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CENTRALIZED VS DISTRIBUTED ENERGY SYSTEMS OPTIONS: DISTRICT HEATING FOR THE ISLE OF DOGS IN LONDON

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ABSTRACT

This work focuses on a multi-scale framework for the design and comparison of low-carbon heat generation solutions to serve the residential and commercial thermal energy demand of high energy density urban areas. The adopted methodology assesses the cost and performance of four configurations integrated in a district heating network: (i) centralised cogeneration with gas turbine and bottoming steam turbine with flexible heat-to-electricity ratio; (ii) centralised cogeneration with gas-fired internal combustion engine; (iii) distributed building-integrated ground-source heat pumps for domestic hot water only; and (iv) distributed building-integrated ground-source heat pumps for both domestic hot water and space heating. Cost and performance data were obtained by conducting relevant market research and developing a simplified heat pump thermodynamic model. The different configurations are evaluated utilizing whole-year space heating and hot water demand profiles for the Isle of Dogs area in East London, UK. Scale effects are included by considering various technology size scenarios and the results indicate that a 50 MW centralised internal combustion cogeneration system appears to be the most profitable option, while the competitiveness of building-integrated heat pumps is dependent on their size.

Keywords: Combined heat and power, Distributed energy, District heating, Heat pumps, Urban energy systems

1. INTRODUCTION

Heat and electricity networks had been traditionally relying on fossil fuels, burning coal, oil and gas to generate electricity and using natural gas as the energy vector to provide heat. The energy mix is, however, continuously changing [1] and highly influenced by climate change [2]. The optimal decarbonisation pathways require simulations that can capture interactions across multiple scales: from different energy transport networks to the trade-offs between possible technology configurations and components.

In the UK, the emissions from space heating and hot water in residential and commercial sectors account for 83% of the total country's heating emissions [3], while heat accounts for 44% of the country's total energy consumption [4], demonstrating the urgency of redefining how heat is generated and delivered to consumers. Combusting gas in boilers is exergetically wasteful, therefore combined heat and power (CHP) technologies and heat pumps have a large role to play in the venture for decarbonisation of heat [5–7]. The development of district heating networks (DHNs) shows significant potential in high energy density areas [8, 9]. A spatial methodology including detailed pipe network and pumping costing has been explored in the work of Pirouti et al. [10], while the work of Delangle et al. [11] presents a comparison of centralised natural gas CHP engines, water-source heat pumps, natural gas boilers and biomass boilers. The utilization of geothermal and waste heat for district heating is studied in the work of Hast et al [12], which shows the significant emission reductions that district heating can achieve. Emission reductions are also shown to be potentially very high when heat pumps are integrated in the UK heating network, as demonstrated by the report of the Department of Energy & Climate Change (DECC) [13]. The report emphasizes the importance of low network temperatures to maintain low network losses and high coefficients of performance (COPs). Although the existing literature has dealt with various DHN design methodologies, low effort is being devoted in capturing the multi-process characteristics of technologies at the component level.

This paper aims to: (i) examine the economic performance of two different centralised CHP configurations for district heating: one which involves a combined-cycle gas turbine (CCGT) with flexible heat-to-electricity ratio and another which utilizes a gas-fired internal combustion engine (ICE); (ii) perform market research and utilizes a heat pump thermodynamic model to estimate costs and the COP of small-scale ground-source heat pumps (GSHPs); (iii) compare the two centralised options against distributed GSHPs while also investigating a case where the hot water demand is satisfied by the GSHPs and the space heating demand by the DHN; and (iv) evaluate different size scenarios for each possible pathway and therefore captures the significance of scaling effects. To achieve this, Section 2 describes the methodology used in building the model and the key performance indicators (KPIs) used to assess the examined configurations. The performance analysis is presented in Section 3, while Section 4 provides some conclusions and states the future objectives in the effort for integrated design and interaction of low-carbon heat generation solutions.

