**Potential of treated wastewater as an energy source for district heating: incorporating social elements into a multi-factorial comparative assessment for cities.**

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## ABSTRACT

Recovering waste heat from urban infrastructures is gaining greater importance in the context of decarbonisation. However, evaluating the feasibility of waste heat recovery projects requires a holistic analysis of potential impacts, which includes social elements that are often overlooked. This paper introduces a novel methodology for assessing the competitiveness of waste heat integration into district heating, based on a multi-factorial decision support tool that incorporates energy poverty as a key performance indicator, in addition to energy, environmental and economic factors. The comparative assessment is based on the implementation of large-scale heat pumps recovering wastewater heat, a resource of great potential that is still underutilised in Europe. The methodology is tested in the cities of London and Riga, which are in countries with significantly different stages of DH development. In London, an emerging market with high growth potential, and in Riga, where there is a well-established DH system. The study has shown that waste heat can significantly reduce consumers' bills for heating, which was observed in all analysed scenarios. The social benefit decreases when the replaced technology involves biomass heat-only boilers or combined heat and power. The methodology presented is generic and can be applied to other locations and heat sources.

## KEYWORDS

District heating; waste heat; excess heat; wastewater heat potential; social aspects; energy poverty; heat tariff.

## INTRODUCTION

Heating and cooling account for around half of the EU's energy consumption [1]. In large European capitals, they are often provided with centralised heat and cold supply systems. To achieve the EU's climate change mitigation goals for 2030 and, in the longer term, national decarbonisation strategies in the field of heating and cooling, measures to phase out fossil fuels must be introduced as soon as possible, as well as initiatives to promote energy efficiency in all stages of heat supply - at heat source, transmission and end-user levels [2]. District heating (DH) is considered an energy efficient technology if it uses at least 50% of renewable energy, 50% of waste heat, 75% of co-generated heat or 50% of a combination of such technologies. This follows the objectives of the EU Member States as set out in the Directive 2012 /27/EU of the European Parliament and of the Council on energy efficiency [3].

* 1. **Potential advantages of heat recovery from the treated WW and its integration with urban DH systems**

One potential source of low-carbon heat that could replace fossil fuels is to use waste heat from essential processes, which is normally rejected to the environment. The use of waste/excess heat can support the decarbonisation of DH systems, whilst also ensuring the economic feasibility of transitioning towards low-temperature 4th generation DH (4GDH) [4]. The present study investigates the opportunity to recover heat from wastewater treatment plants (WWTPs), a source of great potential. There are several positive preconditions for heat recovery from treated WW and its integration into DH systems: the wastewater has a stable flow rate and temperature, and heat supply and demand are well aligned with each other [5]. Although WW temperatures tend to be higher at the discharge of buildings and in sewers, recovering heat from treated effluent involves much higher flow rates that are suitable for district-scale applications, as WWTPs are typically deployed to treat sewage from entire towns or large parts of cities [6]. Recovering heat from treated effluent also has the advantage of avoiding the risk of fouling, and greater heat extraction rates can be achieved, as it is undesirable to reduce the temperature of the wastewater entering a WWTP.

The use of waste/excess heat provides a route to decarbonise DH systems, while also ensuring the economic feasibility of transitioning towards 4GDH operation [4]. The potential for integrating WW heat into DH systems under different conditions has been investigated in other studies. Due to the low temperature of WW, upgrade by a heat pump is required, and heat can be recovered at different stages of the sewage collection and treatment process [7]. Whilst Culha et al. [8] investigated the potential to recover heat from sewer pipes, Lagoeiro et al. [9] estimated the potential for recovering heat from treated effluent in the UK. As previously discussed, WWTPs offer a significant potential for district-scale applications, and WW effluent temperatures are often above ambient, as the biological sewage treatment process results in some heat generation associated with oxidation [10]. This means WH recovery from the effluent of treatment plants can also help to minimise thermal pollution in water bodies caused by the discharge of treated effluent [11]. Furthermore, bacteria used in WW treatment are highly sensitive to temperature, with reduced activity being observed at temperatures below 10°C [12], which affects cleaning efficiency. Recovering heat from the treated effluent then becomes an interesting option, due to its minor impact on the treatment process and low fouling risk. Additionally, heat recovery systems utilising treated effluent tend to have higher capacities and are typically linked to DH networks [13].

