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Research paper

Heat recovery opportunities from electrical substation transformers

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A R T I C L E I N F O

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ABSTRACT

The transformation of voltages in electrical substations leads to energy losses in the form of waste heat; the quantity of which depends on transformer size and electrical loading. This paper investigates how a novel waste heat source, namely transformer waste heat could be harvested and distributed via district heating networks. Firstly, the investigation considered nameplate heat loss factors to quantify the theoretical waste heat potential from electrical substation transformers in England, Wales and Northern Ireland, which varied from 3.0 to 5.4 TWh a^{-1}, equivalent to between 0.7 and 1.25% of annual heat demand for these countries, depending on loading assumptions. A number of heat recovery approaches which could be integrated with existing transformer cooling systems were then proposed. A spreadsheet model was then developed to simulate heat recovery from a transformer, together with the upgrade of the recovered heat using a heat pump prior to delivery via district heating. The model was used to evaluate the merits of capturing transformer waste heat losses, estimated using industry supplied electrical loading data, to meet different heat network demands based on an existing network, compared to conventional heating technologies. Findings suggest that the system proposed can achieve levelised costs that are up to 17% lower than the running costs of air-source heat pumps, whilst reducing emissions by almost 80% when displacing gas boilers. The methodology hereby described can also be used to evaluate the feasibility of recovering transformer waste heat in other countries.

1. Introduction

With a growing concern and increased awareness over the threat presented by the climate crisis, many countries have been working to decarbonise their energy systems by accelerating the uptake of clean energy sources and cutting down greenhouse gas (GHG) emissions from a wide range of sectors. In 2019, the United Kingdom became the first major economy to commit to a legally binding target of reaching net-zero emissions by 2050 (CCC, 2019). This ambitious goal was motivated by the progress made by the UK in recent years, as national emissions fell by 48.8% between 1990 and 2020 (DESNZ, 2021a). This achievement is mainly attributable to the increasing shares of renewable energy generation in the UK's electricity production mix, which reached a record of 42.6% of the power generated in 2020 (DESNZ, 2022a); a number expected to grow in future years.

As the UK aims to further reduce its contribution to climate change and deliver net-zero GHG emissions, decarbonising the built environment becomes one of its main challenges, as the sector is responsible for 30% of emissions in the country, with 79% of those resulting from heating (DESNZ, 2021b). This is associated with the dominance of fossil fuels in the UK's heating sector, with 85% of British households being heated by natural gas, and only 5% having low-carbon heating technologies (ESC, 2020). The ongoing decarbonisation of the electricity grid, together with the current dependence of the heating industry on natural gas, make the electrification of heat, e.g. using heat pumps (HPs), an opportunity to help reduce the carbon footprint of UK buildings, as recognised by the UK Government's Heat and Buildings Strategy (DESNZ, 2021b).

Furthermore, due to the post-pandemic economic recovery and the Russo-Ukrainian War, a surge in gas prices has triggered a cost-of-living crisis in the UK, with inflation reaching its highest rate in 40 years (Bank of England, 2022). For that reason, the reliance of the UK and Europe on fossil fuel gas to meet their heating needs has been highlighted as an issue for energy security and fuel poverty. While 40% of the total gas consumed in Europe is imported from Russia (IEA, 2022), the UK has been severely affected by the rise in wholesale gas prices in the international market, which had already increased by nearly four times prior to the war, from January 2021 to January 2022 (ONS, 2022).

One potential source of low-carbon heat that could replace natural gas heating is to use waste heat from essential processes, which is

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normally released to the environment. The current study investigates one such heat resource, namely waste heat generated by transformers in electrical substations. Firstly, the reasons for heat being generated by transformers and the main cooling methods used are discussed, then options for heat recovery from transformers, e.g. by integrating with the cooling system, are considered. The transformers most suitable for implementing heat recovery systems are considered and their spatial distribution across the UK are presented in the form of Geographic Information System (GIS) maps. Subsequently, a spreadsheet model was developed to simulate the recovery of the combined waste heat from two transformers, together with upgrade of the recovered heat using a HP prior to delivery of the heat to users via a district heating network (DHN). The model was used to evaluate the performance of the transformer heat recovery system when supplying different sizes of network with a range of heat demands. The transformer waste heat system was also compared with alternative heat sources, such as gas boilers and air source heat pumps (ASHPs), when supplying the same quantity of heat to the network. This entailed evaluating the waste heat recovery (WHR) system in terms of its relative savings in energy, CO_2e emissions and costs when compared to conventional heating systems. Finally, the conclusions from the study are presented, together with recommendations for the next steps to be taken in the development of these heat recovery systems.

2. Low-grade waste heat and district heating networks

Reusing recovered low-grade waste heat generally involves transferring the heat to water, e.g. using a heat exchanger, and then using the water to transport the heat to end users via a pipework system. This is often termed a DHN (Energy Saving Trust, 2021). Using DHNs for distributing waste heat is generally only economically viable if located in an urban area with a dense population of potential users, and with the waste heat source nearby. The earliest DHNs used high-temperature (i.e. 100 °C and above) steam and water, e.g. 1st and 2nd generation (1G and 2G) of district heating (Lund et al., 2014). However, subsequently operating temperatures have steadily decreased for successive generations of DHN i.e. 3G, 4G and 5G networks, with the latest (5G) networks operating at close to ambient temperature (Revesz et al., 2020). Typically, 4G networks operate with supply temperatures of 50-60 °C, whilst 5G systems operate at a lower supply temperature range (15–25 °C). The lower distribution temperatures associated with the 4th and 5th generations improve the economics of using waste heat from low-grade heat sources (Lund et al., 2021). This low-temperature waste heat can be either used directly or after upgrade by a HP, which can be used in conjunction with the DHN to boost the temperature either for transfer from the waste heat source to the DHN, or prior to transfer from the DHN to users (Foster et al., 2016).

For this reason, opportunities for WHR at low temperatures (<100 °C) have been increasingly reported in the literature in recent years, particularly with the advent of 4G and 5G networks. These novel generations have accelerated the uptake of unconventional heat sources for district heating. For instance, Davies et al. (2016) introduced different cooling approaches for data centres and their heat recovery potentials, whilst Wahlroos et al. (2018) reported a case study on the potential to utilise data centre waste heat for a 3G DHN, demonstrating how operating costs are reduced for higher shares of waste heat utilisation. District heating is particularly attractive in cities, where heat generated during the operation of urban infrastructures can be exploited, such as sewage collection/distribution systems and underground railways. Cipolla and Maglionico (2014) have identified key locations for heat recovery from the sewage network in Bologna, Italy, whilst Dénarié et al. (2021) have estimated the Italian nationwide potential for heat recovery from wastewater treatment plants as 31 TWh a^{-1}. For underground railways, Lagoeiro et al. (2022) reported how waste heat from the London Underground could reduce carbon abatement costs by 18.1% against individual ASHPs, based on the concept of the Bunhill 2 project in Central London (Islington Council, 2020). Supermarkets and retail refrigeration represent another low-temperature heat source of interest for district heating, as reported in the findings of the ReUseHeat project (Persson et al., 2020). This research project investigated a range of low-grade heat sources and estimated the European potential to be 1410 PJ.a^{-1} (392 TWh a^{-1}) of accessible waste heat, considering the 28 EU countries as per 2019 (including the UK). Another heat source of great potential that is currently underrepresented in the literature is electrical substation transformers, which are applied to step up and down voltages for the transmission and distribution of electricity. Waste heat generated by electrical transformers is generally within the range of 20–70 °C, as reported by Strbac et al. (2014), meaning HP upgrade would be often needed prior to its reuse for the provision of space heating and hot water in buildings.

3. Waste heat from transformers

3.1. Literature review

There are a limited number of studies that have analysed the potential to recover and reuse waste heat from electrical transformers. A report from Imperial College London and Sohn Associates (Strbac et al., 2014) investigated energy losses in electricity distribution networks and proposed a concept for heat recovery from a 15 MVA water-cooled transformer. A similar concept involving an oil-to-water heat exchanger has been proposed in another UK study, which looked at the economics of recovering waste heat from a transformer belonging to a British distribution network operator (DNO) (Arup, 2018). More recently, Petrović et al. (2022) estimated that 280 GWh.a^{-1} could be delivered in Denmark via DHNs that use transformer waste heat. In this case, the heat would be captured from the warm air exiting an air-cooled transformer using an air-to-water HP, with an estimated average COP of 4 being reported. A similar concept involving an air-cooled transformer was reported by Dorotić et al. (2022), who showed how DHN supply temperatures have a significant impact on the system's levelised costs. Although highly promising, heat recovery from electrical transformers has not materialised into many practical projects to date. A pilot project is currently being developed to trial this technology by the UK's transmission network operator (TNO) (SSE Energy Solutions, 2021). This paper aims to complement the earlier work by comparing different heat recovery options and analysing the impacts of load variation in greater detail. Furthermore, this study is also aimed at investigating the waste heat potential from electrical substation transformers in the UK, an important emerging district heating market.

3.2. Transformer heat losses

There are two types of losses that occur in transformers, namely load losses and no-load losses. Load losses occur due to the resistance of the copper windings and are proportional to the electrical current squared. On the other hand, no-load losses arise from both hysteresis losses and eddy current losses, which occur whenever the transformer is energised, but no power delivery i.e. load, is required. The no-load losses are constant, while the load losses vary with the power drawn from the transformer. The total losses from the transformer are the sum of the load and no-load losses (Kennedy, 1998). Manufacturers provide nameplates for their transformers which typically contain rated values for both types of losses at full capacity, in kW of heat per kVA of capacity. Using nameplate losses for different transformer manufacturers, a correlation was established to estimate the waste heat recoverable from electrical substations as a function of transformer capacity and percentage loading (Bowman, 2019). In this case, loading, or load factor, is defined as the ratio between the current flowing through a transformer, induced by the connected loads, to the rated current, which is the primary (design) current used for performance specifications of a transformer (IEEE, 2000), whereas the capacity represents the apparent power of the transformer when submitted to its rated current.

