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Decarbonisation pathways for fossil fuel-based district heating networks using heat pumps

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ABSTRACT

Decarbonising the energy sector is crucial for addressing climate change concerns. Traditional UK district heating networks heavily rely on large, centralised gas-fired plants driven by economies of scale. However, the changing energy landscape necessitates a shift towards low-carbon alternatives in existing heating systems. This study fills a significant knowledge gap by examining strategies to decarbonise district heating networks (HN) through the integration of heat pumps (HPs) at different temperatures. It comprehensively assesses cost-effectiveness, energy efficiency, and operational carbon emissions. The findings emphasize the seamless integration of HPs into diverse settings, enabling them to extract heat from air, ground, or water sources and resulting in substantial carbon savings. Moreover, harnessing waste heat from the London Underground presents a substantial opportunity for emission reductions. Nevertheless, the viability of biogas is limited in densely populated areas like London. This research makes a noteworthy contribution to UK decarbonisation efforts, offering a practical roadmap for widespread adoption of HPs and a sustainable future.

Keywords: Decarbonisation, Energy sector, District heating network, Heat pump

1. INTRODUCTION

Climate change is occurring at a significant scale, being primarily caused by human-induced greenhouse gas (GHG)emissions. The Paris Agreement, adopted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), set out a global target of keeping global temperature increases below 1.5°C from pre-industrial levels. An additional requirement to the Agreement was for all signatories to create plans for reducing GHG emissions (Coyne, 2019). The Department for Business, Energy, and Industrial Strategy (BEIS) estimates that the United Kingdom's contribution to achieving the 1.5°C target would involve reducing emissions by 58%-62% below 1990 levels by 2030 (BEIS, 2021c).

In 2016, heating production and distribution accounted for 37% of total GHG emissions in the UK (BEIS, 2018b). The Climate Change Committee (CCC) advises that by 2050, 80-90% of houses and all non-residential buildings utilise low-carbon heat sources to meet the aim of net-zero emissions (CCC, 2019b). The most challenging component of achieving this target is expected to be decarbonising the heating sector. There are several strategies for reducing carbon emissions from heating systems, including switching to electric heat sources such as Heat Pumps (HPs), using alternative gases such as hydrogen or biomethane in place of natural gas, and adopting renewable technologies such as biomass (CCC, 2019a). These strategies can be implemented by utilising Heat Networks (HNs), which can provide either or both heating and cooling to clusters of nearby buildings (Werner, 2017).

The HN market in the UK is relatively small compared to other European countries (Werner, 2017), serving only 3% of the country's total heat demand (BEIS, 2020). However, government estimates suggest that by 2050 HNs could provide enough energy to heat 17% of households (BEIS, 2020). Currently, most HNs in the UK rely on combined heat and power (CHP) plants and large-scale boilers that use natural gas (BEIS, 2021a). In 2019, natural gas was the primary energy source for CHP systems, accounting for the vast majority (69%) of the fuel used (BEIS, 2021b). Thus, to achieve the UK’s ambitious decarbonisation targets, transitioning HNs to using other low-carbon alternatives is imperative. Therefore, a comprehensive approach incorporating a range of technologies is required to decarbonise the UK's HNs on a large scale effectively and HPs will play a vital role in this process. This study aims to examine the current state of the HN market in the UK and propose the most viable and low-carbon alternatives, with a particular focus on heat pumps.

The primary goal of this research is to explore the various scenarios in which heat pumps can be seamlessly integrated into HNs and to evaluate their performance in terms of operational metrics such as energy consumption, running costs and carbon emissions. By filling an existing knowledge gap on how to effectively decarbonise existing HN schemes in the UK, this research aims to contribute to the country's ambitious decarbonisation targets and provide a roadmap towards climate-neutral communities and industries in the future.

2. CURRENT STATUS OF HEAT NETWORKS IN THE UK

According to latest figures (BEIS, 2020), there are approximately 17,000 heat networks (HNs) in the UK, serving nearly 480,000 consumers. In 2013, there were an estimated 2,000 networks and 211,000 users (BEIS, 2013). Currently, there are 990 HN projects seeking investment through the UK government's Heat Network Development Unit (BEIS, 2022b). HNs provide approximately 12,000 GWh of heat annually, with around 6,500 GWh serving the domestic sector and 5,500 GWh serving non-domestic buildings. This accounts for about 3% of the UK's domestic heat demand (Werner, 2017).

HNs in the UK primarily rely on gas boilers (56%) and combined heat and power (CHP) systems (32%). Other energy sources like large-scale biomass, energy from waste, and heat pumps are also utilized (ADE, 2018). Nonetheless, HNs are moving towards heating technologies with a lower carbon footprint, and networks in the planning or construction phase are likely to include more heat pumps, energy from waste, and efficient gas-fired CHP instead of relying on gas boilers.

CHP systems have been considered more efficient than gas boilers, but the decreasing carbon savings and heavy reliance on natural gas hinder decarbonisation goals in the UK (Busch et al., 2017). This dependence exposes the country to volatile gas prices and international energy market fluctuations, potentially leading to fuel poverty and compromising energy security. Transitioning to low-carbon alternatives like heat pumps is crucial for overcoming these challenges and achieving decarbonization. Heat pumps are an established technology that can deliver immediate carbon savings without further advancements. However, despite their potential, their current deployment level is still low, which presents a substantial obstacle to realising their full benefits (EHPA, 2022).