Despite the many advantages of recovering treated WW heat and reusing it via urban DH systems, there is still insufficient research to provide a comprehensive methodology for evaluating its potential benefits holistically. This gap is addressed in this article, which proposes a novel methodology for assessing waste/excess heat applications combining technical, economic, environmental and social key performance indicators (KPIs).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Nomenclature** | |  | Annual electricity consumption, MWh/year | |
| *Abbreviations* | |  | Annual heat losses, MWh/year | |
| AHP | Analytic hierarchy process |  | Annual amount of heat, MWh/year | |
| B | Biomass |  | Linear heat resistance, mK/W | |
| CAPEX | Capital expenditure |  | Area of an average family apartment, m2 | |
| CHP | Combined heat and power |  | Annual avoided heating costs, EUR/year | |
| CO2e | CO2 emissions equivalent |  | Share of avoided heating costs, % | |
| DH | District heating |  | Share of avoided emissions, % | |
| ELECTRE | Elimination and choice translating reality |  | Share of recovered heat, % | |
| EU | European Union |  | Annual specific heat consumption, MWh/m2 per year | |
| 4GDH | 4th generation district heating |  | Temperature, °C | |
| HDD | Heating degree days |  | Annual system’s operating time, h/year | |
| HOB | Heat-only boilers |  | Value-added tax | |
| KPI | Key performance indicators |  | Electrical energy consumption for the heat pump, MWh | |
| MCDA | Multi-criteria decision analysis |  | | |
| NG | Natural gas | *Greek letter* | | |
| O&M | Operation and maintenance |  | Coefficient of performance | |
| OPEX | Operational expenditure |  | Loan repayment term, years | |
| PROMETHEE | Preference ranking organisation method for enrichment evaluation |  | Share of technology, % | |
| TOPSIS | Technique for order of performance by similarity to ideal solution (TOPSIS) |  | | |
| *Subscripts* | | |
| UK | United Kingdom |  | | Overlap of supply and return pipe temperature fields |
| WH | Waste heat |  | Produced electricity by the CHP | |
| WSM | Weighted sum method |  | Produced heat energy by the CHP | |
| WWSHP | Wastewater-source heat pump |  | CO2e emissions equivalent | |
| WWTP | Wastewater treatment plants |  | Hour | |
|  |  |  | Electric power | |
| *Variable* | |  | Heat pump | |
|  | Annual cost, EUR/year |  | Fuel | |
|  | Heat pump capacity, MW |  | Heat pump | |
|  | Coefficient of performance | *i* | *i* -*th* scenario | |
|  | Annual amount of CO2e equivalent emissions, tCO2e/year |  | technology investment | |
|  | Carbon emission factor for resources, tCO2e/MWh | *j* | j-*th* technology | |
|  | Annual fuel consumption in the DH system, MWh/year | k | Number of heating network section | |
|  | Avoided CO2e emissions costs, EUR/tCO2e | n | nth resources | |
|  | Annual household income, EUR/year |  | Operation and maintenance | |
|  | Length of the heating network, m |  | Other | |
|  | Levelized cost of heat, EUR/MWh |  | Return heat carrier flow | |
|  | Minimum |  | Supply heat carrier flow | |
|  | Installed capacity of technology, MW |  | Ground | |
|  | Annual loan interest rate, %/year |  | Taxes | |
|  | Heat produced from heat pump, MWh | z | Total number of sections in the network | |
|  | linear heat losses, W/m | 1 | Initial DH system structure | |
|  | Heat demand, MW | 2 | Final DH system structure with installed WWSHP | |

* 1. **Overview of multi-factorial methodologies for the assessment of DH performance**

