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Demand side management in urban district heating networks

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HIGHLIGHTS

- Realistic method for DSM was developed for a district heating network.
- The method was applied in a real DHN in Denmark.
- Sensitivity of the optimal solution to energy, comfort and pumping costs is analyzed.
- Result shows up to 11% energy cost saving.

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ABSTRACT

This paper proposes a realistic demand side management mechanism in an urban district heating network (DHN) to improve system efficiency and manage congestion issues. Comprehensive models including the circulating pump, the distribution network, the building space heating (SH) and domestic hot water (DHW) demand were employed to support day-ahead hourly energy schedule optimization for district heating substations. Flexibility in both SH and DHW were fully exploited and the impacts of both weekly pattern and building type were modelled and identified in detail. The energy consumption scheduling problem was formulated for both the individual substations and the district heating operator. Three main features were considered in the formulation: user comfort, the heat market and network congestion. A case study was performed based on a representative urban DHN with a 3.5 MW peak thermal load including both residential and commercial buildings. Results show an up to 11% reduction of energy costs. A sensitivity analysis was conducted which provides decision makers with insights into how sensitive the optimum solution is to any changes in energy, user comfort or pumping costs.

1. Introduction

According to the Danish National Energy plan, the electricity and heating sector should be 100% renewable energy based by 2035 [1]. Such ambitious targets demand considerable efforts in energy conservation and the integration of renewable energy sources (RES) into energy systems. Over the years, a large number of RES, such as wind power plants, have been connected to the energy system in Denmark. Meanwhile, the Danish Building Regulations now require newly constructed buildings to achieve a progressively lower energy consumption [2]. These new developments demand the rethinking and redesign of the current energy system and a transition to a smart energy system [3]. Digital solutions are starting to be utilised to upgrade current infrastructure to enable agile system operation. To put it in another way, the energy system must accommodate an increasing proportion of intermittent RES production and must also adapt to a changing load profile. Smart grid [4] and 4th generation district heating [5] represent the state-of-the-art research concepts in the electricity and heating sectors. This paper aims to contribute to this increasingly important research area by developing a comprehensive demand side management (DSM) mechanism to improve the energy efficiency of a district heating network (DHN) and to provide solutions for congestion management. To be more precise, the DSM implemented in this paper can be further categorized by demand response according to the classification proposed by Palensky et al. [6] and the term congestion will refer throughout the paper to the reduced quality of service that occurs when a DHN is required to deliver more heat than its designed capacity.

A comprehensive survey of bottlenecks in Swedish DHNs carried out

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Nomenclature

c	water specific heat [kJ/(kg°C)]
d	inner pipe diameter [m]
E	energy [MWh]
H	scheduling horizon [h]
k	substation performance indicator [kWh/kg]
L	pipe length [m]
$\mathbf{L}$	set of pipes [–]
$\dot{m}$	mass flow rate [kg/s]
N	number [–]
p	pressure [kPa]
P	electric power [kW]
t	time period [hour]
U	heat transfer coefficient [kW/(m²·K)]
W	weighting factor [–]
$\mathbf{Y}$	network incidence matrix [–]

Abbreviation

CHP	Combined Heat and Power
DH	District Heating
DHN	District Heating Network
DHW	Domestic Hot Water
DHO	District Heating Operator
DSM	Demand Side Management
LTDH	Low-Temperature District Heating
SH	Space Heating

Greek symbols

δ	temperature change [°C]
Δ	difference [–]
η	efficiency [–]
ϵ	modelling error [°C]
$\varkappa$	friction factor [–]
Ω	set of decision variables [–]
ρ	water density [kg/m^3]
τ	temperature [°C]
ϕ	thermal power [kW]
ξ	friction coefficient [kPa·s^2/kg^2]

Subscripts and superscripts

a	ambient
c	critical
cir	circulation loss
cw	cold water
i	building index
in	incoming
l	pipe index
min	minimum
n	node
p	pipe
q	load node
r	return
s	supply

by Brange et al. [7] indicates that network congestion is a concern of the majority of the DH companies. Their research shows that half of the bottlenecks originated from network expansion, followed by densification of load connections and the interconnection of multiple DHNs. Moreover, network congestion is a hurdle for reducing heat loss, which is the leading cause of the degradation of district heating (DH) system performance and an increase in operating costs. Li and Svendsen [8] have shown that current heat loss could be further reduced by decreasing the network dimension and the supply temperature. Researchers have been investigating low-temperature district heating (LTDH) and ultra-low-temperature district heating with a supply-return temperature difference of less than 30 °C [9]. According to the first law of thermodynamics, for the same heat exchange, the lower the temperature difference is, the higher the flow rate needs to be. That said, decreasing both network pipe dimension and supply temperature conflicts with the goal of congestion management if no other measures are implemented in an existing DHN. Brange et al. further observed that congestion is currently often solved by using the peak load boiler in the operation phase and increasing pipe dimension at the design phase. In order to compare with other alternatives, they further conducted life-cycle cost analyses on these solutions and found that DSM was advantageous [10].

Despite the need for congestion management and the benefits of a DSM programme, its adoption in the DH sector is limited [11,12]. There are two main reasons. Firstly, the metering and communication infrastructure is cost-prohibitive. The relevant stakeholders thus are reluctant and extremely cautious in their investments. Secondly, although extensive research has been carried out on DH, the research community lacks studies on the detailed analysis of benefits of applying DSM to DHNs. Consequently, district heating operators (DHOs) are not convinced about its benefits and how the cost could be offset, which is critical in developing their business models. In fact, this is also a common concern in other energy sectors such as power system. To this end, DHOs lack the motivation to adopt DSM in their networks.

The authors believe that the uptake of DSM is promising with the adoption of substation metering mandated by the regulatory institution. For instance, EU has instructed its member states to adopt smart energy metering [13], with the goal of improving consumer awareness of energy consumption. This makes it possible to engage consumers in DSM programmes. In Denmark, DHOs have started to investigate dynamic tariffs for optimized network operation [11]. This provides a good use case for the DSM programmes. Furthermore, the investigation of DSM is encouraged by the heat market in Copenhagen, which plays an important role in load allocation.

In the electricity sector, the development of DSM started relatively early and it has been an increasingly important area in the research community [14,6]. One of the lessons learned is to avoid the side-effects of DHN operation when designing a DSM program. To give an illustration of this argument, price-based DSM could potentially create a concurrent load response if the controllers receive a universal price signal and make uninformed decisions without knowing the system status.

In view of these opportunities and challenges, in this study we set out to develop a realistic DSM mechanism that makes use of metering data, thermal flexibility, current heat market setup and DH substation technology to improve the DHN operation.

This paper is organized as follows: the next section presents a comprehensive review of the state-of-the-art research on the operation and optimization in DHNs. Section 3 provides the system configuration and modelling details. Following this, Section 4 describes a real DHN on which all the analyses in this paper are based. Section 5 further develops three different control strategies for comparison. A case study was performed with all the results summarized in Section 6. Implementation of the developed DSM is also briefly discussed. Finally, Section 7 draws conclusions and makes remarks on future work.

2. State-of-the-art DHN operation and optimization

The DSM proposed here aims at improving DHN operation and thus this section is dedicated to a review of current literature on DHN