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Strategic techno-economic assessment of heat network options for distributed energy systems in the UK

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ABSTRACT

Distributed energy systems facilitated by heat networks are rising in the UK as a viable option to decarbonise the heating sector, particularly at a community level (up to several MW). However, in this respect there is lack of suitable modelling tools and studies to assess the techno-economic performance of heat network options in different areas at a strategic level. Therefore, this paper presents a generic and comprehensive model to perform heat network design and assessment according to specified input criteria and assess operational, capital, and overall costs of multiple alternatives. More specifically, the model developed can provide strategic information on the feasibility and performance of heat network options with different operational temperatures, load densities, network lengths, cost parameters, pipe types, dwelling connection types, etc. (which are key to address the utilisation of different local supply sources in distributed energy systems). Generic test networks were used for strategic analysis, which resemble typical topologies used for electrical networks in the UK in urban, sub-urban, semi-rural, and rural areas. Numerical case studies and sensitivity analyses were carried out to assess different options and the main drivers in different scenarios. As a general result, twin pipes emerge as the most viable alternative.

1. Introduction

Heat represents a major contribution to energy consumption and GHG (Greenhouse Gas) emissions in a number of countries worldwide and in particular in the UK, where emissions from heat measure at 38% of all carbon dioxide emissions and 32% of all GHG emissions [1]. These result from energy use for heating purposes in the order of 44% (as of 2011) of the total energy consumption [2]. De-carbonisation of the heat sector is thus seen as key to meeting the challenging targets set for GHG reduction by the UK government (a reduction in the carbon account of 34% by 2020 and 80% by 2050 from a 1990 baseline [3]). To address this issue, alternative heat strategies have been put forward and are being discussed [2,4]. Amongst others, DH (District Heating) options based on heat networks [2] are gaining interest, with the aim of connecting relatively large sets of customers to relatively decentralised low-carbon heat generation systems. In this light, heat networks would represent an enabling technology for widespread development of distributed energy systems, particularly at a community or district level, with typical sizes of up to several MW of peak heat demand. For instance, DH-based distributed energy systems of relatively small scale could be supplied by distributed cogeneration plants fed on natural gas or biomasses; alternatively, other low carbon sources such as centralised electric heat pumps fed on renewable electricity, biomass-based boilers, solar thermal plants, and so on could be used for local heat production [5]. However, while heat networks for distributed energy system applications clearly represent a promising solution from an environmental standpoint as enabler of various potential low carbon supply technologies, their techno-economic feasibility in the UK is unclear as yet. In fact, there is very little experience on heat networks in the UK (only 2% of the heat demand is currently being met by DH [6]). Hence, even though there is significant potential for distributed energy system applications at a community level (an estimated 70% of heat consumption is from domestic, commercial and public buildings [7]) there is concern about the infrastructure cost that a dramatic shift from the current status quo might bring about.

A study aimed at analysing the operational performance of heat networks along with its economics in a UK context has been carried out in Ref. [8]. However, the study does not address investment aspects of different alternatives. On the other hand, various reports have analysed the potential for applying DH schemes in the UK [9,10]. However, there is no comparison between different types of pipes and different operational parameters such as network

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Nomenclature

Acronyms

DH	district heating
DHW	domestic hot water
GHG	greenhouse gas
HE	heat exchanger
HW	hot water
LT	low temperature
SH	space heating

