

Review

Opportunities for Integrating Underground Railways into Low Carbon Urban Energy Networks: A Review

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Abstract: Cities demand vast amounts of energy for their everyday operation, resulting in significant degradation of energy in the form of heat in the urban environment. This leads to high cooling requirements in cities, while also presenting the opportunity to reuse such waste heat in order to provide low-carbon heating for buildings and processes. Among the many potential energy sources that could be exploited in urban areas, underground railway tunnels are particularly attractive, as the operation of the trains produce considerable amounts of heat throughout the year. This paper reviews how secondary energy sources in urban areas can be integrated into heating and cooling networks, with emphasis on underground rail tunnels. This involves investigating potential urban waste heat sources and the existing state-of-the-art technologies that could be applied to efficiently recover this secondary energy, as well as analyzing how district heating and cooling networks have been a key mechanism to allow for a smooth transition from current fossil fuel based to future low-carbon energy sources.

Keywords: waste heat recovery; district energy; heat networks; heat pumps; railway tunnels; London Underground; low-carbon heating

1. Introduction

Cities consume about 70% of the world's resources and hence are major consumers of energy and significant contributors to greenhouse gas (GHG) emissions. This is due to the density of urban population, the intensity of related economic and social activities, and also to the inefficiency of the built environment [1]. It is estimated that two-thirds of the world's energy is consumed in cities, which account for more than 70% of global CO₂ emissions [2]. This demonstrates how cities are already at the forefront of climate change mitigation and reveals the great challenge that lies ahead, as the future expansion of cities will increase the demand for services and resources in the urban environment. For that reason, increasing the efficiency of buildings and energy systems, as well as introducing innovative low carbon approaches to meet energy requirements in urban areas is critical if the world is to meet its target of limiting global warming to 1.5 °C above pre-industrial levels [3].

Currently, around 12.5% of the world's population still has no access to electricity and the growing efforts to universalize energy access is likely to increase global energy demand by at least a quarter by 2040 [4]. This growing demand, mostly related to urban areas in emerging economies, will have to be dealt with in a time when urgent action is required to change the global energy matrix, as nearly 91% of the world's total primary energy supply came from fossil fuels in 2016 [5]. This scenario highlights the important role to be played by energy efficiency measures and zero/low carbon energy sources in speeding up the energy transition required to tackle climate change. Much of the intensive energy consumption in cities worldwide can be attributed to the built environment, as buildings and their

construction processes account for around 40% of global CO₂ emissions and 36% of final energy use, with 36% of building energy consumption being related to heating [6]. This shows the potential impact that decarbonization of heating and investments in energy efficiency could have in achieving the world's energy targets.

1.1. Europe

In Europe, according to the authors of [7], around 50% of the energy consumed in 2015 was for heating and cooling purposes, with nearly 31% being related to space heating and domestic hot water. Despite representing such a vast proportion of energy use, only 19.1% of the heating and cooling demands in 2016 were met using renewable energy sources [8]. Up to this date, the shares of renewables used to provide heating and cooling vary widely amongst European countries due to different historical developments of national energy systems, which are affected by many factors such as economic stability, local climate and availability of fossil fuels, and policy frameworks and drivers. Figure 1 shows the shares of renewable energy sources used for heating and cooling for the European Union (EU) and the United Kingdom (UK), both highlighted in blue, and the other 27 member countries.

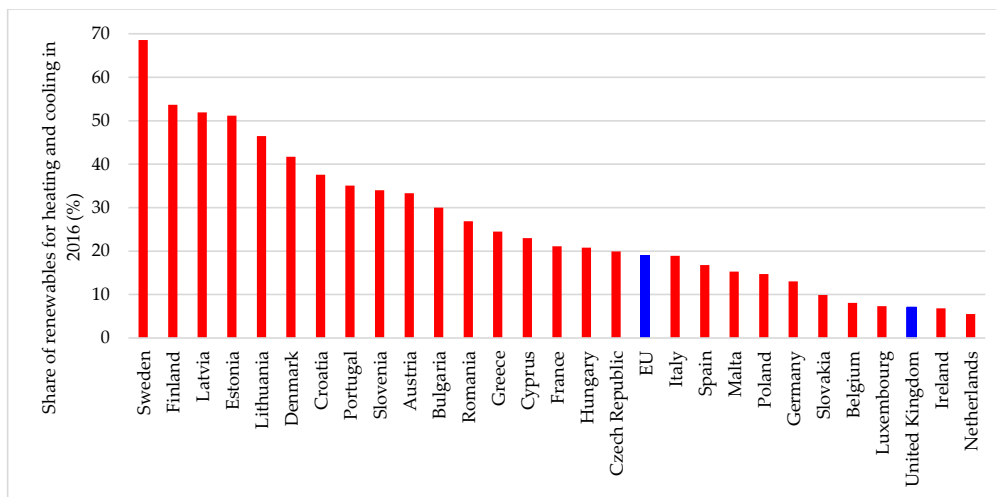


Figure 1. Shares of renewable energy sources used for heating and cooling for the EU and its 28 member countries in 2016 [8].

1.2. The United Kingdom

The UK has one of the lowest shares of renewable energy used to provide heating and cooling in Europe, with only 7% of its demand being met with renewables, as shown in Figure 1. This demonstrates the challenge that will be faced in the coming years as the UK aims to decarbonize its economy and reduce GHG emissions by 80% by 2050 in comparison to 1990 levels, with the latest report by the Committee on Climate Change (CCC) asking for a new set of policies to achieve a more ambitious target of net-zero GHG emissions by 2050 [9]. The heating and cooling industry will play an important role in achieving that goal, particularly as heating and cooling account for approximately a third of carbon emissions and around half of the energy consumption in the UK [10]. In order to stimulate low carbon heating, the UK government set in place the Renewable Heat Incentive (RHI) in 2011, a financial refund linked to the quantity of heat generated from renewable sources. However, this incentive will expire in March 2021, and it is still not clear what the Government's plans are in terms of encouraging low carbon heat sources in the next decades, which will be a key driver to decarbonize the energy sector in the UK.