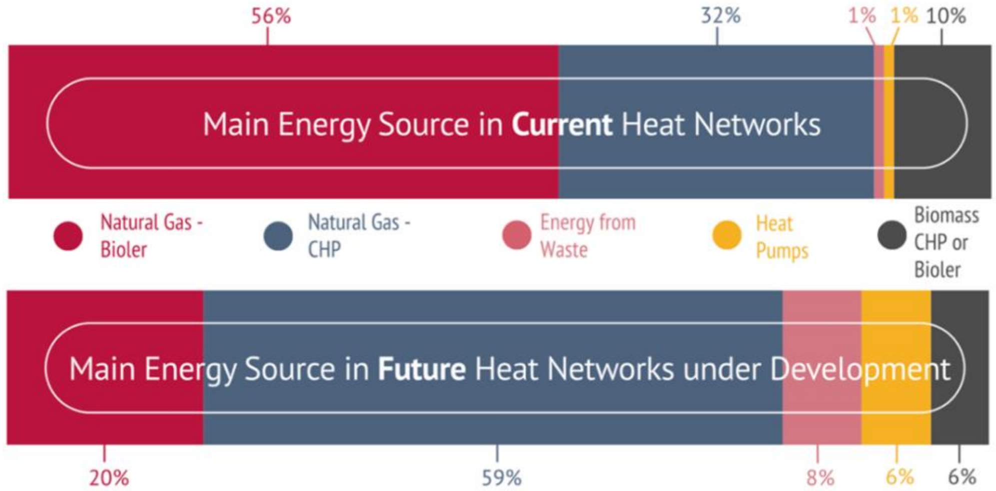


Figure 1 - Main energy source in current and future heat networks in the UK (ADE, 2018).

3. HEAT PUMPS IN THE UK

3.1. Overview

Heat pumps (HPs) are a technology that utilises electrical energy to transfer thermal energy from a low-grade heat source to a high-grade heat sink. The efficiency of this process is measured by the coefficient of performance (COP), which is the ratio of the electrical input required to the total heat output. The COP depends on the temperature difference between the heat source and the heat sink, and higher temperatures in the heat source result in improved energy efficiency (Gaur et al., 2021). Additionally, newer-generation HNs, characterized by low distribution temperatures, have the potential to increase the operational efficiency of HPs, particularly when used in conjunction with high-temperature heat sources. This is due to an achieved reduction in the temperature difference between the heat source and the heat sink (GLA, 2018).

HPs with high COPs require minimal electrical inputs and thus result in low carbon intensities per unit of delivered heat, which will tend to zero as the electricity grid becomes decarbonised (GLA, 2018). This is evident when comparing HPs to conventional technologies such as natural gas boilers and electric space heaters, as depicted in Figure 2. By running on electricity in a highly efficient process, HPs make the most of the recent growth in renewable electricity generation to provide a cleaner source of heat. Furthermore, the utilisation of waste heat can result in even higher COPs and further reduction of carbon intensity. Waste heat is a readily available resource in urban areas, as commercial and industrial activities generate significant amounts of thermal energy during their day-to-day operations.

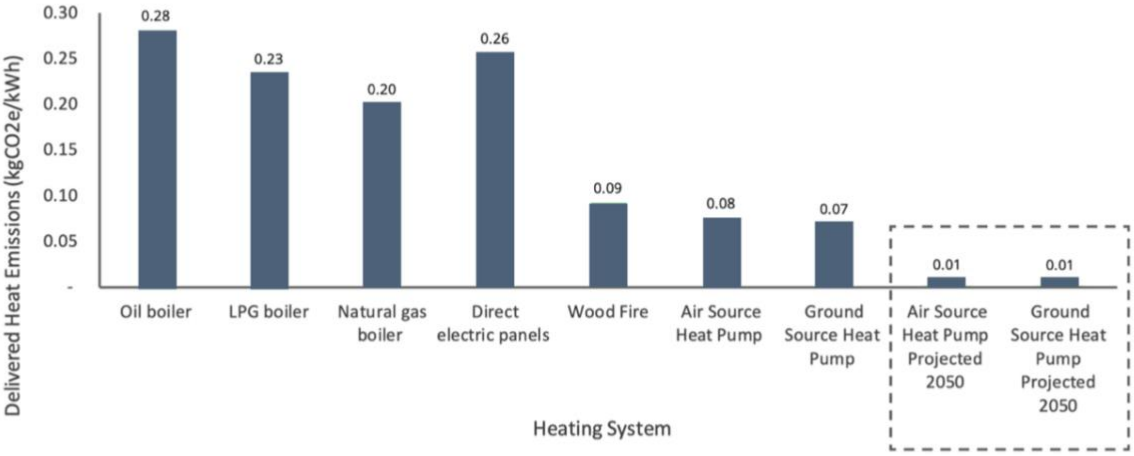


Figure 2 - Emissions from common heating systems in 2019 (EHPA, 2022).

