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Potential use of district heating networks and the prospects for the advancements within urban areas of Nottingham as a case study

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ABSTRACT

Buildings in urban areas significantly contribute to global energy consumption, necessitating solutions to reduce energy demands and mitigate environmental impacts. This study investigates district heating networks in urban areas, using Nottingham as a case study. A literature review addresses key barriers to decarbonising building energy in the UK, focusing on: (1) Information, engagement, and behaviour, (2) Strategy, policy, and regulation, (3) Infrastructure, (4) Supply chain and skills, and (5) Distribution of costs and impacts. The study examines the network's location, current processes, energy performance, and potential future impacts. Heat mapping and energy flow assessments identify areas for energy savings, guiding system optimisation. The findings suggest that increasing the energy output from the heat station to the network can enhance performance. The analysis highlights the potential of a life cycle perspective for district heating networks, proposing a framework that considers all stages from material sourcing to system utilisation. This approach helps assess environmental impacts, including greenhouse gas emissions and resource depletion, identifying opportunities to improve resource efficiency and reduce environmental impacts. By evaluating current sustainability goals and regulatory compliance, the study provides insights into the environmental and social implications of the district heating network's operations, pinpointing areas for improvement. It emphasises the need for continuous optimisation and innovation throughout the network's life cycle. The potential of a full life cycle assessment (LCA) approach is highlighted to evaluate four main future advancements: (1) heating network with added energy storage, (2) advanced system operations through model predictive control (MPC) for demand prediction, (3) general network improvements, and (4) network expansion. Overall, this study aims to enhance the sustainability, efficiency, and resilience of district heating networks, contributing to the transition towards sustainable energy systems while ensuring environmental and economic viability over time.

1. Introduction

Based on the most recent forecasts, significant shifts are occurring in the climate, which is anticipated to impact the adaptability of energy systems in buildings. With the ongoing rise in global temperatures, there will likely be an increased demand for cooling during the summer and a reduced need for heating in winter in the United Kingdom. This indicates a need for substantial changes within the built environment sector, aimed at addressing future energy requirements and mitigating adverse environmental effects.

In response, research-based technological advancements and strategies have been developed and implemented across various small and large-scale energy systems. However, there is a need to review these current developments and innovative technologies to ensure they can fulfil future needs. Key strategies for building energy decarbonisation are set to address climate change comprehensively. Based on current strategies that have been reviewed and evaluated, a comprehensive analysis includes various aspects such as efficiency, sustainability, reliability, environmental impact, and economic viability (Lopion et al., 2018). Common strategies applied include scenario-based analysis towards specific energy systems, involving different modelling strategies to represent a series of potential current and future scenarios based on

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variations in energy demand, technological advancements, policy changes, and market conditions.

For example, the Future Energy Scenarios (FES) (Future Energy Scenarios FES and ESO, 2024) is designed to apply research and modelling through scenario-based approaches via the Electricity System Operator (ESO) on the National Grid. This aims to maintain system reliability, improve system functions and performance, and balance electricity supply and demand across all markets on the network. Another approach includes a multicriteria evaluation of district heating system options conducted by Ghafghazi et al. (2010)., which involves understanding the viewpoints of different stakeholders and how communication affects their preferences about criteria weights and their rankings and opinions on various types of energy systems. This indicates that concerns within communications can impact the types of energy systems used. Furthermore, many studies have considered aspects of social equity by evaluating energy systems in terms of their energy affordability and distributional impacts on vulnerable communities. Studies by Baker et al., 2021 and (Fragkos et al., 2021) indicate that equity considerations can ensure that energy policies and investments benefit all segments of society equitably.

Other strategies used to evaluate the current energy system include the Energy Return on Investment (EROI) (Carbajales-Dale, 2023), which calculates the ratio of usable energy obtained from a particular energy source to the amount of energy expended to obtain it. This provides insights into the efficiency and viability of energy production methods. By evaluating EROI, energy sources can be prioritised based on their net energy yield. However, this type of evaluation is very broad and is ideally conducted on specific types of energy sources and their consumption based on major energy carriers (Murphy et al., 2022). More specifically, other types of assessments, such as the Reliability and Resilience Assessment (Jasiunas et al., 2021) evaluates the ability of energy systems to deliver a consistent and uninterrupted power supply. This involves considering factors such as infrastructure robustness, maintenance requirements, and vulnerability to natural disasters or system failures, helping to identify potential weaknesses and improve system resilience.

In addition, the Environmental Impact Assessment (EIA) (Environmental Impact Assessment (EIA), n.d.), evaluates the environmental consequences of energy systems, including air and water pollution, habitat destruction, and greenhouse gas emissions. This helps identify mitigation measures and sustainable practices to minimise negative environmental impacts. By employing these evaluation strategies, stakeholders can gain a comprehensive understanding of current energy systems, identify areas for improvement, and make informed decisions to transition towards more sustainable, efficient, and resilient energy systems. However, each type of assessment has its benefits and limitations and is designed for Novelty, Aims and Objectives

The following reviews existing approaches used to assist the decarbonisation of building energy in the UK, and address the cross-cutting barriers of (1) information, engagement, and behaviour; (2) strategy, policy, and regulation; (3) infrastructure; (4) supply chain and skill; and (5) distribution of costs and impacts, there is a highlighted potential for advancements within district heating networks in urban areas.

Based on the current regulatory frameworks, strong collaborations among governments, industries, and communities are essential for successfully decarbonising building energy through a holistic approach. Given that district heating systems and networks vary in scale, coverage, heat generation, ownership, and management across the UK, an in-depth analysis of each system is necessary to determine its feasibility for future use. This suggests a demand for a framework that allows for the identification of impacts based on a life cycle perspective for any type of district heating system.

The following points highlight the limitations hindering the widespread application of these approaches and emphasise the need for an effective assessment approach towards existing district heating systems and networks:

1. Information, Engagement, and Behaviour: There is a need for better information dissemination and engagement strategies to influence public behaviour towards adopting sustainable energy solutions.
2. Strategy, Policy, and Regulation: Coherent and supportive policies and regulations are crucial to drive the adoption and implementation of decarbonisation technologies.
3. Infrastructure: The existing infrastructure must be assessed and upgraded to support the integration of renewable energy sources and efficient heating technologies.
4. Supply Chain and Skills: Developing a robust supply chain and skilled workforce is necessary to implement and maintain advanced heating systems.
5. Distribution of Costs and Impacts: Equitable distribution of costs and benefits must be ensured to gain public and stakeholder support for decarbonisation initiatives.

To overcome these limitations and drive the decarbonisation of building energy to incorporate with the potential solutions addressed in Section 2.2, it is essential to develop a comprehensive framework that assesses the life cycle impacts of district heating systems, considering their diverse characteristics and operational contexts.

Our contributions are in the following aspects: to assess the status of building energy systems that adopt district heating and explore an approach based on life cycle perspectives to help assess the resilience of energy systems to future uncertainties and identify strategies for adaptation and mitigation. It includes an outline the current status and potential use of district heating networks, focusing on prospects for their advancement. We use an existing district heating network in Nottingham, United Kingdom, as a case study to illustrate these points. his study includes an analytical analysis of the current building and energy status in the UK. It outlines the current government support and regulations regarding various energy systems, highlighting the limitations of district heating in the UK and identifying solutions for assessing existing district heating networks. Various methods will be explored and applied to analyse the existing district heating network. This includes an assessment of energy flows to identify issues within current district heating networks. Based on our understanding of the system and processes of the district heating network, we conducted an assessment of energy flows to identify problems in current networks. This analysis will lead to the establishment of a lifecycle assessment approach to further investigate potential enhancements for district heating systems and networks.

2. Building energy

As buildings account for a significant portion of global energy consumption and greenhouse gas emissions, key strategies for building energy decarbonisation are crucial in addressing climate change. This section explores and reviews current methods implemented for the decarbonisation of building energy in the UK. Achieving significant reductions in carbon emissions from buildings ideally requires a multifaceted approach. This approach combines energy efficiency improvements, electrification, renewable energy integration, policy support, and public engagement. However, many of the approaches currently implemented have limitations in certain aspects and do not fully provide effective building energy-saving solutions.

2.1. Decarbonization oF building energy in the UK: barriers

The decarbonisation of building energy in the UK is a critical aspect of the country's efforts to combat climate change and achieve net-zero carbon emissions by 2050 (Department for Energy Security and Net Zero, 2023). Buildings significantly contribute to carbon emissions due to their energy consumption for heating, cooling, lighting, and other purposes (International Energy Agency, 2023). Decarbonising building energy involves transitioning away from fossil fuels and adopting cleaner, more sustainable energy sources. According to a report by

EnergyREV (EnergyREV, 2024), a systematic approach was adopted to review the potential of smart local energy systems. These systems operate close to the demand of homes, businesses, and communities, utilising advanced smart technology to address future-driven, short-term, and inter-seasonal energy demands. However, cross-cutting barriers across five key aspects play a crucial role in the success of building energy decarbonisation efforts. These barriers currently pose potential hurdles that require further exploration, development, and widespread adoption of innovative systems and approaches. The following introduces the five key aspects with an in-depth analysis of each.

2.1.1. Information, engagement and behaviour

Providing energy consumption awareness through methods that induce rapid changes involves informing occupants about their energy usage, enabling them to make informed decisions on reducing energy consumption. This includes insights into peak energy times, energy-efficient practices, and the impact of individual behaviours. Morton et al. (2020) (Empowering and Engaging European building users for energy efficiency, 2020) identify common challenges in addressing inefficient energy behaviours and highlight the need for engaging building occupants in energy conservation. This engagement encourages the adoption of energy-efficient behaviours and appliances by ensuring these technologies are user-friendly, thereby promoting their acceptance and contributing to building energy decarbonization. Effective interventions may include smart thermostats, energy-efficient lighting, and other technologies that optimise energy use (Rissman et al., 2020; Metallidou et al., 2020). The successful operation of such technologies maximizes system efficiency and enhances user engagement. However, it is essential to maintain a balance between energy conservation and occupant comfort to ensure the effectiveness of overall energy-saving measures (Chenari et al., 2016). Currently, few systems provide real-time feedback on energy consumption, which helps users understand the immediate impact of their actions. Even when feedback monitoring systems are implemented, Fredericks et al. (2020) find that little has changed in occupants' perceptions and experiences regarding energy feedback (Fredericks et al., 2020). This suggests a need for more effective approaches, such as smart meters or mobile apps, to motivate users to make sustainable choices. The IEA report on 'Better Energy Efficiency Policy with Digital Tools' highlights the potential of digitalisation in enhancing energy efficiency policies (IEA., 2021).

In addition to technologically driven factors that directly impact effectiveness, societal and community influences also play a significant role. Social influences, based on people's engagement and active involvement in adopting sustainable behaviours, enhance knowledge and understanding of equipment use and environmental impact. Awareness in workplaces, educational institutions, and residential communities is crucial for promoting sustainable practices. Hargreaves et al. (2011) highlight the importance of this awareness in fostering sustainable behaviour (Hargreaves, 2011). Goggins et al. (2022) (Goggins et al., 2022) suggest that social engagement can drive variations in demand response initiatives, contributing to reduced energy consumption by prioritising sustainable building practices and influencing decision-makers. In summary, the information, engagement, and behaviour of building users are integral to successful building energy decarbonisation. Empowering and involving users increases the likelihood of achieving significant reductions in energy consumption and greenhouse gas emissions within buildings.

2.1.2. Strategy, policy and regulation

Through the reviews of UK and EU policies on energy, (Economidou et al., 2020) and (Hamza and Gilroy, 2011) indicate a lack of long-term strategy and fragmented policies, placing consumers at risk due to thermally inefficient buildings. A comprehensive, well-implemented strategy supported by clear policies and regulations is essential to provide the necessary structure, incentives, and guidance to drive positive change.

Various guided frameworks, including the "Net Zero by 2050" from the International Energy Agency (International Energy Agency, 2021) and the UK government's "Net Zero Estate Playbook" (GOV.UK, 2021a), have been introduced to offer a well-defined strategy for building energy decarbonisation. These frameworks outline goals, targets, and steps needed to achieve them, involving all stakeholders in the process and driving market transformation by offering incentives for the adoption of energy-efficient technologies and practices. Financial incentives, tax credits, and subsidies encourage the deployment of sustainable solutions. These frameworks set regulatory standards, requiring certifications for energy efficiency, renewable energy use, and sustainable building practices to ensure buildings meet specific criteria for reducing carbon emissions. Constant monitoring and enforcement, along with penalties for non-compliance, serve as deterrents and ensure adherence to sustainability requirements (GOV.UK, 2022).

To ensure the sustained success of building energy decarbonisation efforts, policies and regulations provide a crucial foundation for long-term planning. Additionally, they address climate resilience by incorporating measures to enhance a building's ability to adapt to changing climate conditions over time. The guide published by the HM Government in 2011, "Climate Resilient Infrastructure: Preparing for a Changing Climate" (GOV.UK, 2011), outlines the government's vision and strategies for addressing challenges and barriers related to climate change, prioritising infrastructure resilience. These efforts align with global commitments to reduce greenhouse gas emissions, such as those of the United Nations Net Zero Coalition (United Nations, 2023). By adhering to international agreements, countries contribute to collective efforts to mitigate climate change. Communication strategies play a vital role in raising public awareness about the importance of building energy decarbonisation. Research conducted by Wahlund and Palm (2022) and Haf et al. (2020) suggests that well-designed awareness and behaviour change campaigns can effectively motivate people to reduce energy consumption. Informed citizens are more likely to support and participate in energy-saving initiatives. Engagement among government agencies, industry stakeholders, and the public through a multi-stakeholder approach ensures that diverse perspectives are considered, leading to more comprehensive and effective strategies. Encouraging innovation through progressive research and development in renewable energy projects, energy-efficient technologies, and sustainable building practices further accelerates progress toward decarbonisation.

2.1.3. Infrastructure

Infrastructure serves as the bedrock of sustainable and low-carbon solutions, providing the physical and technical foundations necessary to drive decarbonisation efforts within the built environment. As highlighted by McKinsey and Company (2023), without robust infrastructure, long-term decarbonisation strategies are at risk.

An integral aspect of infrastructure lies in energy supply and distribution. The type of energy system in place, its operational and management systems, and its resilience to adaptation measures are crucial considerations. The UK Energy Research Centre (2022) (UKERC., 2022) underscores the significance of infrastructure in transitioning to sustainable and low-carbon energy systems. It forms the backbone of these transitions, facilitating the distribution of low-carbon energy efficiently and effectively.

The success and adaptability of infrastructure are contingent upon the energy technologies implemented. This encompasses renewable energy sources, smart grids, energy management systems, and the potential adoption of energy storage facilities. Moreover, infrastructure encompasses various energy systems, such as district heating and cooling systems, waste heat recovery systems, and technological methods for building retrofits. Each of these components plays a vital role in shaping the sustainability and resilience of infrastructure in the face of decarbonisation challenges.

2.1.4. Supply Chain and Skills

In addition to robust infrastructure, a well-functioning supply chain and a skilled workforce are fundamental pillars for effective building energy decarbonisation. These components ensure the availability of sustainable technologies, support the affordability of solutions and contribute to the successful implementation and ongoing performance of energy-efficient measures.

A study by Zhang et al. (2022) highlights how barriers such as the "lack of support from supply chain partners" and "uncertainty in return on investment" significantly impact the economic performance associated with carbon neutrality initiatives (Zhang et al., 2022a). These barriers underscore the importance of a well-managed supply chain for successful decarbonisation efforts. McKinsey and Company (2022) also emphasises the need for clear directions to address the lack of investment in training, skills, capabilities, and partnerships within businesses (McKinsey and Company, 2022). Reskilling and rebuilding supply chains through valuable business models are essential to ensure the availability of sustainable and energy-efficient technologies. Access to high-quality, environmentally friendly materials and equipment is critical for implementing energy decarbonisation measures in building projects. Collaboration throughout the supply chain fosters innovation, leading to the development of cutting-edge technologies and materials that enhance energy efficiency. Partnerships between manufacturers, suppliers, and research institutions play a pivotal role in driving advancements in sustainable building technologies. Considering affordability is also crucial, from the cost of production to compliance with regulations. Continuous development and the implementation of training programs and educational initiatives ensure that the workforce possesses the necessary skills for building retrofits, renewable energy installations, and the use of advanced technologies. In summary, a well-functioning supply chain and skilled workforce are essential for the successful implementation of energy-efficient practices and innovative solutions in building energy decarbonisation efforts. Collaboration, innovation, affordability, and skill development are key factors driving progress in this critical area of sustainability.