Sustainable heating is also a problem at a city level in the UK. In London, nearly 90% of the heating sources used to warm buildings are gas-fired boilers, posing a threat not only in terms of climate change

but also for air pollution [11]. London's 3.5 million homes produce one third of the capital's total GHG emissions and nearly 75% of the energy consumed by homes is used to provide space and hot water heating. Meanwhile, workplaces account for approximately 40% of the city's emissions, with half of their energy demand being related to heating [11]. The Greater London Authority (GLA) has a bold plan to make London a zero carbon city by 2050, which is aligned with the latest recommendation from the CCC for the national emission reduction target. It is clear that, if London and the UK want to decarbonize their energy systems, their heat generation needs to be transformed to be based on low carbon heating alternatives.

For a metropolis such as London and other cities in the UK and around the globe, waste heat recovery systems represent a unique opportunity to make use of the surplus heat that is wasted in a variety of urban infrastructures, as has been identified in [9,11]. In addition to using low carbon heat, these systems unlock the potential to generate and distribute energy locally through district energy networks, which increase the efficiency of the overall energy system, helping to reduce the carbon footprint associated with heating while also tackling fuel poverty. This paper aims to explore the opportunities of waste heat recovery in the urban environment, with particular focus on recovering heat that is generated in underground railway tunnels, and its distribution through district heating networks (DHNs), showing how the combination of these technologies can become a key tool for changing the provision of heating in the smart cities of the future.

2. District Energy

District energy systems, or district heating and cooling (DHC), can be defined as networks that provide either heating or cooling from a central point of generation to multiple buildings within a district, neighborhood or city [12]. These systems have been widely applied as a way to provide low carbon energy to end users, leading to significant financial and environmental benefits. From an economic perspective, DHC systems benefit from economies of scale, as utilizing the energy produced from one larger source can often be more efficient than using a variety of smaller sources. In terms of environmental benefits, heating and cooling networks allow the use of locally available energy sources that can be renewable or based on the recovery of energy that would otherwise be wasted, increasing the overall efficiency of the energy system. Another advantage of district energy systems is their flexibility; by enabling the integration of a diverse number of energy sources, end users are not dependent upon one single source, which leads to greater energy security and permits alternating the different energy sources used in order to guarantee the most cost-effective and low carbon operation of the energy system.

A similar definition is provided in [13], which also calls for the adoption of a modernized definition of district energy, combining decentralized power generation and DHC networks. This involves integrating renewable electricity to networks that recover and distribute low-grade heat and cold to end users, helping to balance intermittent renewable power generation by converting it to thermal energy when costs are low and storing that energy to be used seasonally or during daily peak demands. The integration of decentralized power to district energy systems enables the optimized use of energy resources by matching local energy production and demand, an essential feature of future energy systems, particularly as it helps to alleviate high peak demands that can stress the electricity grid. Photovoltaic (PV) panels represent an example of a decentralized renewable power sources that can provide low carbon energy with lower transmission losses to meet the demand for thermal energy, whether it relates to heating or cooling requirements. In temperate climate countries, such as the UK, heating represents a significant reason for energy consumption and carbon emissions, which makes heat networks an important technology to make heating cleaner and more affordable, helping to fight climate change while expanding energy access. For that reason, this paper focuses on the delivery of heat through district energy systems, showing how district heating can trigger the potential to recover waste heat generated in urban environments.

District Heating

Heat networks represent an interesting alternative to deliver cost-effective low carbon heat, as they enable the use of a wide range of low carbon sources, including renewable and waste heat, and are able to incorporate new buildings and heat sources as the network grows, being particularly attractive in urban areas, where concentrated demands minimize distribution costs and heat losses. As they allow heat generated from different sources to be used, DHNs also avoid a lock-in to technologies that may become obsolete in future decades. This feature provides a key mechanism to allow a smooth transition from current fossil fuel based heating to future low carbon thermal grids.

The recovery of urban waste heat represents a low carbon alternative to conventional heating methods that is often only feasible when district heating is deployed, as it allows the waste heat to be efficiently distributed to where end users are located. Using locally produced heat lowers the cost of heating when fuel prices are high or environmental taxes or fees apply, cutting costs related to heat provision and therefore helping to reduce fuel poverty [14]. In the UK, heat networks supply only around 2% of the overall heating demand [15], while in London, approximately 6% of the energy demand is supplied via district systems [11]. However, national and local authorities have recognized the importance of heat networks and are planning to promote the use of DHNs as a key future policy. The CCC [9] has indicated that low-carbon district heating will play an important role in decarbonizing the heating of buildings, helping to achieve the proposed net-zero GHG emission target by 2050, while the London Environment Strategy [11] has already set a target of meeting 15% of the capital's energy demand using district schemes and renewable sources.

Historically, the evolutionary trend amongst district heating has been towards lower operating temperatures, higher energy efficiency and lower use of fossil fuels as heat sources. Over the years, district heating has evolved significantly, from 1st Generation District Heating (1GDH), categorized by using steam as the heat carrier [14], to recent 4th Generation District Heating (4GDH) and 5th Generation District Heating and Cooling (5GDHC). The 4GDH is defined by low temperature water networks based on the use of renewable and waste heat sources, being linked to electrical grids to form smart energy systems [16]. As for 5GDHC, it not only involves smart coupling of sectors, but also the provision of both heating and cooling through the same network operating at very low temperatures, with negligible thermal losses and a high energy efficiency [17]. These two generations will define the future of district energy, which will increasingly involve the use of renewable and waste heat as the main sources of energy, shifting the heating sector towards decarbonization, smart coupling and greater efficiency. In cities, the operation of several infrastructures generates significant amounts of heat, making waste heat based district heating a particularly interesting opportunity in urban areas. The following section aims to explore the benefits and challenges of exploiting waste heat from a variety of sources in the urban environment.

