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Cost-minimised design of a highly renewable heating network for fossil-free future

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ABSTRACT

This research presents technical and cost-minimised design to decarbonise the heating network by using large-scale heat pump and thermal heat storage. In this paper, real hourly heat-consumption and heat-production cost data for the city of Aarhus, Denmark are used for calculating techno-economic feasibility of coupling the heating network with electrical grid. An optimum solution is suggested for the entire network with least amount of backup generation capacity, thermal heat storage capacity, natural gas boiler capacity and levelised cost of energy. Aarhus constitutes 5% of the Denmark's total heat demand and 4% of electrical load demand. This can be fulfilled with 160 MW of rated wind generation capacity, 35 MW of solar PV generation capacity, 45 MW of backup generation capacity, 221 MW of natural gas boiler capacity and 3.4 GWh of thermal heat storage capacity. The levelised cost of energy shows that, the coupling between the electrical grid and heating sector reduces the cost by more than 50% to 45 € /MWh. However, the cost-minimised design is possible with wind/solar mix of 85% and renewable energy penetration of 100%. Sensitivity analysis concedes that, the 100% decarbonisation of heating sector relies heavily upon the cost assumed for wind generation and solar PV generation, instead of the operation and maintenance cost for heat pump. Furthermore, the reduction in cost for wind generation and solar PV generation leads to the decrease in levelised cost of energy. Whereas, the reduction in cost for heat pump, thermal heat storage capacity and natural gas boiler capacity leads to an increase in renewable energy penetration. Sensitivity analysis further reveals that, increasing thermal heat storage capacity and the cost of selling excess renewable energy does not have major impact upon the levelised cost of energy and can be instrumental for the economic viability of fossil-free future.

1. Introduction

With the Paris agreement (COP21) intact, the global reduction in greenhouse gas (GHG) emissions have become the key goal in transition towards the clean, sustainable and low-cost energy systems [1]. Several energy statistics exhibit that the United States, European Union (EU-28), China and India are accountable for 61% of all global emissions [2]. The EU is also determined to make radical reduction in GHG emissions primarily through the electrification of the heating sector by 2050 [3]. In recent studies, Lund et al. [4] have discussed the important relationship between smart energy systems and heating network and Markovska et al. [5] elaborated the main challenges of energy supply security in twenty-first century. Likewise, Connolly et al. [6] provided the detailed mapping of EU heat demand and identified the potential for district heating by 2050. Lund et al. [7,8] discussed that the heating network contributes more to energy-losses than the electrical grid network and therefore, the forefront in achieving future targets of CO_2 emissions reduction should be the decarbonisation of heating sector.

Furthermore, Mathiesen et al. [9] and Connolly et al. [10] have presented the technical-economic aspects of 100% renewable energy based smart energy systems for the EU and suggested the interconnection between multiple energy sectors as well as implementation of coherent smart energy system approach for the least cost solution. Hansen et al. [11] and Xiong et al. [12] have provided a comprehensive heat road-map strategy for achieving energy efficiency in the heating sector in Europe and China, respectively. Few researchers have also presented geographical Atlases for the spatial distribution of heat demand in Europe.

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Nomenclature

α^W	share of wind generation in total renewable energy generation
Δ_E	electrical mismatch
Δ_H	heat mismatch
γ	gross share of renewable energy penetration
$\mathscr{K}^B$	backup generation capacity
$\mathscr{K}^E$	thermal heat storage capacity
$\mathscr{K}^N$	household natural gas boiler capacity
$\langle . \rangle$	time average of all 8760 h in an year
B	backup generation
E	energy content from thermal heat storage
G	generation
G^S	solar PV power generation
G^W	wind power generation
L_E	electrical load demand
L_H	heat demand
N	energy content from household natural gas boiler
P^{ex}	excess generation
Q_{dhw}	domestic hot-water demand
Q_{sh}	space-heat demand
r	discount rate
T	lifetime of technology
t	index representing hour in a year
V	net-present value
V_{elec}	net-present value of electrical grid technologies
V_{heat}	net-present value of heat-coupling technologies
CCGT	combined cycle gas turbines
COP	coefficient of performance
DC	Direct current electrical grid
DH	district heating network
DHW	hot-water required for household activities
HP	large-scale heat pump
LCOE	levelised cost of energy
PV	solar photo-voltaic
SH	space-heat required to heat buildings
TES	centralised thermal heat storage