The correlation was developed by means of a multiple polynomial regression method using loss factors for a range of medium-sized transformers (ranging between 25 and 125 MVA). This correlation relates the heat loss with loading and capacity variables and can be used to provide an estimation of waste heat output for any given transformer. For a rated loading ($L = 1.0$, i.e. 100%), the losses are equivalent to 0.7% kW/kVA, which matches closely with the rule of thumb value for transformer losses of 0.5% in thermal kW per kVA of capacity (Faulkenberry and Coffer, 1996). However, transformers can have several different designs that lead to different levels of heat loss. For that reason, detailed heat recovery design should be performed on a case-by-case basis and informed by the rated losses factors that are provided by manufacturers in nameplates. The correlation deployed in this study, shown in Eq. (1), should therefore only be used as a high-level tool for indicating the feasibility of heat recovery projects.

$$\dot{Q}_{heat\ loss} = C \times \left(0.0065L^2 + 0.0005\right) \tag{1}$$

Where: $\dot{Q}_{heat\ loss}$ is total heat loss in kW; C is the total capacity of the transformer in kVA; and L is the electrical loading, expressed as a fraction of the total heat load capacity.

3.3. Transformer temperatures, cooling methods and potential for heat recovery

Brief descriptions of the different types of cooling systems used for transformers, together with schematics, are provided by Daware (2014). Transformers can be divided in two types, namely: (i) dry type transformers; and (ii) oil immersed transformers. The dry type transformers use air as the coolant, either natural or forced (air blast) circulation, and are suitable for transformers up to 15 MVA capacity.

Generally, for transformers with capacities > 15 MVA, heat dissipation from the core and windings is regulated by either natural or forced circulation of mineral oil through the transformer core, i.e. entering at the bottom and exiting at the top. This is termed the internal (or primary) cooling medium. The heat extracted by the oil is then transferred to an external (or secondary) cooling medium, e.g. air or water, which is again regulated by either natural or forced flow. The different cooling system configurations are described by a series of letters, for example: ONAN indicates naturally circulated oil as primary coolant and naturally circulated air as secondary coolant; ONAF indicates naturally circulated oil as the primary coolant, with forced air as the secondary coolant; and OFWF indicates forced oil circulation as primary coolant with forced water circulation as secondary coolant.

The potential for incorporating heat recovery into different transformer cooling methods has been reviewed previously (Strbac et al., 2014). Only transformers using oil circulation primary coolant systems were considered, since for transformers using air as the primary coolant (i.e. < 15 MVA), the quantity of waste heat was likely to be small and heat recovery was considered to be difficult. Strbac et al. (2014) concluded that oil natural/ air natural (ONAN) cooled transformers are typically small and free standing and it was likely to be difficult to harvest the heat, so these systems had low potential for heat recovery. Oil natural/ air forced (ONAF) cooled transformers and oil forced/ air forced (OFAF) cooled transformers were both considered to have medium potential for heat recovery, due to the oil-to-air heat exchanger generally being located in the open air and thereby limiting the opportunity for harvesting the heat. However, oil forced/ water forced (OFWF) cooled transformers were considered to have high potential for heat recovery, since this system offered higher waste heat outputs and enable greater control of the WHR process. ONAF cooling systems are typically used for transformers of between 30 and 60 MVA capacity, and OFAF and OFWF cooling systems for transformers with capacities > 60 MVA (Daware, 2014). The current study has focused on the potential for heat recovery from two large transformers (each of 150 MVA capacity) using a OFWF cooling system.

The highest temperatures in the transformer are within the windings, termed the hot-spot temperature, which is typically 15 K higher than the top oil temperature, which is defined as the average temperature of the oil exiting the transformer and the oil pocket temperature (representing the temperature of the oil in the transformer oil tank) (Roslan et al., 2017). The maximum allowable temperature rise above the external cooling medium, for the winding hot spot, is 78 K and the maximum rise for the top liquid temperature is 60 K (BSI, 2011). In the current study, the top and bottom liquid temperatures for a transformer operating under a range of specified electrical loadings were estimated using the method described by Petrović et al. (2022), whereby the steady-state top oil temperature rise was calculated as:

$$\Delta\theta_{to} = \Delta\theta_{tor}\left(\frac{1+RK^2}{1+R}\right)^x \tag{2}$$

Where: $\Delta\theta_{to}$ is the steady-state top oil temperature rise in K; $\Delta\theta_{tor}$ is the rated steady-state top oil temperature rise in K, assumed to be 55 K; R is the ratio of load losses to no-load losses at rated load; K is the current load, as a fraction of total capacity; and x is the oil exponent, assumed to be 1 for a forced oil cooled transformer. The steady state bottom oil temperature rise is calculated as:

$$\Delta\theta_{bo} = \Delta\theta_{to} - \left(\Delta\theta_{tor} - \Delta\theta_{bor}\right)\left(\frac{1+RK^2}{1+R}\right)^x \tag{3}$$

Where: $\Delta\theta_{bo}$ is the steady-state bottom oil temperature rise in K; $\Delta\theta_{bor}$ is the rated bottom oil temperature rise in K, assumed to be 33 K. Other parameters are as defined above.

The top and bottom oil temperatures θ_{to} and θ_{bo} were calculated from the top and bottom steady-state oil temperature rises $\Delta\ \theta_{\mathrm{to}}$ and $\Delta\ \theta_{\mathrm{bo}}$ by adding them to a reference temperature θ_{ref}, which for OFWF cooled transformers was represented by the water temperature at the inlet to the oil-to-water heat exchanger (in the case of OFAF cooled transformers, the ambient air temperature should be used as θ_{ref}). Eqs. (2) and (3), reported by Petrović et al. (2022), are derived from equations in the International Standard for transformers (IEC, 2018). These equations were applied in this investigation to calculate the outlet (top) and inlet (bottom) oil temperatures for the transformer cooling system, which were assumed equivalent to those entering and leaving the heat recovery heat exchanger. The resolution and range of applicability for these equations will be investigated in future planned experimental work.

3.4. Heat recovery approaches for transformers

Recovering heat from transformers requires linking of the WHR system to the existing cooling system. As indicated in 3.3 above, the internal cooling medium for the transformers of interest is usually oil, which is circulated through the core either naturally or by pumping (i.e. forced). The heat carried by the oil is then transferred (using a heat exchanger), to an external medium, generally either ambient air or water. Recovering the heat for transfer to a DHN (other than for a 5G network or ambient loop), generally requires its temperature to be first upgraded using a HP. Therefore, a HP evaporator heat exchanger would be placed either within the primary or secondary coolant loops to absorb the waste heat, and the HP would then be used to increase its temperature before delivery to the DHN. A number of options for configurations for transformer heat recovery systems are presented in Fig. 1(a) to (c), although other configurations are possible.

For each of the transformer heat recovery systems proposed, it is assumed that the original cooling system would be left in place to act as a backup, in case of failure of the WHR system. Protection of critical infrastructure using backup systems to provide resilience is common practice in industry. It was noted in a previous study (Strbac et al., 2014) that forced cooling systems for transformers will require some form of backup system to cool the transformer in the case of system component,

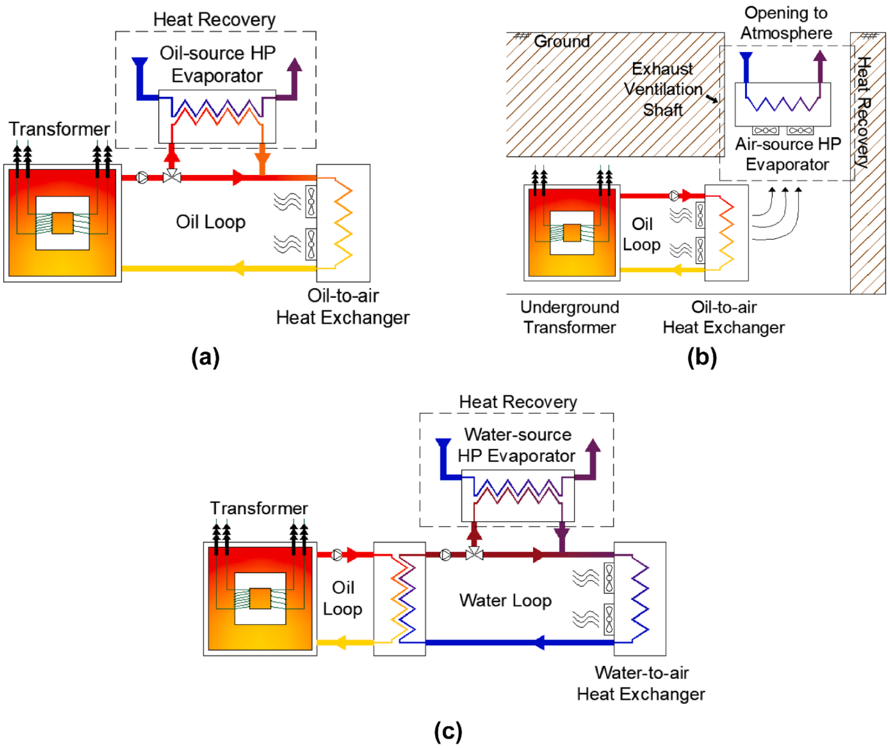


Fig. 1. Potential electrical transformer heat recovery options, for: (a) oil-forced air-forced (OFAF) cooling system; (b) subterranean oil-forced air-forced (OFAF) cooling system; (c) oil-forced water-forced (OFWF) cooling system.

e.g. water pump, failure. Heat recovery systems could either be incorporated into new transformer designs or retrofitted to existing transformer cooling systems.