Multi-criteria decision analysis (MCDA) methods are often used to evaluate the sustainability of DH systems, because the goal of sustainability is multidimensional and includes economic, environmental, and social factors (indicators). This is a significant challenge for complex infrastructure projects such as DH, which involve many different elements and stakeholders (e.g. heat production plants, district-scale distribution infrastructure, several end users, etc), each described by a diverse set of parameters [14]. Therefore, MCDA methods are particularly useful when considering possible DH development scenarios, as these often involve a combination of perspectives from different interested parties (e.g. DH operators, end-users, municipalities) which may often be conflicting [14]. Within the larger framework of the energy transition, the implementation of 4GDH systems is often studied by determining the balance between the economic feasibility of DH development scenarios and the level of carbon emission reduction in the mid-and long-term perspectives [15], [16]. Some examples of commonly applied methods for renewable energy planning and energy sustainability assessments include the analytic hierarchy process (AHP), the technique for order of performance by similarity to ideal solution (TOPSIS), the weighted sum method (WSM), the elimination and choice translating reality (ELECTRE), and the preference ranking organisation method for enrichment evaluation (PROMETHEE) [17]. Similarly to these, the MCDA process in sustainable energy decision making consists of several steps: criteria selection and their normalisation, criteria weighting, determination of performance of alternatives by using one of MCDA methods, and finally – decision making [14]. Selecting appropriate and reliable criteria is the first and one of the most important steps in analysing the performance of DH systems, forming the basis for further decision making, which must consider technical, energy, environmental, economic, and social factors or indicators that are relevant to DH system modelling and design.

There are several articles that have studied the integration of various types of WH in urban DH systems. For instance, Ðurdevič D etl. studied energy indicators (heat demand of the DH system) and concluded that a significant share of heat demand for the city of Rijeka (Croatia) could be met by heat recovered from WW [18]. Often, the integration of WH into DH is studied considering economic indicators, such as payback period, and environmental indicators, such as avoided carbon emissions. Somogyi et. al. [19] investigated the possibility of integrating low-temperature heat from WWTPs into DH systems in Hungary. The authors concluded that in 12 cases the payback period was below 5 years, when compared to DH supplied with natural gas.

However, there is a general lack of studies in current literature on the social implications of reusing WH, which is often not contemplated in feasibility assessments. Social factors are not sufficiently investigated when assessing the possibility of implementing heat recovery solutions for DH systems, not even for a widely known heat source as WWTPs. The social element represents a key pillar for sustainability and awareness of social benefits associated with large-scale energy projects is likely to bring support for the rapid implementation of such systems. Therefore, this study aims to address this gap by investigating how to incorporate social KPIs into the MCDA method for DH projects using WH, which is then tested with two case studies of WWTPs in the cities of Riga, Latvia, and London, UK.

## Energy poverty and the impacts of integrating WW heat into DH systems

There is a limited number of studies that link the planned DH system transformation into the 4GDH concept with the opportunity of protecting households from energy poverty, which is a multidimensional, dynamic, and transversal issue [20]. Most existing studies on social impacts of DH focus on issues arising from legacy systems in well-established DH markets, which mostly rely on fossil fuels and often perform poorly with high operating temperatures. A Hungarian study investigated energy poverty risks on dwellings connected to inefficient DH [19], whereas another study indicated how Czech local authorities are sceptical of low-carbon DH and its ability to reduce the energy vulnerability of connected end-users [20].

On the other hand, there is an increased interest from emerging DH markets, such as the UK, on the social implications of district energy systems. A recent survey by the UK Government showed how stakeholders perceive DH as a technology that can deliver against decarbonisation targets whilst also alleviating fuel poverty [21], but there are still concerns over the lock-in of consumers to inefficient DH systems, a risk that is expected to be mitigated through regulation [22]. One of the main challenges of decarbonisation is associated with increasing heating costs for end-users [23], and the exploitation of waste/excess heat sources has been indicated as a form of increasing the energy efficiency of DH systems, making them more cost-effective [24]. Translating these benefits into social implications has been pointed out as a key decision factor for policy makers [25], and a review paper has indicated how this challenge has been largely unaddressed in the current literature [26].