Main symbols

i	customer's node index
h	hourly time step index
k	network branch index
$G_i(h)$	hourly mass flow rate [kg/s]
$H_i(h)$	hourly average heat demand [kW]
c_p	specific heat capacity of water [kJ/kg/°C]
t_1	supply pipe water temperature [°C]
t_2	return pipe water temperature [°C]
G_{cap}	pipe capacity [kg/s]
ρ	water density [kg/m^3]
D	internal diameter of pipe [m]
w_{max}	maximum (design) water velocity [m/s]
Δp_{dk}	distributed pressure losses [bar]
Δp_{ck}	concentrated pressure losses [bar]
Re	Reynolds number
e	pipe roughness [m]
$Y_i(h)$	substation hydraulic losses [bar]
q_1	thermal loss in supply pipe [W/m]
q_2	thermal loss in return pipe [W/m]
q_{tot}	thermal loss from both supply and return pipes [W/m]
t_g	ground temperature [°C]
U	heat loss coefficients or linear thermal transmittances [W/m/°C]
K_S	heat exchange coefficient of the substation [kWh/year/°C]
t_S	mean temperature of the substation [°C]
t_a	ambient temperature at the substation location [°C]
φ_S	nominal heat capacity of dwelling substation [kW]
B_s	coefficient depending on type of substation and its insulation level
D_S	coefficient depending on type of substation
L_S	substation overall annual thermal losses [kWh/year]
t'	mean water temperature in the primary circuit of the substation [°C]
t''	mean water temperature in the secondary circuit of the substation [°C]
L_{th_tot}	total annual thermal losses in network [kWh/year]
H_{tot}	total annual heat demand of network [kWh/year]
C_F	total network annuitized fixed cost [£/year]
C_o	total network annual operational cost [£/year]
CHD	cost of Heat Distribution [pence/kWh]

temperatures, nor comparison of the performance in different areas. It is therefore difficult to draw more informed conclusions in terms of techno-economic implications of different solutions. Recent studies mostly in Northern European countries have addressed the feasibility of LT (low temperature) operation of DH for low energy buildings (see for instance Ref. [11]), to decrease thermal losses. In addition, the associated costs have also been shown to be lower than for higher temperature networks [12]. The applicability of DH in low heat density areas is also expected to be dependent upon potential cost reductions in the DH networks [6], possibly through lower costs of purchasing and laying network pipes [13,14]. However, systematic analysis of LT solutions in different areas, and in the UK in particular, is missing. In this respect, comparison of DH networks to gas networks for heat supply was performed with an economic focus in Refs. [15], and it was found that DH schemes serve as a better option in areas of high densities only; however, a systematic comparison of different network types and operating characteristics was not carried out. Another study with a focus on the design of heat networks for DH was done to evaluate the applicability of biomass based heat supply [16]. The study employed a network design methodology similar to the one used in this paper; however the assessment of heat networks was performed for very specific cases. A similar but again specific study has also been performed for a geothermal DH system in Ref. [17]. Other studies such as [18] have considered different dwelling substation types. However, no techno-economic assessment of options for direct and indirect dwelling substation connections, which can have several implications in terms of network design, was carried out.

On these premises, the primary aim of this work is to perform a strategic assessment of the techno-economic performance of various heat network options for distributed energy systems (in the order of up to several MW) in different areas. In order to do so, a generic and comprehensive model has been purposefully built to perform heat network design according to specified input criteria and then to assess operational, capital, and overall costs of different alternatives. More specifically, the model developed can provide strategic information on the feasibility and performance of alternative heat network options under different conditions such as operational temperatures (key to address a variety of local heat supply technologies for distributed energy systems), heat load densities, network lengths, cost parameters, types of pipes, dwelling connection types, and so forth. Specific sets of generic test networks are used for the strategic analysis, which resemble typical topologies used for electrical network in the UK in urban, sub-urban, semi-rural, and rural areas. For each case, the network is populated with relevant load models for both residential and commercial buildings (and for both space heating – SH – and domestic hot water – DHW) based on estimated typical consumers' breakdown in the given areas. Numerical case studies have been carried out with applications to DH systems that could typically be set up in different areas in a UK context.

The paper is organised as follows: Section 2 describes the strategic tool developed to design generic heat networks and analyse the costs and performance of different options. Section 3 provides the data used as input to the developed tool and operational details of the heat networks that are used for the generic UK test case studies. The results are presented in Section 3, with also comprehensive sensitivity analyses carried out in order to identify and quantify the main techno-economic drivers and implications of different alternatives under different conditions. Finally the conclusions drawn from the studies and insights for future work are presented in Section 4.

2. Strategic network assessment model

A techno-economic assessment model was specifically developed in order to analyse performance and overall cost (operational and investment) of different DH options. Calculations were automated through a tool supported by Visual Basic programming. Following a bottom up approach, consumers' hourly heat demands