3.2. Market review

It is clear that installing HPs is essential to immediately reducing carbon emissions from heating and meeting the net zero emissions target by 2050; there is a pressing need for implementing policies to ensure necessary changes are made to facilitate the broad adoption of HPs (Carmichael, 2022).. The European Heat Pump Association's 2022 market report reveals that approximately three million HP units were sold in the EU in 2022, with the UK having the worst track record amongst the analysed countries (see Figure 3). With Finland, Norway, and Sweden having the highest number of units sold, the UK falls behind with only 59,862 units sold that same year. In contrast, in Norway, one-third of households have HPs, which represent 95% of heating systems in new homes. Similarly, in France, the number of HPs sold yearly is 8-10 times higher than in the UK (EHPA, 2022). In order to effectively decarbonise the heat supply, it is estimated that this number will need to rise to over one million annual installations by the mid-2030s (Ralston, 2022). Achieving this requires a concerted effort from both government and the industry to reverse the trend and encourage the long-term growth of a healthy HP market, ultimately leading to significant reductions in emissions from heating.

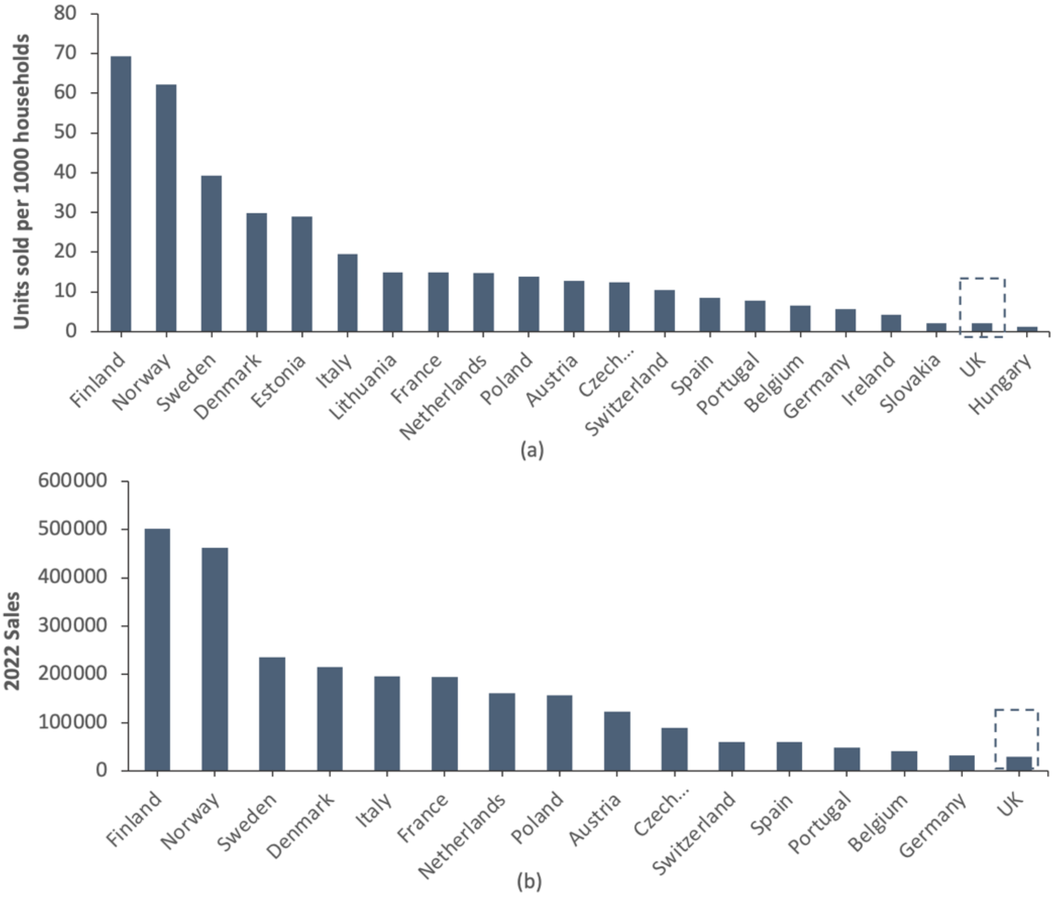


Figure 3- Heat Pump Sales and Deployment in Europe in 2022 (a) Sales, (b) Deployment per 1000 Households (EHPA, 2022)

3.3. Heat pumps in District Heating Networks

Heat pumps (HPs) can be integrated into heat networks (HNs) in various configurations. However, challenges arise due to the high operating temperatures of conventional HNs and the relatively low temperature of available heat sources, resulting in low efficiencies. To address these challenges, innovative approaches have been developed. These include using multiple HPs operating over smaller temperature ranges, utilizing new refrigerants, and redesigning heat networks to operate at lower temperatures (GLA, 2018). Case studies in the UK and Europe demonstrate different integration methods. Retrofitting HPs into existing district heating systems, such as the Citigen network in London, can provide a low-carbon heat source and reduce carbon footprints (e.on, 2020). Another approach involves using a low-temperature HN combined with distributed HPs in buildings to upgrade heat at or near the point of use (EHPA, 2022). Additionally, buildings can be linked through a network that serves as a heat source or sink for reversible HPs, integrating heating and cooling efficiently (Carmichael, 2022). It's important to note that these examples represent only a few possibilities for HP integration into HNs, as the most suitable approach depends on factors like available heat sources, system design, and expected energy demand (GLA, 2018).