2.1.5. Distribution of Costs and Impacts

In addition to the above aspects, the following presents the importance of equitable distribution of costs and impacts in building energy decarbonization. Zhang et al. (2022) underscore the need for a fair and equitable approach to the distribution of costs and impacts in building energy decarbonisation efforts (Zhang et al., 2022a). Achieving widespread acceptance and success in these endeavours requires ensuring that the benefits of sustainability are accessible to all, thereby creating a supportive environment for the long-term transition to a low-carbon built environment. Within the UK, the 2016 final report of the Energy Market Investigation highlights high uncertainty regarding how costs should be distributed, with relative electricity prices inflated and gas prices not reflecting externalities (Witcomb et al., 2016). This underscores the importance of considering co-impacts and performing thorough cost-benefit analyses to inform investment decisions. Decision-makers must understand the distribution of costs to identify economically viable and socially acceptable strategies.

Collaboration across sectors is crucial for addressing challenges and finding solutions that benefit multiple stakeholders (Roadmap2030.ceres.org). Understanding government subsidies and incentives aids in determining the amount of support for those facing higher initial expenses. Involving the private sector enables the scaling up of initiatives and drives innovation in the building industry. Lin and Zhai (2023) emphasise considering the distribution of costs during stages of user adoption of energy-efficient practices (Lin and Zhai, 2023). Financial incentives, awareness campaigns, and education programs can encourage user adoption, ensuring the affordability and public support necessary for the widespread implementation of decarbonisation initiatives.

Equitably distributing costs and impacts ensures that the benefits of building energy decarbonisation reach all socio-economic groups, preventing disparities in access to clean and efficient energy solutions. Fair distribution of costs makes energy-efficient technologies more affordable for homeowners, businesses, and institutions, fostering public support for decarbonisation efforts. Hence, this approach is vital for creating a sustainable and inclusive transition to a low-carbon built environment.

2.2. Decarbonisation of building energy in the UK: potential solutions

Based on the identified aspects, along with the strengths and missed opportunities in the current UK government's heat decarbonisation strategies, there is potential for enhancement. Guidance derived from these key aspects can collectively contribute to the overarching goal of decarbonising building energy in the UK, aligning with the country's commitment to reducing greenhouse gas emissions and mitigating climate change.

In summary, the following six aspects (Sections 2.2.1–2.2.6) explores the current and potential solutions that would be crucial for forming collaborations among the government, industries, and communities. These collaborations are essential for the successful delivery of decarbonised building energy through a holistic approach.

2.2.1. Energy Efficiency Improvements and Building Codes

The UK government is actively promoting the retrofitting of existing buildings to improve energy efficiency. This initiative includes financial incentives, grants, and programs to encourage property owners to upgrade insulation, heating systems, and windows. Based on the RICS policy paper (RICS, 2020), the current landscape of retrofitting policy drivers, regulations, technical processes, and fiscal levers is explored, identifying both gaps and opportunities. This paper aims to pinpoint where industry standards and tools can overcome barriers and enhance the value of retrofitting. Additionally, the Future Homes Standard Ministry of Housing, 2019), established as a policy initiative, aims to improve the energy efficiency of new homes. This standard, expected to be implemented in 2025, will require new homes to produce 75–80 % lower carbon emissions compared to current standards. This suggests that retrofitting existing buildings with energy-efficient technologies and insulation can significantly contribute to energy and emission reductions. Moreover, the implementation of stringent energy efficiency standards for new constructions is also crucial.

Energy efficiency standards vary across countries and regions, with specific codes and regulations currently in place. However, common principles and practices promote energy efficiency in new buildings, including the Building Regulations in England and Wales (GOV.UK, 2010). These regulations, divided into 18 separate parts and regularly updated, aim to improve energy efficiency standards for new constructions and major renovations. They play a crucial role in setting minimum requirements for insulation, heating systems, and overall energy performance. Strengthening building codes and standards ensures that new constructions and renovations meet high energy efficiency and sustainability criteria, and enforcing regulations mandates the use of low-carbon technologies and materials in building projects.

In addition to building regulations, Energy Performance Certificates (EPCs) (GOV.UK, 2017) are mandatory for buildings in the UK and provide an energy efficiency rating. The energy efficiency of a property is rated on a scale from A to G, with A being the most energy-efficient and G being the least efficient. This rating is determined based on factors such as insulation, heating systems, and energy usage. The government continues to use EPCs as a tool to encourage property owners to improve the energy performance of their buildings.

However, solely relying on current building regulations and the understanding of a building's energy performance cannot directly inform how a building can be improved towards energy reductions. Instead, these can be utilised to inform whether novel and new smart building technologies designed to optimise energy consumption can be an effective approach.

2.2.2. Renewable energy integration and electrification of energy systems

The use of renewable energy sources such as solar, wind, and biomass for heating and electricity generation in buildings has been a significant focus in recent years as part of efforts to reduce greenhouse gas emissions and transition to a more sustainable energy system. Several factors have contributed to this integration to enhance the encouragement of such developments and applications. One factor is the government policies. The UK government has implemented various policies and initiatives to promote renewable energy integration. These include the Renewable Energy Directive (European Commission, 2022) which sets targets for renewable energy generation, and the Contracts for Difference (CfD) scheme (Department for Energy Security and Net Zero, 2022) that provides financial support to renewable energy projects. Furthermore, the Green Homes Grant (Department for Business, 2020) was a short-term program aimed at supporting homeowners in England with grants for energy-efficient home improvements. However, this programme faced challenges including, implementation challenges due to delays in processing applications and difficulty in finding qualified tradespeople to carry out the necessary work, funding issues with concerns to the allocation and management, impact from the COVID-19 pandemic and also public criticism, resulting it to be ultimately discontinued in March 2021, six months after it was launched. Hence, this indicates that not all, renewable energy-based schemes are long-term effective, and the UK government remains committed to supporting energy efficiency measures. One aspect is the continuous increase in the integration of renewable energy sources into various types of energy systems.

The Heat and Buildings Strategy (GOV.UK, 2021b) is another policy set by the UK government with plans for decarbonising heating in buildings. This includes a focus on transitioning away from natural gas for heating and promoting the use of low-carbon alternatives such as heat pumps. In addition, technologies such as solar thermal, geothermal, biomass, and waste heat recovery can be utilised to further reduce the carbon footprint of these existing systems such as district heating. Effectively, this suggests all guides and policies introduced by the government are towards the promotion of the adoption of heat pumps for space heating and water heating or other low-carbon technologies to shift from fossil fuel-based heating systems to more viable heating solutions.

2.2.3. Carbon capture and storage (CCS)

Large-scale impacts can be vital towards the decarbonisation of energy and with the current use of burning fossil fuels in power generation and industrial processes, it is vital to have solutions that explore and implement carbon capture technologies for high-emission industries and larger buildings. In the UK, the Carbon Capture and Storage (CCS) technology (National Grid, 2023) is designed to capture carbon dioxide (CO2) emissions preventing it from being released into the atmosphere where it contributes to climate change. The captured CO2 is then transported to a storage site, typically deep underground, where it is securely stored to prevent it from re-entering the atmosphere. Effectively, this suggests that CCS has the potential to play a significant role in contributing towards solutions in reducing greenhouse gas emissions and mitigating climate change, particularly in industries and sectors where it is difficult to decarbonise through other means (Sandunika et al., 2023). However, CCS technologies are still relatively expensive and face technical, economic, and regulatory challenges that need to be addressed to realise their full potential as a climate mitigation strategy.

2.2.4. Smart grids and demand response

Smart grids and demand response are complementary technologies that work together with other aspects to optimise the operation of electricity networks, reduce energy costs, and enhance grid reliability and resilience. Through the review of solutions towards supporting the low-carbon energy future given by Cruz et al. (2018) and Koirala et al. (2018) on community energy storage (CES) as a potential solution for sustainable energy systems, both studies indicates that by

empowering consumers to participate actively in energy management and facilitating the integration of renewable energy sources, these innovations play a crucial role in transitioning towards a more sustainable and flexible energy future. Developing smart grids to optimise the distribution of electricity and accommodate fluctuations from renewable sources through solutions reviewed by Aghaei and Alizadeh, 2013 along with the implementation of demand response programs to encourage users to adjust their energy consumption based on grid conditions and renewable energy availability. While smart grids and demand response (DR) offer significant benefits for enhancing the efficiency and resilience of electricity systems, they also face several limitations and challenges. This includes the requirement of substantial upfront investment in infrastructure upgrades, including advanced metering systems, sensors, communication networks, and grid automation equipment. Limited funding or regulatory barriers may hinder the widespread adoption of smart grid solutions, particularly in regions with ageing infrastructure (Norouzi et al., 2022). In addition, there is lack of standardised protocols and interoperable technologies can impede the seamless integration of different smart grid components and systems. Incompatible communication protocols and vendor-specific solutions may hinder data exchange, interoperability, and system scalability. This also can lead to a reduction in reliability and resilience, giving new risks that include vulnerabilities, such as equipment failures, communication outages, and interoperability issues that suggest that improved regulations to new smart grid designs that address challenges in policy changes are required. Currently, addressing these limitations and challenges will require coordinated efforts from policymakers, regulators, utilities, technology providers, and consumers to unlock the full potential of smart grids and demand response in building a more efficient, reliable, and sustainable energy future.

2.2.5. Public awareness, engagement with financial incentives and support

Along with current limitations and challenges as addressed above, other factors include public awareness and engagement, coupled with financial incentives and support, which are crucial components of successful energy decarbonisation to lead to improvements in terms of public awareness and engagement (Demski, 2021). Educating the public about the importance of reducing carbon emissions from buildings and the benefits of energy efficiency through encouraging individuals and businesses can assist towards the adoption of more sustainable practices and technologies in buildings. Furthermore, the provision of financial incentives, grants, and subsidies to promote the adoption of low-carbon technologies and energy-efficient practices are beneficial through socio-economic aspects (Qadir et al., 2021). Facilitating access to financing options for building owners and developers to invest in sustainable and decarbonised solutions can empower individuals, communities, and policymakers to take meaningful action, drive market transformation, and accelerate the transition to a sustainable, low-carbon energy future.

2.2.6. Research and Innovation

Research and innovation play a pivotal role in driving energy decarbonisation efforts by developing and advancing new technologies, processes, and solutions to reduce greenhouse gas emissions and transition to a sustainable energy system. Investing in research and development to explore new technologies and solutions requires technology development. Based on Schot and Steinmueller's study (Schot and Steinmueller, 2018), research and innovation drive the development of novel technological solutions that contribute to enhancing energy efficiency across various sectors, including industry, transportation, and buildings. Through advancements in materials science, engineering, and process optimisation, researchers develop energy-efficient technologies and practices that reduce energy consumption, lower operating costs, and minimise greenhouse gas emissions. It also has a reduction in costs, while also providing scientific evidence, data-driven insights, and technological solutions to inform policymakers and support evidence-based decision-making. By demonstrating the feasibility, benefits, and potential impacts of clean energy policies and regulations, research and innovation help build political consensus, shape policy agendas, and drive ambitious climate action UK parliament, 2023 Whereby, encouraging innovation in areas such as energy storage, advanced building materials, and sustainable design practices. However, as discussed previously, similar challenges are faced within the research and innovation aspects. Yet, this should be overcome to offering promising opportunities to accelerate the transition to a sustainable, low-carbon energy future.

2.3. District heating

Based on the above aspects, it indicates the most important areas that should be considered when seeking and implementing solutions towards energy decarbonisation. Influenced via various streams to enable efficient and environmentally friendly solutions for providing heat to communities and based on the growing emphasis on sustainability and reducing carbon emissions, district heating is a form of energy system that could evolve and expand in the future, including in 2024 and beyond.

2.3.1. Overview

District heating systems can be more energy-efficient than individual systems. Centralised facilities often use combined heat and power (CHP) plants that simultaneously generate electricity and heat, increasing overall energy efficiency compared to separate power and heating systems. These systems are often designed with redundancy and backup options, enhancing reliability, which is particularly important in extreme weather conditions or during peak demand periods when individual systems might struggle to meet the demand, indicating their reliability and resilience to cope with changes (IEA, 2024).

CHP plants used in district heating can utilise a mix of energy sources, including renewable and low-carbon options, to reduce environmental impacts. This reduces greenhouse gas emissions compared to individual heating systems, especially if the centralised facility incorporates sustainable energy sources. Advancements in technology and infrastructure lead to improved energy efficiency in the expansion of district heating networks to cover larger regions IEA, 2024; Reda et al., (2021). Additionally, there are trends towards decentralising district heating networks through smaller-scale systems serving localised areas or individual buildings. This approach can increase resilience, reduce transmission losses, and allow for more flexibility in integrating diverse energy sources. According to Hepple et al. (2023a), continuous advancements in district heating have been made through smart controls, advanced heat pumps, and better insulation to minimise heat losses during distribution. Moreover, some systems now use heat recovery methods to reutilise what was otherwise considered waste heat, such as industrial waste heat or excess heat from power generation. This helps to utilise resources that might otherwise go to waste.

Other solutions include integrating energy storage technologies, such as large-scale batteries or thermal storage systems. Reviews by Odoi-Yorke et al. (2023) and (Hepple et al., 2023b) on the optimisation of thermal energy storage systems and (Sifnaios et al., 2023; Odoi-Yorke et al., 2023) on the impact of energy storage systems suggest the potential of using energy storage systems with district heating as a valuable strategy, enhancing the flexibility and reliability of district heating networks. These solutions help manage fluctuations in energy supply and demand, optimising system performance.

District heating can also contribute to more efficient urban planning by eliminating the need for individual heating units in every building, leading to more aesthetically pleasing and streamlined architecture, and potentially freeing up space for other uses (Sifnaios et al., 2023). The IEA advances the incorporation of digital technology and data analytics to enable smarter, more adaptive district heating grids (IEA., 2021). Strategies such as predictive maintenance (Lygnerud et al., 2023), demand forecasting (Pourbozorgi Langroudi et al., 2021a), and dynamic pricing mechanisms (Pourbozorgi Langroudi et al., 2021a) can all contribute to more efficient operation and better service delivery. While enhancing district heating systems typically involves substantial infrastructure investments, they offer long-term planning benefits, providing a stable and consistent heat supply over many years. This can be attractive for urban planners and developers looking for sustainable and future-proof solutions.

Such analysis suggests that district heating is likely to remain a key component of sustainable energy systems in the future, playing a crucial role in reducing carbon emissions, enhancing energy security, and promoting local economic development. The specific trajectory of development will depend on various factors, including technological innovation, policy frameworks, and market dynamics. Public-private partnerships and innovative financing mechanisms may also play a significant role in supporting infrastructure development (Saloux and Candanedo, 2018). Therefore, to drive greater advancement in the use of district heating, government policies and financial incentives that promote clean energy and reduce greenhouse gas emissions are crucial for continuing the expansion of district heating systems.

Overall, the current advancements in district heating and cooling systems focus on sustainability, efficiency, and the integration of multiple energy sources, with the latest 5th generation emphasising these aspects. The following sections explore existing research developments within the use of district heating in the United Kingdom, focusing on the advancement of technologies incorporated into current district heating systems and the identification of opportunities for potential enhancements.

