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On the way towards smart energy supply in cities: The impact of interconnecting geographically distributed district heating grids on the energy system

D.F. Dominković [a, *], I. Bačeković [b], D. Sveinbjörnsson [a, 1], A.S. Pedersen [a], G. Krajačić [c]

[a] Department of Energy Conversion and Storage, Technical University of Denmark (DTU), Roskilde, Denmark
[b] Aalborg University, Aalborg, Denmark
[c] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia

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ABSTRACT

A linear continuous optimization model with an hourly time resolution was developed in order to model the impact of subsequent interconnections of different DH grids. The municipality of Sønderborg was chosen for a case study and interconnections of five currently disconnected DH grids were assessed. Moreover, the impact of industrial waste heat on the DH supply was also assessed. In the reference year (2013) two out of four interconnections proved to be economically viable. The results for the future energy system (2029) showed that interconnecting geographically distributed DH grids reduces primary energy supply by 9.5%, CO_2 emissions by 11.1% and total system costs by 6.3%. Inclusion of industrial waste heat in the fully interconnected DH grid reduced primary energy supply for an additional 3%, CO_2 emissions for an additional 2.2% and total system costs for an additional 1.3%. The case of the future energy supply system with interconnected DH grids and installed industrial waste heat recuperation results in the lowest primary energy demand, emissions and costs. Finally, the benefits of the interconnected DH grid, in terms of system flexibility, CO_2 emissions, total costs and energy efficiency, proved to be much greater in the future energy system.

1. Introduction

Worldwide, understanding the harmful consequences of climate change is receiving ever more attention. During the 2015 Paris Climate Conference (COP21), the first ever legally binding global climate deal was agreed upon, committing all the countries involved to make an impact on the climate change, starting from the year 2020. The parties agreed to keep the global temperature rise below 2 °C compared to the pre-industrial level, and aiming for the maximum increase of only 1.5 °C. Carbon neutrality is aimed for by the second half of the century [1]. Moreover, the focus of the 2016 Climate Change Conference in Marrakech (COP22) was on adopting a work plan, developing a framework for implementation and discussing possible issues of the COP21 agreement, with the main emphasis on overcoming barriers for the agreement to become fully operational [2].

Reviewing the energy planning models available, Mancarella [3] made a comprehensive paper about the concepts and evaluation methods of multi-energy systems. The author summarized the general motion towards the integrated energy system planning, as opposed to the classical approach to energy system planning where its sectors are treated separately. Furthermore, one of the main conclusions was that the integrated energy system modelling is beneficial compared to the classical approach. The integrated energy system planning also goes by the name of "the smart energy system" approach, where the power, heat and gas sectors (including mobility) are modelled together in order to detect synergies between the sectors and achieve a cheaper and technically more robust energy system [4]. It is an especially useful approach in modelling 100% renewable energy systems. The study in Ref. [5] indicates that the holistic approach of smart energy systems, where different sectors are integrated and district heating (DH) is the major link between the heat and electricity sector in urban areas, can help to avoid large-scale integration of costly electricity storage.

* Corresponding author.
E-mail addresses: dodo@dtu.dk (D.F. Dominković), ibacekovic@gmail.com (I. Bačeković), ds@planenergi.dk (D. Sveinbjörnsson), alpe@dtu.dk (A.S. Pedersen), goran.krajacic@fsb.hr (G. Krajačić).
[1] Current affiliation: PlanEnergi, Copenhagen, Denmark.

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Increasing the DH share is one way of improving the energy efficiency in energy systems where a heating demand is present. Furthermore, it allows a better integration of the power and heating sectors which facilitates the integration of intermittent energy sources, such as wind power and photovoltaics. Xiong et al. [6] showed in the case of China that implementation of the scenario with the expanded DH grid could lead to the 50% reduction in the primary energy supply for the building heating sector compared to the reference case. Moreover, total system cost in the heating sector would be approximately 15% lower compared to the reference case. The EU recently released its first ever heating and cooling strategy where the European Commission argued that a strategy of decarbonising the heating and cooling sectors would save around €40 billion in gas imports and €4.9 billion in oil imports yearly [7].

Böttger et al. showed for the case of Germany that electric boilers can be a promising technology for balancing the power grid. Thus, integration of power and heating systems proved to be beneficial for the whole energy system [8]. Capuder & Mancarella argued that although there is a growing interest in the integrated energy planning approach, it is still arguable to which extent the efficiency can be improved from coupling different energy vectors [9]. They developed a synthetic mixed-integer linear optimization model suitable for evaluating the characteristics of different multi-generation options. They concluded that flexible integrated schemes with combined heat and power plants (CHP) and electric heat pumps, supported by thermal energy storage, can bring a significant operational and investment cost savings. Moghaddam et al. developed a comprehensive model for self-scheduling of an energy hub to supply cooling, heating and electrical demands of a building [10]. Although they focused on the building level of planning, they also showed the importance of integrated planning of different energy needs. One important way a future district heating system could develop in is the utilization of excess heat from industry and agriculture. This would allow increased energy efficiency in the system as less heat would be lost in industrial processes, as well as increase the competition among the DH suppliers, compared to the common monopolistic position of heat suppliers today. A regional case study of utilizing excess heat was done by Sandvall et al. for the case of Sweden [11]. Their results are not straightforward and show that from the system's point of view, CO_2 emissions only decrease in the long run, while in the short run they can even increase.