4. CASE STUDY: DECARBONIZATION OF THE CITIGEN DISTRICT HN

4.1. Overview

The Citigen scheme is a tri-generation HN located in the City of London which serves the Barbican Centre, Barbican Estate, and surrounding areas. The scheme provides heat, electricity, and cooling to the area through a single plant. The plant uses natural gas as its primary fuel source and generates electricity through two CHP engines (See Figure 4) (e.on, 2018). The heat generated by the CHP system is then used to produce hot water for space heating and domestic hot water. The excess heat is also used to drive absorption chillers, which provide chilled water for air conditioning. The system has a total installed capacity of 8.6 MW of electricity and 33.2 MW of thermal energy (e.on, 2013), providing heat and electricity to approximately 11,300 households and businesses (e.on, 2018). The HN has flow and return temperatures of 95°C and 72°C, respectively. Recently, Citigen has started the commission of a HP-based system with a capacity of 4MW, aiming to provide heat to an additional 2000 households. The refrigerant used in the commissioned HP is R1234ze. This transition aimed to reduce carbon emissions and improve the environmental performance of the network (e.on, 2020).

This case study entails a comprehensive examination of the potential of HPs as a viable alternative to traditional fossil fuel-based heating systems in terms of replacing the CHP engines of the Citigen district HN. Additionally, this paper also explores the potential of using biogas as a fuel source in the network’s CHP engines. A combination of quantitative and qualitative methods is used to analyse the data and draw conclusions. This study aims to thoroughly examine the potential of alternative heating systems in terms of their carbon savings, heating costs, space requirements, and noise levels. The results of this study will provide insight into the broader implications of integrating HPs into district heating systems and under which circumstances they can be an effective decarbonisation option for existing district heating systems.