2.3.2. District heating in the UK

In recent years, there has been a growing recognition of the potential benefits of district heating, including increased energy efficiency, reduced carbon emissions, and improved resilience to energy supply disruptions. District heating in the UK has been gaining traction as a sustainable solution for heating homes and buildings. Currently, district heating schemes supply around 2 % of the UK's heat. But it is estimated that 50 % of buildings in the UK are located in areas that have suitable density for heat networks, indicating the potential for a far greater impact (Li et al., 2019). Hence, the government has set ambitious targets to decarbonise the heating sector, and district heating is seen as a key part of the solution.

The International Energy Agency (IEA) Technology Collaboration Programme on District Heating and Cooling (GOV.UK, 2021c) provides a platform for international cooperation and knowledge sharing in this field. It aims to facilitate the deployment of district heating and cooling systems worldwide by promoting best practices, supporting research and development, and addressing technical and policy challenges. In alignment with this programme, the UK's government has put efforts in district heating to align with the goals of the IEA programme, as both focus on promoting the adoption of efficient and sustainable heating and cooling systems. Through the participation of this programme, UK benefits from international expertise and experience, access to cutting-edge technologies and innovations, along with assistance in accelerating its deployment and maximise its benefits with opportunities for collaboration with other countries facing similar challenges. Furthermore, it elaborates UK policies and initiatives aiming to promote the development of district heating networks across the country.

Through such influence of the UK government guidance on Heat Networks (Veolia UK, 2024; IEA., 2024) provides information, guidelines, regulations, and other resources related to the planning, implementation, and management of heat networks in the country. It covers aspects such as energy efficiency, environmental impact, regulatory requirements, and best practices for the development and operation of heat networks. Hence, it has been effectively used within the government's Heat Network Transformation Programme (HNTP) through working with industry and local authorities and investing in funds and programmes to develop new heat networks and improve existing ones. This suggests that district heating and networks are popular within the UK and there is continuous regulation that involves compliance with standards and guidelines to ensure the safety, reliability, and efficiency of these systems, contributing to the goal of improving energy efficiency, reducing carbon emissions, and enhancing the resilience of the UK's heating infrastructure. However, while district heating systems across the UK share the fundamental concept of centralised heat distribution, they can vary significantly in terms of scale, heat generation sources, ownership models, and regulatory frameworks. The following section explores existing district heating network and systems currently present across the UK, identifying the scale and coverage, the process of heat generation applied, the system operations and also the energy performance of each system.

District heating systems in the UK vary in size, complexity, and source of heat generation, but they generally operate by distributing heat from a central source through a network of insulated pipes to provide heating and hot water to multiple buildings (GOV.UK, 2016). Distinctively across the UK, there are large-scale urban networks and smaller-scale local systems. The large-scale urban networks serves the densely populated urban areas and can consist of extensive networks of pipes connecting numerous buildings. Examples include the district heating network currently present within large cities including the Citigen in London E.On, the Manchester Civic Quarter Heat Network [72], and the Birmingham District Energy Scheme (Birmingham District Energy, 2021) varies in sizes based on its desired purposes. Smaller-scale local systems are located across the UK and serve smaller communities, industrial estates, or individual developments. These systems may be more localised and serve a limited number of buildings. Variations also depend on the adopted type of heat generation. Many of these utilise CHP plants, which simultaneously generate electricity and heat. These plants can use various fuels, including natural gas, biomass, or waste heat from industrial processes. For instance, the district heating scheme in Nottingham Enviroenergy District Energy,) utilises a waste heat recovery approach that captures waste heat from industrial processes or power generation facilities and redistributes it through the network, reducing waste and improving energy efficiency. Furthermore, some build upon the concept with a growing emphasis on integrating renewable energy sources such as biomass, geothermal, solar thermal, and heat pumps into district heating systems to reduce carbon emissions and reliance on fossil fuels.

Variations to district heating schemes across the UK are dependent upon its type of ownership and management. Some district heating networks are owned and managed by local authorities or municipal entities, while others may be operated by private companies under contract (Veolia UK, 2024). Whereby this also leads to the incorporation of private investors and energy companies in developing and operating district heating networks, either independently or through public-private partnerships. Overall, while district heating systems across the UK share the fundamental concept of centralised heat distribution, they can vary significantly in terms of scale, heat generation sources, ownership models, and regulatory frameworks. However, they all contribute to the goal of improving energy efficiency, reducing carbon emissions, and enhancing the resilience of the UK's heating infrastructure.

Across the UK, district heating (Heat Networks) has been particularly attractive across built-up areas including city regions with vast amounts of new build developments and campuses, and for some rural off-gas grid communities areas (GOV.GOV.UK Heat Networks Zoning Social Research Final report report, 2022).

Tables 1–9 presents a summary of the most popular heat networks across the UK with the identification of the type of heat generation adopted via district heating, the ownership and management, the

Table 1
Summary of the district heating network in London [E.On,].

Location:	London	
District Heating Network	Citigen	
Features:	Largest urban heating & cooling tri-generation plant in London Consists of the Citigen London CHP plant	
Coverage:	Primarily serves the area around the Barbican Estate and the Golden Lane Estate in the City of London.	
Supply:	Heating	Hot water
Building Type:	Residential	Commercial
Limitations:	Specified location Dependent upon a centralised system	High initial costs Limited flexibility for individual consumers
Project Challenges	Plant/ site situated inside two irregular multi-level buildings, of which the Central Cold Store is a grade II listed building.	Site logistics with on-going internal demolition works, refurbishment & construction.
Future Projections:	Expansion/ development	Larger coverage

Table 2
Summary of the district heating network in Birmingham (Birmingham District Energy, 2021).

Location:	Birmingham
District Heating Network	Birmingham City Council's District Energy Scheme (BDEC) 2003 EQUANS and Birmingham City Council
Features:	3 district energy network schemes 1. CHP in Broad Street (Trigeneration – heat, power and cooling) 2. Aston University CHP Schemes 3. Birmingham Children's Hospital (heat and power)
Coverage:	Birmingham city centre and adjacent areas: Train station International airport Libraries Recreational centres
Supply:	Heating & cooling Hot water
Temperatures:	100°C/60°C Hot water flow/return temperatures
Building Type:	Residential Commercial
Electricity:	Electricity supplies synchronised with the National Grid
Limitations:	0.5°C temperature loss per km of pipe
Project Challenges	Partnership between EQUANS and Birmingham City Council
Future Projections:	Key development on residential/ mixed-use developments, educations institutions, hospital.

Table 3
Summary of the district heating network in Manchester (⟨Vitalenergi.co.uk⟩, 2024).

Location:	Manchester
District Heating Network	Manchester Civic Quarter Heat Network (CQHN) Manchester City Council
Features:	Supply to specific buildings within the city centre with a centralised heating system
Coverage:	Specific buildings: Manchester Town Hall Central Library Manchester Central Convention Centre The Bridgewater Hall Heron House Manchester Art Gallery
Supply:	Heating Electricity
Future Projections:	Coverage may be extended to a larger region

Table 4
Summary of the district heating network in Salford, Greater Manchester (Vital Energi, 2024a).

Location:	Salford, Greater Manchester
District Heating Network	Salford MediaCityUK MediaCityUK - Trigeneration Scheme Landsec and The Peel Group (MediaCityUK)
Features:	Centralised designated area
Coverage:	Office spaces, television studios, residential buildings, retail outlets, hotels, and leisure facilities.
Supply:	Heating & cooling Electricity

Table 5
Summary of the district heating network in Oldham, Greater Manchester (Heat Networks, 2023).

Location:	Oldham, Greater Manchester
District Heating Network	St Marys Heat Network (Oldham) Town Centre Minewater District Heat Network Oldham Council
Features:	Use heat reclaimed from the floodwater in disused coal mines underneath the Town Centre
Coverage:	Oldham Town Centre Town Centre buildings, including heritage buildings Old Library and the Performance Space, other Council, and residential sites.
Supply:	Heating Hot water
Project Challenges	Location - extensive network of disused coal mines underneath the town centre.
Future Projections:	Working with First Choice Homes to explore the potential of linking the heat network with the existing heat network at St Mary's social homes.

features of each network, along the identification of the benefits and limitations of each system and network to seek the potential areas for improvement and developments.

Based on the current systems in place across the UK, including those established over 40 years ago and newly built ones, it is evident that all systems have benefits related to their specific features, designated sites, locations, applications, and usages. However, they all share common limitations and challenges. These include the need to adopt and identify ways to enhance performance and efficiency, as well as exploring possibilities for greater coverage to enable widespread adoption of district heating within the UK. Additional challenges faced by these heating networks include high upfront investment costs, the need for continuous coordination among different stakeholders, and addressing technical and regulatory hurdles throughout the system's process.

To resolve these issues, various methods should be explored, and assessment methods identified to evaluate these existing systems. Therefore, by identifying the issues related to general building energy decarbonisation within the UK and examining various district heating schemes, this study combines both aspects to investigate a suitable assessment method for reviewing and assessing existing energy schemes within the UK.

3. Summary

There are a range of assessment methods available that are ideally suited for evaluating the performance of existing district heating systems and networks. These include tools like energy management systems (EMS), which are software-based tools used to monitor, control, and optimise the operation of district heating systems. EMS collect data on energy consumption, production, and distribution, allowing operators to analyse performance and identify areas for improvement.

Other methods include simulation techniques to assess the behaviour of district heating systems under different conditions. By inputting parameters such as weather data, building characteristics, and equipment performance, engineers can evaluate system performance and identify potential optimisation strategies. Additionally, the installation of flow meters and sensors throughout the district heating network can measure parameters such as flow rates, temperatures, and pressures. This data is

Table 6
Summary of the district heating network in Glasgow (invest-glasgow.foleon.com, 2024).

Location:	Glasgow
District Heating Network	Glasgow City Council and associated stakeholders Joint partnership between Viridor and Glasgow City Council (GCC)
Features:	Currently has 8 district heat networks – current & ongoing (2023 – 2030)
Coverage & Supply:	Glasgow City Council District Heating Network -High-density buildings -Heating, Hot water Hillpark Energy Centre -Social Housing properties -Heating, Hot water -Biomass boilers and gas-fired boilers to generate heat East End Energy Centre -Dalmarnock area -Residential and commercial buildings -New developments, Athletes' Village (Commonwealth Games Village District Heating) -Heating, Hot water Clyde Gateway District Heating Scheme Clyde Gateway area -Utilise waste heat from industrial processes and other sources -Low-carbon heating -Home businesses, and community facilities St. Vincent Street District Heating Network: -Smaller-scale scheme in Glasgow's city center -Heating, Hot water -Commercial buildings
Limitations & Project Challenges	Extracting the natural heat from the River Clyde by using water source heat pumps Using the energy from waste created at plants such as the Glasgow Recycling and Renewable Energy Centre, - drawing heat from deep geothermal wells, - tapping into the city's wastewater system, - extracting the heat found in flooded, former mine workings, - capturing waste heat from buildings such as distilleries, supermarkets, data centres, laundrettes and bakeries
Future Projections:	Currently extending the network to Polmadie and Gorbals, Glasgow City (new projects) along proposal to harness the power of the River Clyde Scheme 1: Polmadie Scheme 2: Gorbals District

Table 7
Summary of the district heating network in Sheffield (Veolia, 2024).

Location:	Sheffield
District Heating Network	Sheffield district Energy Network Sheffield City Council
Features & Coverage:	−6000 residential dwellings across the city −1000 supplied from a low carbon energy source generated from Sheffield's non-recyclable waste. −5000 dwellings are supplied from gas and biomass. -Companies, universities, hospitals, leisure facilities, households −1000 properties utilising pay-as-you-go (PAYG) energy technology. Others unmetered supply on flat rate
Supply:	Heating Hot water
Project Challenges	Upgrade of the heating systems in 6999 residential properties by 135 plant rooms
Future Projections:	AI tool to increase the heat delivery capability by 25 % Data-driven thermohydraulic modelling tool used to optimise the network pressure and temperature of the 44 km network connecting 125 commercial and public sector buildings.

Table 8
Summary of the district heating network in Southampton (2024)).

Location:	Southampton
District Heating Network	Southampton District Heating Scheme (SDES) (1986) EQUANS Southampton City Council - Southampton Geothermal Heating Company Ltd. Works through a Joint Co-operation Agreement between City Council and Cofely
Features & Coverage:	Serves buildings within 2 km radius of the energy centre One of the Largest commercially developed CHP/district energy scheme in the UK, Started 28 years ago (1986) Densely populated urban areas with a high concentration of buildings, including residential, commercial, and public facilities: -Swimming & Diving Complex -Shopping Centre -Southampton Solent University -Civic Centre—5 Hotels-Royal South Hampshire Hospital-Offices Complexes
Supply:	Heating & cooling Electricity
Limitations & Project Challenges:	1 C temperature loss per km of pipe 80c/50c hot water flow/ return temperatures
Future Projections:	New technologies being actively considered: - Biomass - Woodchip- Energy from Waste- Anaerobic Digestion- Fuel Cells

Table 9
Summary of the district heating network in Milton Keynes (ThamesWey, 2024).

Location:	Milton Keynes
District Heating Network	ThamesWey Central Milton Keynes (TCMK) ThamesWey Central Milton Keynes Ltd
Features & Coverage:	Two CHP units fuelled by natural gas Central Milton Keynes The Hub, (a development comprising hotels, apartments and offices), Vision, (a development comprising apartments, commercial outlets and a large supermarket store) and The Pinnacle (the largest office development in Milton Keynes)
Supply:	Heating & cooling Electricity
Limitations & Project Challenges:	Risks and funding -Organisational contractor capacity -Funding and inflation -Legislative changes in the residential sector -Introduction of a regulated heat market and heat zoning
Future Projections:	Supply to new residential area in the west end of Central Milton Keynes

used to assess the performance of individual components and optimise system operation, feeding into energy audits that involve site inspections, data collection, and analysis to evaluate the overall performance of district heating systems.

However, despite these ideal methods, many district heating systems in the UK run inefficiently due to insubstantial assessments. Limitations within the majority of current district heating networks include a lack of data availability and quality, challenges in integrating data from different sources, and difficulties in modelling the interactions between system elements. Therefore, there is a demand for an effective approach that can address these limitations and improve the accuracy, reliability, and usability of assessment tools for district heating systems.

One alternative method is the use of life cycle assessments (LCA) to evaluate the environmental impact of district heating systems over their entire life cycle, including construction, operation, and decommissioning. This approach helps stakeholders understand the sustainability implications of different design and operation choices. However, no studies have adopted LCA for network-based systems; instead, studies have only applied LCA to single, smaller-scale local enclosed systems, not to existing large-scale urban networks currently in use.

A comprehensive approach would combine commonly used assessment methods with data collection from site inspections and energy management systems. This data would be analysed to identify opportunities for energy savings and efficiency improvements, which would then be further assessed in terms of energy and emissions from a life cycle perspective. This approach provides a holistic view of the system, considering all stages from material use in construction to system production and utilisation. Understanding the operations of the system network allows for the assessment of environmental impacts associated with each stage of the district heating network's life cycle, including greenhouse gas emissions, energy consumption, and resource depletion. Opportunities for improving resource efficiency can be identified by minimising energy and material losses throughout the network's life cycle, leading to reduced resource consumption and lower environmental impacts.

Additionally, this approach can identify cost-saving opportunities by optimising the use of resources, reducing energy consumption, and minimising maintenance and operational costs over the network's lifespan. The assessment can support sustainability goals and regulatory requirements, providing insights into the environmental and social implications of the district heating network's operations and identifying areas for improvement. Continuous improvement can be achieved by identifying areas for optimisation and innovation throughout the district heating network's life cycle.

As this framework approach is established, it can be beneficially adopted as a guide for assessing other existing district heating network systems and schemes. This allows for the identification of energy efficiency, reliability, and sustainability, as well as potential developments and modifications that can be applied.

4. Framework approach and assessment

Based on the previous section, which identified the status, issues, and techniques used to assist the decarbonisation of building energy, along with an introductory review of district heating within the UK, the following framework approach presented in Fig. 1 is proposed. This framework outlines the areas explored in this study and the techniques applied to further assess an existing district heating network, as outlined in the aims and objectives.