2. MODEL DESIGN

In this section, four proposed pathways for meeting the thermal energy demand in high-population-density areas are described, based on which we proceed to examine whether more detailed thermo-economic models (thermodynamic, sizing/costing, and market research) are required to capture realistic technology characteristics. An overview of the possible pathways is shown in Figure 1. In all simulations, the demands for hot water and space heating are met hourly for a period of one year. Natural gas is imported at a specified cost, while the thermal output of the generation systems is never allowed to exceed demand, such that no heat is wasted. Electricity can be exchanged with the grid. The installation/operation costs and thermal losses of the DHN are estimated using existing network information as recorded by DECC [14]. Heat exchangers are assumed to be required at the supply side.

2.1 Pathway *A: Centralised CCGT CHP*

In a CCGT system, a gas turbine compresses air and mixes it with natural gas to produce electricity. The hot exhaust gases are used to generate steam, which is then passed to a steam turbine to produce more electricity. The use of an extraction/condensing turbine allows some heat to be extracted at an earlier stage and higher temperature so that it can be used for district heating [15]. This means that the system can have a flexible heat to electricity ratio. The operation strategy of the CCGT CHP system can vary according to the thermal demand at any given time: when the thermal demand is low, the system operates at a high electrical efficiency mode, but as demand increases above the maximum thermal output of the system, the system switches to a high thermal efficiency mode.

The system also has auxiliary boilers whose size is decided based on the peak thermal demand. A thermal hot water storage unit of predetermined size is also incorporated. In case of low demand, the CCGT CHP system is switched off and demand is met by this back-up equipment. As the system switches from high electrical efficiency mode to high thermal efficiency mode, the electrical efficiency range changes from 45% to 39% while thermal efficiency increases from 23% to 29% can range , which correspond to the assumptions for large-scale CCGT CHP for system sizes above 40 MWe [13]. In this model, the same performance is assumed for smaller systems (above 10 MWe).

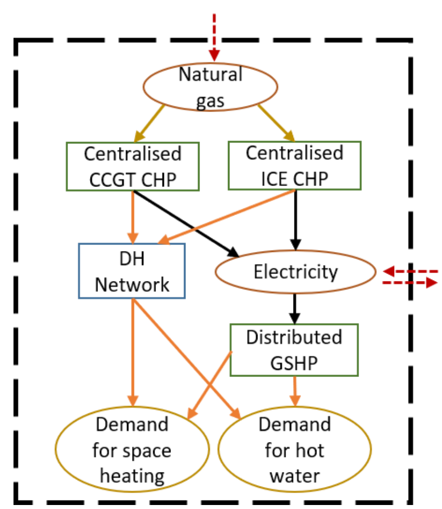

Figure 1 Pathways under investigation for the provision of heat

2.2 Pathway B: Centralised ICE CHP

Recovering heat from the exhaust gases and jacket water of ICEs is another well-studied option [16, 17] for electricity and heat cogeneration. Unlike with CCGT CHP systems, the electrical and thermal efficiencies of ICE CHP systems are fixed. Market research was conducted and based on information collected from UK manufacturers of large-scale ICE CHP units (>4 MW), the electrical and thermal efficiencies were set at 40% and 42%. When the thermal demand exceeds the system's maximum thermal power, auxiliary equipment is again utilized.

2.3 Pathway C: Centralised ICE CHP for space heating and distributed GSHP for hot water

This scenario involves a mixed centralized-distributed approach. The centralised ICE CHP system is utilized to serve the space heating demand through the DHN, while building-integrated GSHPs meet hot water demands. This means that during periods of low space heating demand (e.g. summer) the thermal and pumping losses of the DHN are avoided. The size of the GSHPs is determined by the hot water peak demand in an averagely-sized building of the area of interest. The model also incorporates distributed hot water storage at individual dwelling level.

2.4 Pathway D: Distributed GSHPs

The fourth solution involves no DHN and the demand for heat is met only by building-integrated GSHPs and associated hot water storage. This requires purchasing all electricity from the grid. The GSHPs should be larger than in Pathway C, since they need to satisfy higher demands.