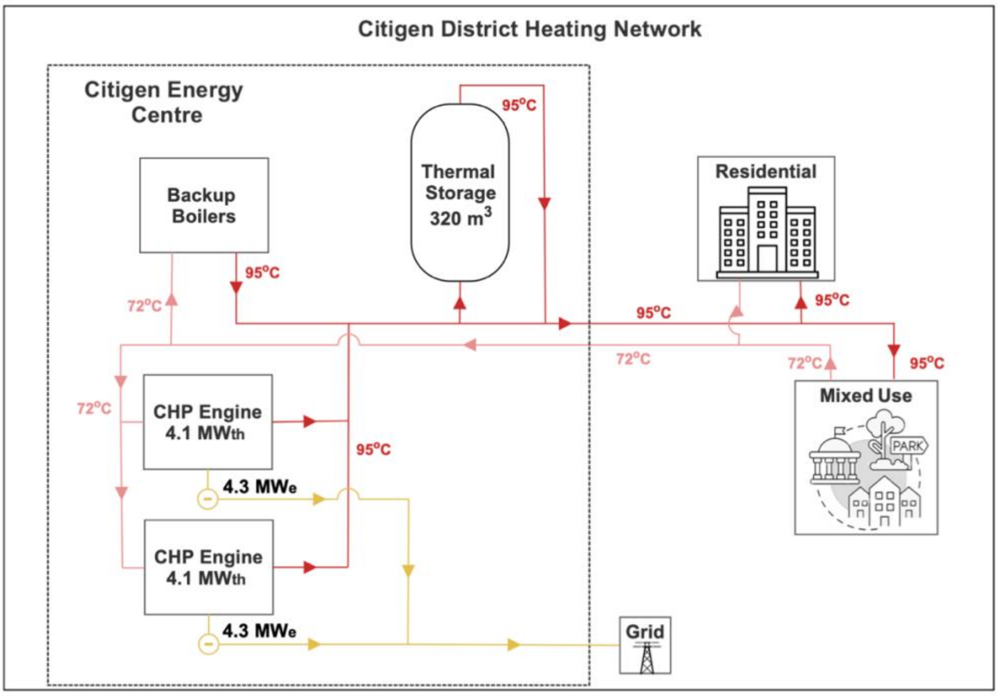


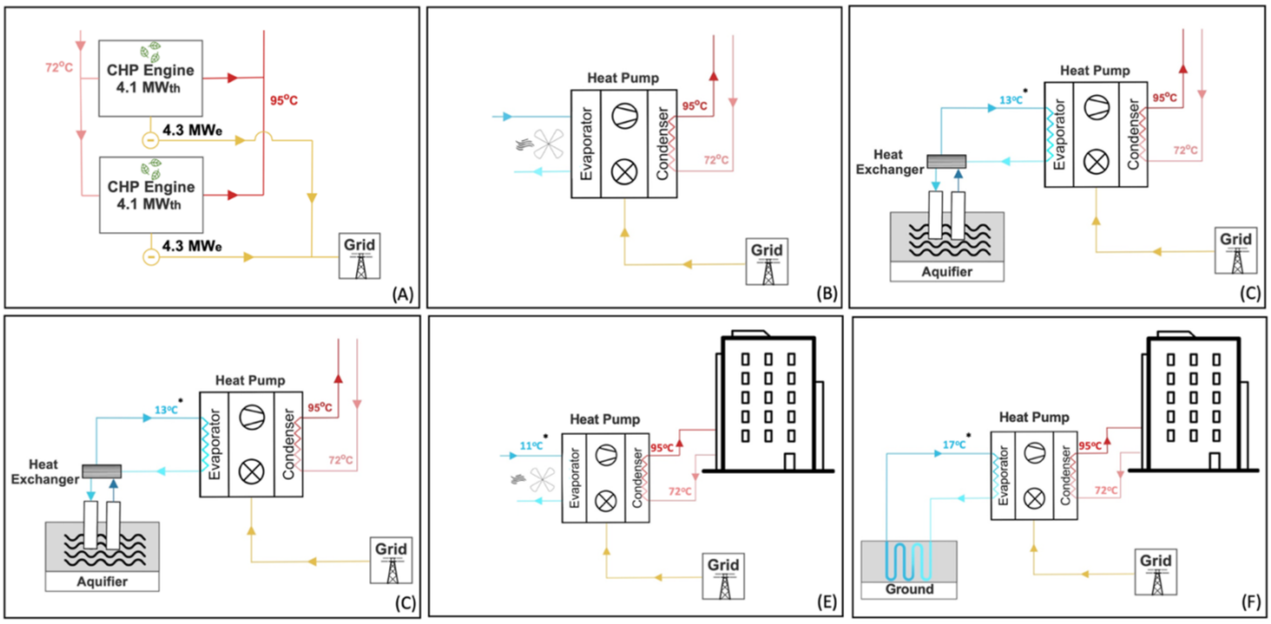
Figure 4 - Schematic of the Citigen District Heating Network.

4.2. Scenarios development and analysis

This study evaluates alternative heating systems as replacements for the carbon-intensive combined heat and power (CHP) engines of the Citigen district heating network (HN). Six scenarios are compared (Figure 5), including biogas substitution for natural gas in the CHP engines and integration of different heat pump (HP) types (air-source, water-source, and waste heat-based HP). Additionally, the study examines the potential of communal air and ground source HPs replacing the CHP-based network at each connection in the reference case scenario (Table 1). A detailed description of each scenario can be found in Table 1.

Assumptions include a 10% distribution loss factor for the district heating network, while building distribution losses are assumed consistent across scenarios. The reference case utilizes gas-fired CHP with thermal and electrical efficiencies of 42.17% and 44.1% respectively (MWM, 2019). The HP scenarios' coefficient of performance (COP) is modeled based on heat source temperature and will be determined later.

The referenced CHP engines provide approximately 3.1 MWth to 11,300 households and businesses, serving as the thermal output for all examined cases. In addition to heat, CHP-based scenarios generate and sell electricity to the grid. In contrast, HP-based scenarios consume grid electricity for heat production while accounting for the lost benefits from CHP-generated electricity sales. Thus, this investigation aims to identify the most viable and cost-effective alternative heating system to replace the carbon-intensive CHP engines in the Citigen district HN.



* Average Temperature

Figure 5 - The scenarios considered in this study.

Table 1 - Detailed description of the examined scenarios.

Scenario	Network Type	Fuel Source	Technology	Brief description
REF	District	Natural Gas	CHP	Reference case considering current Citigen heat sources.
A	District	Biogas	CHP	The fuel source of the reference case scenario is changed to biogas.
B	District	Electricity	Air-source heat pump (ASHP)	Heat is harvested from atmospheric air at an annual average of 11°C (WS, 2022).
C	District	Electricity	Water-source heat pump (WSHP)	Heat is harvested from ground aquifers at an annual average of 13°C (Icax, 2020).
D	District	Electricity	Waste heat-based heat pump (WH-HP)	Heat is harvested from London underground waste heat at an annual average of 21°C (TfL, 2020).
E	Communal	Electricity	Air-source heat pump (ASHP)	Heat is harvested from atmospheric air at building level, at an annual average of 11°C (WS, 2022).
F	Communal	Electricity	Ground-source heat pump (GSHP)	Heat is harvested from underground heat at building level, at an average of 17°C (BGS, 2020).

4.2.1. COP Dimensionless Analysis

This section presents a detailed analysis to estimate the COP of HP systems using different heat source types: air-source, ground-source, water-source, and waste heat recovery. A mathematical model was developed using Engineering Equation Solver (EES) software. The model calculated the COP for various evaporating and condensing temperatures, using R1234ze as the refrigerant. The COP was assessed with the condensing temperature ranging from 50°C to 100°C, with a 10°C increment, as shown in Figure 6. The analysis revealed a consistent trend: the COP decreases as the condensing temperature increases, while it increases as the temperature difference between evaporation and condensation decreases. To establish a regression model, the COP was expressed as a function of the aforementioned parameters.

$$COP = \left(0.09187 - 0.0053T_{evap} + 0.0033T_{cond} - 3\times10^{-6}{T_{evap}}^{2} + 1.3\times10^{-5}{T_{cond}}^{2}\right)^{1/_{-0.878743}} \quad \text{Eq. (1)}$$

Where T_{evap} is the HP evaporating temperature and T_{cond} is the condensing temperature. The proposed regression model, determined through this analysis, has an R-squared value of 98%, indicating a high degree of correlation between the data and the model. This suggests that the model can accurately predict COP values for a given set of evaporating and condensing temperatures with high confidence levels.