3. Urban Waste Heat Sources

The integration of waste heat into urban energy systems provides a wide range of possibilities as heat can be recovered from any heat source of sufficient temperature. Many authors have investigated the potential of recovering and reusing waste heat in cities, and this paper aims to review these opportunities. The sources analyzed include data centers, electrical systems (i.e., cable tunnels and substations), industrial plants, railway tunnels, sewage systems and supermarkets. Due to its typical low grade, waste heat found in cities can be well integrated into district heating, being able to supply heat to a network either with or without upgrade by a heat pump, depending on the generation of the network and its related operating temperatures. Table 1 compares the aforementioned urban waste heat sources based on a review of related studies in current literature. Each source is summarized according to its typical temperatures, its availability in the urban environment, its seasonal availability, as well as particular advantages and any restrictions related to recovering waste heat from them. References to the authors reporting each study used to produce this analysis are also shown in the table. The following subsections describe each of the researched urban waste heat sources in more detail.

Table 1. The categorization of urban waste heat sources.

Waste Heat Source	Typical Temperatures	Availability	Seasonality	Advantages	Restrictions	Ref.
Data Centers	10 to 20 °C (chilled water) 25 to 45 °C (air) 50 to 60 °C (liquid)	Can be located in urban centers or in remote areas	Operates constantly throughout the year	The heat recovery system can add resilience to the standard cooling system	As operation is constant, heat recovery needs to be included early in design stage	[18–20]
Electrical Cable Tunnels	6 to 19 °C (cold led) 27 to 32 °C (heat led)	Available in cities with underground power cables	Operates constantly throughout the year	Can also provide cooling to the tunnels depending on method	Temperature variation for cold led systems can affect efficiency	[21]
Electrical Substations	40 to 70 °C (oil) 30 to 42 °C (water)	Available in urban areas, but not widely	Operates constantly throughout the year	Depending on cooling method, can be easily connected to heat recovery system	Retrofitting is likely to be a challenge as transformers need constant cooling; access an issue for security	[22,23]
Industrial Plants	30 to 100 °C (heating) 100 to 300 °C (cooling)	Usually located in outskirts of cities, in areas not so densely populated	Operates constantly throughout the year	Heat can be available at much higher grades, being able to supply cooling via absorption chillers	Disruption in production or site closure can affect the heat supply; distance from cities might pose a challenge	[24–26]
Sewage Systems	9 to 29 °C	Sewers widely available in cities, treatment plants usually in outskirts	Operates constantly throughout the year	It is a relatively stable heat source, proving to be more reliable than ambient air	Biofilm can accumulate on the heat exchanger, reducing its efficiency	[27,28]
Supermarkets	<35 °C	Widely available in cities, especially in central areas	Operates constantly throughout the year	Overall energy efficiency of supermarket is increased, particularly in mild climates	Higher heat recovery rates increase power consumption; Mismatch between peak heat generation and demand	[29,30]
Underground Railway Tunnels	15 to 18 °C (Glasgow) 20 to 32 °C (London)	Limited to cities with metro systems	Operates constantly throughout the year	Can also provide cooling to the tunnels depending on method	Mismatch between peak heat generation and consumer demand	[31,32]

3.1. Data Centers

The potential of recovering waste heat from data centers was investigated by the authors of [18–20], who highlighted the high energy consumption associated with cooling systems in data centers and indicated how recovering low-grade waste heat from these systems can increase the operating efficiency of data centers. The authors of [19] showed how a data center can be cooled by air, liquid or a combination of the two (hybrid cooling). Air cooling involves the deployment of computer room air conditioners (CRACs) or computer room air handlers (CRAHs), which circulate cold air through the racks. Most existing data centers operate with air-cooled systems, as shown by the authors of [18], who also described the typical operation of these systems, where the heat picked up by the air is rejected to chilled water loops, which then dump the heat to the atmosphere, typically through chillers or cooling towers. As air has a low heat carrying capacity, it needs to be supplied at lower temperatures to the racks, so waste heat can be harvested from the CRAC or CRAH return air at temperatures varying from 25 to 45 °C. There is also the possibility to recover waste heat from the chilled water return stream, usually at temperatures between 10 and 20 °C. As for liquid cooling, which includes both hybrid and all liquid systems, the heat is removed by direct contact between the coolant liquid and the electric parts of the server. As liquids have higher heat carrying capacities than air, liquid cooling systems operate with lower temperature differences, which leads to the possibility of extracting waste heat at higher temperatures, normally varying from 50 to 60 °C [19]. Data centers can be located either in rural or urban areas, so their availability as a heat source will vary depending on local conditions. As they are required to run constantly for reliability purposes, data centers generate waste heat that could be exploited all year round. The main restriction is also related to the continuous operation; as downtime and service disruption need to be minimized for data reliability and security reasons, retrofitting waste heat recovery systems into existing data centers is often not feasible.