The figure presents the exploration process adopted to focus on district heating and energy decarbonisation (highlighted in the bottom left, purple area). An extensive literature search was performed to identify publications on existing studies, reports, policies, and research related to building energy decarbonization in the UK. We searched peer-reviewed journals, conference papers, technical reports, and books from the last decade (with some exceptions) using the Scopus and ScienceDirect search engines. The search utilized keywords such as "energy decarbonisation in the United Kingdom," "UK energy policies," and "energy reduction strategies in the UK built environment." Articles were selected based on their titles and abstracts. Following a data collection process of identification, screening, eligibility analysis, and inclusion using the PRISMA method, research articles, review papers and reports were reviewed. Additionally, for the section on district heating within the UK, we selected reports and guides by local councils and energy companies. This provided a direct understanding of the latest status of the system and its energy impacts in the UK. Effectively, based on the process shown in the diagram, these findings suggest potential advancements in district heating networks and schemes. The following section presents the discussion and findings on this topic.

Case. Study: Nottingham

As discussed in Section 2.3, district heating networks across the United Kingdom differ in various aspects, including their methods of

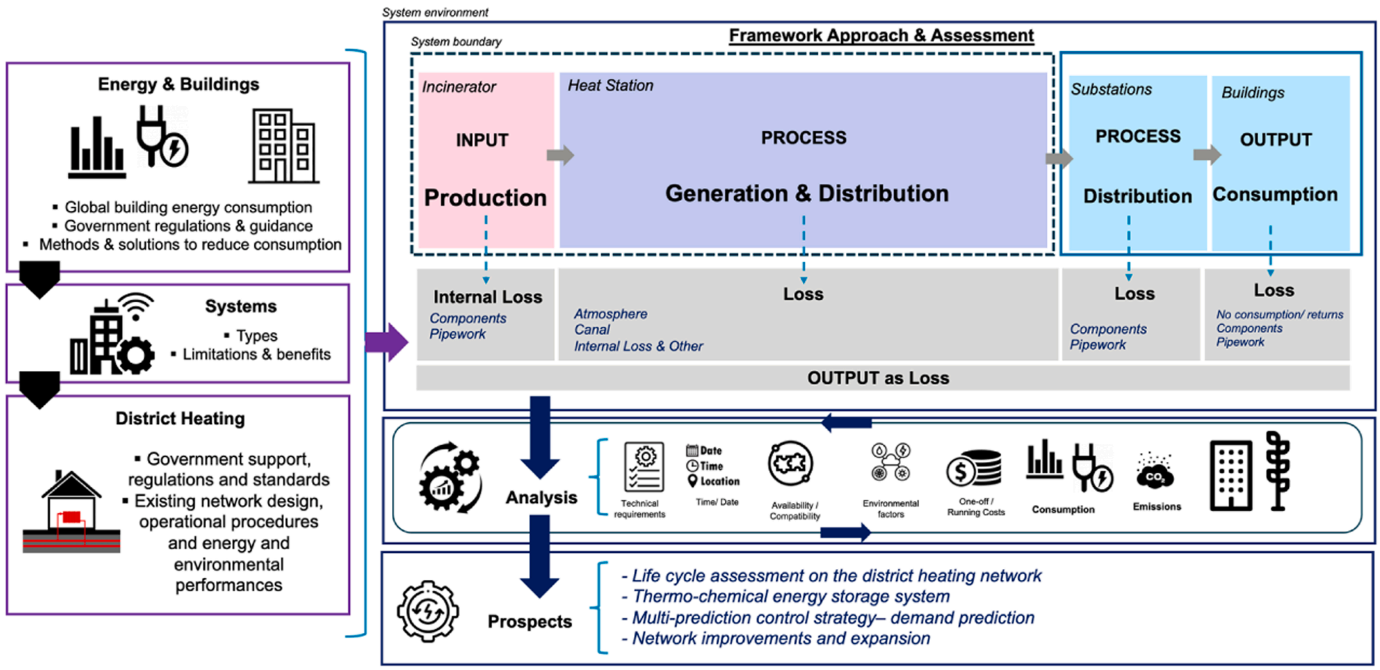

Fig. 1. Proposed review methodology and approach applied in this study.

operation, size, and the impact of their location. To apply the proposed review methodology indicated in Fig. 1, a suitable district heating network case study should be selected. An exploration of the networks shown in Tables 1–9 suggests that an in-depth review requires a comprehensive understanding of the system and its operational processes. However, few studies use case studies of UK district heating networks, possibly due to limited information and data availability. Consequently, studies such as (Bush et al., 2016; Millar et al., 2019; Energy Systems Catapult, 2014) tend to focus on the analysis and discussion of UK district heating systems as a whole, rather than on individual networks, systems, and processes. To demonstrate the feasibility of the proposed methodology for a district heating network, and with the support of the UK Engineering and Physical Sciences Research Council (EPSRC) under Grant Ref: EP/V041452/1, along with project partners Nottingham City Council and EnviroEnergy, this study focuses on the district heating schemes in Nottingham.

Nottingham is a city in the East Midlands region of England, United Kingdom. The city has a blend of medieval and modern architecture, with historical and cultural attractions. It's a city which offers a range of amenities, including shopping centres, restaurants, theatres, and parks.

In terms of buildings, Nottingham has a mix of historic architecture and modern developments. The city centre features buildings dating back centuries, such as Nottingham Castle, the Lace Market area with its former lace factories converted into trendy apartments, offices, and shops. Additionally, Nottingham boasts modern structures including shopping centres and contemporary office buildings. When it comes to population, Nottingham, England, was estimated to be around 330,000 people (Nottingham City Council, 2019) with Nottingham being in the top 10 most populated cities in the UK as compared to major cities in the UK including, London, Birmingham, Manchester, Glasgow and Leeds. Fig. 2 presents the population density across Nottingham (Census, 2021).

When it comes to energy, Nottingham is like many cities globally. Actively working to decarbonise its building energy sector through making efforts to become more sustainable and reduce its carbon footprint (Nottingham City Council, 2024, 2022). The city has implemented various initiatives to promote renewable energy, energy efficiency, and environmental conservation. This includes investments in renewable energy sources such as solar and wind power, as well as initiatives to improve energy efficiency in buildings and reduce emissions. Furthermore, Nottingham is known for its pioneering work in community energy projects, whereby the Nottingham District Heating Network is located within the city region and aims to provide affordable and sustainable energy to residents Enviroenergy District Energy,). Overall, Nottingham is actively working towards becoming a more sustainable and environmentally friendly city in terms of its energy usage and building practices.

4.1. District heating in Nottingham

District heating systems in Nottingham, England, have been an integral part of the city's efforts to reduce carbon emissions, improve energy efficiency, and provide affordable heating solutions to residents and businesses Enviroenergy District Energy i Enviroenergy,). The city has been proactive in promoting and implementing district heating schemes as part of its broader sustainability initiatives. several district heating networks in operation, serving both residential and commercial buildings. These networks utilise a centralised system to produce and distribute heat to multiple buildings within a specific area.

In Nottingham, there are two prominent district heating networks in the city. This includes the Nottingham District Heating Network located in the city centre region of Nottingham, which is operated by the Nottingham City Council and is part of the district heating project in Nottingham under scheme by EnviroEnergy (2024). The system utilises a combination of sources for heat generation, including biomass, natural gas, and waste-to-energy technologies. This diversified approach helps to enhance resilience and reduce reliance on fossil fuels (FCC Eastcroft, 2024). The other district heating networks includes a smaller scale one located within the University of Nottingham (Jones, 2019).

4.1.1. Infrastructure, system components and process

In this study, a focus is given to the Nottingham District Heating Network (Eastcroft, 2024). The Nottingham District Heating Scheme was established in 1972 under a 60-year agreement between the City Corporation and the National Coal Board. The scheme continues to be the most extensive municipal district heating network in the United Kingdom, with the incinerator currently has the license to burn up to 200,000 tonnes of municipal solid waste per year, along with 30 km of

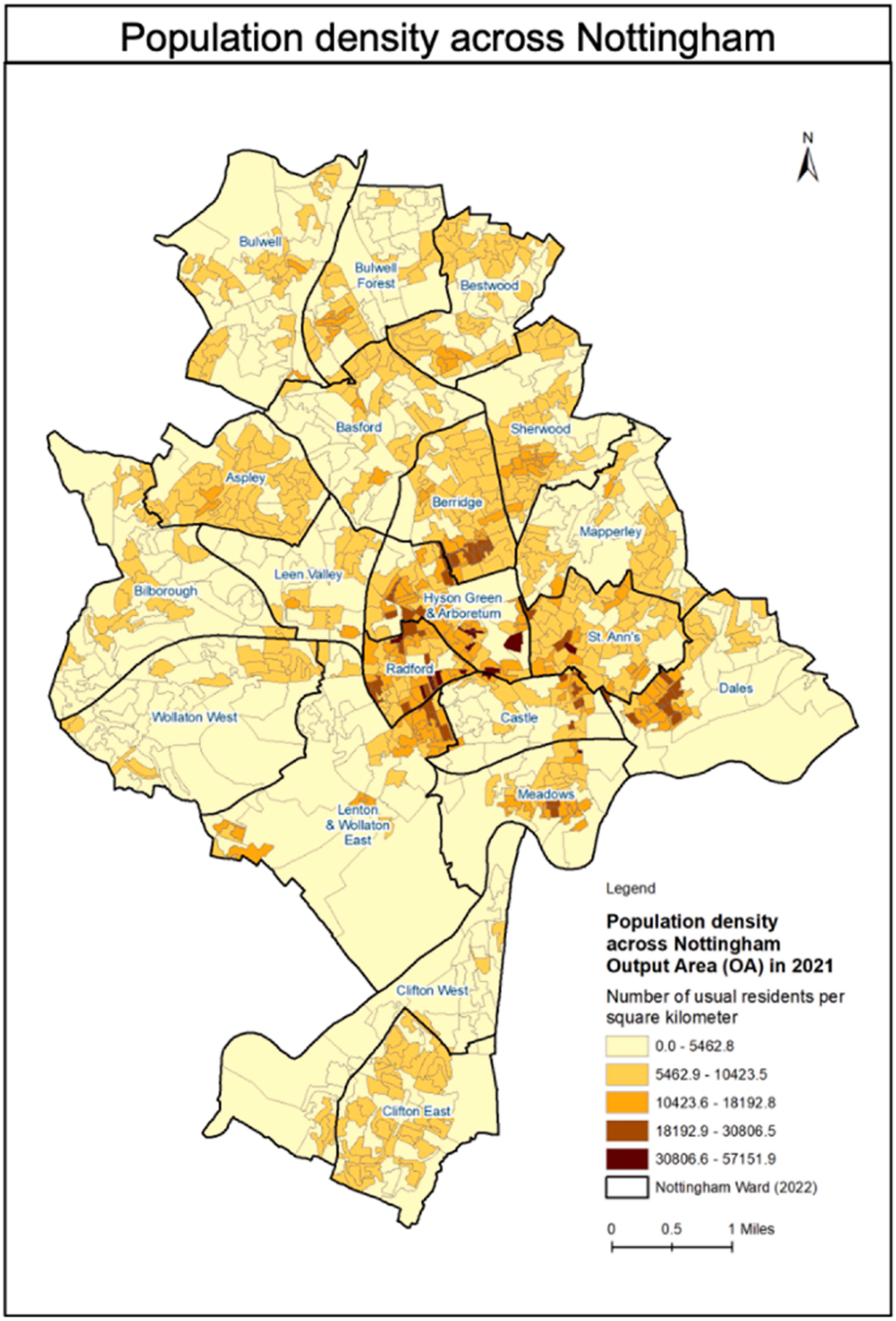

Fig. 2. Population density across Nottingham Output Area (OA) in 2021 (Bush et al., 2016).

distribution pipework to serving over 4500 residential consumers and around 120 non-domestic public and private heat consumers. Currently, the Nottingham City Council (NCC) owns all the assets involved in the scheme. It has a contract with FCC Environment for the operation of Eastcroft Incinerator (FCC Eastcroft, 2024). Under this contract, NCC delivers municipal waste to FCC, paying a reduced gate fee. It delivers non-hazardous waste from households and businesses within Nottingham and the wider county for treatment by high-temperature incineration and energy recovery at East Croft Incinerator. Residual waste is brought to the facility after recyclable materials have been separated out either at home, household waste recycling centres or other waste recycling and treatment facilities. Heat energy recovery applied reduces vast amounts of waste sent to landfills with the energy recovery process generates steam that is supplied to Enviroenergy Limited through pipelines. Therefore, at the London Road Heat Station (LRHS) steam is purchased from FCC by NCC (which then seeks to recover the cost from Enviroenergy) as an annual Steam Charge. The Steam Charge corresponds to FCC's relevant annual operating costs Enviroenergy District Energy,.

The site is bounded by the main London Road, Canal Street and the Beeston to Nottingham Canal. The installation is known as the London Road Heat Station (LRHS) and stands adjacent to London Road. As given in Fig. 3, the network consists of three main stages. The incinerator is the location where energy production from waste takes place. While the

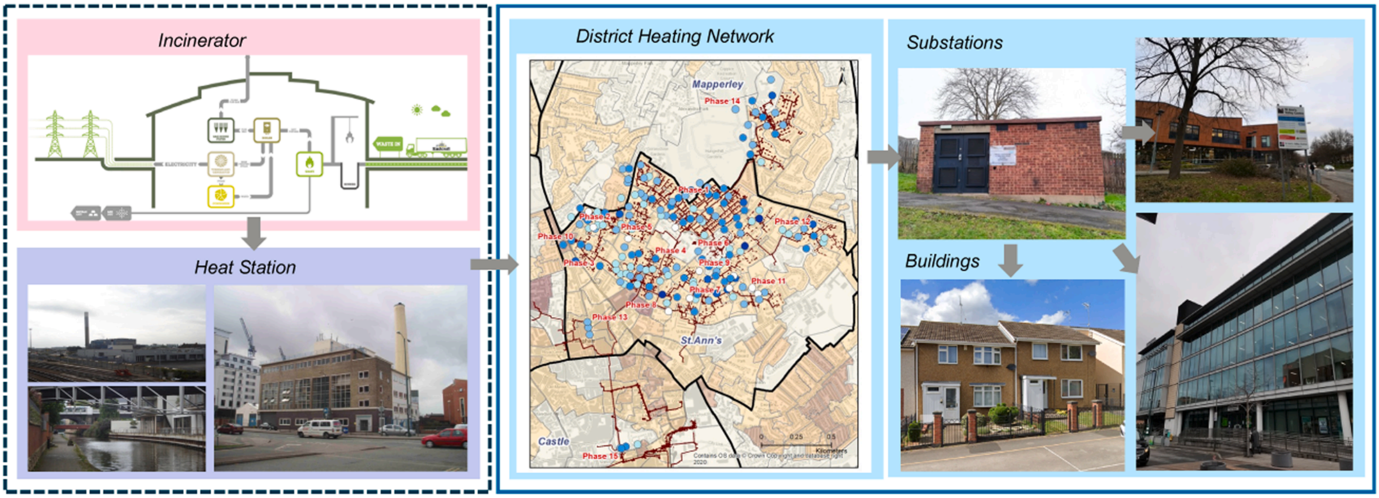

Fig. 3. Heat generation and distribution across the Nottingham District Heating Network.

heat station is the distribution network. In its original form, the principal source of heat for the scheme is high-pressure steam, that is generated from the Eastcroft Incinerator (1). Eastcroft raises steam at a pressure of 30 bar g and 385°C. There are currently two incinerator lines at Eastcroft, each rated at 26 tonnes per hour of steam, i.e. a total of 52 tonnes/hour. The energy from waste provides around 310,000MWh of high-pressure steam at 380°C and 24 bar to Enviroenergy. Whereby, it is then sent to the London Road Heating Station (2 - LRHS) where it is used to generate heat and electricity through an extraction condensing steam turbine, this is a form of combined heat and power (CHP). The turbine can modulate the quantity of steam that is extracted from the turbine for district heating (thereby reducing the electrical output), using an extraction valve. The output from the incinerator was given after generation and was then either used for district heating or rejected via the air-cooled dump condensers. London Road in turn supplies feed water back to Eastcroft for use as boiler feed water. Electricity is generated as a form from the excess steam which powers the London Road Heat Station and is also supplied to nearby local buildings within the Nottingham City area (FCC Eastcroft, 2024).