Fig. 1 (a) shows a cooling system consisting of oil circulating through the transformer core, which is then pumped through an externally located oil-to-air heat exchanger, to dissipate the heat to the atmosphere. To recover this heat, the heated oil exiting the transformer is first passed through an oil-to-refrigerant heat exchanger, the HP evaporator, whereby most of the heat carried by the oil is transferred to the HP and upgraded before delivery to a DHN. Any remaining heat carried by the oil is dissipated using the original (legacy) oil-to-air heat exchanger. Recovering the heat directly from the oil leaving the transformer core, as shown in Fig. 1 (a), has the advantages of permitting the maximum quantity and temperature of waste heat to be captured, i.e. least heat loss, of the three configurations considered. Recovering heat at higher temperatures also offers the best opportunity for reuse, particularly if HP temperature upgrade is needed before delivery to a DHN, by minimising the electrical energy input needed. However, there are a few potential drawbacks for this recovery method. For example, there may be limited space for installation of an oil source HP evaporator heat exchanger between the transformer and existing oil-to-air heat exchanger. Also, installation of a new heat exchanger in the oil loop will increase the pressure drop, requiring increased pumping power for the oil loop. In addition, any leak in the oil source HP evaporator could risk contamination of the oil and the heat recovery system would require complex control systems (Strbac et al., 2014).

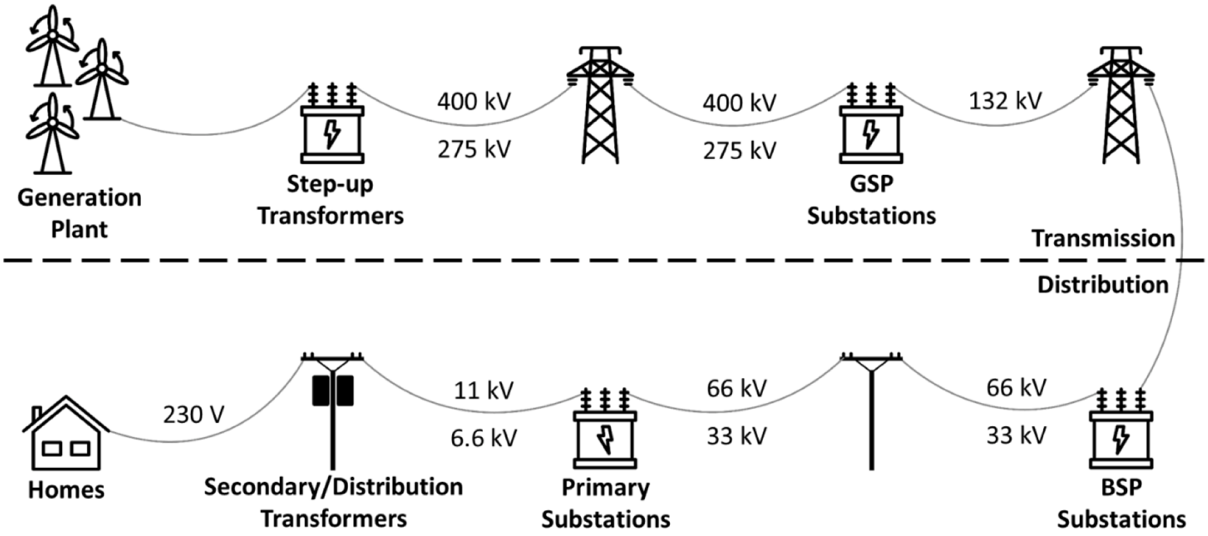


Fig. 2. Types of substations in operation in the UK and their typical operating voltages.

In Fig. 1 (b), the transformer is sited in a subterranean location. The cooling system normally operates similarly to that shown in Fig. 1 (a), with oil circulated through the transformer core and then pumped through an oil-to-air heat exchanger, where the heat is dissipated to the air, and then extracted to the outside via a ventilation shaft. The heat recovery system involves transferring heat from the shaft air to a HP using the evaporator, an air-to-refrigerant heat exchanger, located in the ventilation shaft. Advantages of configuration 1 (b) include that installation would result in minimal interference with the standard operation of the cooling system, and transformer cooling would continue normally in the case of failure of the heat recovery system. Also, since the heated air exhausted from the transformer passes through a ventilation shaft, heat losses from the exhaust air are reduced compared to an uncontained oil-to-air heat exchanger in the open air. A disadvantage, however, is that the temperatures for the recovered will be lower than, for example, configuration 1 (a), since there will be a temperature drop at the oil-to-air heat exchanger and a second temperature drop, due to the approach temperature needed, for the air-source HP evaporator heat exchanger. There will also be some heat loss from the exhausted air into the surrounding ground and due to heated air bypassing the HP evaporator.

Fig. 1 (c) again involves circulating oil through the transformer core to remove the heat, with the oil then pumped through an oil-to-water heat exchanger transferring the heat to water, which is then dissipated through a water-to-air heat exchanger. The heat recovery system involves placing a water-source evaporator within the (secondary coolant) water loop. In the case of configuration 1 (c), installation of a water source HP evaporator within the water loop (which is likely to be larger than the oil loop), is likely to be relatively straightforward, although there will be some increase in the pressure drop in the water loop and this may require a small increase in pumping power. The temperature of the heated water in the water loop is expected to be greater than for the heated air exhausted from the oil-to-air heat exchanger in configuration 1 (b), although less than that of the heated oil used as the HP heat source in configuration 1 (a). One advantage of configuration 1 (c) is that most of the generated heat is captured by the cooling water using an oil-to-water heat exchanger. The heated water can then either be used directly, or upgraded by using a HP. However, a key benefit of this method is that it enables good control of the heat recovery process (Strbac et al., 2014).

3.5. *Types of transformers suitable for applying heat recovery systems*

Large scale electrical power generation sites are generally located remotely to urban areas, and electricity often needs to be transmitted over long distances, i.e. several hundred kilometres, from power stations to end users. To minimise losses, long distance electricity transmission is carried out at high voltages (HV), e.g. 400 kV in the UK. At the end of the main transmission lines, electrical substations known as Grid Supply Point (GSP) substations are sited, containing transformers to step down the voltage, e.g. from 400 to 132 kV. These substations have capacities of several hundred MVA and are typically located in less populated areas (Bowman, 2019). Bulk Supply Point (BSP) substations contain transformers which further step down the voltage, e.g. from 132 to 33 kV. BSPs generally have slightly lower capacities than GSPs and are typically located on the edge of large towns (Bowman, 2019). Primary substation transformers then step down electricity voltages again, e.g. from 33 to 11 kV. These substations have lower capacities, of the order of tens of MVA and are located in urban areas close to residential streets and commercial areas (Bowman, 2019). Secondary or distribution substations, are located close to end users and reduce the voltage from 11 kV to 400 V or 240 V, in the UK, prior to use, but have much lower capacities than primary substation transformers. Fig. 2 provides a diagram showing the different types of substations used throughout the transmission and distribution networks, highlighting their typical operating voltages.

Bowman indicated that the most useful types of electrical substations for heat recovery are BSP and Primary substations (Bowman, 2019). There are estimated to be of the order of 5800 substations of these types in the UK (Northern Powergrid, 2015). DHNs provides only a small proportion (2%) of the UK's heating at present, but a large expansion of district heating is planned in the next few years, as part of climate neutrality plans (CCC, 2019). Electrical substations in the UK are widely distributed and could provide a useful low-carbon heat source for many of these networks.

4. UK potential for substation transformer heat recovery

4.1. *Estimation of national waste heat potential*

The total waste heat generated from electrical substations annually has been calculated by applying Eq. (1) to all transformers of 60 MVA and above located across England, Wales and Northern Ireland. Scotland has not been included in this investigation as its waste heat potential has been reported elsewhere (Sinclair and Unkaya, 2020). A threshold value of 60 MVA has been chosen as, for a loading factor (L) of 0.5, or 50%, this would equate to an annual thermal energy output of approximately 1.2 $\mathrm{GWh.a^{-1}}$, which meets the lower threshold for rural networks to receive funding from the UK's Green Heat Network Fund (GHNF) (DESNZ, 2022b). As waste heat generation (i.e. heat loss from the transformer) is a function of loading, the calculations are sensitive to the assumptions made regarding the value of this parameter, which depends on the power demand on the substation at any particular time. This uncertainty was accounted for in the analysis by considering a range of loading factors L, from 0.4 to 0.6, based upon typical values reported by Strbac et al. (2014). The calculations also assume a continuous operation for transformers (i.e. for 8760 h annually), and uncertainty around downtime for maintenance is covered by the loading range considered.

Utilising waste heat from substations, with capacities in the range of 60 to 80 MVA, might in some cases necessitate combining them with another low-carbon heat source, in order to meet the higher demand threshold of 2 $\mathrm{GWh.a^{-1}}$ for urban heat networks required by the GHNF (DESNZ, 2022b). In fact, many electrical substations have more than one transformer, so heat can be recovered from two or more transformers for these sites, enabling the minimum heat demand requirement to be easily met. Also, some transformers may have higher average loadings than the highest figure of 0.6 (60%) assumed here, for example 0.7 or 0.8 (70 or 80%), which again would allow the minimum heat demand requirement to be met from a single 60 MVA substation transformer. The potential for heat recovery from transformers should therefore be evaluated on a site-by-site basis.

The results from this analysis, with a breakdown of waste heat output per country, are presented in Fig. 3 (a), considering different loading factor assumptions from 0.4 (40%) to 0.6 (60%). It can be observed that most of the waste heat is produced in England, which accounts for 88% of the total estimated annual value. A percentile distribution of the waste heat output for different transformer capacity ranges, for a loading of 50%, is shown in Fig. 3 (b), highlighting how 45% of the waste heat is generated at the 20% largest sites, which have a transformation capacity higher than 276 MVA.

In terms of the temperatures of the waste heat generated by transformers, these vary with the loading level and the reference temperature used. For the present study, a OFWF cooled transformer was assumed with a water inlet temperature of 20 °C. Based on Eq. (2) and a reference temperature of 20 °C, transformer loadings of 40%, 50% and 60% (i.e. 0.4, 0.5 and 0.6), as shown in Fig. 3 (a), would result in oil temperatures leaving the transformer of 33, 37 and 43 °C, respectively.