3.2. Electrical Systems

Electricity distribution networks and systems also represent an interesting source of waste heat, as the distribution of power and its transformation have considerable electrical losses due to resistive heating as stated on Joule's First Law, which describes the heat generated when an electric current is passing through a conductor. The authors of [21] investigated how electricity cable tunnels in London could be used for heat recovery purposes by proposing two different methods based on an air/water heat exchanger connected to a heat pump. The "cold led heat recovery system" involves providing cooling to the cable tunnels by recovering heat from ambient air, which would then be cooled down and supplied to the tunnels. This design option can potentially reduce cable temperatures, which is beneficial particularly in terms of reducing operational costs associated with cooling (i.e., air flow rates and related fan power required) and permitting higher electrical loadings to be used. The other proposed method, the "heat led heat recovery system", involves extracting heat from the hot air coming from the cable tunnels. Although this design option leads to a higher heat pump coefficient of performance (COP), it does not provide cooling to the cable tunnels.

Another interesting opportunity involves recovering secondary energy from transformers at electrical substations, as explored by the authors of [22–24], who showed how different transformer cooling systems have varying potentials for waste heat recovery, highlighting how the Oil Forced Water Forced (OFWF) method, which is based on using oil and water pumps to optimize the cooling process, is particularly interesting. This is due to the fact that almost all of the heat generated can be captured by the cooling water, which can then be used to distribute the heat more efficiently, particularly as water is a good medium for heat transportation. Another advantage of OFWF is that it allows for the waste heat recovery process to be controlled by adjusting the speed of the pumps. The authors of [22] also indicated that the typical operating temperatures of a cooling system for a 15 MVA transformer would be from 62 to 70 °C on the oil side and from 30 to nearly 42 °C on the water side. The potential to recover waste heat from transformers was also investigated by the authors of [23], who analyzed the benefits of recovering heat from transformer oil, with varying temperatures between 40 to 60 °C, using

either only an oil–water heat exchanger to provide local domestic hot water heating or a heat pump to provide either domestic hot water or heat for a district network.

3.3. Industrial Plants

Waste heat recovery can also be achieved in Industry, which involves many energy intensive processes that generates substantial amounts of recoverable surplus heat. This potential in the UK was investigated by the authors of [24], who demonstrated how heat is generated at different grades by analyzing 425 industrial sites. This means that waste heat can be exploited in different ways, e.g., to generate electricity, to produce cooling or to meet heating demands. They [24] also reported recoverable waste heat at temperatures from 40 to over 550 °C, and highlighted that connecting these waste heat sources to heat networks can be very beneficial in terms of reducing energy use and GHG emissions associated with heating. Approximately 70% of the surplus heat identified was below 100 °C, being suitable for district heating networks. The possibility of using waste heat to drive an absorption chiller, which could potentially be exploited for district cooling, was also investigated, being identified as an efficient use for excess heat at temperatures from 100 to 300 °C. The authors of [25] focused on the potential of recovering low grade waste heat from the food processing industry in the UK, showing how different processes in this industrial sector have varying waste heat outputs, ranging from 30 to 250 °C. The authors concluded that direct use of the surplus heat nearby by using heat exchangers is the most economical technology, but indicated the high potential of using either compact heat exchangers, heat pumps or absorption chillers for waste heat exploitation. When looking at the benefits and challenges of using low-grade industrial heat for district heating, the authors of [26] emphasized that most high-temperature waste heat is used within the factory for the purpose of generating power, but that there is still an opportunity to exploit waste heat at lower temperatures, mostly between 30 and 200 °C. The authors analyzed metalworking factories in China and demonstrated that the majority of the unexploited waste heat is usually below 100 °C. These available sources within industries could be exploited by district energy schemes, even though industrial plants are usually far away from dense residential districts.

3.4. Sewage Systems

Sewage systems and treatment plants generate waste heat and are usually closer to dense heat demands that could be efficiently met with district heating. Heat can be recovered from wastewater using a heat exchanger and upgraded by a heat pump. Wastewater can be used at different stages, so the system can be implemented to recover waste heat within households, from sewer systems or at treatment plants. This possibility was highlighted by the authors of [27], who investigated the feasibility of recovering heat from wastewater in Bologna, Italy, by analyzing varying flow and temperatures at several locations of the city's sewage system. The authors found that wastewater temperatures vary from 10 to 22 °C, proving to be especially advantageous during winter months, when there is a peak heat demand and sewage temperatures vary between 11 and 16 °C, while air temperature can drop below 0 °C. Heat recovery from wastewater was also researched by the authors of [28], who analyzed 27 design options for heat recovery heat exchangers that could be applied to sewage systems, as well as showed successful commercial projects that have been implemented in Germany, Japan and Switzerland. The authors highlighted that recovering waste heat from treatment plants is more efficient and technically feasible, although the distances between the plant and consumers usually pose a challenge. The authors of [28] also reported that temperatures for wastewater typically vary from 9 to 14 °C during winter and can reach up to 29 °C in summer.

3.5. Supermarkets

Another potential secondary energy source in urban areas is supermarkets. As food storage requires significant refrigeration, vapor-compression refrigeration systems need to be deployed, which in turn generate significant amounts of heat at their condenser side. Control strategies to optimize heat

recovery from CO₂ (R744) refrigeration systems in supermarkets were discussed by [29], who presented a case study for a refrigeration system of a supermarket in the northern UK, from which heat could be recovered at a maximum temperature of 35 °C. The control strategy involved manipulating head pressure to achieve different heat recovery potentials. Although high potential can be achieved with high pressures, this comes at the cost of increasing compressor power consumption, which can end up reducing the cost-effectiveness of the waste heat recovery system. Another challenge presented by the authors of [29] was that the heat load produced from a refrigeration system is proportional to the cooling required, so less heat can be recovered in winter months, when there is less demand for refrigeration but a peak demand for heating. However, the benefits of recovering waste heat from condensers are still considerable, as shown by [30], who investigated how a supermarket CO₂ refrigeration system with heat recovery would perform, in comparison to a R134a/CO₂ cascade refrigeration system along with a R410A heat pump being used to supply hot water and space heating to the building. It was discovered that the waste heat recovery system operates very efficiently during the winter months, as it would be able to replace the heat pump, but during summer the proposed solution would actually be more energy intensive than the reference case. This makes waste heat recovery from supermarkets particularly interesting for colder countries; annual energy savings of up to 6.5% were achieved in the simulation in milder climates, while modeling the system in a warmer climate led to an increase in annual energy consumption of 1.1%.