In addition, there is backup capacity for the district heating which is currently provided by two gas-fired steam boilers sited at the LRHS site. They supply saturated steam to the district heating system via pressure-reducing valves. These boilers are for heating only and are not capable of generating electricity via the steam turbine if the incinerator is out of action. Two small coil boilers are also available for backup for limited periods. One further source of heat for the scheme is the heat recovery circuit; utilising high-temperature hot water, produced at the Eastcroft complex using heat recovery economisers, and feeding back to the Direct Contact Heaters supplying the district heating mains. Enviroenergy has a separate hot water contract to buy this energy which feeds directly into the District Heating Water at London Road.

According to Vital Energi (Vital Energi, 2024b), due to the long establishment of the heating network and the success it has over time, it has become a "role model'" and has been toured by organisations and departments such as the Green Investment Bank, the Department of Energy and Climate Change (DECC) and the Department for Business, Innovation and Skills (BIS). However, through the investigation of the scheme's potential development and plans, it aims to revert and form a heat recovery system by taking energy from flue gases and to also evaluate the relocation of the London Road Heat Station adjacent to the incinerator to align with FCC's future plans. Effectively, based on the aim of this paper and the objectives set, it will feed as initial insights towards the feasibility of this development plan based on the investigation of the district heating network.

4.1.2. Network Connectivity and Distribution

The following presents the exploration of the network distribution of the heat energy scheme. The primary district heating network is extensive, covering a linear distance of around 6500 m, some are directly buried (pre-insulated), some are located in tunnels (post-insulated mineral wool insulation) and some are located in purpose-built ducts (post-insulated). As presented in Fig. 4, substations from the London Road Heat Station on the Nottingham District Heating Network were colour-coded and classified into 12 different categories. Located within specific areas across the network, each of these 42 substations was categorised based on its location and the usage of each of the buildings connected to the substation in each of these areas. Each substation outreaches to various commercial buildings and residential buildings within housing estates on both the Northside and Southside of the heat station that covers areas including the Nottingham City Centre, St Ann's and Snienton.

Table 10 presents further details of each substation. Based on the colour classification and the area coded in Fig. 4, associated details were highlighted in this table. Furthermore, descriptions on the type of substation and the connected buildings were also given. For example. Areas within the "red" colour region were located within St Anns, Nottingham and it was named as a housing area, due to all buildings located in the area being mostly residential buildings, schools and community centres. Whereas the 'purple' area was classified as the area where all buildings were part of the Nottingham Trent University City Campus. Such identification of the associated building types in each area would therefore reflect upon the energy demand and usage within each area, indicating more understanding towards the operations of heat energy within the district heating network.

Taking the area of St Anns, Nottingham encased within the area labelled as 'Housing Area (St Anns)' in Table 10 and Fig. 4. This is one of the residential area in Nottingham that is majority served by the Nottingham District Heating Network through the provision of heat and hot water to around 5000 homes (Open Data Communities, 2024). Most houses located within this region are Terraced House with an average 4 rating of C/D with a tenancy of 'Mostly- Rented (Social)'. Based on such information and the understanding of the types of residential and commercial buildings connected within this region, if further details can be provided by the Nottingham City Council along with existing data such as those provided by the UK Government, Energy Performance of Buildings Data for England and Wales (Vital Energi, 2024b) on building property details and description (building material U-Values etc.) the energy performance of each building can be predicted which can be used to monitor the actual energy demand required through a comparison with the actual energy consumption by these buildings, resulting

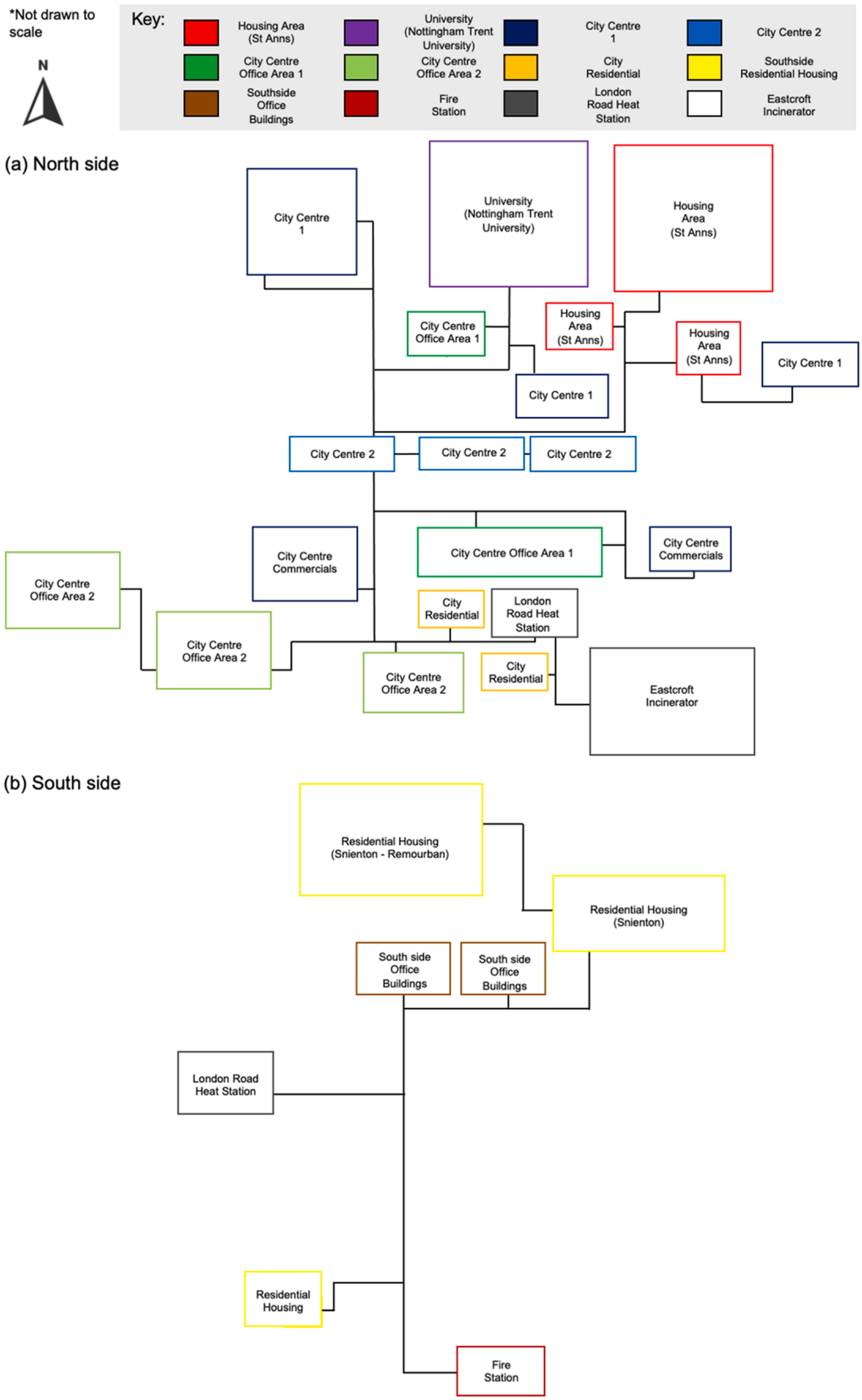

Fig. 4. Schematic diagram of the Nottingham District Heating Network (not drawn to scale).

Table 10
Description of the substations connected to the Nottingham District Heating Network Scheme.

Area	Colour	Assigned colour code	Substation/ Plant room		Connected building types
			Name	Type/ Description	
Region: North side					
Housing Area (St Ann's)			Phase 1	Primary	- Residential - Community centre - School
			Phase 2	Primary	- Residential -Phase 2 MHT substation - Community Centre - Residential Complex
			Phase 3 & 4 / 10	Primary	- Residential - Community Centre - Residential complex x3 - School Hostel
			Phase 5	Primary	- Residential - School - Residential Complex x2
			Phase 6	Primary	- Residential - School - Residential Complex
			Phase 7, 8, 9, 11	Primary	- School - Residential Complex x4
University (Nottingham Trent University City Campus)			S.H.S. (Barnes Wallis Building)	Primary	- S.H.S. (Barnes Wallis Building) Teaching/ Seminar Building)
			Byron	Primary	- Byron Residence Building
			Bonington	Primary	- Bonington Gallery multi-services/ facility building (Gallery space, café, art shop, teaching/ meeting rooms and studio space)
			Dryden Centre	Primary	- Dryden Enterprise Centre (Office and workspace building)
			Maudslay	Primary	- Maudslay Building (Teaching/ seminar building)
			Newton	Primary	- Newton Building (Teaching/ seminar and social space)
City Centre 2			Victoria Residential	Primary	- Nottingham's Victoria Centre flats
			Victoria Commercial	Primary	- Nottingham Victoria Centre (shopping centre)
			Hilton Hotel	Secondary	- Hilton Hotel Nottingham
City Centre 1			Victoria Baths	Primary	- Victoria Leisure Centre - Nottingham
			YMCA	Primary	- YMCA housing
			VAC (Voluntary Action Centre)	Primary	- Nottingham Community and Voluntary Service (NCVS) Centre
			Royal Concert	Primary	- Theatre Royal & Royal Concert Hall Nottingham
City Centre Commercials			Theatre Royal	Primary	
			CAN	Primary	- Nottingham Contemporary

(continued on next page)

Table 10 (*continued*)

			Ice Stadium	Primary	- National Ice Stadium
			Broadmarsh Centre	Primary	- Broadmarsh Shopping Centre
City Centre Offices 1			E.On	Primary	- E.On office building
			Council House	Primary	- Nottingham Council House, Loxley House (Office building)
			Stoney Street	Primary	- Offices
			Skills Hub	Primary	- Nottingham College City Hub
City Centre Offices 2			Capital One	Primary	- Capital One office building
			Capital One Site One	Primary	- Capital One office building
			Magistrates & Bridewell	Primary	- Nottingham Justice Centre (Nottingham Magistrates' Court)
			Archives	Primary	- Nottinghamshire Archives (records storage facility)
			Inland Revenue	Primary	- HM Revenue & Customs (Nottingham inland revenue tax office building)
City Residential			Canal Street Development	Primary	- Residential buildings (flats) on Canal Street, Nottingham
			Jury's Inn	Supplied by Heat recovery plant room	- Leonardo Hotel Nottingham - Formerly Jurys Inn
Eastcroft			E. Croft Depot		Eastcroft Incinerator
			E. Croft H. Recovery Plant Room		
			E. Croft Clinical Waste		
Region: South Side					
Southside residential housing			Remourban	Primary	Residential buildings
			Bentink & Manvers	Primary	Bentinck, Manvers and Kingston Court tower blocks (flats)
			Bentink	Secondary	
			Manvers	Secondary	
			Kingston	Primary	
			Kingston	Secondary	
			Laceworks	Primary	The laceworks student accommodation
Southside office buildings			BioCity Science	Primary	BioCity Nottingham (laboratory and office space)
			BioCity Innovation	Primary	
			BioCity S. Adams	Primary	
			BioCity Laurus	Primary	
Fire Station			Fire Station	Primary	Nottingham Fire Station

towards a solution towards minimising energy wastage within such district heating network. In addition, this can also result towards a better understanding of the exact number of houses connected to the network as according to the Nottingham City Council, the exact number of houses connected to the network in the region is unknown.

4.1.3. Location and Energy Distribution

To provide an understanding of the distribution of population density, domestic energy consumption, the energy usage type within the central region of the City of Nottingham and specifically on the area within the district heating network, data from Census 2021 at the most granular Output Area (OA) level were obtained and analysed. OA level data were converted to analyse at postcode level across the district heating network residential areas to help identify potential factors for further analysis through postcode level mapping and data analysis. Table 11 describes the data type obtained from Census 2021 to conduct such analysis.

As indicated, Nottingham has 1006 OAs, this indicates that each OA comprises 40-250 households or resident population of 100-625 persons. Through such information, Fig. 5 presents the results from postcode level mapping indicating the coverage of households that utilises district heating and the indication of the Nottingham District Heating Network with the pipeline marked in red (right). Through such comparison, it shows the region in which Nottingham District Heating Network serves and the high percentage in which it covers across the City of Nottingham, specifically in the St Anns region.

Fig. 6 comparatively shows the population density across the Nottingham AO area with the district heating coverage. Results indicate that the St Ann's region not only has a high percentage of households with district heating but also reflects upon the high population density. Through the mapping of the Nottingham District Heating Network pipeline on these figures, it suggests that the operation of the district heating network must be effective in order to assist the decarbonisation of building energy across Nottingham.

Table 11
Description of the data type obtained from Census 2021 on domestic energy consumption, population density and district heating.

Data	Data level	Data information
Nottingham DHN residential addresses	Address (converted to postcode)	• "Property info" excel file: a list of the 5207 residential addresses in the 15 Phases of Nottingham District Heating Network (DHN), with data on their house number, street, postcode, and phase. • 186 unique postcodes are found from the residential addresses, with missing and/or inaccurate postcodes and phase information updated/fixed.
Annual total domestic energy consumption	Postcode	• Total domestic energy consumption (kWh): total domestic gas consumption + total domestic electricity consumption. • 2021 data from GOV.UK: domestic gas consumption data from mid-May 2021 to mid-May 2022 (GOV.UK, 2021a); domestic electricity consumption data from Febuary 2021 to January 2022 (GOV.UK, 2021b). • Missing data: 14 of the 186 postcodes are missing total domestic energy consumption data (i.e., missing both gas and electricity data), with 99 postcodes missing gas data and 15 postcodes missing electricity data.
Population density	Output Area (converted to postcode)	• Population density from Census 2021 data (GOV.UK, 2021c): Number of usual residents per square kilometre. • In Nottingham, there are 1006 Output Areas (OAs, each OA comprises 40−250 households or resident population of 100−625 persons) according to Census 2021 geographies (Office for National Statistics, 2021).
Central heating type of district heating	Output Area (converted to postcode)	• Percentage of households with district heating as central heating type • Data from Census 2021 https://www.nomisweb.co.uk/datasets/c(2021t)s046) on type of central heating in household.

4.2. Nottingham district heating network postcode data analysis

As indicated by Table 12, the St Ann's region of the Nottingham District Heating Network covers up to 15 phases and is supplied by 6 primary substations from the London Road Heat Station. The following presents the use of Census 2021 OA postcode data as summarised in Table 11 through 186 unique postcodes listed for all 5207 residential addresses across the 15 Phases in Nottingham District Heating Network to perform further investigation into this residential area (St Anns region) into the total annual domestic energy consumption 2021, number of address within this area, the population density and the district heating network coverage of the OA the postcode.

Using such data given in Table 11, Fig. 7 indicates the annual total domestic energy consumption across the St Ann's region of Nottingham along with the population density based on the Nottingham Output Area. Although the total domestic energy consumption (gas and electricity) cannot be distinguished between the type of energy system used (whether it is from the Nottingham District Heating Scheme or not), however, it presents the distribution of the energy consumption across the different phases within the region. Through such results (population and energy consumption), the data can be further examined towards the clarification and optimisation of the required heat energy at specific areas correlated to the amount of heat energy provided through each substation in this specific area. In addition, based on the closer figure focusing on the results for Phase 1, it subsequently provides postcode data results on the annual domestic energy consumption across houses on specific streets in this area. This area covers 17 unique postcodes and varies in the number of houses per postcodes. Generally, the greater number of houses located within one postcode results in a higher energy consumption value.