4.2. *Spatial distribution of transformers in the UK*

The spatial distribution of electrical substations with capacities greater than 60 MVA across England, Wales and Northern Ireland, is shown in Fig. 4 (a). A more detailed map showing electrical substations

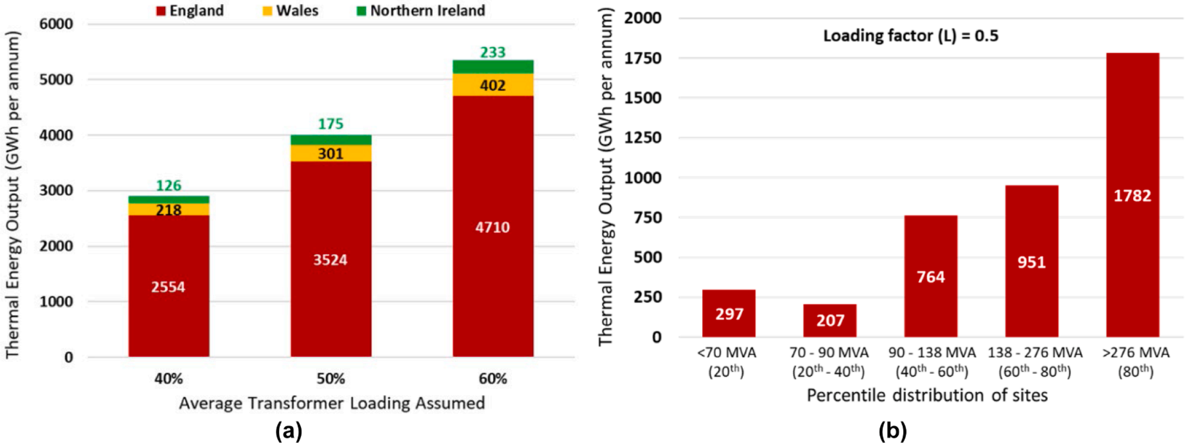


Fig. 3. (a) Estimated annual waste heat output from electrical substations for England, Wales and Northern Ireland, considering different loading factors; and (b) the total annual waste heat output for different site size percentile ranges.

in the Greater London area is shown in Fig. 4 (b) below. All sites were colour-coded to represent which range of annual heat output they fall into, which was calculated using Eq. (1) and assuming a loading factor of 0.5. Fig. 4 (a) shows a concentration of substations in urban areas, for example, clustered around the major cities of Newcastle, Liverpool, Manchester, Leeds, Birmingham and London. The high heat densities associated with these cities represent a great opportunity for the development of heat networks, as identified by DESNZ [2021c]. The Greater London area shown in Fig. 4 (b) has the largest concentration of substations in the UK, with potential for providing more than 5000 MWh of waste heat per annum. Many primary substations (of a suitable size for heat recovery) are sited close to industrial districts and are also likely to be located close to other large users, e.g. university campuses.

Despite having a significant potential, not all substations might be located in areas where a DHN is economically feasible. Petrović et al. (2022) accounted for this by estimating a practical waste heat potential, which considered the distance between substations and existing DHNs in Denmark, a country with a consolidated district heating market, where approximately two thirds of households are connected to a DHN (Johansen and Werner, 2022). In the UK, district heating is still very incipient, with only 2% of heat demand being met by heat networks (which includes communal schemes) (DESNZ, 2021c). Therefore, in order to present a more realistic figure of waste heat potential, the breakdown of electrical substation transformers that are located in predominantly urban areas has been investigated, as shown in Table 1. This analysis was carried out following DEFRA's Urban–Rural classification (DEFRA, 2016), which considers areas with more than 74% of the population in urban settlements to be predominantly urban.

Table 1 provides a breakdown of the number of transformers belonging to each substation type (Primary, BSP and GSP). The percentage of sites located in predominantly urban local authorities is also shown, along with the estimated annual waste heat output for each substation type. As expected, primary and BSP substations tend to be

Table 1
Number of sites, capacity ranges, locality breakdown and annual heat outputs for different substation types.

Substation type	Number of sites	Capacity range (MVA)	Percentage of urban waste heat	Total waste heat output (GWh a^{-1}), loading $L = 0.5$
Primary	298	60–323	77%	516
BSP	745	60–414	60%	1,622
GSP	293	240–1460	52%	1,862
Total	1,336	60–1460	58%	4,000

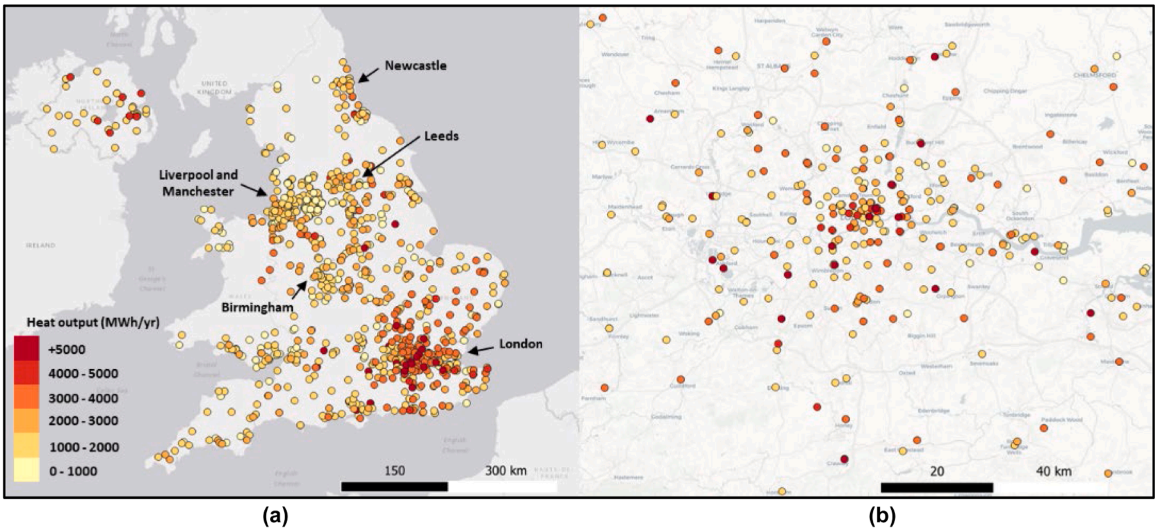


Fig. 4. Locations of electrical substations: (a) across the UK (excluding Scotland); (b) in the Greater London area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

located in urban areas, but it was interesting to note how a significant number of GSPs (52%), which have higher capacities and outputs, are also urban. Overall, approximately 2.3 TWh of waste heat is released annually in urban areas, which represents 58% of the estimated theoretical potential. In future work, it is planned to map the location of suitable substations to determine their proximity relative to potential users of recovered heat, and thereby identify specific opportunities.

5. Modelling of heat recovery system for transformers

5.1. Overall system model

To evaluate the potential of WHR from electrical substation transformers as a heat source for district heating, a complete heat recovery, upgrade and distribution system for delivering the recovered heat to end users was simulated using a spreadsheet model. A schematic showing the main components of the system modelled is shown in Fig. 5.

The recovery of the waste heat from the transformer was assumed to be based on the oil-forced water-forced (OFWF) system shown in Fig. 1 (c), whereby the primary coolant was mineral oil which was pumped through the transformer core removing the heat generated, and then transferred to a secondary coolant water loop. The reasons for selecting configuration 1 (c) compared to configurations 1 (a) and 1 (b) have been discussed in 3.4. To recover the heat for reuse, a water-source HP evaporator was introduced into the water loop between the oil-to-water and water-to-air heat exchangers. The HP then upgraded the recovered heat (which was typically at temperatures between 20 and 40 °C) to the temperature required for delivery to a DHN, which for the current model was assumed to be 75 °C, with a return temperature for the network of 55 °C. These temperatures were chosen as they correspond to the operating temperatures of a DHN in Central London that has been used as reference for this study (Lagoeiro et al., 2022). The heat delivery (i.e. high-temperature) side of the HP also incorporated a short-term thermal energy store (TES) to help balance the supply of heat against the DHN demand. There was also the option to deliver heat to the DHN from additional heat sources, for times when the DHN heat demand exceeded that of both the recovered transformer heat and the TES combined. The transformer recovered heat supply, DHN demand and heat stored in the TES were estimated at hourly intervals throughout the year, i.e. for 8760 hours.

5.2. The case study: heat recovery from a transformer in Central London

In order to assess the benefits of recovering and reusing waste heat from transformers, the developed model was applied to a case study in Central London, where an electrical substation with two 150 MVA transformers is located in close proximity to an existing DHN. Annual heat demands from residential buildings connected to the network were provided by Islington Council and used in three different scenarios to model the benefits of heat recovery for different network sizes. The DHN size was varied by assuming it would connect to a different number of buildings in each of the modelled scenarios, which are described in Table 2 and illustrated in Fig. 6. For all scenarios, it has been assumed that a new DHN would be built, connecting a new energy centre at the electrical substation to end users. The route of the proposed network for the largest scenario (C), which includes 5 residential buildings, is also illustrated in Fig. 6. Scenarios A and B would follow the same route but connect to a smaller number of buildings, as indicated in Table 2.

It is seen that, although following a similar overall pattern of higher heat demand in the winter and low demand during the summer (4000–6000 h), there are some differences in the annual heat demand profiles for the three different scenarios (A, B and C), in addition to the increasing overall heat demand. Scenario A shows the least variation in heat demand across the year, while scenarios B and C show a more distinctive difference in heat demand between summer and winter. In addition, scenario C shows much greater hourly variation in demand throughout the year. These differences in annual hourly heat demand present a significant challenge for matching the transformer recovered heat supply with the heat demand for the three different scenarios.

5.3. Transformer heat loss model

Annual hourly electrical loading data for a pair of transformers were provided by a UK-based electricity DNO. The transformers were operated with N+1 redundancy to provide resilience of power output in the case of single component failure, or when one of the transformers was taken offline for maintenance. Therefore, heat was assumed to be recovered from both transformers, providing a continuous combined output. The loading profile provided was used to calculate the hourly heat losses for a one-year period from two 150 MVA transformers (T1 and T2) using Eq. (1), described earlier. The results for heat output for T1 and T2 were then combined to provide the heat source profile used in the overall system model, covering the period from 1st January to 31st December, as shown in Fig. 7.