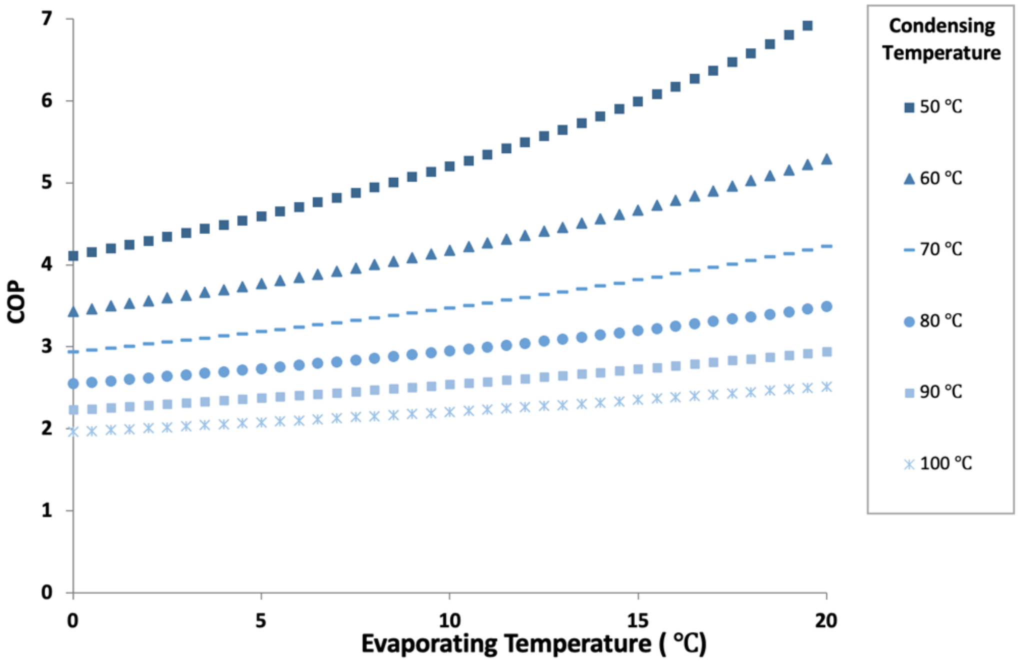


Figure 6 - Estimated COP for a different values of heat pump's evaporating and condensing temperatures.

Data was collected from various sources (WS, 2022), (BGS, 2020), (Icax, 2020), (TfL, 2020) to provide an accurate representation of the average performance of each HP scenario. Figure 7a illustrates the average system COP for different distribution temperatures, with an estimation drawn based on a distribution temperature of 95℃, which is the distribution temperature of the Citigen HN. Additionally, the average system COP was estimated for each scenario over the year, as illustrated in Figure 7b. From the data presented in these figures, it can be observed that the waste heat heat pump (WH-HP) scenario exhibits the highest COP among all the scenarios studied, likely due to the utilization of high temperature waste heat as the heat source. Conversely, the air-source heat pump (ASHP) scenario has the lowest observed COP. Table 3 presents the estimated COP for each scenario, as well as the system efficiencies of the CHP-based scenarios.

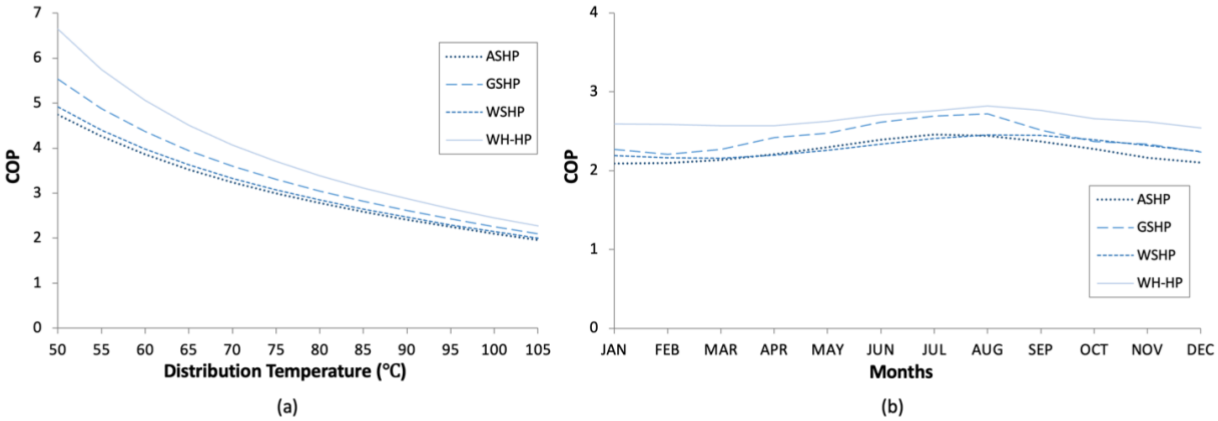


Figure 7 - Estimated COP for HP scenarios (a) at several distribution temperature (b) at 95℃ distribution temperature.