Based on the residential area that covers the region where all 15 Phases in the St Ann's region are located within the Nottingham District Heating Network Scheme, Fig. 8 presents a graph plot comparing the annual total domestic energy consumption (gas and electricity) with the number of addresses per postcode in each phase, along with the population density and the predicted percentage of household connected with the district heating network. Results indicate that as the population across the area does not have a high correlation with the energy consumption. Similarly to the previous data results, the number of addresses per postcode does have positive correlation with the total energy consumption. Furthermore, the amount of household with district heating remains to have little/ no correlation with the energy consumption. This effectively, shows the influence of the district heating network scheme being implemented and established for a long time, indicating no impact between the type of energy system used with the amount of energy consumed.

4.3. Performance metrics on energy demand and supply

The previous section utilised postcode data and heat mapping to provide an insightful analysis of the District Heating Network across Nottingham, indicating domestic energy consumption in the region. However, district heating-specific consumption and commercial buildings were not explored. This omission points to the need for a deeper investigation into the network scheme through advanced data analysis and a thorough examination of energy flow within the system. Understanding these dynamics is critical for optimising the performance of the district heating network and ensuring it meets both current and future energy demands effectively.

Performance metrics are vital tools for assessing the efficiency and effectiveness of the district heating network. These metrics, which may include energy efficiency ratios, thermal losses, and system reliability indices, provide quantifiable data that help stakeholders understand

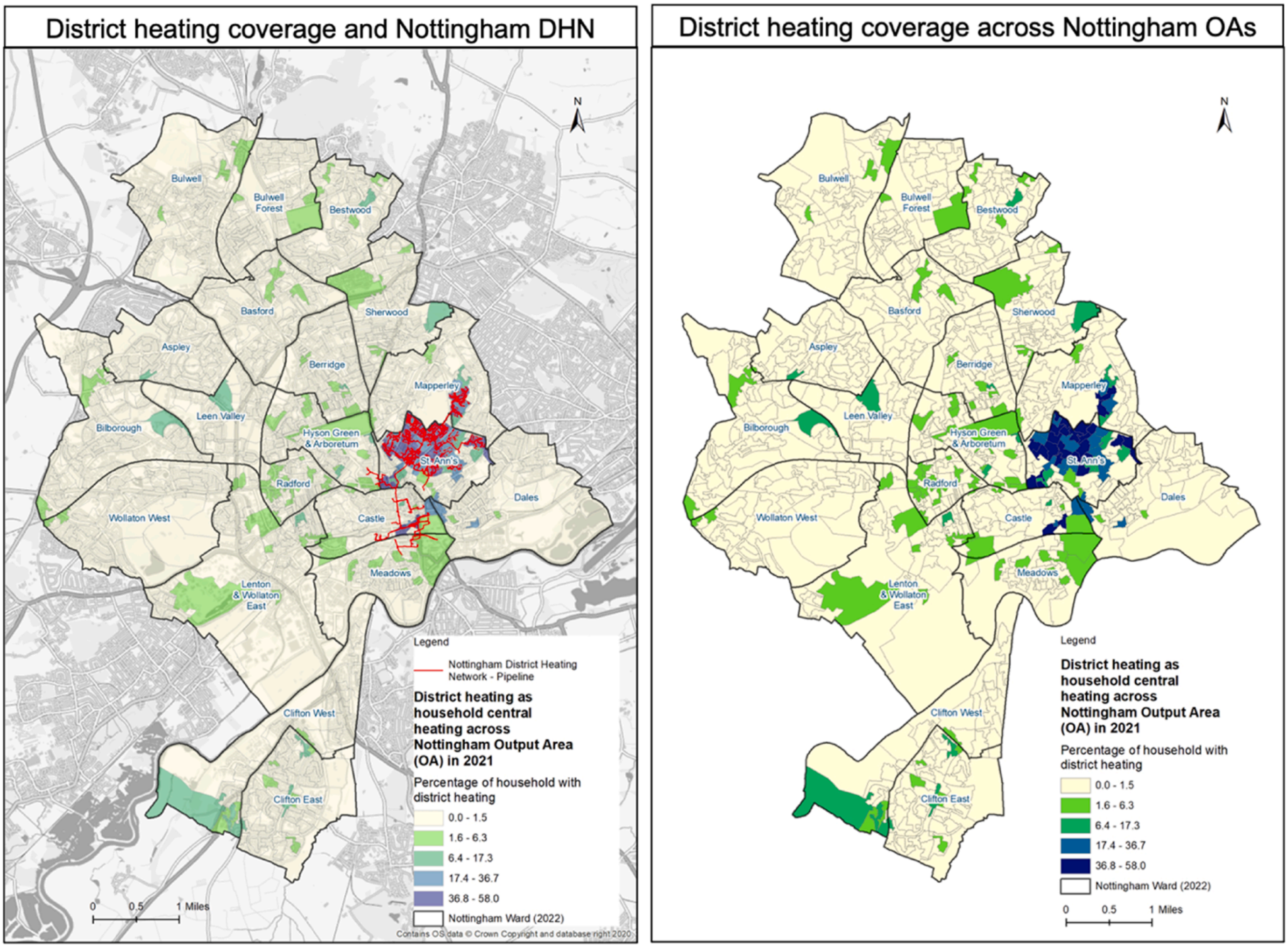

Fig. 5. District heating coverage across Nottingham according to the Census OA data (2021) and the pipeline of the Nottingham District Heating Network marked in red.

how well the network is operating. By regularly monitoring these performance indicators, it becomes possible to identify areas where the network may be underperforming and to implement targeted improvements. This can result in significant cost savings, enhanced energy security, and a reduced carbon footprint for the region.

Energy demand and supply analysis within the district heating network is essential for matching energy production with consumption patterns. Variations in energy demand across different times of the day, seasons, and building types (residential vs. commercial) require a dynamic and responsive energy supply system. By analysing the demand patterns in more detail, the network operators can better understand peak demand times and adjust supply strategies accordingly. This includes potentially integrating renewable energy sources or employing energy storage solutions to balance supply and demand efficiently. The analysis also involves investigating the supply side, particularly the sources of energy feeding into the district heating network. Understanding the energy flow to the end consumers is crucial. Any inefficiencies or bottlenecks in the energy flow process could lead to energy losses or reduced service quality. Therefore, a comprehensive analysis of the energy supply chain, from production to consumption, can identify opportunities for improving the overall efficiency of the network.

Below are two sets of analyses:

Analysis 1: Utilisation of Meter Readings Across Substations

The first analysis centers on the utilization of meter readings from all substations within the Nottingham district heating network. Substations act as intermediary points between the energy generation sources and the end consumers, making them critical nodes in the energy distribution process. By analysing meter readings from these substations, we can gain insights into energy distribution patterns and consumption behaviours across different areas of the network. This analysis can identify discrepancies between predicted and actual energy use, highlight areas of higher-than-expected energy loss, and reveal differences in consumption between residential and commercial users. Such detailed data is invaluable for optimising the distribution system, ensuring that energy is delivered where and when it is needed most efficiently. This analysis involves the utilisation of meter readings from all substations within the regions indicated in Fig. 4. It aims to provide a comprehensive understanding of energy distribution and consumption patterns across different areas of the network.

Analysis 2: Energy Flow Process from the Incinerator to the London Road Heat Station

The second analysis focuses on the energy flow process from the incinerator to the London Road Heat Station, a critical segment of the Nottingham district heating network. This process is crucial as it represents the primary pathway through which energy is generated, converted, and eventually distributed across the network. By mapping out this flow, we can identify key points where energy may be lost, such as during conversion processes or through heat dissipation in transit. Understanding these points of energy loss is essential for enhancing the

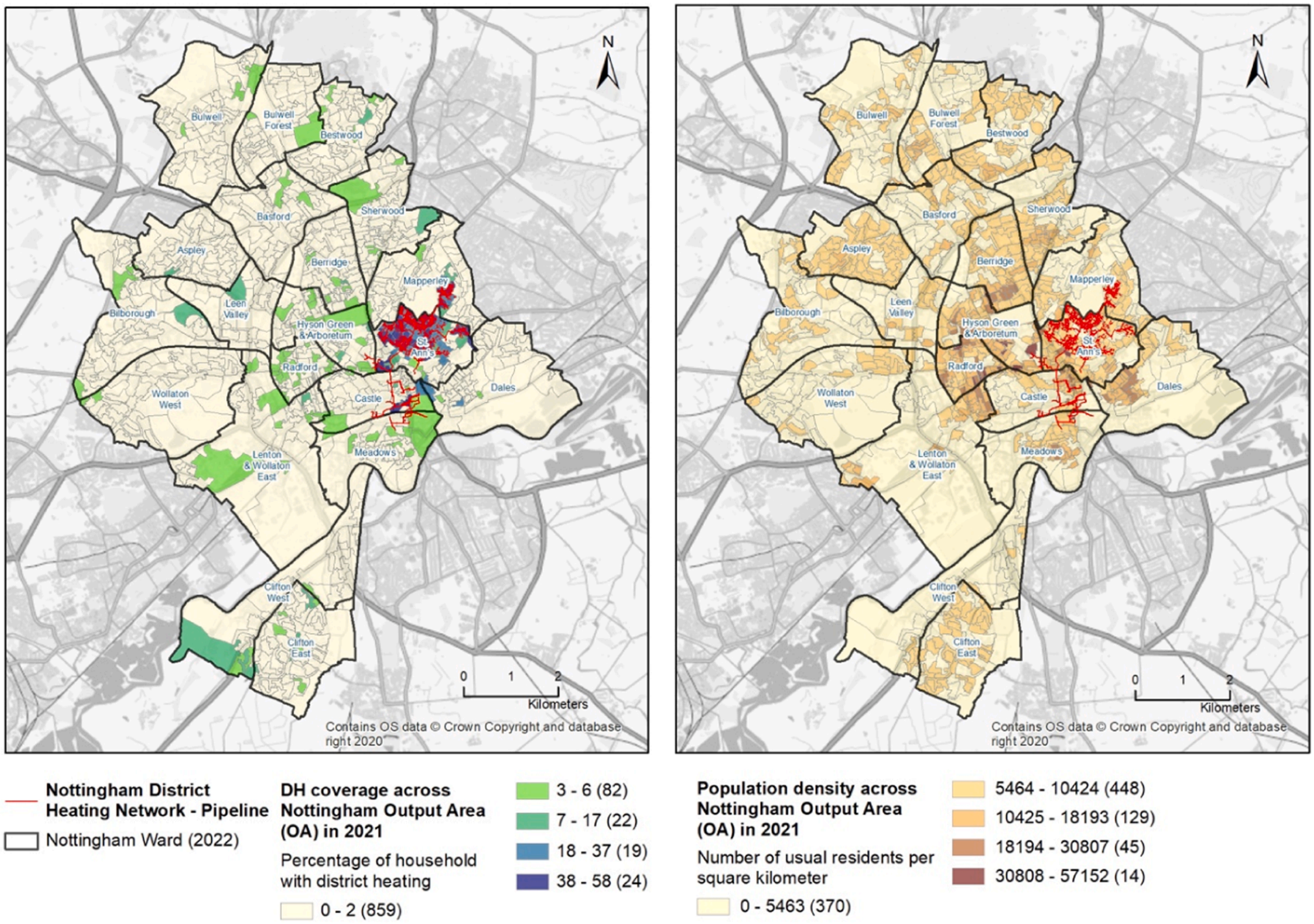

Fig. 6. District heating coverage across Nottingham according to the Census OA data (2021) (left) and the indication of the population density across Nottingham AO area (right).

Table 12
Description of the data obtained to perform an analysis of the Nottingham District Heating Network through postcode analysis.

Nottingham District Heating Network (DHN)	
Number of Ward covered	3 (i.e., St. Ann's, Castle, Mapperley)
Number of Output Area (OA) covered	47
Number of Street included	134
Number of Postcode included	186
Number of Address included	5207

overall efficiency of the district heating system. Moreover, by pinpointing areas where energy flow can be improved, this analysis supports the development of targeted strategies to reduce losses, such as improving insulation, upgrading system components, or integrating more efficient technologies. This aims to identify points of energy loss and potential areas for efficiency improvements within the system.

This emphasise the importance of detailed data and performance metrics in optimising district heating networks, particularly in terms of energy demand and supply. By leveraging advanced data analytics, Nottingham's District Heating Network can become more efficient, reliable, and better aligned with the energy needs of both residential and commercial users.

4.3.1. Analysis 1: Meter readings: 2021 – 2022

Fig. 9 illustrates the annual percentage distribution of energy flow across various regions of the Nottingham District Heating Network from October 2021 to October 2022, both annually between October 2021 and October 2022 in (a) and monthly in (b). This analysis offers insights into how energy consumption is distributed among different areas, which are connected to the network, and helps us understand the underlying patterns of energy usage across different types of buildings. The distribution of energy throughout the year in each specific area/region corresponds to the results from Fig. 6, which depicts district heating coverage across Nottingham according to the Census OA data (2021) and the population density across the Nottingham AO area.

The monthly meter readings in (b) suggest that energy distribution from London Road to these network areas is solely dependent on the types of connected buildings and their usage. For instance, the largest share in energy consumption within the residential areas mostly largely covered by the housing area indicated in red, making up over half of the total energy distribution. This is consistent with typical residential energy demands, which remain stable throughout the year due to the continuous need for heating and hot water. The high percentage reflects the extensive coverage of residential buildings within the district heating network and their steady energy demand, regardless of seasonal variations. Another significant portion of energy flow is directed towards city residential areas. Like the general housing areas, these regions show consistent energy consumption patterns, driven by the needs of daily living, particularly for heating during colder months and hot water throughout the year.

Furthermore, office buildings indicated by the 'City Centre and 'City Centre Offices' demonstrate lower energy consumption compared to

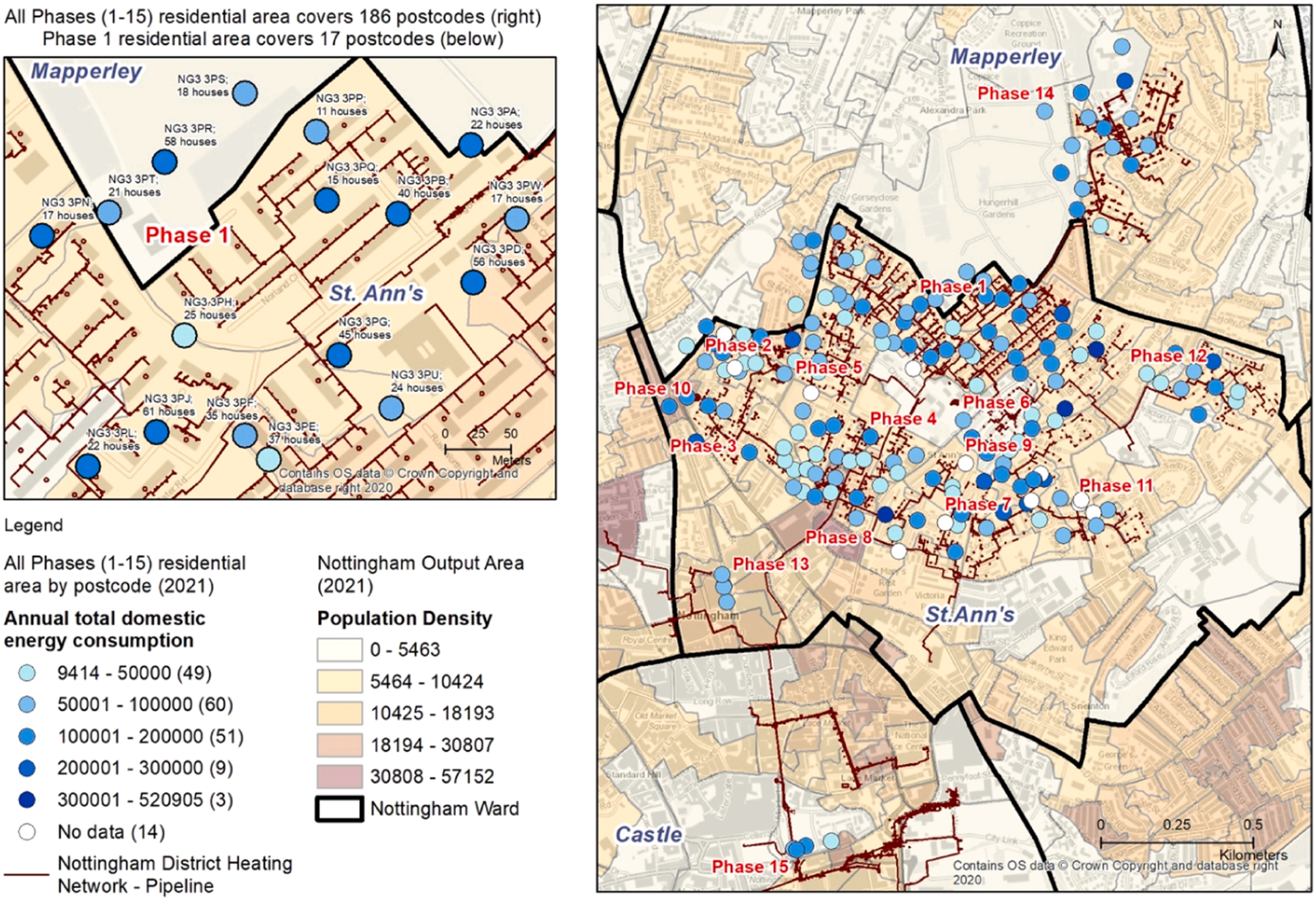

Fig. 7. Annual total domestic energy consumption across the St Ann's region of Nottingham along with the population density based on the Nottingham Output Area (2021).