The combined heat output profile for transformers T1 and T2 shown in Fig. 7 follows a similar pattern to the transformer loading profile. It is seen in Fig. 7 that there is a steady minimum combined heat output for the two transformers, although there are quite large variations in heat output during the first 4 months of the year (0–3000 h) and particularly during the last month of the year (8000–8760 h). Comparing the

Table 2
The connected buildings, heat demands and network lengths for each of the modelled scenarios.

Scenario	Connected buildings	Annual heat demand (MWh)	Peak heat demand (kW)	Network length (m)
A	1 and 2	2,526	877	1,082
B	1, 2 and 3	4,024	1043	1,602
C	All (1, 2, 3, 4 and 5)	5,411	1245	2,302

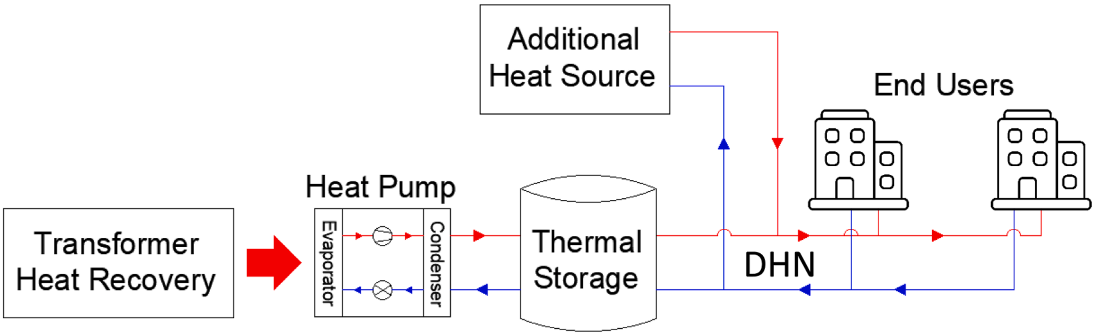
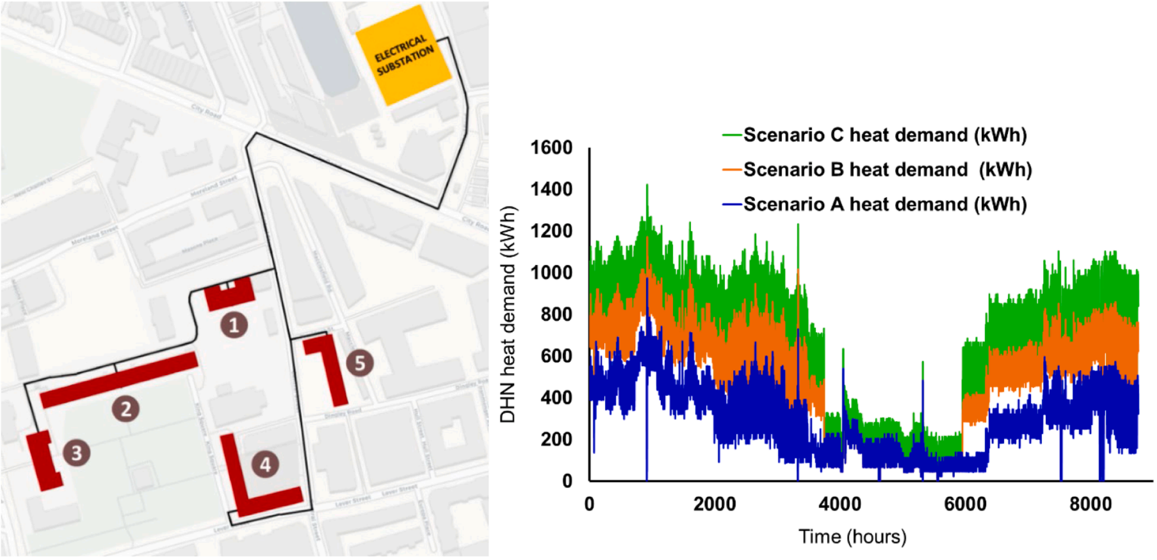


Fig. 5. Overall waste heat recovery and reuse system.



(a)

(b)

Fig. 6. The DHN for the case study, with the connected buildings (a) and hourly demand profiles of each scenario (b).

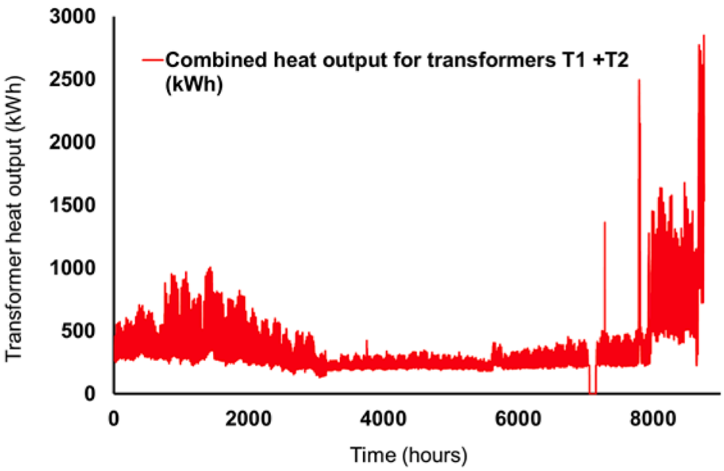


Fig. 7. Combined heat output for transformers T1 and T2, based on the correlation provided in Eq. (1).

combined heat output profile for the transformers (Fig. 7) with the DHN heat demand profiles shown in Fig. 6, it is seen that there are differences, so to efficiently meet the heat demand with waste heat from the transformers is likely to require a number of control measures. The model therefore incorporated control technologies such as a variable speed HP for upgrading the varying supply of transformer recovered heat and thermal storage to regulate the delivery of heat to the DHN. In addition, the HP was switched off at certain times, for example when the heat supply available was lower than the minimum capacity of the HP, or when the TES was fully charged. This avoided inefficient use of the input electrical energy for the HP or generating waste heat in excess of that needed to meet demand.

5.4. Modelling of secondary coolant system

As indicated earlier, the transformers modelled used OFWF cooling. The heat loss, i.e. heat output, from the transformer core and the temperatures of the oil exiting and returning to the transformer, i.e. top and bottom oil temperatures, were estimated using Eqs. (1)–(3). The heat carried by the oil was then transferred to the secondary coolant (water) by means of an oil-to-water heat exchanger. The water circulating in the secondary coolant loop was assumed to have an inlet temperature to the oil-to-water heat exchanger of 20 °C, with the outlet temperature calculated from the incoming oil temperature, assuming 100% of the heat was transferred. The 20 °C minimum water temperature for the secondary coolant was also used as the reference temperature for determining the top and bottom oil temperatures, as specified in the international standard for power transformers (IEC, 2018). As previously described, a HP evaporator was introduced into the water loop to recover the transformer heat for reuse. The heat carried by the water loop was then recovered and upgraded by the HP to the required temperature for distribution by the DHN.

5.5. Heat pump (HP) model

An approach temperature for the HP evaporator of 5 °C was used for recovery of heat from the water loop. However, an approach temperature of 2 °C for the HP condenser was assumed for delivery of heat to the DHN at 75 °C, so a condenser temperature of 77 °C was used in each case. The coefficient of performance (COP) for the HP was calculated using the CoolPack software (CoolPack, 2012), based on a standard single cycle, with ammonia (R717) as refrigerant, for a range of evaporating temperatures. A correlation between COP and evaporating temperature was determined and then incorporated into the model. In order to deal with the varying HP evaporator capacity required to absorb the transformer recovered heat, while maintaining the efficiency (i.e. COP) of the HP, a variable speed HP was used. The HP was assumed to provide speeds and capacities ranging from 25 to 100% of its maximum heat delivery capacity. Different maximum HP heat delivery capacities were selected for the three different DHN heat demand scenarios, based on the highest hourly heat demand that could be met by the upgraded waste heat available, for each scenario. The HP was switched off at capacities of less than 25% and it was assumed that the heat demand would be met from other sources at these times. The HP was also switched off when the waste heat available exceeded the heat demand and the TES was fully charged, to avoid wasting HP input energy. In this case, for the next hourly time step, it was assumed that the heat demand could be met by the TES and no other heat source input was needed. The heat delivered to the DHN by WHR/ HP system and the energy input required for each hourly set of operating conditions were then estimated using the model.

5.6. Thermal energy store (TES) model

The model uses a short-term thermal energy store (TES) to maximise the use of the transformer waste heat by addressing the issue of inconsistent short-term i.e. varying heat demand and waste heat fluctuations, which can lead to both waste heat losses and HP electrical energy input wastage. The thermal energy store (TES) was connected within the DHN in order to store excess heat delivered by the HP at the network delivery temperature of 75 °C. The TES was assumed to consist of a large, sealed, tank, filled with water, initially at the network return line temperature of 55 °C. In order to charge the TES, when the heat output from the HP exceeded the network heat demand, the excess heat (in the form of hot water from the network flow, i.e. delivery line) was added at the top of the TES. This displaced the lower temperature (55 °C) water from the bottom of the tank which was then added to the network return line. Discharging (i.e. using the heat) from the TES, when available, involved drawing the high temperature water from the top of the tank and adding it to the network flow line, while replacing the displaced water in the TES from the network return line. Within the TES, the hot and cold water were assumed to remain stratified in layers, separated by a thermocline transition layer. In practice, the transition layer would slightly reduce the quantity of heat that could be recovered from the TES during discharge, and there would also be some heat loss through the walls of the TES, however, for the purposes of the model, these factors have been neglected. A storage capacity volume of 100 m^3 (equivalent to a thermal capacity of 2291 kWh) was used in the present study. The effectiveness of the TES in regulating the delivery of heat to the DHN for the three different scenarios was compared using the model. The results are reported in Section 6.1.