An investigation by Ziemele et. al. [27] evaluated the potential of heat recovery from treated WW and its reuse in DH through absorption HPs in three capitals of the Baltic countries – Tallinn, Riga, and Vilnius. The study assessed the economic benefit of incorporating WW heat into a DH system using a multi-dimensional approach. In this case, energy poverty was indicated by the share of avoided heating costs after following the installation of an absorption HP in the DH systems. Considering that the DH systems of Tallinn, Riga and Vilnius are well developed and operate in similar market and economic conditions, the shares of avoided heating costs in relation to household income were 3.75%, 3.66% and 4.14% in Tallinn, Riga, and Vilnius, respectively.

A metric commonly used in the UK to demonstrate the social impacts of energy costs is fuel or energy poverty. The definitions of fuel poverty vary across different UK countries; in 2021, a new fuel poverty metric was introduced in England, which considers a fuel poor household as one with a property energy efficiency rating of D or below, and that is left with a residual income below the official poverty line after their heating bill is paid [28]. Fuel poverty is therefore affected by three main factors: household income, fuel costs and energy consumption (the energy efficiency of the home), and its impact is often measured in terms of the fuel poverty gap, which represents the reduction in fuel costs needed for a household not to be in fuel poverty. With that in mind, this study is aimed at building upon previous research by evaluating the social impact of recovered heat from treated WW in terms of its ability to reduce energy poverty and potentially overcome it. Although this metric is not common in Latvia, a similar indicator will be used in the Latvian context to analyse how the integration of waste heat into DH systems can support cities with completely different levels of economic development and DH maturity.

## Motivation of this work

Considering the aforementioned shortcomings of previous research studies, a hypothesis is proposed: cities have a high potential for integrating recovered heat from treated WW through large-scale heat pumps connected to DH systems. The introduction of these technologies unlocks the potential for significant emissions savings, especially in DH systems with a large proportion of fossil-fuel based technologies moving cities towards carbon neutrality. In addition, the introduction of waste heat into DH can lead to significant energy cost savings, which in turn impact heating bills for connected households, therefore reducing the risk of energy poverty.

This study is therefore aimed at investigating the wider impacts of utilising WH in DH systems, using WWTPs as case studies, by applying several KPIs related to environmental, economic, and social spheres. Further analysis of these KPIs is the basis for the decision-making process. The impacts of waste heat utilisation are also compared in the capital cities of two countries – Latvia and the UK – where socioeconomic conditions are different, and the DH industry has contrasting levels of maturity. Another novelty associated with this investigation is the introduction of the fuel poverty metric to analyse the social impacts of waste heat. Although WWTPs are used as case studies, the methodology is generic and could be applied to other waste heat sources. Additionally, the research of social indicators together with technical, environmental, economic and governance assessments provides a holistic overview of WH integration in a context of change towards the 4GDH.

## BACKGROUND INFORMATION (Current District Heating Landscape for Riga and London)

In order to test the proposed MDCA approach with emphasis on social value, this study involves two countries with significantly different economies and stages of development of their DH industries. In the capital of Latvia, Riga, there is well-developed DH system that covers approximately 56% of the total heat demand of the city, whereby 70% of the consumers are residential. While in London, only around 2% of the population is supplied with centralised heating and hot water (Table 1), which combines both district and communal systems.

Table 1 shows the difference in scale and DH coverage in both cities: while Riga has only 614 thousand inhabitants, London is a metropolis of 8.8 million people. Also, population density is 2.8 times higher in London. However, DH has been prioritised in Riga over time, with a consolidated DH landscape, whereas in London heating is mainly supplied through individual or communal gas boilers. Currently, London has a growing DH market with high development potential, while Riga has a mature DH system with more than half-a-century old tradition. Development of DH systems in London is justified by the economic and environmental benefits of centralised heat supply in densely populated cities.