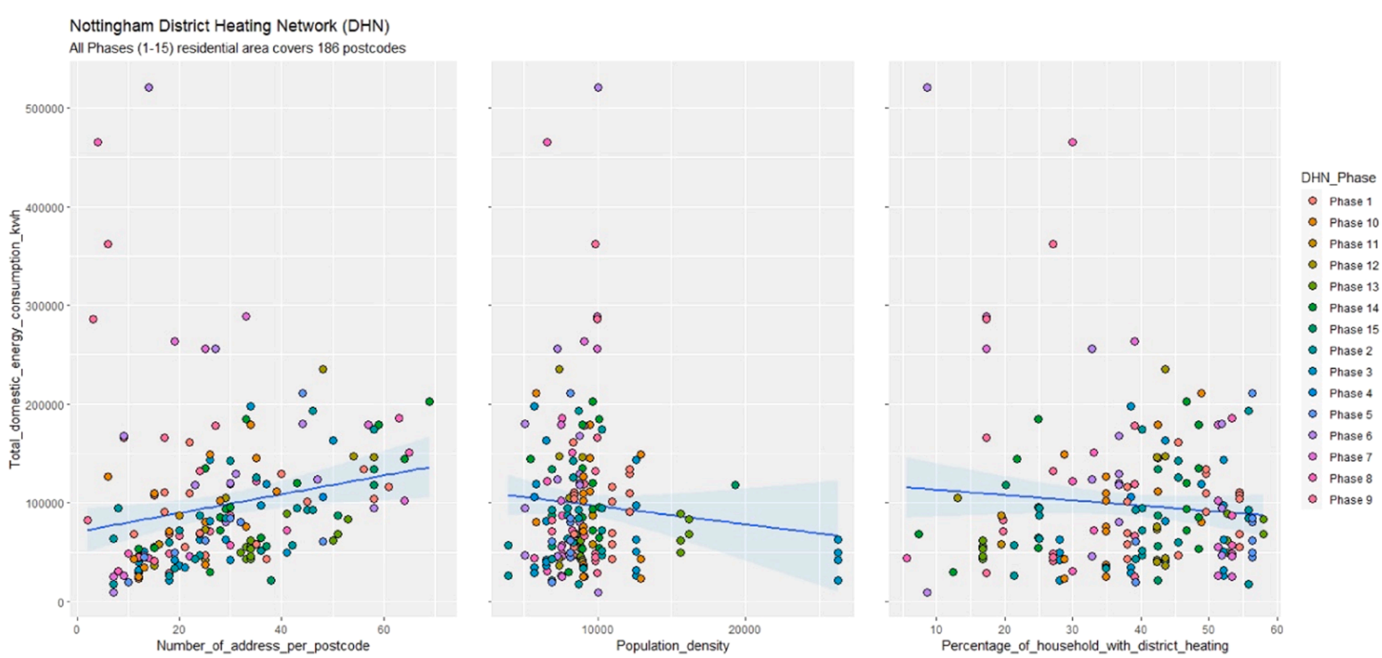

Fig. 8. Graph plot comparison of the total domestic energy consumption across the number of addresses per postcode, along with the population density and percentage of household with district heating within Phase 1 – 15 of the St Ann's area.

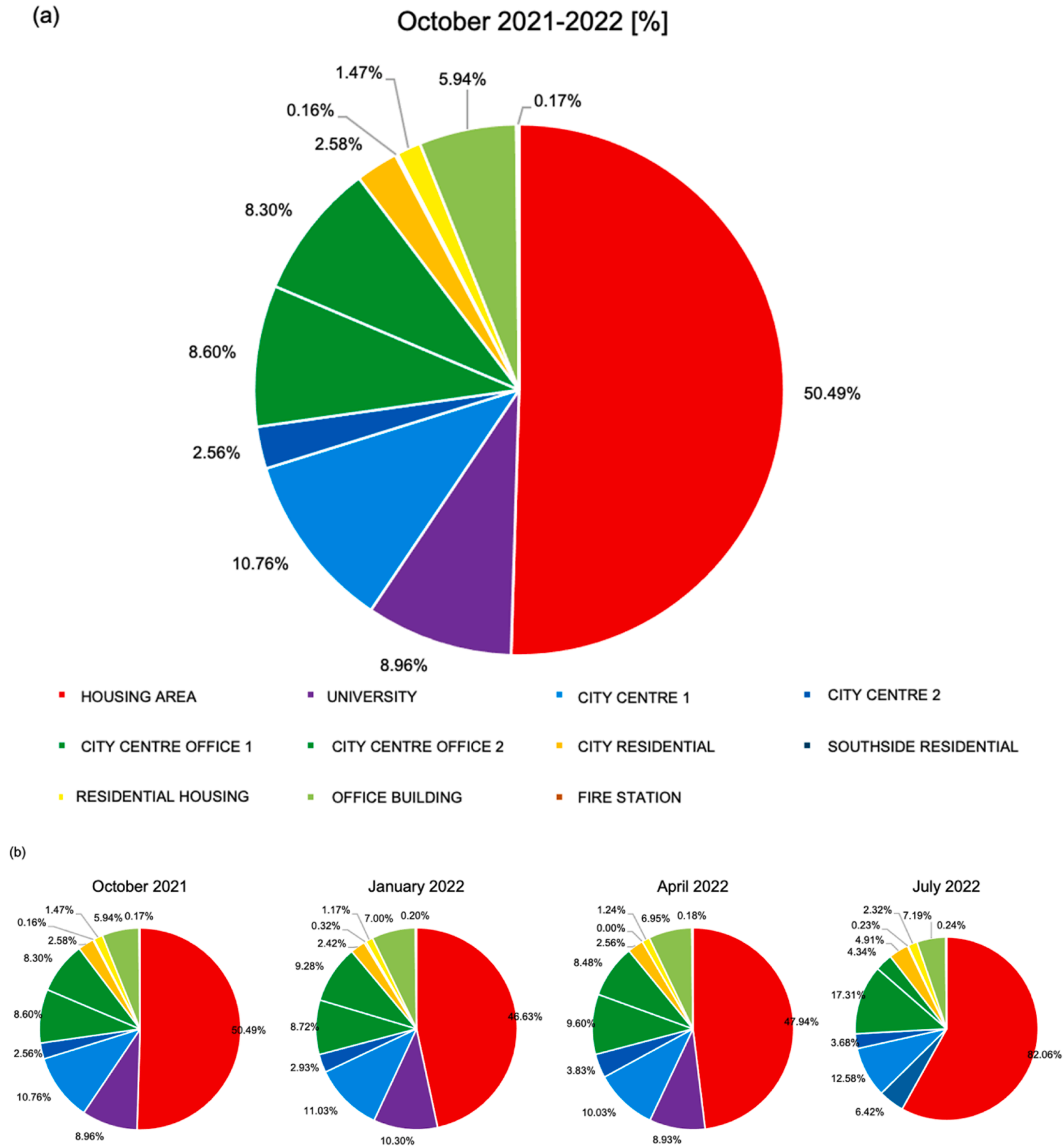

Fig. 9. Percentage of energy flow across various region of the Nottingham District Heating Network (a) annually 2021–2022, (b) monthly.

residential areas. The demand is likely tied to business hours and operational days, with possible reductions during weekends and holidays. The energy usage in these buildings may fluctuate based on occupancy rates, working hours, and the efficiency of the heating and cooling systems. Similar to the city centre offices, this category likely represents a cluster of commercial buildings with energy demands closely related to business operations. The slightly higher percentage suggests either a larger area or higher energy requirements due to factors like older, less efficient building structures or extended operational hours.

Conversely, in the 'University' area (indicated in purple), shows a noticeable share of the energy distribution, which corresponds with the operational needs of large institutional buildings. The energy demand in this region is likely characterised by high variability, with significant reductions during academic breaks, particularly in the summer months, as observed in Fig. 9(b). This pattern highlights the potential for energy-saving strategies, such as reducing heating supply during periods of low occupancy.

City Centre 1 and City Centre 2 regions represent mixed-use areas with a combination of commercial, residential, and public service buildings. The energy consumption in these areas likely reflects the diversity of building types and uses, leading to varying energy demands throughout the year. Fire Station (0.17 %): The minimal energy consumption observed in the fire station category is indicative of the specialised and possibly limited operational needs of such facilities, which may not require substantial heating or cooling compared to other building types.

These findings indicate that, based on past energy flows and meter readings, adjustments and optimisations to energy outputs from the heat station can be made. This would enable the district heating network to become more efficient and effective for future use.

Effectively, as indicated by the analysis of energy flow across these different regions of the Nottingham District Heating Network, it suggests several avenues for optimisation. Given the seasonal and usage-based variations in energy demand, particularly in non-residential areas like universities and office buildings, there is potential to dynamically adjust the energy output from the heat station. For example, reducing energy supply during university holidays or scaling up supply during peak office hours can improve overall efficiency. In addition, regions with higher energy demands, such as residential areas and city centre offices, may benefit from targeted efficiency improvements, such as better insulation, upgraded heating systems, or the integration of smart thermostats to reduce unnecessary energy consumption. This also suggests that through understanding the specific energy needs of different regions allows for more informed decisions regarding the expansion or upgrade of district heating infrastructure. For instance, regions with lower energy consumption, might be prioritised for future network expansions or efficiency retrofits to enhance their energy performance.

Therefore, such analysis highlights the importance of understanding and responding to the distinct energy demands of various regions within the district heating network. By aligning energy supply with actual consumption patterns based on the inclusive of making seasonal adjustments, variable energy demands with potential optimisations based on fluctuating energy usage, the Nottingham District Heating Network can be made more efficient, sustainable, and capable of meeting the specific needs of its diverse user base.

4.3.2. *Analysis 2: Energy flow process*

This section presents an analysis of the energy flows from the incinerator (a) to the Heat Station (b), before the energy is distributed across the network (c) to the end consumers. The aim is to identify inefficiencies and potential areas for optimisation to improve the overall efficiency and sustainability of the system. Fig. 10 and Table 13 illustrate the energy flow process and identify areas where energy losses

Table 13
Description of the various positions across the Nottingham District Heating Network as indicated by the energy flow process in Fig. 10.

Region	Position	Description
Incinerator	M1	Steam output from the municipal waste
	L1	System losses at incinerator
	L2	Transmission losses within incinerator and heat station
Heat Station	M2	Steam output from turbine (CHP)
	M3	Losses between M2 and M5 (dump)
	L3	Losses to the canal (river dump)
	L4 / M4	Steam output as dump (to atmosphere)
	M5	Heat output from Heat Station to District Heating Network
	L5	Losses within the transmission between the heat station and the district heating network
District heating network	S_{all}	Heat output at the District Heating Network (total from all substations)
	L6	Losses within the transmission within the district heating network (substations to buildings)

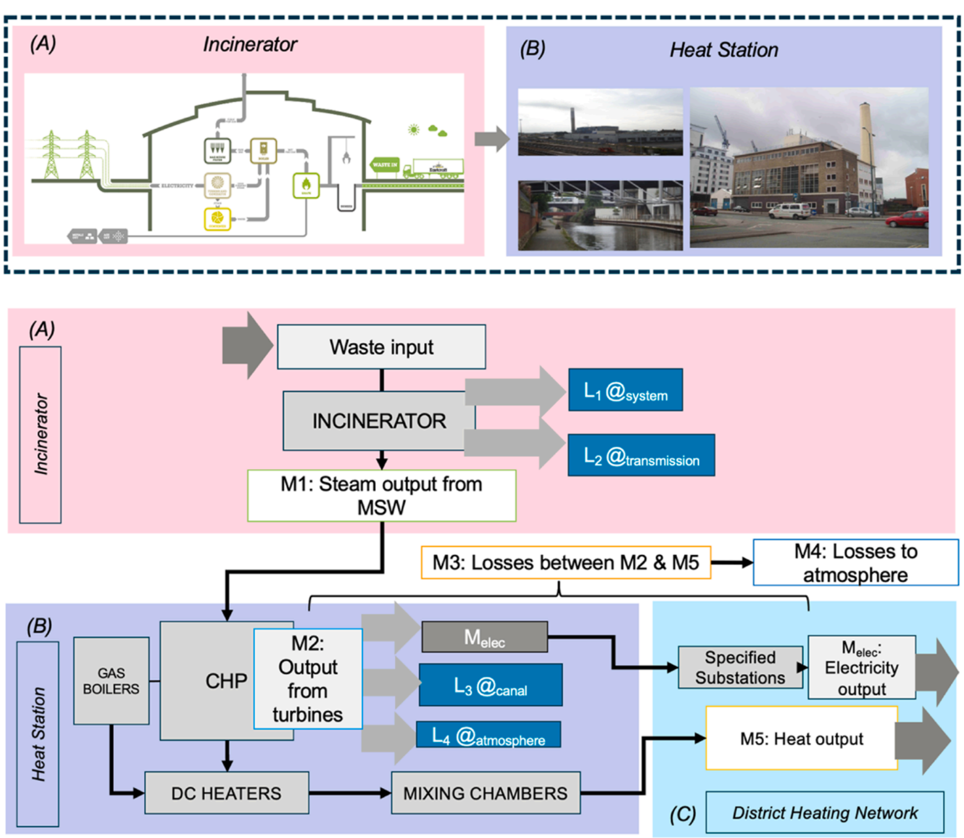

Fig. 10. Energy flow process across the incinerator to the heat station and the district heating network.

occur.

The initial stage of the energy flow begins at the incinerator, where municipal waste is burned to generate steam (M1). This steam is then transported to the heat station, where it is converted into heat energy for the district heating network. During this stage, several losses occur. This includes system losses within the incinerator (L1) and transmission losses (L2). L1 losses are attributed to inefficiencies in the combustion process, heat exchange, and steam generation. Enhancing the incinerator's operational efficiency. For example, by optimising combustion conditions or improving heat recovery mechanisms, could reduce these losses. L2 losses occurs as the steam travels from the incinerator to the heat station, energy is lost due to heat dissipation along the transmission lines. Insulating steam pipes more effectively or reducing the distance between the incinerator and the heat station could help mitigate these losses.