Table 2 - Estimated COP and efficiencies for the studied scenarios.

Scenario	COP	Thermal Efficiency	Electrical Efficiency
REF	-	42.7%	44.1%
A	-	42.7%	44.1%
B	2.4	-	-
C	2.5	-	-
D	2.9	-	-
E	2.4	-	-
F	2.6	-	-

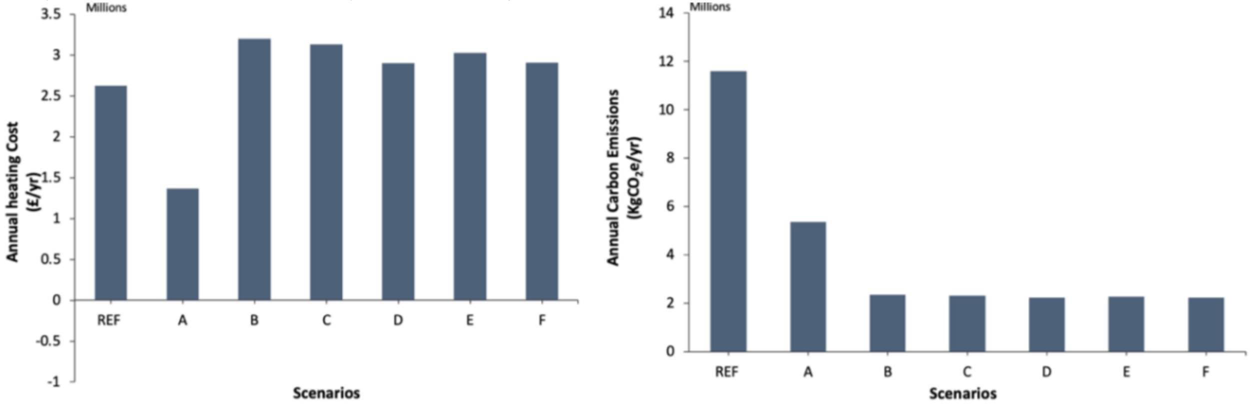
4.2.2. Heating Cost and Emissions Assessment

This investigation comprehensively evaluates the annual heating costs and carbon savings associated with each studied scenario compared to the reference case. The cost analysis considers the energy running costs for all investigated technologies when meeting the same demands for heating, while the carbon savings calculations are based on the carbon intensity of the fuels used to meet the reference loads.

Data was collected from the BEIS' most recent central forecasts (BEIS, 2023), which both consider commercial and public, the fuel costs and carbon factors were estimated over 20 years (2020-2040). This method resulted in average energy tariffs of 15.3 p/kWh for electricity, 6.5 p/kWh for natural gas and 4.5 p/kWh for biogas (BEIS, 2022a). To account for the revenue generated by cogeneration, an electricity export price of 5.3 p/kWh was used (BEIS, 2023). The average energy tariffs estimated in this study remain relevant in today's energy market, as the current energy crisis in the UK has resulted in increased energy prices for both residential and commercial consumers. Despite this, the values presented in the study provide a useful benchmark for evaluating the cost-effectiveness of different energy sources and technologies. For the same study period, the average carbon factors were 0.184 kgCO2e/kWh for natural gas and 0.06 kgCO2e/kWh for electricity, reflecting the anticipated decarbonization of the electricity grid in the following years (BEIS, 2023). Similarly, the average carbon factor for biogas was reported to be 0.085 kgCO2e/kWh (BEIS, 2018a).

The results of this study are highlighted in Figures 8a and 8b, which illustrate the annual heating costs and annual emissions of all the studied scenarios, respectively. It can be observed that the utilization of heat pumps can increase heating costs; however, this is offset by the significant reduction in annual carbon emissions. As demonstrated in Figure 9, the substitution of natural gas with biogas in scenario (A) resulted in a significant decrease in additional heating cost by -48.05% compared to the reference case and a notable increase in carbon savings by 53.80%. Additionally, it is noteworthy that the carbon savings from heat pump-based scenarios were almost identical. In contrast, the utilization of waste heat in scenario (D) and the communal ground source heat pump of scenario (F) resulted in the lowest additional cost compared to the reference case. Based on the results, it can be inferred that the scenario that would represent an optimum solution would be the one that offers the best trade-off between additional heating costs and carbon savings. In this case, the fourth scenario (D) would be considered the optimum solution, as it has the lowest increase in additional heating costs while still providing a high level of carbon savings.

Nonetheless, the selection of the optimal scenario depends on specific priorities and constraints. The suitability of biogas relies on the availability of feedstock and may be influenced by seasonal variations(Scenario A). On the other hand, the implementation of heat pumps necessitates significant investment, while waste heat utilization relies on a consistent heat source (Scenario D). Furthermore, it is crucial to consider the possibility of limited access to land for ground source heat pumps (Scenario F) and the potential impact on the environment, such as noise and vibration.