3.6. Underground Railway Tunnels

Railway tunnels represent a reliable waste heat source in cities where public transportation heavily relies on underground metro systems. The potential to recover secondary energy from underground railway tunnels in the UK has been investigated by the authors of [31,32], who analyzed the environment of the subway systems of Glasgow and London, respectively. The authors of [31] highlighted how this opportunity can help in achieving the UK targets for decarbonizing the heating sector through the application of heat pumps, which can reach better performance with warmer and stable source temperatures. The authors measured the annual temperatures for a station of the Glasgow subway and showed how they range from 15 and 18 °C, while the outside average temperatures can range from 4 to 16 °C, indicating how heat pumps can operate more efficiently using the underground air as a heat source. The potential of exploiting the London Underground's waste heat was investigated by the authors of [32], who showed that average platform temperatures can be as high as 20 °C on a cold winter's day and reach up to 32 °C during summer. The authors also analyzed different design options for placing a heat recovery heat exchanger either within stations or in the ventilation system of the network, and highlighted how solutions that hinder the ability to deliver a reliable train service are unlikely to be considered by the Underground operators.

As cities all over the globe aim to reduce their carbon footprints, electrifying the heating sector so that it incorporates renewable energy sources, particularly in colder climates, is fundamental. Therefore, heat pumps will play an essential role in the path towards decarbonization and using them in the most efficient way, exploiting any available waste heat source, is a priority. Amongst all the sources described, underground railway tunnels are particularly interesting for cities such as London, where buildings have high heat demands, heat supply is very carbon intensive, as described in [11], and a long subway network covers a considerable area of the city. However, many challenges are involved in exploiting waste heat from underground metro systems and it is important to carefully select the most suitable technology to recover waste heat from the tunnels, maximising energy efficiency without posing any risks to the safe and reliable operation of urban mobility systems.

4. Waste Heat Recovery from Railway Tunnels

According to the authors of [33], at the end of 2017, 178 cities in 56 countries worldwide had metro systems, carrying a total of 168 million passengers per day on average. From 2012 to 2017, annual ridership of urban railway systems grew by 19.5%. These transport systems are likely to further grow

in the future as urban population increases worldwide, particularly in metropolises of developing countries. A number of recent studies have addressed the potential to recover waste heat from railway tunnels, focusing on different technologies that could be applied to effectively retrieve the energy that is dissipated in the form of heat during the operation of underground trains. It is noteworthy that energy can be recovered from underground trains in different ways. For instance, regenerative braking can convert the kinetic energy of a moving train into other forms of energy that can be stored by batteries or capacitors, slowing the vehicle down while also reducing the heat being generated by braking friction. However, as this paper focuses on the recovery of energy in the form of heat from urban infrastructures, as well as their potential as low carbon sources for heating, only technologies related to the recovery of waste heat will be discussed.

A summary of a range of investigated technologies that involve waste heat recovery from underground railway tunnels is presented in Table 2. The table also indicates the location where the technology was implemented/simulated; the temperatures and medium considered for the heat source; the calculated heat extraction rates; and the related risk of service disruption when installing each of the technologies. It also includes references to the authors reporting each study. Regarding the “risk of service disruption” category in the table, a low risk means that the implementation does not hinder or only slightly affects the operation of the trains, while a medium risk represents the need for a partial disruption of the transport service, and a high risk implies the need to suspend operation during the installation of the related technology. As daily urban life depends on transport links, whether people are commuting to work, for leisure and business activities or going back home, urban transport systems are at the core of most modern cities, meaning that any service disruption should be avoided as much as possible, as it can lead to considerable impacts on urban economy and quality of life.

Table 2. Potential technologies for waste heat recovery from underground railway tunnels.

Technology	Location	Heat Source Medium	Heat Source Temperature	Heat Extraction Rate	Service Disruption	Reference
Ground-water used in platform air handling units	London, UK	Air	22 to 32 °C	50 kW/unit	Medium	[34,35]
Energy pile walls and diaphragm walls	Vienna, Austria	Air/ground	>20 °C	30 W/m ² of earth-contact area	High	[36]
Energy foundation slabs	Vienna, Austria	Ground	>20 °C	10 to 30 W/m ² of earth-contact area	High	[36]
Absorber pipes attached to geotextile between tunnel linings	Stuttgart, Germany	Air	6.5 °C	20 W/m ² of tunnel surface area	High	[37]
Embedded absorber pipes in tunnel segments	London, UK	Air	17 to 36 °C	7 W/m ² to 30 W/m ² of tunnel surface area	High	[38]
	Turin, Italy	Air/ground	14 °C	53 W/m ² of tunnel surface area	High	[39]
Ground source heat pumps next to tunnels	London, UK	Ground	20 to 30 °C	20 to 29 W/m of borehole length	Low	[40,41]
Heat exchangers within ventilation shafts	London, UK	Air	20 to 28 °C	900 kW/shaft	Low	[42]

A groundwater-based air handling units (AHU) system, using either seepage water or aquifer groundwater, has already been applied to cool stations of the London Underground (LU) network [34]. Seepage groundwater is particularly interesting as over 30 million liters of water already need to be constantly pumped out of the Underground network. Therefore, using it for cooling/heating represents an efficient solution energy wise, as shown by the authors of [35], who investigated the performance of a groundwater cooling trial based on 3 fan coil units at Victoria station. The authors showed that the proposed technology had a third of the cost and a fourth of the energy consumption and carbon emissions of a conventional vapor-compression system. Although the warmed water represents a large

potential source for waste heat recovery, this technology might be limited to use at station platforms only, as the deep tunnels of the London Underground are too narrow to fit fan coil units. In addition, the installation of platform AHU is likely to cause train service disruptions.