**Table 1.** Characteristics of the cities of Riga and London cities their DH coverage.

|  |  |  |
| --- | --- | --- |
| Parameters | Riga (2021) | London (2021)[29] |
| Area, km2 | 307 | 1,572 |
| Population | 614,618 | 8,796,600 |
| Density, pop/km2 | 2002 | 5596 |
| Total produced heat, GWh | 3,700 | 2,241 |
| Total DH sales, GWh | 3,280 | 1,600 |
| Share of inhabitants served by DH, % | 56 | 3 |
| Specific heat losses, % | 11.3 | 28.9 |
| Linear heat consumption density, MWh/km | 4.13 | N/A |
| Trench length of DH pipeline, km | 800 | N/A |

**Fig.1**. Share of used fuel (energy carrier) in the DH system.

The current DH landscape in Riga and the UK (breakdown for London not available) [30] shows that two fuels dominate these systems: natural gas (NG) and biomass (B) (Figure 1). NG is used as the main fuel in both cities. The renewable energy resources (RES) share has increased in the last few years, reaching 33.4% in Riga in 2021 and 8.7% in the UK in 2018. Biomass combustion technology is the most common form of renewable heating in Riga. Regarding the current technologies in the Latvian capital, 53% of heat in 2021 was produced using combined heat and power (CHP, consisting of 40.5% NG and 12.5% B) and 47% with heat-only boilers (HOB, consisting of 28% NG, 19% B).

The context for London is quite similar to that of the UK, where HP technologies are gaining greater traction and public support as the main alternative for decarbonising heat supply in buildings. This is reflected in the UK Government’s Heat and Buildings strategy [31], which set a target of increasing the shares of heat demand met by low-carbon DH networks to 20% in 2050, with mention to greater roles expected from HPs and waste heat. The Greater London Authority aims for London to become a carbon neutral city by 2030 [32], and their plans include having 2.2 million heat pumps in operation and 460,000 buildings connected to DH by then. A common challenge for the DH systems of both cities is therefore related to the need to decarbonise and transition towards modern 4th and 5th generation DH systems. Both cities are served by large WWTPs, the treated WW of which is discharged into open water areas: Riga - the Riga Gulf of the Baltic Sea, and London - the Thames.

## METHODOLOGY

### Methodology Algorithm

The research methodology includes 7 interrelated steps to evaluate the implementation of wastewater-source heat pump (WWSHP) technology and its advantages and limitations, and this is based on a multi-factorial assessment for various DH system development scenarios (Fig.2). The first two steps of the methodology – namely initial data and spatiotemporal analyses of supply and demand in potential consumption areas – were comprehensively described in previous studies [5], [27], and involve obtaining heat demand data for the investigated DH networks in Riga and London, as well as ambient and effluent temperature data for the WWTPs of interest in both locations.

As only annual heat demand data was available, an hourly demand profile was created following the heating degree days (HDD) approach reported in [33]. In this case, it was assumed that space heating would only be required for ambient temperatures below 16°C and that 20% of the annual heat demand was associated with domestic hot water and therefore had a constant profile throughout the year. The calculation of the hourly heat demand profile enabled identifying the peak demand (, MW) for each of the case studies, which was then used to determine the capacity of the WWSHP through an optimisation process (Fig. 2, step 3). In this case, the objective was to minimise the levelised cost of heat (LCOH, EUR/MWh) from the WWSHP by changing its capacity (, MW), as shown in Eq.1. More details on the LCOH calculations will be provided in the description of step 5 of the methodology shown in Fig. 2.

|  |  |
| --- | --- |
|  | (1) |

The optimisation was subject to constraints that the heat pump capacity could never exceed the hourly peak demand for the respective DH system (, MW) and that the heat generated by the WWSHP should not exceed the heat demand of the DH network. Another constraint relates to the hourly (at every d hour) heat production from the heat pump (), which should match the hourly heat demand unless it is higher than its capacity (, MW). Once the hourly heat production is known, the electrical energy consumption for the heat pump (, MWh) can be calculated by dividing the heat produced by the hourly coefficient of performance () of the WWSHP, as shown in Eq. 2.