Persson et al. [13] quantified the voulume of excess heat in EU countries and Möler et al. [14] calculated the heat demand as per-building level. Ashfaq et al. [15] mapped the energy saving potential with the implementation of district heating networks and heat pump technologies. Petrovic et al. [16] provided a comprehensive insight for heat Atlas as a tool for exploring different renewable energy scenarios.

Furthermore, Grundahl et al. [17] and Dominković et al. [18] have investigated case studies for the Danish heating network and concluded that, the future expansion of district heating networks into heating grids along with the integration of waste heat sources is the only way forward towards the economic feasibility. Thellufsen et al. [19] studied the Danish energy systems and calculated that the energy saving benefits are more with the synergy of both electrical and heating networks. Ashfaq et al. [15] discussed the significance for utilisation of excess renewable energy generation into decentralised municipal district heating networks. Rolando et al. [20] recommended the cross border interconnection of electrical grids, whereas Thellufsen et al. [21] suggested the cross sector interconnection of renewable energy sources for increasing the efficiency of European energy systems.

The current heating network is mostly supported by the co-generation of combined heat and power plants (CHP) or stand-alone fossil-fuel boiler systems. While, taking them out of the network without techno-economic feasibility analysis will have a massive impact. Pensini et al. [22] have calculated the cost-effectiveness for the electrification of heating sector in PJM interconnection of United States, but still there is limited knowledge regarding the economic feasibility for the transition of European energy system. This research addresses these issues and fills-in vital gap by providing a combined techno-economic analysis and investigates:

- Will the coupling of heat and electricity sector be techno-economic feasible?
- What will be the hourly intra-day energy trend of heat demand, thermal heat storage and natural gas boiler profile through-out the year?
- Will the heat-coupling be cost-effective in comparison to the current conventional heating network?
- How does the variations in renewable energy penetration (γ) and wind/solar mix (α^W) affect the levelised cost of energy (LCOE)?
- What is the optimum strategy for the decarbonisation of heating network by electrification?

In this paper, the concept of fully renewable electrical grid and heating network based on fluctuating weather patterns is introduced for the decarbonisation of heating network. The technical analysis is done by analysing the hourly actual intra-day energy demand profiles and heat-consumption data. The economic-analysis is performed by calculating LCOE for the proposed energy system and compared with the current heat-production cost from conventional sources. Later, a sensitivity analysis is performed to find the cost-minimised configuration with variations in cost-assumption, renewable energy penetration (γ) and wind/solar mix (α^W). In the end, the technology which defines the cost-minimised solution is identified.

The paper proceeds as follows: the methodology for techno-economic analysis of electrical grid, heating network and cost modelling is discussed in Sections 2.1, 2.2 and 2.4, respectively. Then, results for the technically optimal network with reduced backup generation capacity, thermal heat storage capacity and natural gas boiler capacity are provided in Section 3.1 and the LCOE for economically optimal network configuration with variation in renewable energy penetration and wind/solar mix is calculated in Section 3.2. Subsequently, the sensitivity analysis is performed to analyse the effect on the cost-minimised design solution with variations in cost assumption for different technologies in Section 4.1. Finally, the effect with selling excess generation and results for the cost-effective strategy are concluded in Sections 4.3 and 5, respectively.

2. Methods and modelling

This analysis considers a futuristic highly renewable energy based network, where the wind and solar PV are taken as renewable energy sources and other sources are assumed as instantaneous backup power generation sources (conventional energy generation, hydro-electric storage lakes, biomass). The modelling