(a) (b)

Figure 8-Comparison between different scenarios in terms of (a) annual heating cost, and (b) annual carbon emissions

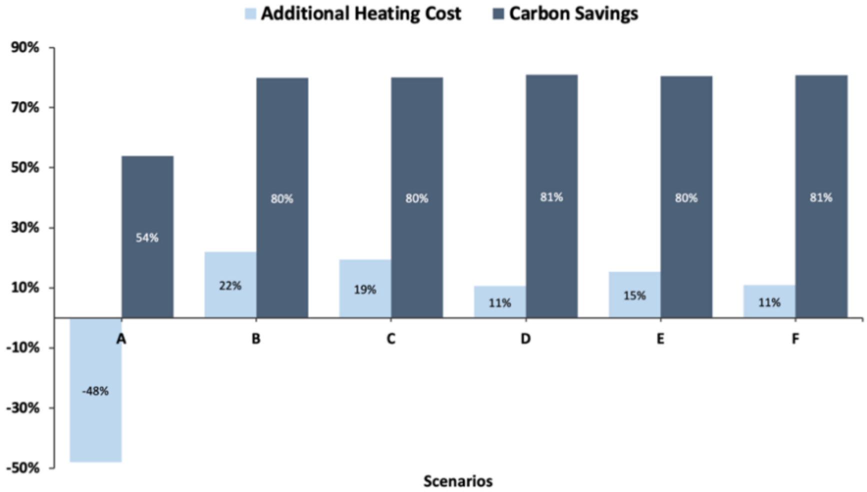


Figure 9-Performance of different scenarios compared to the reference case.

4.2.3. Space and Noise Impacts Assessment

A qualitative analysis was conducted to assess the potential impact of the studied scenarios on noise, space, and vibration. Data on each heat pump system's space requirements and noise levels were obtained from a comprehensive review of case studies (Wagner et al., 2020), (Zhang et al., 2020), (GLA, 2018) and industry standards (BSI, 2017). The information collected from these sources was used to determine the space and noise implications of each heat pump system. The data included information on the location of equipment, overall space required and noise levels at different distances from the equipment and during different times of the day.

Compared to a reference scenario, it is clearly illustrated how heat pumps affect space requirements and noise levels. Scenario (A), which uses biogas as a fuel source, doesn't have additional space or noise implications compared to the reference scenario. This is advantageous as it allows for sustainable energy production without compromising on space and noise factors. The impact of space is an important consideration when evaluating the use of heat pumps, particularly in the district and communal heating networks. Compared to a traditional district heating system, heat pumps can have different space requirements, which can be divided into two categories: district energy centre and building level. These space requirements are illustrated in Table 3.

When installing heat pumps in densely populated areas like central London, noise levels are an important consideration. Factors such as heating source, location, and design influence noise emission characteristics. Ground-source heat pumps generally produce low noise levels, while air-source heat pumps can generate higher levels. To mitigate noise impact, appropriate noise reduction strategies like proper installation and acoustic screening should be implemented. Considering vibration, heat pump systems are generally not a significant source. However, assessing the equipment's location and potential impacts on the building structure and surrounding environment is crucial. Consultation with vibration analysis experts is recommended to address any potential issues.

Table 3 - Additional space implication for the studied scenarios

Scenario	Additional space implications	
	DH Energy Centre	**Building Level**
A	-	-
B	Significant additional space may be required for the installation of ASHP units and associated equipment, such as ductwork and ventilation systems.	-
C	Significant additional space may be required for the installation of WSHP units and associated equipment, such as ground loops and pump stations.	-
D	for the installation of WS-HP units and associated equipment (with access to underground waste heat network).	-
E	-	Additional ventilated space may be required (i.e., a ventilated or open-air plant room)
F	-	Additional space may be required for the installation of the ground loops (i.e., gardens, parking areas or other open spaces)

5. CONCLUSION

This study aimed at evaluating the potential of alternative heating systems as replacements for the carbon-intensive CHP engines of the Citigen district heating network. A comprehensive analysis was conducted, evaluating six distinct scenarios, including the use of biogas and HPs, and results for each scenario were compared to a gas-CHP reference case. The evaluation was based on parameters such as COP, heating costs, carbon savings, and each scenario's noise and space implications.

The results revealed that heat pumps have a crucial role in decarbonising heat networks and are an effective solution to reducing greenhouse gas emissions in the heating sector. Heat pumps are easy to integrate into heat networks, and their ability to extract heat from various sources such as air, ground, or water makes them ideal for use in residential, commercial, and industrial settings. The study also highlights the potential of combining heat pumps with waste heat from the London underground, providing cost savings and substantial emission reductions. The study also examined the potential of biogas to decarbonize heat networks. While biogas has a promising future, it is heavily dependent on the availability of feedstock and less suitable for densely populated areas like London. Finally, the study addressed the noise and space requirements associated with heat pumps and found that these challenges can be effectively managed with proper design and installation. In conclusion, this research contributes to the UK's efforts to achieve its decarbonisation targets and provides a roadmap for communities and industries to tackle climate change. Efforts must be made to promote and support the widespread adoption of heat pumps to secure a sustainable and low-carbon future.

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