evaluation of all potential options for a future sustainable energy system, but also the assessment of its feasibility and the identification of operational bottlenecks. One such bottleneck is the lack of flexibility of the power system with high shares of variable renewable energy sources. Based on this approach, the study of the heating and electricity sector coupling is of outmost importance given the size of the heating sector on one hand and the opportunity of their linkage to integrate more renewable power generation via different thermal energy solutions offers on the other [7,8].

Among other advantages, this linkage may enable thermal energy storage, widely acknowledged as a key enabling technology to decarbonise power systems [9,10]. Off-peak electricity can be used to heat water in storage tanks to perform daily load shifting. Compared to electrical energy storage, thermal energy storage is 100 times cheaper in terms of investment per unit of storage capacity, which makes it an attractive solution to increase flexibility and maximise the use of available energy sources [11].

Combined heat and power (CHP) plants, which can reach an overall efficiency of up to 90% [12], are important elements of this linkage. They have been recognised in the EU as the most efficient way to generate useful energy from fossil-fuelled energy sources [13].

However, despite this high efficiency, the integration of CHP in energy systems with high share of renewable sources may bring negative effects without available thermal storage leading to a reduction of the overall system efficiency [14]. Obligations to satisfy a given heat demand reduces the flexibility of the CHP operation and limits the integration of RES sources. For this reason, thermal storage is not only an attractive solution but also essential to achieve flexible energy systems [15].

The utilisation of CHP and thermal storage with new generation of district heating networks could even maximise the utilisation of both electricity and heating. These new district heating networks, also known as 4th generation district heating systems (4GDH) and characterised by low temperatures (30–70 °C), facilitates the integration of multiple energy sources, even those with low quality from an exergy perspective. The transition to these new 4GDH is expected to take place within the timeframe 2020–2050 [1].

The reduction of the temperature allows the CHP plant to extract heat in a late stage of the expansion process in the steam turbine, reducing the amount of electricity that is lost and consequently increasing the overall CHP efficiency.

To sum up, combined heat and power technologies in combination with efficient district heating networks and competitive thermal storage, set the ground for achieving more flexible and efficient energy systems [3]. All these opportunities may unlock the full potential of district heat networks, which currently have only reached a ten percent share of the total heat supply worldwide, but with high discrepancies between countries [16].

In the literature, a set of studies on the optimal operation of CHP plants have been focused on the minimisation of the power system costs. Under this approach some authors have worked on the validation of different mathematical approaches using linear, mixed-linear or non-linear programming methods [17–20] regardless of the quality of the heat produced and its adequacy to meet specific heat applications. Other authors have studied thermo-economic aspects of the operation of CHP plants to optimise their operation such as temperature and pressure of the input steam flow and mass flows rates from an energy and exergy economic approach [21].

To a certain extent, and driven by the evolution of modern

thermal networks that allows a wide range of operating temperatures, this work focuses on both aspects: the minimisation of the power system costs including the cogenerated heat and the analysis of the quality of the heat based on the demand side temperature requirements. This approach allows a more thorough analysis of the benefits derived from low-temperature heat networks when operating a CHP plant. Thus, the scope of this work is to present a method to co-optimize and analyse the operation of a power and heating system combined with thermal storage under different energy market assumptions and thermal requirements.

This method is based on a detailed model of the short-term operation of large-scale power systems and the results are presented and discussed via a comprehensive scenario analysis of a case study.

The paper is organised as follows: section 2 presents the model implemented, and section 3 sets out the experimental design including the baseline power systems. Section 4 covers results derived from the different scenarios and section 5 present the conclusions of the benefits derived from the linkage between heating and cooling sectors.

2. Methods

2.1. Model background

This work is built upon the Dispa-SET model, an open source unit commitment and dispatch model of the European power system. The aim of this model, implemented as a mixed-integer linear programming, is to optimise, at an hourly time step resolution and with a high level of detail, the short-term operation of large-scale power system, solving the unit commitment problem. The objective function of this model minimizes the total power system costs, which are defined as the sum of different cost items, namely: start-up and shut-down, fixed, variable, ramping, transmission-related and load shedding (voluntary and involuntary) costs. The results include the optimal mix of power plants production, including renewable sources, that satisfies electricity demand at minimum cost over one year. All the modifications performed for this paper are released as version 2.2, which is available online¹ [22].

To assess the interaction between heating and electricity sectors, a heating module has been developed and integrated into the existing model. It includes two main elements; the formulation of cogenerated steam-driven plants module that produce both power and heat and the thermal heat storage module. In the following section a detailed explanation of the CHP and storage models is provided.

2.2. CHP model

In this section the background for the proposed CHP model and its mathematical formulation are presented.

2.2.1. CHP categories and operation regions

In order to model the different operation alternatives provided by CHP, we have taken advantage of the pioneering work developed in [23]. Accordingly, steam-based CHP plants fall into two categories: plants with a backpressure turbine and plants with an extraction/condensing turbine.

In the first group, the different energy production options are given by a bundle of fixed relations between the electricity and the heat production depending on the required output temperature of

¹ www.dispaset.eu.

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