5.7. Assessment of levelised costs and carbon emissions

The spreadsheet model linked all the various components of the transformer WHR system to predict the heat available under each hourly set of operating conditions throughout the year. This was matched against the heat demands for the range of DHN sizes shown in Table 2. The percentages of heat demand met and heat lost, as well as the energy input needed, were estimated for each set of hourly conditions, and later totalled to determine the annual performance of the system. Electrical energy input for the proposed system was assumed to be used only for the HP, since the electrical pump energy for the forced-oil and forced-water circulation loops were part of the existing transformer cooling system. The outputs from the model were then used to calculate the levelised cost of heat (LCH) of reusing transformer waste heat with a DHN. The LCH can be calculated as shown in Eq. (4), where $CAPEX_a$ and $OPEX_a$ represent, respectively, the annualised capital and operational expenditure associated with the heat recovery scheme, whilst Q_a is the annual heat demand met by the system. The $CAPEX_a$ was calculated separately for each system component (i.e. heat pump, thermal store and DHN), considering the design life (L) of each infrastructure as well as assumed loan repayment period (t) and annual interest rate (i_a), as shown in Eq. (5). As for $OPEX_a$, it combines annual energy running costs (E_a) with both variable ($O\&M_v$) and fixed ($O\&M_f$) operational and maintenance costs, as shown in Eq. (6).

$$LCH = \frac{CAPEX_a + OPEX_a}{Q_a} \tag{4}$$

$$CAPEX_a = \frac{CAPEX(1 + i_a)^t}{L} \tag{5}$$

$$OPEX_a = E_a + O\&M_v + O\&M_f \tag{6}$$

In all scenarios, the loan period for the investment costs was assumed

Table 3
List of assumptions used in levelised cost of heat calculations and their references.

Capital costs			
Assumption	**Value**	**Unit**	**Reference**
Heat recovery system for transformers	968,760	GBP/MW	(Arup, 2020)
Small (∼1 MW) heat pump using waste heat	1,390,957	GBP/MW	[Danish Energy Agency, 2023]
Heat exchanger substation	101,739	GBP/MW	
Pumping station	91,565	GBP/MW	
Small-scale thermal storage tank (steel)	1,170	GBP/m^3	(Revesz et al., 2022)
District heating network	1,170	GBP/m	
Operational costs			
Assumption	**Value**	**Unit**	**Reference**
Commercial/public sector price of electricity in 2025	138.00	GBP/MWh	(DESNZ, 2022c)
Annual heat pump O&M fixed costs	2243	GBP/MW	[Danish Energy Agency, 2023]
Annual heat pump O&M variable costs	3.02	GBP/MWh	
Annual district heating O&M fixed costs	N/A	GBP/MWh	
Annual district heating O&M variable costs	1.53	GBP/MWh	
Annual thermal storage tank O&M fixed costs	56	GBP/unit	
Annual thermal storage tank O&M variable costs	0.79	GBP/MWh	
Financial figures			
Assumption	**Value**	**Unit**	**Reference**
Inflation coefficient from 2015 to 2023	129	%	(Bank of England, 2022)
Exchange rate from EUR to GBP	0.87	N/A	
Inflation coefficient from 2020 to 2023	117	%	
Loan repayment period	10	years	N/A
Loan interest rate	3.5	% p.a.	(European Commission, 2023)
Technology design life			
Assumption	**Value**	**Unit**	**Reference**
Small (∼1 MW) heat pump using waste heat	25	years	[Danish Energy Agency, 2023]
Small-scale thermal storage tank (steel)	30	years	
District heating network	50	years	

to be 10 years with an interest rate of 3.5% (European Commission, 2023), and all the assumptions used in LCH calculations are listed in Table 3. The cost benchmarks were mainly obtained from the Danish Energy Agency's technology catalogue, and values shown in Table 3 are the final benchmarks in GBP after conversion from EUR, considering the inflation and exchange rates also shown in Table 3. The LCH values calculated for each scenario were then compared to the operational costs for alternative forms of heating, which include air-source heat pumps (ASHPs), a low-carbon alternative, and natural gas boilers, the most common heating technology in the UK. In this case, central projections of domestic prices for electricity (£348.30 per MWh) and natural gas (£85.7 per MWh) in 2025 were used, as published by DESNZ (2022c). The carbon emissions of the proposed system were also calculated and compared to the emissions of meeting the same heat demand with gas boilers and ASHPs. The carbon intensity factors for electricity and gas used for this analysis were, respectively, 0.129 tCO_2e per MWh and 0.183 tCO_2e per MWh (DESNZ, 2022c). A typical efficiency of 90% was assumed for gas boilers, whereas a seasonal COP of 2.68 was assigned to ASHPs, based on a survey carried out by the Energy Saving Trust (2013).

6. Results and discussion

6.1. WHR model: outputs and technical analysis

The model was first applied to analyse how the heat recovery system coupled to a 100 m^3 TES tank would perform when connected to the range of DHN sizes described in Table 2, and the results of this analysis are shown in Table 4.

As seen in Table 4, the share of heat demand met by the heat recovery HP reduced as the size of the network increased; whilst 98.4% of the heat demand was met with the HP for scenario A, this share reduced to 83% for scenario B and 66.1% for scenario C. This was associated with the HP capacity being limited by the amount of waste heat available from the transformer, as periods of peak heat demand did not necessarily coincide with hours of higher waste heat generation from the transformers. However, connecting the heat recovery system to higher demands enabled more waste heat to be exploited. It is seen that while only 56% of the available transformer heat was used in scenario A, 75% and 81% of the heat output was used for scenarios B and C, respectively. The results also indicated that thermal energy storage played a greater role in scenarios with lower demands, with approximately 30% of the generated heat stored in scenario A, while only 12.2% and 8.6% were stored in scenarios B and C, respectively. Across all scenarios, the HP seasonal COP was 3.40, which was expected as the control strategy simulated was based on a fixed water inlet temperature of 20 °C being used to cool the transformer oil, with a fixed delivery temperature of 75 °C.

Table 4
Modelling outputs for the transformer heat recovery system for a range of DHN sizes.

WHR/HP/DHN demand parameters:	Scenario A	Scenario B	Scenario C
Annual heat demand (MWh)	2,526	4,024	5,411
Heat generated by HP annually (MWh)	2,734	3,674	3,935
Heat delivered by HP annually, excludes distribution losses (MWh)	2,486	3,340	3,577
Share of heat demand met by HP annually	98.4%	83.0%	66.1%
Annual HP energy consumption (MWh)	804	1,080	1,156
Linear heat density, considering heat generated by HP (MWh/m)	2.53	2.29	1.71
HP capacity, assumed equal to peak heat demand (kW)	877	1,043	1,245
WHR system capacity (kW)	691	822	981
Heat generated to HP capacity ratio (MWh/kW)	3.12	3.52	3.16
Heat stored in TES tank annually (MWh)	819	446	339
Share of heat stored in TES tank	30.0%	12.2%	8.6%
Waste heat from transformer reused annually (MWh)	1,930	2,594	2,779
Share of waste heat available from transformer used annually	56%	75%	81%
Share of annual heat demand met with waste heat	69%	59%	47%

Fig. 8 provides graphical representations of the annual profiles for the HP delivered heat compared to the DHN heat demand for the three different network sizes, i.e. scenarios A, B and C.

It is seen in Fig. 8 (a) that a close match between the HP delivered heat and heat demand was achieved for Scenario A, but the heat demand slightly exceeded the HP delivered heat for Scenario B in Fig. 8 (b), and heat demand markedly exceeded the HP delivered heat for Scenario C in Fig. 8 (c).

Fig. 8 (b) and (c) show substantially more hourly variation in heat demand than for Fig. 8 (a), and, since a greater proportion of the waste heat was used for scenarios B and C, there was a greater degree of variation in the HP delivered heat. As a result of the control strategy of switching off the HP for capacities less than 25% of the maximum, for the higher HP capacities used for scenarios B and C, the HP was switched off increasingly frequently, as seen in Fig. 8 (b) and (c).

Overall, a fairly close match between the available waste heat supply (after HP upgrade) and the DHN heat demand was achieved for all three scenarios. However, this involved the implementation of three different control strategies within the model and suggests that matching a variable waste heat source supply, e.g. from transformers, against a varying DHN heat demand using minimal input energy is a significant challenge.

6.2. Economic and environmental performances

A comparison of the levelised costs for the WHR/ HP system against the running costs for gas boilers and ASHPs is shown in Fig. 9. The contributions of different costs to the final levelised figure of each scenario are also indicated. As it can be observed, Scenario B obtained the lowest LCH value of £107.58 per MWh, as opposed to £112.10 and £117.44 per MWh for Scenarios A and C, respectively. The analysis of the LCH breakdown provides some interesting insights into the key contributors to the levelised cost of waste heat. Scenario C, for instance, obtained a much higher contribution from DHN CAPEX (£23.14 per MWh). This is associated with a much longer network – approximately 50% longer than Scenario B – being required to connect to buildings 4 and 5, while only increasing the overall heat demand by 34%. This emphasised the relevance of high heat demand densities to the economics of district heating.

Another key contributor to the different LCH achieved was the CAPEX for the heat generation and storage infrastructure. Although Scenario A benefitted from a higher linear heat density (2.53 MWh/m), it still required significant CAPEX for the generating plant due to its high peak demand. WHR, HP and TES CAPEX contributed with £45.10 per MWh to the LCH of Scenario A, whereas Scenario B had the lowest contribution of £39.60 per MWh, which is strongly related to the higher ratio of heat produced to system capacity (3.62 MWh/kW), as shown in Table 2. This means the HP from Scenario B produced more heat per kW of installed capacity than in the other scenarios.