2.5 Heat pump thermodynamic model

To correctly capture the performance of GSHPs a study of the UK heat pump market was conducted, recording the characteristics of more than 100 currently advertised heat pumps from more than 15 UK suppliers. The study shows that for residential and commercial applications the compressor is always one-stage, while in more than 80% of the cases the refrigerant is R410a.

In manufacturer datasheets, the performance of heat pumps is usually represented by a measured COP at certain specified conditions. However, the temperature difference between heat source and sink can have a huge effect on the COP, which can in turn have a significant effect on the results obtained by system-level models, such as the one described in this work. For this reason, the approach proposes a simplified steady-state thermodynamic model of a low-temperature single-stage-compressor which uses R410a as the refrigerant and assumes isenthalpic expansion and no pressure losses. The model is based on simple energy balances for each of the components of the vapour refrigeration cycle. Due to the ability of GSHPs to operate close to their designed load, the compressor isentropic efficiency is assumed 80%. The relationship between temperature difference and COP is examined and the model's performance is tested using average COPs at conditions specified in manufacturer datasheets. Then, the model is utilized to estimate the COP of GSHPs considering a UK ground temperature of 10 °C and a hot water temperature of 45 °C. Since this should typically be at least 55 °C, the cost required to boost the temperature from 45 °C to 55 °C once a day at the supply side is incorporated in Pathways C and D.

2.6 Evaluation of cost and performance

The capital costs of the CCGT and ICE CHP systems are obtained using correlations developed from estimated prices of such systems at different scales according to DECC [13]. These are given for CCGT CHP sizes higher than 40 MWe and for ICE CHP sizes smaller than 3.7 MWe, however, they are here assumed to be true for wider ranges. For the GSHPs, costing information was collected for more than 50 different-size units between 5-150 kWth from UK suppliers. Using this data and assuming installation costs add about 60% to the total GSHP price [18], a similar cost-size correlation was developed. All cost assumptions are listed in Table 1.

The evaluation of different pathways happens with the use of two KPIs: (i) the levelized cost of thermal energy (LCE); and (ii) the performance index (PI). Also, to capture how scale effects impact the result, a group of different scenarios k is considered for each pathway i, where each scenario corresponds to a different size of the main technology of interest. The total investment cost is therefore equal to:

$$TIC_{i,k} = \sum_{j} CAPEX_{i,k,j} d_{i,k,j} P_{i,j,k} + P_{\mathrm{DH}} len \quad (1)$$

where j represents each possible technology (CCGT, ICE, back-up boilers, thermal storage, heat exchangers), $CAPEX$ the investment cost, d the number of units, P the nominal capacity, P_{DH} the DHN unitary investment cost and len the DHN length required. The total investment cost is annualized assuming a technology lifetime of 20 years and a discount rate of 5%. The annual operation and maintenance cost is calculated as:

$$O\&M_{i,k} = \sum_{j} OPEX_{i,k,j} E_{i,k,j} + OM_{\mathrm{DH}} P_{\mathrm{DH}} len + P_{\mathrm{G}} C_{\mathrm{G},i,k} + +P_{\mathrm{PE}} E_{\mathrm{P},i,k} \quad (2)$$

where $OPEX$ is the operation and maintenance cost of each technology per unit of energy, E the total energy output in a year, OM_{DH} the operational and maintenance cost of the DHN as a fraction of the total investment cost, P_{G} the natural gas price, C_{G} the total gas consumption in a year, P_{PE} the price of purchasing electricity and E_{P} the total electricity purchased.