|  |  |
| --- | --- |
|  | (2) |

The hourly COP was estimated utilising temperature data for the WWTP effluent for both Riga and London. The WWSHP was modelled utilising the commercial software tool Engineering Equation Solver. The WWSHP model was developed considering ammonia (R717) as the refrigerant, and hourly COP figures were derived assuming supply and return temperatures for the DH system of 69 and 42°C. Modelling assumptions include approach temperatures of 2 and 5K for the evaporator and condenser, respectively, 5K of superheat at the evaporator and an isentropic efficiency of 80%. The COP values obtained for Riga varied from 3.01 to 4.14 (average of 3.70), whereas in London, COP varied between 3.69 and 4.41 (average of 4.05). The calculated electrical consumption for the WWSHP was then utilised in the subsequent steps in the methodology, as it enabled calculating operating costs and emissions associated with the WH recovery system.



**Fig. 2**. Methodology algorithm.

As shown in Fig.1, the existing DH system in each city operates using different technology and fuel mixes. Therefore, the WWSHP integration assessment will consider different scenarios that reflect the initial DH structure for both Riga and London. The first set of scenarios (Sc1) is based on a combination of NG and B HOB technologies in different proportions, whereas the second set of scenarios (Sc2) consists of different combinations of NG HOB and CHP technologies. All modelled scenarios are listed in Table 2, and these represent the fourth step within the research methodology. The proposed multi-factorial assessment enables a comprehensive analysis of heat recovery potential by comparing energy, environmental, economic, and social KPIs in possible future scenarios (Fig.2, 5 step). In order to evaluate economic and social benefits, the levelised cost of heat (LCOH, EUR/MWh) metric was then applied to estimate the costs for each heat production technologies, as shown in Eq. 3.

**Table 2.** Description of the modelling scenarios investigated in this study.

|  |  |
| --- | --- |
| Name of parameter | Scenarios |
| Share of HOB technology by biomass (B) in technologies mix (HOB by B and HOB by NG) | Sc1/0  Sc1/30  Sc1/50  Sc1/70  Sc1/90 |
| Share of CHP technology by NG in technologies mix (CHP by NG and HOB by NG) | Sc2/10  Sc2/30  Sc2/50  Sc2/70  Sc2/90 |
| City | R – Riga, L - London |

|  |  |
| --- | --- |
|  | (3) |

where – fuel costs, EUR/year; – taxes, EUR/year; – electric power costs, EUR/MWh; – electricity consumed from power network, MWh/year; – other costs, EUR/year; – operation and maintenance costs, EUR/year;  – technology investment costs, EUR/MW; – installed capacity of technology, MW; – loan repayment term, years; – loan interest rate, %/year; – generated amount of heat, MWh/year, *j* – technology.

As a result, the in the multi-generative system for *i* scenario was calculated as shown in Eq. 4:

|  |  |
| --- | --- |
|  | (4) |

where is the production tariff for technology *j*, EUR/MWh; is the share of technology *j*.

In addition to the installation of the HP, it would be necessary to build a DH connection line (supply and return) that would supply heat to the existing DH system. Heat losses (, MWh/year) on this pipeline are calculated indicated in Equations 5 and 6 [34]:

|  |  |
| --- | --- |
|  | (5) |
|  | (6) |

where is the system’s operating time, h/year; is the linear heat losses of the heating network section k, W/m; Lk is the length of the heating network for kth section; z is the total number of sections in the network; k is the pipe network section; is the supply temperature, °C; is the return temperature, °C; is the ground temperature, °C; is the insulation material’s linear heat resistance, (mK/W); is the ground’s linear heat resistance, (mK/W); is the additional linear heat resistance from the overlap of supply and return pipe temperature fields, (mK/W).

In the study, special attention was paid to the effect of WWSHP integration on the social well-being of the DH system consumers, using a multidimensional energy poverty analysis [27]. Provided approach combines the three drivers of energy poverty: fuel price, household income and energy efficiency of the house. The quantitative indicators that characterize energy poverty are an avoided heating costs and their share (%) in each *i* scenario:

|  |  |
| --- | --- |
|  | (7) |
|  | (8) |

where the levelized cost of heat in initial DH system structure and – in DH system with the WWSHP, EUR/MWh; is the value-added tax; is the specific heat consumption, MWh/m2 per year; is the area of an average family apartment (50 m2 was adopted for all countries), household income in scenario *i*, EUR/year.