Geothermal energy technologies, which are based on the capacity of the soil to store and provide heat, have also been investigated as a means of recovering waste heat from underground rail networks, resulting in innovative solutions that are both environmentally friendly and cost-effective. The authors of [36,43] investigated how foundations and underground structures, including tunnels, can be designed as thermo-active elements, enabling them to capture heat from their surrounding environment. Based on a case study in Austria, the authors of [36] researched how absorber pipes could be applied to bearing structures, such as bored piles, diaphragm walls and foundation slabs, in order to capture waste heat from railway tunnels and stations in Vienna. The case study results showed that this system was able to provide 150 kW of heating to a school building adjacent to the tunnel, reaching up to 214 MWh in one heating period. This technology is suitable for tunnels built in the cut and cover method, which consists of bored pile walls, as well as reinforced concrete base slabs and roofs. The authors of [36,43] also highlighted the potential of heat extraction based on absorber pipes attached to an energy geocomposite placed between the outer and inner linings of a tunnel, which is applicable to tunnels built in the New Austrian Tunneling Method (NATM), which consists of a primary support of reinforced shotcrete, rockbolts and anchors, and a secondary lining of reinforced concrete. The absorber elements can also be connected to the anchors, an important structure that supports the tunnel excavation and could be utilized as a new energy active element. In Stuttgart, Germany, a similar heat recovery trial was conducted on the city's metro system, where absorber pipes were attached to a geotextile and placed between the tunnel linings. Based on temperature data from the surrounding soil, the tunnel linings and the tunnel air, the authors calculated that heat could be extracted from the tunnels at a rate of 20 W/m² [37].

A different design approach must be taken when dealing with underground rail systems built with mechanized tunneling. A design of railway tunnels with absorber pipes embedded within segments of the tunnel lining, namely the tunnel energy segment (TES) system, was analyzed by the authors of [38], who showed how cooling can be provided to the Crossrail tunnels in London while waste thermal energy is harvested to heat nearby buildings. A finite element thermo-mechanical model was developed using a multi-physics software to simulate the thermal performance of the TES system by analyzing how different heat extraction rates affect the temperature of the heat carrier fluid. The results showed that heat extraction rates are limited by the risk of fluid freezing and can reach up to 30 W/m² [38]. A similar system was proposed by [39], who numerically analyzed the feasibility of developing an energy tunnel in Turin. The analysis was based on the development of a finite element thermo-hydro model to simulate the heat transfer between absorber pipes within a tunnel and its surrounding environment. The proposed design also consisted of embedded pipes within precast concrete tunnel linings and could operate in cooling and heating modes. Thermo-active tunnels and ground structures can achieve high heat extraction rates, however, these technologies can only be applied to new underground railway developments and are not suitable to recover heat from existing tunnels. For that reason, geothermal technologies must be incorporated into geotechnical design at an early stage, helping to establish a multidisciplinary cooperation between the teams responsible for designing the bearing ground structure and the heat recovery system, which can reduce delays and installation costs associated with energy active structural elements.

A different approach to recover the excess heat that is generated in railway tunnels in London was proposed by the authors of [40,41], suggesting the use of ground source heat pumps (GHSPs) connected to geothermal heat exchangers (GHEs) to collect the heat that is conducted into the surrounding soil during the operation of trains due to the heat sink effect. A finite element model was developed to analyze how GHEs can have their performance enhanced when placed near railway tunnels and how different configurations of GHEs—with varying numbers of rows and loops, sizes, as well as proximity to tunnels—could affect their heat extraction rate. Results showed that the performance of

the system could be improved by up to 43% and the model was validated by comparing simulation results to measured temperature data from the London Underground network. This technology is able to recover heat from existing railway tunnels as it can be deployed independently from the tunnel structural elements. However, the high capital costs related to the excavation of boreholes represent a drawback to the adoption of this heat recovery solution. Another issue related to the development of this technology relates to land ownership, as energy plants would have to be installed along the tunnels, in what could be privately owned areas.

An alternative heat extraction technology was analyzed by the authors of [42], who investigated the potential to recover waste heat from ventilation shafts of the London Underground network by deploying an air to water heat exchanger connected to a heat pump. The potential energy, carbon and cost savings of the system were calculated in a comparison against conventional cooling and heating, based respectively on chilled water systems and gas fired boilers. Results showed that the waste heat recovery system could lead to considerable savings, using 79% less energy, emitting 48% less GHG and costing 82% less than the conventional cooling and heating methods analyzed. A similar scheme is being implemented in the London Borough of Islington and will be further described in the following section of this paper. The scheme, known as the Bunhill Waste Heat Recovery System, is based on the installation of a fan coil heat exchanger within a ventilation shaft of the LU network. The heat captured is distributed to a heat pump, which upgrades it to a suitable temperature for reuse and provides low carbon energy to a local district heating network. As can be seen in Table 2, extracting heat from ventilation shafts represents a great opportunity, as significant heat can be extracted while keeping service disruptions to a minimum. However, there are still some constraints to this technology related to the existing London Underground ventilation system, namely the usual limited space within existing shafts and the low capacity of the fans used for ventilation purposes.