The comparison of LCH against conventional forms of heating also produced interesting results. All scenarios obtained lower LCH than the operational cost of an ASHP, with savings of up to £22.42 per MWh (17.2%) being obtained for Scenario B. This indicates the value of waste heat as a resource that can be exploited to increase the energy efficiency of low-carbon heating systems, helping to reduce costs associated with decarbonisation. However, the levelised costs of heat in all scenarios were higher than the cost of running a 90% efficient gas boiler. A MWh of heat delivered through the best performing scenario (B) would be £12.38 more expensive than producing the same amount of energy with a boiler. This indicates a significant challenge for future policy makers, as the disparity in cost between gas and electricity remains a major

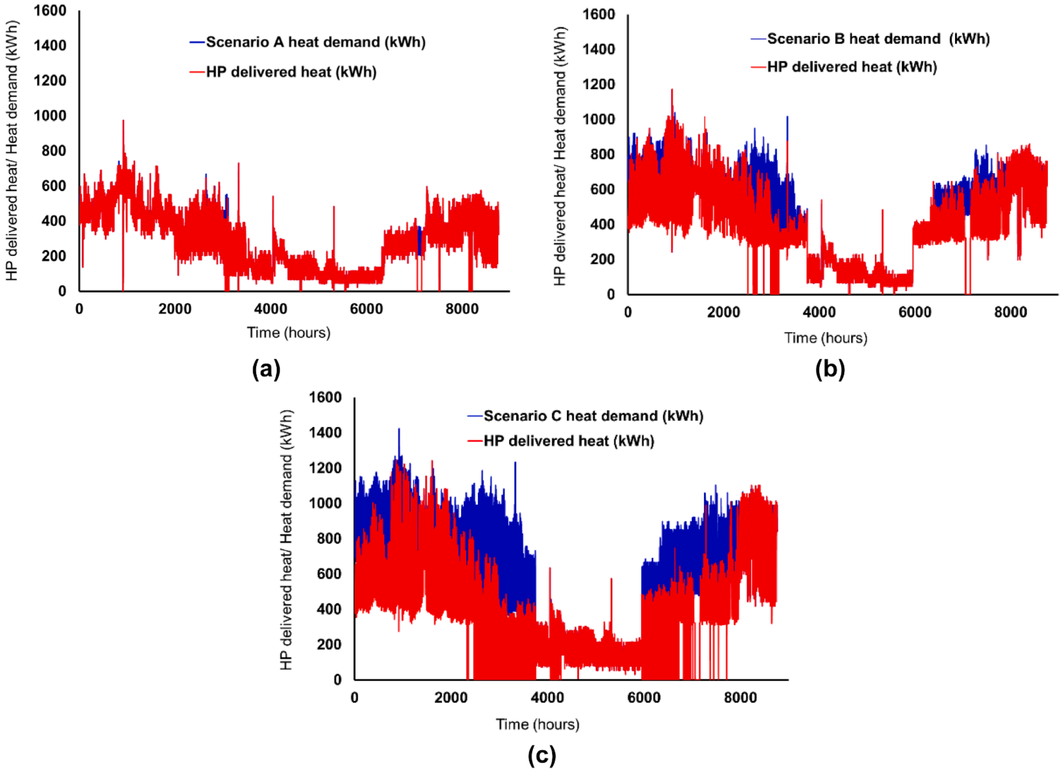


Fig. 8. Annual variation in HP output and total building heat demand for (a) scenario A; (b) scenario B; (c) scenario C.

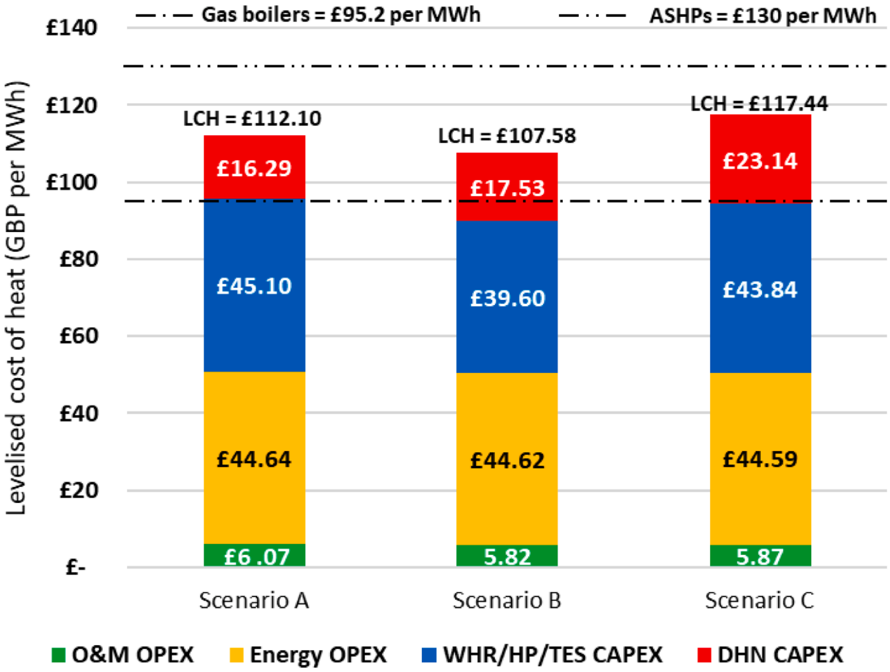


Fig. 9. Levelised cost of heat comparison between each modelled scenario and conventional technologies.

barrier to the widespread adoption of low-carbon heating technologies. Rebalancing gas and electricity costs remains a priority for the UK Government, which plans to put together a strategy for tackling this issue in 2023–2024 (DESNZ, 2023). The energy efficiency gains associated with WHR can also be observed in Fig. 10, which shows the operational carbon emissions of each scenario compared to ASHPs and gas boilers. As it can be seen across all scenarios, the proposed system is able to achieve carbon savings of approximately 13.3% and 79.5% when compared to ASHPs and gas boilers, respectively.

7. Conclusions

The results from the modelling work suggest that recovering and reusing heat from transformers via district heating is feasible in urban settings. The economic analysis was based on real data including industry supplied electrical loading data for transformers and details of an

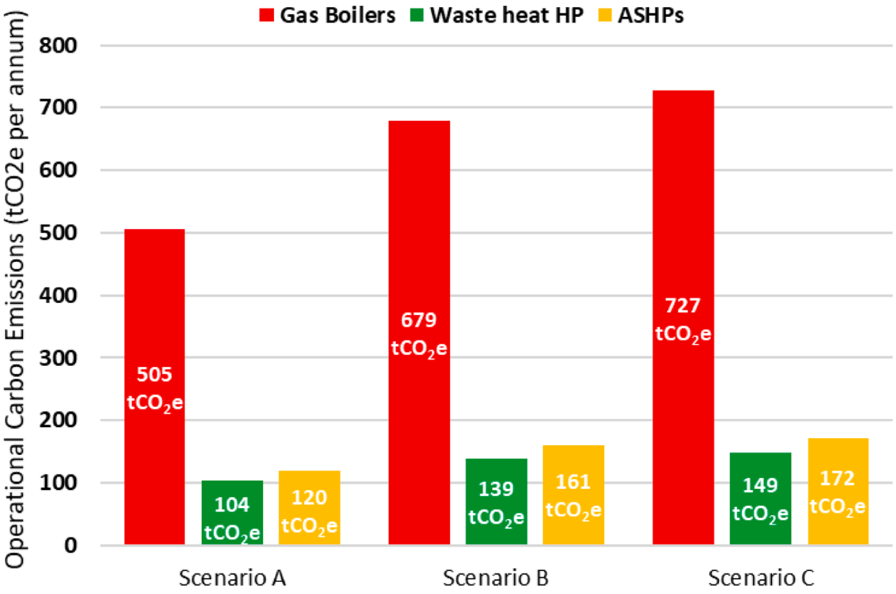


Fig. 10. Operational carbon emissions comparison between each modelled scenario and conventional technologies.

existing heat network, which included hourly heat demand profiles and locations/ distances between heat sources and users, enabling estimation of both operating and capital costs for the overall WHR/ heat delivery system. The results of the analysis demonstrated that the proposed system could achieve a LCH that is up to 17.2% lower than the operating costs of domestic ASHPs. The LCH for the best performing scenario was also only 13.2% higher than the running costs of a gas boiler. With the current and planned support for low-carbon heat networks, such as the GHNF, which funds up to 50% of a project's total combined commercialisation and construction costs (DESNZ, 2022b), waste heat could become more cost-effective than the incumbent technology. There is also a clear environmental benefit, as the higher COPs achieved with waste heat lead to lower operational carbon emissions when compared to ASHPs.

The case study presented provided new and valuable insights on how to best incorporate waste heat from a transformer into a DHN. The shares of waste heat recovered and the total heat demand met varied across different scenarios, which in turn impacted the economics of the system. Although the two scenarios with higher heat demands provided greater opportunities for waste heat integration, their economic performances were highly sensitive to their linear heat densities, as these impacted investment costs significantly. This reinforces the importance of considering the local context when designing a WHR system. An understanding of the heat source and its behaviour is also essential. Waste heat availability is a quadratic function of electrical loading; as this study used a loading profile from a particular substation, a range of transformer capacities and additional annual hourly transformer loading profiles would be needed to further investigate the likely range of operating conditions for such WHR systems. The current study has also highlighted the need for suitable control measures for the transformer WHR system. One such measure is to apply a variable speed HP to maximise heat recovery efficiency and minimise electrical energy consumption when managing the widely varying profiles of transformer loading and heat loss. Due to the fluctuating nature of transformer loading, waste heat output varies significantly, meaning transformers might be best applied in larger networks when combined with a stable primary heat source (e.g. industrial waste heat or geothermal).

There are further benefits for the substation itself, for example by cooling the transformer to lower temperatures than can be achieved by ambient air. This could potentially reduce hot-spot temperatures and enable loadings to be increased without affecting transformer lifespan. The concept proposed in this paper is replicable across many of the primary, BSP and GSP substations in the UK, as well as overseas. A theoretical waste heat potential of 4.0 TWh a^{-1} has been identified from these types of substations in England, Wales and Northern Ireland, equivalent to 0.9% of the annual heat demand for these countries, considering a loading factor of 0.5. Further work is planned to carry out a practical study investigating the installation and performance of a transformer heat recovery system in conjunction with a major electricity DNO in the UK, which should provide further insight into the practicality and viability of these systems.

CRediT authorship contribution statement

H. Lagoeiro: Conceptualisation, Methodology, Data curation, Investigation, Visualisation, Writing – original draft, Project administration. **G. Davies:** Conceptualisation, Methodology, Data curation, Investigation, Writing – review & editing, Visualisation. **C. Marques:** Data curation, Investigation, Funding acquisition. **G. Maidment:** Conceptualisation, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data for which the authors had sharing permission, which include information on substation types and transformer capacities, can be accessed online at: https://doi.org/10.18744/lsbu.92wq6.