The LCE is then calculated as:

$$LCE_{i,k} = \frac{TIC_{\mathrm{ANN},i,k} + O\&M_{i,k} - P_{\mathrm{EE}} E_{\mathrm{S},i,k}}{D_{\mathrm{T}}} \quad (3)$$

Table 1 Economic parameters for the investigated pathways

	Units	Technology configuration			
		Pathway A	Pathway B	Pathway C	Pathway D
CHP CAPEX* [13]	million £/MWe	$1.34P_{\mathrm{CCGT}}{}^{-0.1}$	$0.96P_{\mathrm{ICE}}{}^{-0.15}$	$0.96P_{\mathrm{ICE}}{}^{-0.15}$	-
Building-integrated heat pump CAPEX**	million £/MWth	-	-	$0.18P_{\mathrm{HP}}{}^{-0.39}$	$0.18P_{\mathrm{HP}}{}^{-0.39}$
CHP OPEX [13]	£/MWhe yr	6	10	10	-
Heat pump OPEX [13]	% of HP CAPEX	-	-	0.1	0.1
DHN CAPEX [14]	million £/km	1.2			
DHN OPEX [14]	% of DHN CAPEX	3			
Natural gas supply cost [13]	£/Nm^3	0.3			
Electricity selling price [13]	£/MWhe	70			
Electricity purchase price [13]	£/MWhe	-	-	-	120

* P_{CCGT}, P_{ICE} and P_{HP} are the nominal capacities for the CCGT CHP, ICE CHP and heat pump systems respectively.
** Heat pump CAPEX is obtained using collected cost information from UK suppliers.

where TIC_{ANN} is the annualized investment cost, P_{EE} the price of exporting electricity, E_{S} the total electricity exported and D_{T} the total thermal demand of the year. Comparing projected earnings and anticipated costs is done with the performance index PI, calculated as:

$$PI_{i,k} = \frac{\left[\sum_{t=1}^{20} \frac{R_{i,k,t}}{(1+d)^t}\right]}{TIC_{i,k}} \tag{4}$$

where R represents the net cash inflows/outflows during each year t and d the discount rate.

3. CASE STUDY APPLICATION

The model utilizes hourly demand profiles for space heating and hot water for the Isle of Dogs taken from a previous study [19]. This area which is located in East London, UK, has a mix of about 1,050 domestic and commercial buildings and a population of 42,000 people. Figure 2 shows the hourly and average weekly thermal demand in the residential and commercial sectors during 2014. At its peak, total thermal demand reaches 114 MW.

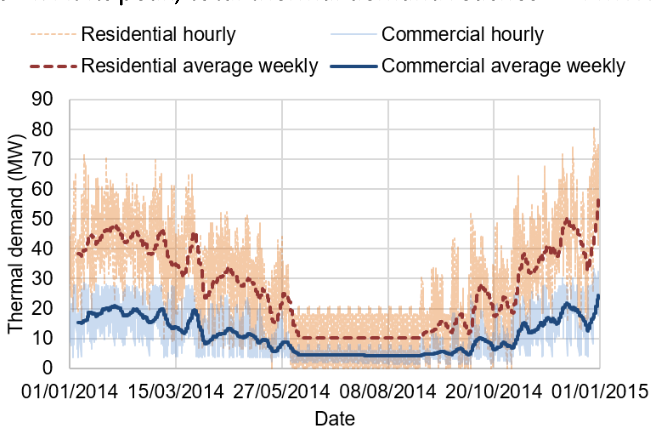

Figure 2 Thermal demand for the residential and commercial sector during 2014 in the area of the Isle of Dogs, London

3.1 *Sizing technologies*

The choice of size for the CCGT CHP system in Pathway A and the ICE CHP system in Pathways B and C has a large impact on the results of the model. In fact, the different costs per unit of output at different scales and the changes in the requirements of back-up boilers influence the investment profitability. For this reason, the model investigates seven different sizes for each pathway. The CCGT CHP size is varied between 0 MWe and 102 MWe and the ICE CHP size between 0 MWe and 60 MWe. At their maximum size, the systems cover about 90% of the thermal energy demand of the year. Testing larger sizes is not necessary, since that would mean that either large amounts of waste heat should be allowed, or the systems would be switched off frequently. The size of building-integrated heat pumps, on the other hand, depends on the thermal demand of the buildings and cannot be varied. In the Isle of Dogs, each building corresponds to about 40 people. In Pathway C, the size of GSHPs is fixed at 16.8 kWth, which is the size required to serve the peak thermal demand for hot water per building. In Pathway D, GSHPs should meet the peak demand for hot water too, so the required size is much higher, at 105 kWth.