5. A Case Study for London

As London is home to the world's first metro system, with a network length of 402 km (45% in tunnels), the 4th longest in the world [33], and 1.35 billion passengers per year [44], underground railways represent a particularly good option for waste heat recovery in the city. The Metropolitan Integrated Cooling and Heating (MICAH) project investigated how the London Underground (LU) network remains relatively warm in most locations throughout the year and that the system could also deliver cooling to the tunnels when required [42]. The Underground has great potential for secondary energy recovery, as the operation of the trains requires considerable energy, which ends up being degraded and released as waste heat, reaching approximately 500 GWh per annum [45]. Over 80% of the heat introduced into the network can be traced back to mechanical losses, related to the running of the trains; mainly, braking friction and resistive losses in the traction-control system, while the remainder can be attributed to commuters, as well as station and tunnel systems [34]. The London clay surrounding the tunnel walls, which acts as the main heat sink, has gradually become heated, leading to higher temperatures for both the surrounding soil and the air in the tunnels. By exploiting the opportunity to recover waste heat from the Underground, it is possible to deliver cooling to the tunnels, which is also beneficial.

The Bunhill Waste Heat Recovery System

This paper was produced as part of a PhD project that aims to investigate the real life performance of the Bunhill Waste Heat Recovery System, a novel scheme based on utilizing the London Underground as a heat source. The waste heat recovery scheme, which is also referred to as Bunhill 2, is the extension of an existing heat network, Bunhill 1, located in the London Borough of Islington. Bunhill 1 deployed a combined heat and power (CHP) unit to produce both electricity and heat, which is distributed via a district heating network in order to supply the local community. The Energy Centre for Bunhill 1 comprises a 1.9 MW_e/2.3 MW_{th} gas-fired CHP and a 115 m³ thermal store. The network currently operates with flow and return temperatures of 95 °C and 75 °C, respectively. A total of 788 homes

within three housing estates and one residential building are being supplied with heat from the network, which also feeds another four commercial buildings and two leisure facilities in Islington. The Bunhill Waste Heat Recovery System followed an effort by Islington Council to further expand the provision of low cost and low carbon heat to its residents. The project is the first of its kind in Europe and is part of the EU CELS IUS Project, which aims to promote the use of sustainable heating and cooling in European cities. The decision to use waste heat sources is also related to the decreasing carbon savings of CHP systems due to the growing decarbonization of electricity in the UK. The scheme is expected to provide heating to 455 dwellings in 5 building blocks of local housing estate and a local primary school. A new mixed use building complex that is currently being developed will also be connected to Bunhill 2, adding 720 residential units, a 160-bed student accommodation and a 125-bed hotel, as well as areas for offices, retail and restaurants as new end users of the network.

Bunhill 2 will collect heat from one of the shafts that constitute the ventilation system of the Underground network. The heat will then be upgraded using a heat pump before being transferred into the DHN, which will be extended to connect the buildings to the new Energy Centre. The first stage of the system involves capturing the heat using an air-to-water heat exchanger in the ventilation shaft. The heat exchanger used for this waste heat recovery system is a fan coil unit. A head house, where the coils were installed, was built on top of the ventilation shaft, which was upgraded to accommodate the variable speed reversible fan that enables the system to work in both Extract and Supply modes. The benefits of operation in these two different modes have been previously investigated by the authors of [42] and consist of reversing the flow direction of the fan, allowing the system to operate by either extracting hot air from the Underground, which can then be used to warm the water in the coils, or using ambient air, which would be cooled by the coils and then supplied to the Underground, with the heat extracted being recovered by the heat exchanger. Extract mode would be used during the colder months of the year, when the heat demand is at its peak and the underground air is warmer, at temperatures from 18 to 25 °C. Supply mode would be used to supply cooling to the Underground during the summer, when ambient temperatures are higher, with a daily average temperature of 17 °C [46]. Throughout the year, heat can be collected at these varying temperatures, which explain the different flow and return operating temperatures of the first water loop, which distributes the recovered heat to the heat pump. A schematic of the ventilation shaft and the head house is illustrated in Figure 2, showing the coil heat exchanger and the reversible fan.

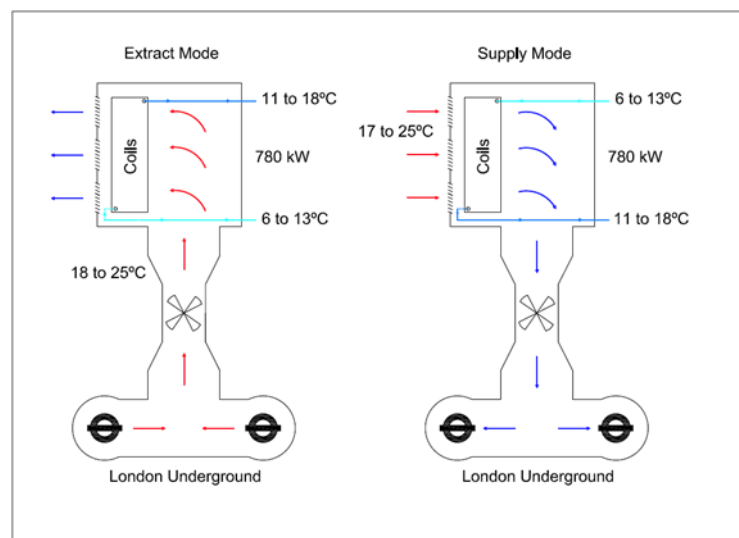


Figure 2. Schematic of the heat exchanger and the ventilation shaft of the Bunhill Energy Centre 2.