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References

Arup, 2018. Northern powergrid LDR tranche 1 - transformer heat recovery transformer heat recovery project report. Available online: https://www.northernpowergrid.com/downloads/339. (Accessed 30 January 2023).

Arup, 2020. Waste Heat Research – Technology Summary Reports. Commissioned by the Department of Business Energy and Industrial Strategy.

Bowman, J., 2019. Project SHOES: Secondary Heat Opportunities from Electrical Substations (MSc Thesis). London South Bank University, London, UK.

British Standards Institute (BSI), 2011. Power Transformers Part 2: Temperature Rise for Liquid Immersed Transformers. BSI, London.

Cipolla, S., Maglionico, M., 2014. Heat recovery from urban wastewater: Analysis of the variability of flow rate and temperature. Energy Build. 69, 122–130.

Climate Change Committee (CCC), 2019. Net zero: The UK's contribution to stopping global warming. Available online: https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf. (Accessed 19 July 2022).

CoolPack, 2012. IPU & Department of Mechanical Engineering. Technical University of Denmark, Available online, . (Accessed 10 July 2022).

Davies, G., Maidment, G.G., Tozer, R.M., 2016. Using data centres for combined heating and cooling: An investigation for London. Appl. Therm. Eng. 94, 296–304.

Daware, K., 2014. Cooling methods of a transformer. Available online: https://www.electricaleasy.com/2014/06/cooling-methods-of-transformer.html. (Accessed 8 August 2023).

Dénarié, A., Fattori, F., Spirito, G., Macchi, S., Cirillo, V.F., Motta, M., Persson, U., 2021. Assessment of waste and renewable heat recovery in DH through GIS mapping: The national potential in Italy. Smart Energy 1, 100008.

Department for Energy Security & Net Zero (DESNZ), 2021a. Provisional UK greenhouse gas emissions national statistics 2020. Available online: https://www.gov.uk/government/statistics/provisional-uk-greenhouse-gas-emissions-national-statistics-2020. (Accessed 23 June 2021).

Department for Energy Security & Net Zero (DESNZ), 2021b. Heat and buildings strategy. Available online: https://www.gov.uk/government/publications/heat-and-buildings-strategy. (Accessed 26 October 2021).

Department for Energy Security & Net Zero (DESNZ), 2021c. Opportunity areas for district heating networks in the UK national comprehensive assessment of the potential for efficient heating and cooling. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1015585/opps_for_dhnnca_hc.pdf. (Accessed 20 July 2022).

Department for Energy Security & Net Zero (DESNZ), 2022a. Digest of UK energy statistics 2022. Available online: https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2022. (Accessed 18 September 2022).

Department for Energy Security & Net Zero (DESNZ), 2022b. Green heat network development fund round 1: Guidance for applicants, 2022. Available online: https://www.gov.uk/government/publications/green-heat-network-fund-ghnf. (Accessed 15 November 2022).

Department for Energy Security & Net Zero (DESNZ), 2022c. Greenhouse gas reporting: Conversion factors 2022. Available online: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022. (Accessed 30 January 2023).

Department for Energy Security & Net Zero (DESNZ), 2023. Shapps sets out plans to drive multi billion pound investment in energy revolution. Available online: https://www.gov.uk/government/news/shapps-sets-out-plans-to-drive-multi-billion-pound-investment-in-energyrevolution#:~:text=Driving%20household%20electricity%20bills%20down,electrification%20for%20households%20and%20businesses. (Accessed 2 August 2023).

Department for Environment, Food & Rural Affairs (DEFRA), 2016. 2011 Rural-urban classification of local authority districts in England: Methodology. Available online: https://www.gov.uk/government/statistics/2011-rural–urban-classification-of-local-authority-and-other-higher-level-geographies-for-statistical-purposes. (Accessed 8 November 2022).

Dorotić, H., Čuljak, K., Miškić, J., Pukšec, T., Duić, N., 2022. Technical and economic assessment of supermarket and power substation waste heat integration into existing district heating systems. Energies 15, 1666, 2022, Available online: https://doi.org/10.3390/en15051666. (Accessed 30 January 2023).

Energy Saving Trust, 2013. The heat is on: Heat pump field trials: phase 2. Available online: https://www.energysavingtrust.org.uk/sites/default/files/reports/TheHeatisOnweb%281%29.pdf. (Accessed 13 April 2021).

Energy Saving Trust, 2021. District heating. Available online: https://energysavingtrust.org.uk/service/district-heating. (Accessed 20 July 2022).

Energy Systems Catapult (ESC), 2020. Decarbonisation of heat: Why it needs innovation. Available online: https://es.catapult.org.uk/brochures/decarbonisation-heat/. (Accessed 23 June 2021).

Bank of England, 2022. When will inflation come down? Available online: https://www.bankofengland.co.uk/knowledgebank/will-inflation-in-the-uk-keep-rising. (Accessed 30 September 2022).

European Commission, 2023. Reference and discount rates (in %) since 01.08.1997. Available online: https://competition-policy.ec.europa.eu/state-aid/legislation/reference-discount-rates-and-recovery-interest-rates/reference-and-discount-rates_en. (Accessed 31 July 2023).

Faulkenberry, L.M., Coffer, W., 1996. Electrical Power Distribution and Transmission, first ed. Prentice-Hall Inc, New Jersey.

Foster, S., Love, J., Walker, I., Crane, M., 2016. Heat pumps in district heating – report for department of energy and climate change. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/502500/DECC_Heat_Pumps_in_District_Heating_-_Final_report.pdf. (Accessed 20 July 2022).

Institute of Electrical and Electronics Engineers (IEEE), 2000. The Authoritative Dictionary of IEEE Standards Terms, Seventh Ed. IEEE, New York, USA.

International Electrotechnical Commission (IEC), 2018. BS international standard IEC 60076-7-2018. In: Power Transformers – Part 7: Loading Guide for Mineral- Oil-Immersed Power Transformers.

International Energy Agency (IEA), 2022. How europe can cut natural gas imports from Russia significantly within a year. Available online: https://www.iea.org/news/how-europe-can-cut-natural-gas-imports-from-russia-significantly-within-a-year. (Accessed 22 June 2022).

Islington Council, 2020. World-First Scheme Is Launched using Waste Heat from the Tube to Warm Homes. two leisure centres and a school in Islington. Available online https://www.islington.media/news/bunhill-2-launch-pr. (Accessed 4 January 2023).

Johansen, K., Werner, S., 2022. Something is sustainable in the state of Denmark: A review of the Danish district heating sector. Renew. Sustain. Energy Rev. 158, 112117.

Kennedy, B.W., 1998. Energy Efficient Transformers, first ed. McGraw-Hill, New York, USA.

Lagoeiro, H., Wegner, M., Revesz, A., Davies, G., Curry, D., Vivian, J., Faulks, G., Murphy, D., Maidment, G., 2022. Recovering Waste Heat from the London Underground: Sizing the Opportunity. In: Proceedings from the World Sustainable Energy Days Young Energy Researchers Conference. Wels, Austria.

Lund, H., Østergaard, P.A., Nielsen, T.B., Werner, S., Thorsen, J.E., Gudmundsson, O., Arabkoohsar, A., Mathiesen, B.V., 2021. Perspectives on fourth and fifth generation district heating. Energy 227, 120520.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J.E., Hvelplund, F., Mathiesen, B.V., 2014. 4Th generation district heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy 68, 1–11.

Northern Powergrid, 2015. Adapting to climate change. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/478920/clim-adrep-northern-powergrid-2015.pdf. (Accessed 20 July 2022).

Office for National Statistics (ONS), 2022. Energy prices and their effect on households. Available online: https://www.ons.gov.uk/economy/inflationandpriceindices/articles/energypricesandtheireffectonhouseholds/2022-02-01. (Accessed 22 June 2022).

Persson, U., Averfalk, H., Nielsen, S., Moreno, D., 2020. ReUseHeat project – accessible urban waste heat (revised version). Available online: https://www.reuseheat.eu/wp-content/uploads/2021/02/D1.4-Accessible-urban-waste-heat_revised-compressed.pdf. (Accessed 4 January 23).

Petrović, S., Bühler, F., Radoman, U., McKenna, R., 2022. Power transformers as excess heat sources – a case study for Denmark. Energy 239, 122416.

Revesz, A., Dunham, C., Jones, P., Bond, C., Fenner, R., Mody, S., Nijjhar, R., Marques, C., Maidment, G., 2022. A holistic design approach for 5th generation smart local energy systems: Project GreenSCIES. Energy 242, 122885.

Revesz, A., Jones, P., Dunham, C., Davies, G., Marques, C., Matabuena, R., Scott, J., Maidment, G., 2020. Developing novel 5th generation district energy networks. Energy 201, 117389.

Roslan, M.H., Azis, N., Ab Kadir, M.Z.A., Jazni, J., Ibrahim, Z., Ahmad, A., 2017. A simplified top-oil temperature model for transformers based on the pathway of energy transfer concept and the thermal-electrical analogy. Energies 10 (11), 1843.

Sinclair, C., Unkaya, G., 2020. Potential sources of waste heat for heat networks in Scotland. Available online: https://era.ed.ac.uk/handle/1842/37445. (Accessed 20 July 2022).

SSE Energy Solutions, 2021. SSE and national grid pilot project to use electricity transformers to heat homes. Available online: https://www.sse.com/news-and-views/2021/08/sse-and-national-grid-pilot-project-to-use-electricity-transformers-to-heat-homes/. (Accessed 10 July 2023).

Strbac, G., Djapic, P., Ortega, E., Stanojevic, V., Kairudeen, S., Markides, C., Heyes, A., Aunedi, M., Papadaskalopoulos, D., Brook, R., Hawkins, D., Samuel, B., Smith, T., Sutton, A., 2014. Management of Electricity Distribution Network Losses. Imperial College and Sohn Associates Report. Available online https://www.westernpower.co.uk/downloads/4847. (Accessed 15 November 2022).

Wahlroos, M., Pärssinen, M., Manner, J., Syri, S., 2018. Utilizing data center waste heat in district heating – impacts on energy efficiency and prospects for low-temperature district heating networks. Energy 140, 1228–1238.