In Denmark, due to the first and second oil crises, a paradigm shift towards RES happened during the 1970s, as an effort to increase the security of energy supply. The current Danish Government set a target to phase out use of all fossil fuels and to achieve a low carbon society by 2050 [12]. As a part of the same set of policies, Denmark plans to phase out the use of all coal, as well as oil for heating purposes [13]. As a part of the policy to increase the energy efficiency, Denmark expanded its DH. Today, about 60% of the Danish heating energy demand comes from the DH. In their paper about reaching a 100% renewable energy system of Denmark in 2050, Lund & Mathiesen showed that DH will still represent a major role in meeting the heating needs [14]. The authors argued that DH systems in 2050 would consist of CHPs and boilers, mainly driven by biomass, large-scale heat pumps and excess heat from industrial processes. Moreover, parallel to the penetration of intermittent renewable sources in the power sector, a transition to the low-temperature 4th generation DH systems in the period from 2020 to 2050 has been anticipated [15]. Li & Svendsen developed a model of hypothetical low temperature DH network in Denmark and their analysis concluded that such systems are characterized by significantly lower heat losses than traditional systems, as well as by reduced exergy losses [16]. All of the above proves the importance of the DH in Denmark. Improving any part of the DH system can lead to large savings in the total system costs on a country level. Furthermore, internalizing the external costs can show further benefits of the DH systems. Zvingilaite showed for the case of the Danish heat and power sector that the inclusion of human health-related externalities in energy system modelling can lead to results with an 18% decrease in the total health costs and a 4% decrease in the total energy system costs, compared to models where such externalities are excluded [17].

Some authors have focused on the integration of geographically distributed DHs, on the possibility of establishing pricing mechanisms similar to day-ahead electricity markets and on addressing the problem of the monopolistic position of DH suppliers when they also operate the DH grid. Gebremedhin & Moshfegh first modelled a locally deregulated integrated district heating system [18]. They developed the MODEST tool for analyses and assessed the potential of connecting 7 geographically dispersed DH systems. However, their conclusions were vague and uncertain. Further development of their model was carried out by Karlsson et al. [19]. They concluded that the economic potential for a heat market in three different Swedish DH systems amounts to between 5 and 26 million €/year with payback times ranging from two to eleven years. Moreover, they showed that connecting different DH grids can reduce the total CO_2 emissions. However, their economic indicator is a bit unclear, as it is a mix of a business-economic and a socio-economic one. Syri & Wirgentius developed a model which simulates a day ahead heat market, in the same fashion as the well-known day-ahead electricity spot market operates today [20]. They adopted the model for the city of Espoo in Finland and concluded that an open heat market can be beneficial for all parties involved and significant fuel savings could be achieved. Kimming et al. recently showed the beneficial outcome of vertically integrated local fuel producers into district heating systems [21]. Their proposed integration can lead to the reduction of greenhouse gas (GHG) emissions and lower the production costs/heat price, if there is an incentive to utilize locally produced fuels.

In order to assess both the economic and technical benefits that can be obtained by interconnecting adjacent district heating systems, a model was developed that represents different DH systems with their geographical bounds, together with the power and gas sectors. Moreover, it is an hourly model which can easily cope with modelling of large amounts of intermittent power sources. The model allows users to assess the feasibility of interconnecting different DH systems from a technical and socio-economic point of view, as well as to analyse the possible changes in the scheduling of each heat supplying plant that may occur after the interconnection of systems has been implemented. The novelty of this model compared to the previously developed ones is the representation of the whole energy system together with the representation of physical boundaries of DH systems on an hourly basis, which does not cause problems in modelling the large amounts of intermittent sources. Moreover, it can optimize utilization rates of different energy plants, as well as investments in new ones. The model developed and the results presented could be used for further understanding of impacts of DH systems on the flexibility of the power sector.

As opposed to the electricity grid whose size of the transmission grid allows many different suppliers to connect and interact with different types of demand, DH grids are geographically constrained to usually only densely populated regions. Sometimes heat suppliers are also the owners of the DH grid which then constitutes a complete monopoly. Another solution is when heat suppliers and the DH grid are operated by at least two different independent bodies. The competition among suppliers can lead to the increased operational efficiency and consequently costs of energy production can be reduced, when equal access to the distribution network is

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