The heat pump has the following annual average design parameters: capacity of 1033 kW_{th} and coefficient of performance (COP) of 3.76, with 780 kW of heat being recovered from the ventilation

shaft. Two gas-fired CHP units, each with a design output of $237 \text{ kW}_e/372 \text{ kW}_{th}$, add resilience and flexibility to the Energy Centre, although their output heat could be rejected if not needed. A thermal store of 77.5 m^3 will also be installed in order to add flexibility, helping to manage peak demand. The air that exhausts through the ventilation shaft has temperatures varying from around $18 \text{ }^\circ\text{C}$ to $28 \text{ }^\circ\text{C}$. Thus, the first water loop, which transports the heat from the ventilation shaft to the heat pump, will also work with flow and return temperatures that vary according to the season of the year. The expected operating flow and return temperatures vary from 11 to $18 \text{ }^\circ\text{C}$ and from 6 to $13 \text{ }^\circ\text{C}$, respectively. The heat will be then upgraded and distributed with a flow temperature of $75 \text{ }^\circ\text{C}$, being returned to the heat pump at $55 \text{ }^\circ\text{C}$. Figure 3 shows a schematic of the Bunhill 2 heat network.

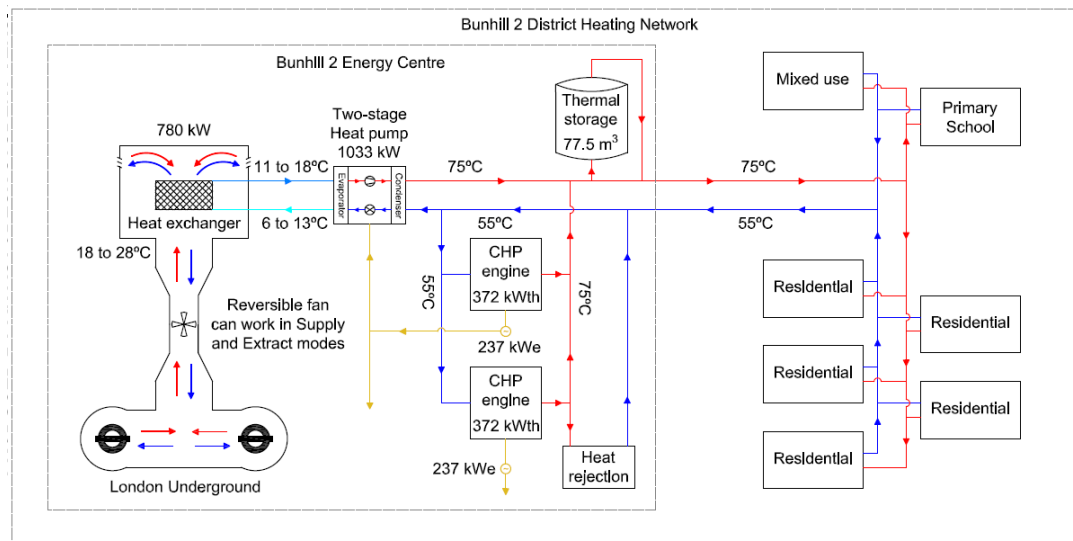


Figure 3. Schematic of the Bunhill Waste Heat Recovery System.

The waste heat recovery scheme will represent a transition for the whole network, which will then operate at lower temperatures, with the supply and return water streams at $75 \text{ }^\circ\text{C}$ and $55 \text{ }^\circ\text{C}$, respectively. This will enhance the system's overall energy efficiency by reducing distribution losses, while also unlocking the opportunity for sector coupling, since renewable electricity could potentially be used to power the heat pump and store excess energy in the form of heat. Even though the Bunhill 1 Heat Network was typically a 3GDH network, this project shows how established 3rd generation networks can be transformed into 4GDH networks by incorporating waste heat sources, unlocking the potential for smart sector coupling and lowering the operating temperatures of the network. In addition, it was demonstrated in [47] that if the whole demand for Bunhill 2 were to be met using only the waste heat recovery part of the system, i.e., a heat pump with a 3.76 COP connected to a DHN, the potential carbon and cost savings that could be achieved would be, respectively, 82% and 14%, when compared to a reference case of each building connected to the network having its own communal gas boiler for heating.

6. Conclusions

Cities are at the forefront of the battle against climate change. As urban areas are predicted to keep growing in the next decades, even more so in emerging economies, the demand for resources in metropolitan areas, including energy, will increase considerably, which means public and private sectors need to rethink the way they manage and use their energy resources. As heating and cooling contribute to a significant amount of energy consumption in most countries, the adoption of sustainable and efficient solutions for thermal comfort provision will be key to meet the requirements of future cities. As shown in this paper, district energy is an efficient and low carbon technology that enables the

recovery of wasted energy and the incorporation of renewables into thermal networks, an essential aspect of future energy systems that can optimize the overall energy efficiency of cities.

Integrating waste heat sources into district energy networks will play an important role in reducing energy losses and enabling smart coupling between thermal and electricity grids. As many cities in the world rely on metro systems as a vital transport modal, the opportunities to recover waste heat from these infrastructures are significant, and many different technologies can be used to exploit the heat that is generated during the operation of underground trains. Moreover, this paper highlighted how currently fossil fuel based district heating systems can benefit from incorporating waste heat from underground railway systems, as it could be noticed from a case study in London.

Overall, DHC networks will play an important role in the energy transition towards low carbon and sustainable heating and cooling in cities. Particularly for heating, connecting district networks to excess heat sources can help reducing the energy that is wasted in urban areas, enhancing the overall energy efficiency of the built environment. Waste heat recovery from underground railway tunnels can be a key technology to make heating systems more efficient, cost-effective and environmentally friendly in many cities throughout the globe, and therefore energy planners, local authorities and private agents need to be aware of this unique opportunity.

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