Once the steam reaches the heat station, it undergoes several processes that involve energy conversion and potential losses. This includes the conversion process as steam is used to drive turbines in the Combined Heat and Power (CHP) system, generating both electricity and heat. However, the process is not fully efficient, leading to electrical losses (Melec) and thermal losses. During this process, the output from the turbines of the CHP (M2) results in electrical losses (Melec), losses to the canal as river dump (L3), and air dump to the atmosphere (L3). These losses are indicated by M3 (losses between M2 and M5) and M4 (losses to the atmosphere). Excess heat is released into a canal, leading to a significant loss of usable energy. Redirecting this heat for alternative uses, such as industrial processes, could reduce these losses. Additional energy is lost to the atmosphere as excess steam is vented. This can be minimised by optimising the system's heat balance and ensuring that as much steam as possible is converted into usable energy.

Hence, M5 is the remaining steam is converted into heat energy (M5), which is then distributed across the district heating network. This conversion process itself is subject to losses, particularly if the heat station's heat exchangers are not operating at peak efficiency.

The final stage of the energy flow involves the distribution of heat energy from the heat station to various substations and end-users across the network. This stage is also characterised by several potential inefficiencies through the transmission losses within the network as L5 and L6. As heat energy is distributed through the network, losses occur due to heat dissipation, particularly in these older and poorly insulated pipes. Upgrading the network infrastructure, such as replacing outdated pipes with modern, insulated ones, could significantly reduce these losses. Furthermore, the district heating network includes primary and secondary substations that manage the distribution of heat energy to different areas. Inefficiencies at these substations, such as outdated equipment or suboptimal routing of energy flows, contribute to overall system losses. Modernising these substations and employing smart grid technologies could enhance the system's efficiency.

Based on an understanding of the energy system operations and energy flow process, Fig. 11 and Table 14 present an example of the distribution in 2021. The data indicates the amount of energy carried from M1 at the incinerator throughout the system and onto the network, highlighting losses at each point. Table 14 provides a monthly distribution for 2021. While the average output across the year was approximately 36.04 %, the data suggests that the results are not dependent on the time or season.

Fig. 12 suggests that the output could be impacted by the amount of energy generated and the demand required. During the summer months (June to August 2021), the output from the heat station to the network is significantly higher than during the rest of the year. This indicates that less heat energy is required for heating during this period and suggests a lower demand for heating, resulting in less efficient energy use as a larger proportion of steam is either dumped or lost. To address this seasonal variation, it is critical to optimise the network's operation based on real-time demand. This could involve the implementation of advanced energy management systems that adjust energy output dynamically according to current demand, thus minimising losses during periods of low heat demand.

The diagram presented in Fig. 13 illustrates the system flow process of the Nottingham District Heating Network. According to this figure, steam generated from the incinerator provides the heat energy distributed to commercial and residential buildings within the district heating network. However, there are notable losses within the primary and secondary substations, modeled losses, and minor leaks.

Additionally, the figure highlights several other types of losses originating from the steam at the incinerator. These include parasitic losses, losses within the heat station, and electrical losses due to the operation of electrical equipment. Similar to the analysis presented in Fig. 12, Fig. 13 shows a significant percentage of losses categorised as 'rejection,' indicated by losses to the canal and air dump.

These findings underscore the need for further advancements in the system and network to potentially improve operational efficiency by reducing these losses. Addressing these issues could enhance the overall performance and sustainability of the Nottingham District Heating Network.

In addition to the valuation based on Analysis 1, Analysis 2 on the energy flow process within the Nottingham District Heating Network reveals several areas where improvements could be made. This includes the potential of upgrading the incinerator's combustion and heat recovery systems could reduce system losses (L1) and increase the amount of energy available for conversion into steam. For the transmission losses, implementing better insulation for steam transmission lines and optimising the routing of energy flows could decrease losses both between the incinerator and heat station (L2) and within the district

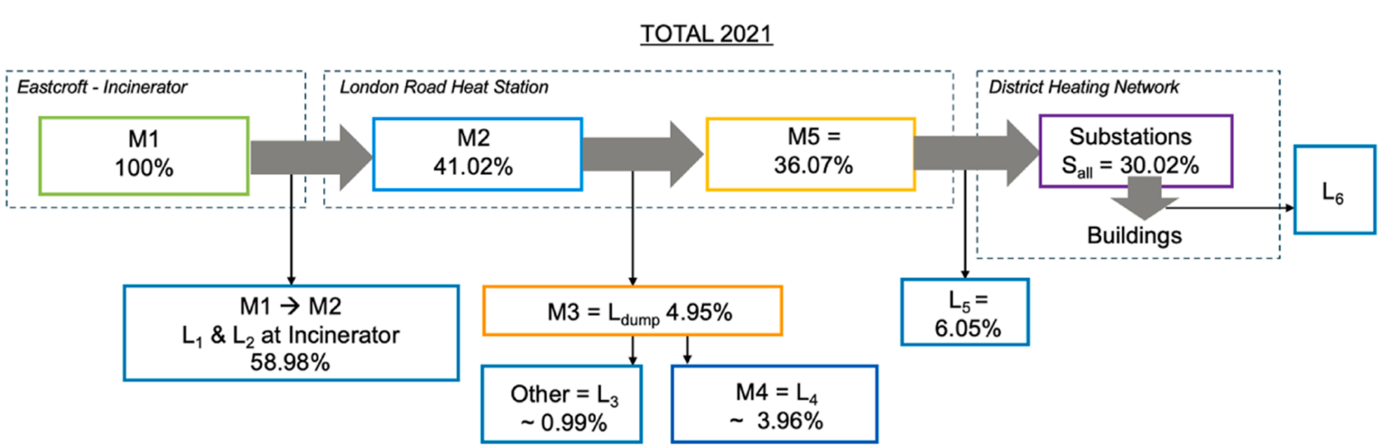

Fig. 11. Example energy flow process across the system network with the percentage distribution of energy flow.

Table 14
Breakdown of the energy flow across the different positions on the Nottingham District Heating System in 2021.

Date/ Month	Position						
	M1	M2	M3		M4		M5	
		From M1	From M1	From M2	From M1	From M2	From M1	From M2
Jan−21	100.00 %	49.30 %	0.00 %	0.00 %	0.00 %	0.00 %	49.30 %	100.00 %
Feb−21	100.00 %	46.32 %	0.00 %	0.00 %	0.00 %	0.00 %	46.32 %	100.00 %
Mar−21	100.00 %	37.34 %	0.00 %	0.00 %	0.00 %	0.00 %	37.34 %	100.00 %
Apr−21	100.00 %	35.16 %	0.00 %	0.00 %	0.00 %	0.00 %	35.16 %	100.00 %
May−21	100.00 %	27.59 %	0.72 %	2.63 %	0.57 %	2.06 %	27.02 %	97.94 %
Jun−21	100.00 %	45.12 %	24.47 %	54.24 %	19.26 %	42.69 %	25.85 %	57.31 %
Jul−21	100.00 %	78.81 %	12.85 %	16.30 %	10.12 %	12.85 %	68.69 %	87.15 %
Aug−21	100.00 %	29.39 %	12.64 %	43.00 %	9.94 %	33.84 %	19.44 %	66.16 %
Sep−21	100.00 %	35.27 %	14.58 %	41.33 %	11.48 %	32.53 %	23.80 %	67.47 %
Oct−21	100.00 %	42.53 %	15.32 %	36.02 %	12.06 %	28.35 %	30.47 %	71.66 %
Nov−21	100.00 %	49.60 %	9.70 %	19.55 %	7.63 %	15.39 %	41.96 %	84.61 %
Dec−21	100.00 %	54.14 %	0.00 %	0.00 %	0.00 %	0.00 %	54.14 %	100.00 %
Total	100.00 %	41.02 %	6.30 %	15.35 %	4.95 %	12.08 %	36.07 %	87.92 %

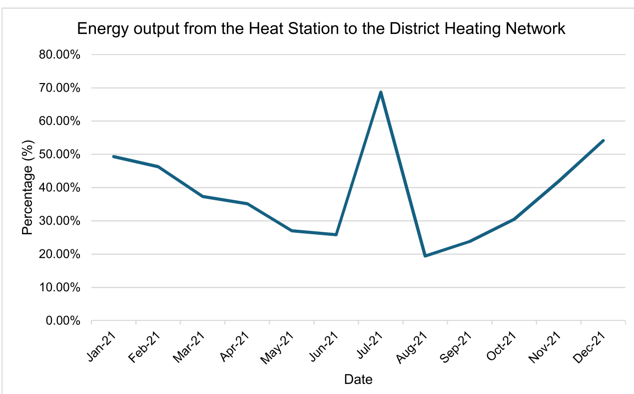

Fig. 12. Percentage of heat output from the heat station to the District Heating Network during 2021.

heating network (L5 and L6).

At the heat station, improvements in terms of the efficiency of the CHP operations should be considered. This benefits through the reduction of electrical losses and mimisation of the large quantity of losses through the river and air dumps (L3 and L4). At the distribution across the network, it includes the consideration of seeking solutions towards upgrading the network infrastructure. Replacing outdated pipes and substations with modern, energy-efficient alternatives could further reduce transmission losses and improve the overall efficiency of the network. Furthermore, implementing smart energy management system that adjusts output based on real-time demand could help to optimise energy flows throughout the year, particularly during periods of low demand.

Hence, by addressing these inefficiencies, the Nottingham District Heating Network can enhance its operational performance, reduce energy waste, and improve its overall sustainability. These improvements will not only benefit the environment by reducing emissions but also provide economic benefits by lowering operating costs and improving service reliability for end-users.

4.4. Potential advancement of district heating network schemes

Based on the results and findings presented in this section, it is evident that further investigation into the current system, network processes, and distribution mechanisms is necessary before implementing any adjustments or changes to align with the FCC scheme's potential developments and plans.

The demand for an effective approach that can address these limitations underscores the need to improve the accuracy, reliability, and usability of assessment tools for district heating systems. Life cycle

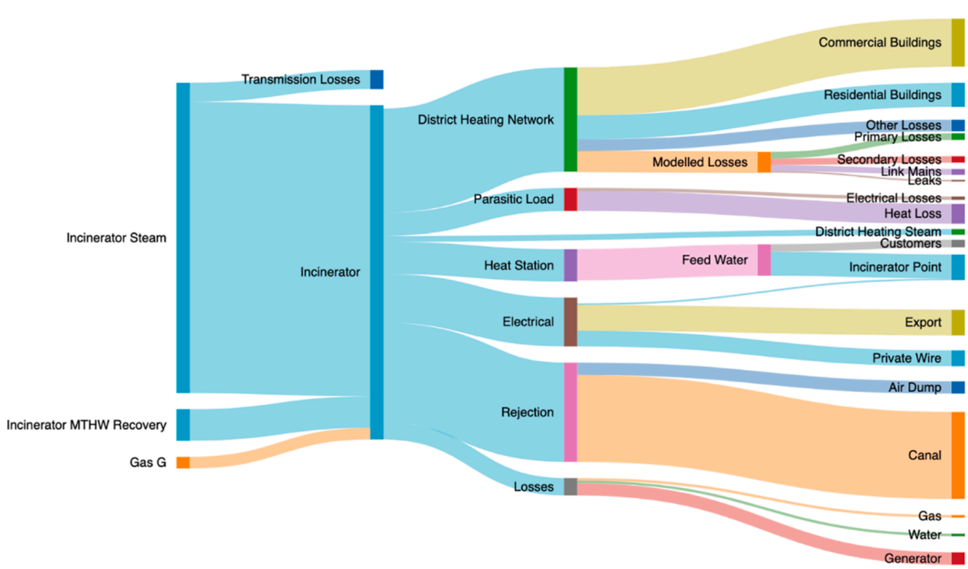

Fig. 13. Sankey diagram indicating the system flow process of the Nottingham District Heating Network.

assessments (LCA) could serve as an alternative method to evaluate the environmental impact of district heating systems throughout their entire life cycle, including construction, operation, and decommissioning. This method would help stakeholders understand the sustainability implications of various design and operation choices. However, to date, no studies have conducted life cycle assessments on a network-based system. Existing studies have focused on single, smaller-scale local enclosed systems rather than on large-scale urban networks currently in use.

Following the analysis of the Nottingham District Heating Network and existing reviews on using the LCA approach for energy systems, further investigation into district heating networks through this assessment method is warranted. This investigation should include:

1. An assessment of the current district heating energy system.
2. An assessment of the system after modifications have been implemented.
3. An assessment considering potential improvements, system developments, and expansions.

Applying this approach would establish a framework that enables advancements to existing district heating systems and networks. This framework would empower them to become effective solutions that address the current cross-cutting barriers within existing energy systems and networks. By doing so, stakeholders could make informed decisions that enhance sustainability and performance, ensuring that district heating networks meet future energy demands efficiently and responsibly. Effectively, this emphasises the demand for continuous improvement by pinpointing areas for optimisation and innovation through a full LCA approach to evaluate the feasibility of four main future advancements in the district heating network of the selected case study: (1) heating network with added energy storage, (2) advanced system operations through model predictive control (MPC) strategy for demand prediction control, (3) general network improvements, and (4) network expansion. Overall, this aims to enhance the sustainability, efficiency, and resilience of district heating networks, contributing to the transition towards more sustainable energy systems and ensuring they remain environmentally sustainable and economically viable over time.

5. Conclusions and future works

The present study investigated the current status, potential use, and prospects for advancements within district heating networks in urban areas, using Nottingham as a case study. A literature review was conducted to explore existing approaches that assist in the decarbonisation of building energy in the UK and address key cross-cutting barriers, namely: (1) Information, engagement, and behaviour, (2) Strategy, policy, and regulation, (3) Infrastructure, (4) Supply chain and skills, and (5) Distribution of costs and impacts. This review highlighted the potential use and future advancements of district heating networks in urban areas of the United Kingdom.

The study focused on identifying the location of the network, examining the current system processes and operations, and analysing past energy performance and distribution. This analysis aimed to estimate the potential future impact on energy distribution and losses across the Nottingham District Heating Network. Heat mapping and energy flow assessments indicated areas where energy savings could be achieved, guiding system optimisation to enhance future performance. The findings suggest that the energy output from the heat station to the network can be increased.

By analysing specific areas of the network and the usage and demand requirements of individual connected buildings, a more strategic approach to system operations can be developed. This includes adapting technological advancements such as implementing energy storage. However, to further advance the network, the study suggests conducting a life cycle analysis of the district heating network in future research. This holistic view would consider all stages from material sourcing and network construction to system production and utilisation. Understanding the network's operations can lead to an assessment of the environmental impacts associated with each stage, including greenhouse gas emissions, energy consumption, and resource depletion. Identifying opportunities to improve resource efficiency by minimising energy and material losses throughout the network's life cycle can lead to reduced resource consumption and lower environmental impacts.

To make this feasible, future work should develop a lifecycle assessment (LCA) approach to evaluate existing district heating networks. This would involve following the guidelines of the British Standard for Environmental Management (BS EN ISO 14040) and Life Cycle Assessment (ISO 14044). The tasks include assessing the current Nottingham DH system and the Nottingham DH Network with the VTTESS-Hnet system. This will provide results that highlight the potential advancements of the Nottingham Energy Systems and present an adaptable approach for performing LCAs on other district heating systems.

CRediT authorship contribution statement

Rabah Boukhanouf: Writing – review & editing, Supervision. **John Calautit:** Writing – review & editing, Supervision. **Jo Darkwa:** Writing – review & editing, Supervision. **Serik Tokbolat:** Writing – review & editing, Supervision. **Paige Wenbin Tien:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yuan Feng:** Investigation, Formal analysis, Data curation. **Mark Worall:** Writing – review & editing, Supervision, Data curation.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author.

Data availability

Data will be made available on request.

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Data access statement

No new data were created during this study. The project partners, Nottingham City Council and Enviroenergy provided supporting data on the Nottingham District Heating Scheme. Other forms of data were gathered through open sources provided by the UK Government (GOV.

UK), Office for National Statics Census Data 2021. All have been directly cited within the text.

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