In order to explore how population density affects the profitability of distributed GSHPs in comparison to a DHN, different GSHP sizes are considered in Pathway D, varying from 21 kWth (8 people per building) to 147 kWth (56 people per building). Table 2 presents all the size scenarios tested for the four pathways.

3.2 *Heat Pump Model*

The relationship between COP and heat source/sink temperatures obtained from the heat pump thermo-dynamic model is presented using the performance map

Table 2 Size sensitivity for the different case studies

Pathway*		Size sensitivity - scenario						
		1	2	3	4	5	6	7
A	Size of CCGT CHP (MWe)	0	17	34	51	68	85	102
B	Size of ICE CHP (MWe)	0	10	20	30	40	50	60
C	Size of ICE CHP (MWe)	0	10	20	30	40	50	60
D	Size of GSHP (kWth)	21	42	63	84	105	126	147
***Seven scenarios simulated for each pathway using different sizes for: CCGT CHP system, ICE CHP system and the GSHPs as shown. All other assumptions remain the same.**								

in Figure 3. The model is validated using manufacturer datasheets. Most datasheets record the unit's COP for a heat source temperature of 0 °C and a heat sink temperature of 35°C. The average value obtained from the conducted market research is 4.39, while the thermodynamic model predicts 4.34. Similarly, some manufacturers provide the COP at heat source and sink temperatures of 0 °C and 45 °C respectively; the average value is 3.48, while the model predicts 3.54. The model is therefore considered suitable to estimate the COP of GSHPs at source and sink temperatures of 10°C and 45°C, which is not recorded in datasheets. This is equal to 4.32.

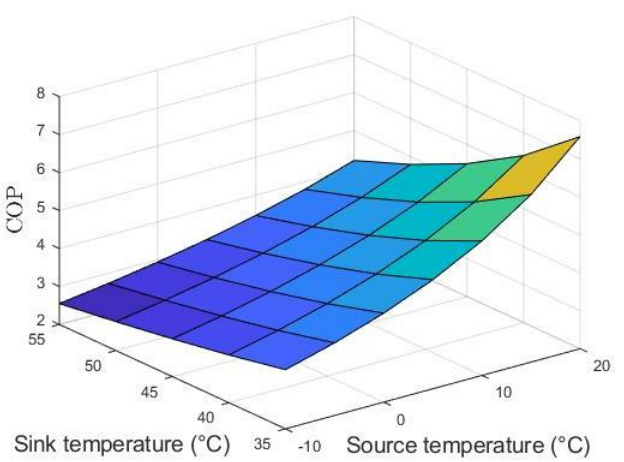

Figure 3 COP and heat source/sink temperature relationship for single-stage-compressor low-temperature R410a heat pump

3.3 Evaluating financial KPIs

The obtained LCE and PI for the considered pathways and each size scenario are presented in Figure 4. As shown, the centralised ICE CHP pathway appears to be the more profitable at all considered sizes and the optimum size is shown to be about 50 MW, at which it achieves an LCE of £32.14/MWh and a PI of 1.10. In the integrated centralised and distributed generation pathway, the optimum size of the ICE CHP system shows to be slightly smaller (30MW), however the PI of this configuration never exceeds the centralised only pathway (maximum is 0.66), mainly due to the very high capital costs of installing both centralised cogeneration and distributed GSHPs. The centralised CCGT CHP system, although it has the lowest LCE of all pathways at its maximum considered size (102MW), shows to have a fairly constant and low PI (about 0.40) at all tested sizes. This is attributed to the fact that, although the system has flexible heat-to-electricity ratio, its thermal efficiency is significantly lower than that of the ICE CHP system.

The results of Pathway D, which represents the pathway in which heat is provided solely by distributed GSHPs, are particularly interesting because the LCE and PI are highly dependent on the size of the heat pumps. In the case of small GSHPs (< 50 kW), the PI is very low or even negative. However, as the size increases, they become a more profitable choice than centralised CCGT system and the integrated centralised/distributed case, achieving a high PI of 0.91 at the maximum considered size of 147 kWth, which corresponds to 56 people per building. It is important to state that in the case of the Isle of Dogs, the estimated size of building-integrated GSHPs is 105 kWth, which corresponds to size scenario 5. In this scenario, the PI is 0.61, which is significantly better than the PI of the centralised CCGT CHP pathway but still significantly lower than that of the ICE CHP pathway.

4. CONCLUSIONS

This paper shows results from a performance and cost analysis of four possible pathways for heat supply in the residential and commercial sector. The explored options are: (i) centralised CCGT CHP system with flexible heat-to-electricity ratio; (ii) centralised ICE CHP system; (iii) integrated centralised ICE CHP system with distributed GSHPs; and (iv) only distributed GSHPs. The work utilizes market research and a thermodynamic heat pump model to capture the required technology characteristics. The model captures the significance of scale effects by testing various technology size scenarios for each pathway and compares the levelized cost of thermal energy and performance index.

The model utilizes hourly demand data for hot water and space heating for the Isle of Dogs area in London, UK, and the results show that a centralised gas-fired ICE system of a size of about 50 MW results the most profitable option, achieving a performance index higher than 1. Furthermore, the effectiveness of building-integrated heat pumps is highly affected by their size;

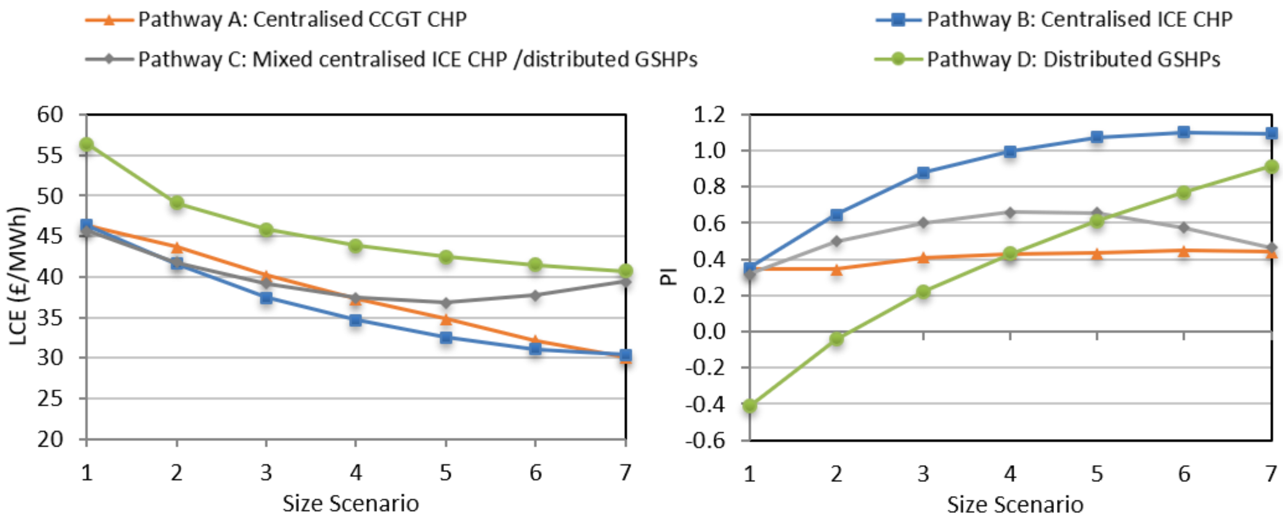

Figure 4 Simulation results for each pathway and size scenario: (i) Levelized Cost of Thermal Energy (ii) Performance Index

they can become competitive in areas where the number of people per building exceeds 50.

The end-goal of this research is the optimal design of heat generation technologies for their optimal utilization in district heating systems. Future work will therefore focus on two main areas: (i) development of thermo-dynamic CHP models and expansion of the heat pump model; and (ii) application of these models in interaction with the system-level model described in this work so that they do not only provide information about the performance of the technologies, but can also be used to optimally design them at the component and material level for their best utilisation in the system.

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