When estimating the social impact of the WWSHP technology, its potential to reduce vulnerability and improving well-being was determined based on its contribution to reduce the energy poverty. As previously mentioned, the English fuel poverty metric is based on a property’s energy efficiency rating, as well as on its residual income after a heating bill is paid. Measuring the impact of WH on a dwelling level would therefore require an understanding of the energy efficiency rating of connected buildings, as well as the income of each individual household. Therefore, as this represents a system-level analysis, the metric of the fuel poverty gap has been applied to evaluate the impacts of WH on energy poverty. The fuel poverty gap is often used to indicate the reduction in fuel costs sufficient to bring the net household income above the official poverty line [35]. In 2022, 13.2% of households in London were fuel poor and the reported average value for the fuel poverty gap was £223 (€257). As for Riga, it has been reported that 15.9% of the population was at risk of poverty in 2022 [36]. Data from the Ministry of Welfare suggests that 70,954 households were receiving support in 2019, with average payments of €194 each [37]. As the fuel poverty gap is dependent upon several factors and is not commonly used in Latvia, the average payment for housing support was used as the reference value for estimating how waste heat integration to DH can help to alleviate energy poverty in Riga.

The share of recovered heat (, %) comparing to produced heat in the DH system is calculated as follows:

|  |  |
| --- | --- |
|  | (8) |

where *d* – operation hours of the WWSHP, – the thermal capacity of heat produced at the WWSHP in each d hour, – produced heat in the DH system by using *j* technology in each *d* hour.

As mentioned above, heat recovery from treated WW contributes to the decarbonisation of the DH system. The share of avoided emissions (, %) are used to assess the degree of decarbonisation and are calculated as follows:

|  |  |
| --- | --- |
|  | (8) |
|  | (9) |

where – the fuel consumption in the DH system, MWh per year; – the initial amount of CO2e emissions, tCO2e/year; – the amount of CO2e emissions after WWSHP installation, tCO2e/year; – the carbon emission factor for nth resources.

The CO2e emission factors were chosen based on the national data from Latvia and the UK (Table 3). Table 3 shows the carbon emission factors adopted in this investigation for different energy sources.

**Table 3.** Carbon emission intensity factors for different fuels used in the analysis.

|  |  |  |
| --- | --- | --- |
| Resource | Riga (Latvia) | London (UK) |
| Natural gas | 0.202 | 0.202 |
| Wood chips | 0.040 | 0.040 |
| Electrical power | 0.109 | 0.193 |

Carbon emission calculations for CHP technology is based on the Alternative Generation Method also known as the Efficiency Method [38]. The method allocates CO2e emissions and resources to the heat and power production in proportion to the fuel needed to produce the same amount of heat or power in separate plants. To determine the fraction of total emissions to allocate to heat and electricity production was used following equation:

|  |  |
| --- | --- |
|  | (10) |

Where – annual amount of carbon emissions produced for the heat energy share, tCO2e per year, – annual amount of the produced heat energy by the CHP, MWh per year; – annual amount of the produced electricity by the CHP, MWh per year; – assumed efficiency factor for individual electricity generation (assumed 0.46); – assumed efficiency factor for individual heat generation (assumed 0.9); – total direct emissions for the CHP system, tCO2e per year.

To consider costs of environmental impact of the installed WWSHP technologies, avoided CO2e emissions costs were determined ( , EUR/tCO2e):

|  |  |
| --- | --- |
|  | (11) |

When implementing the decarbonisation strategy of DH systems, operators are mainly guided by cost-benefit analyses. In step 6 of the study, the environmental impact of the installed WWSHP technologies is presented based on the calculation of avoided CO2e emissions costs, supplemented by a benchmarking method. At this stage, carbon quota prices and constrains related to the economic and environmental validity of the DH system are established.

In the past year, fuel and electricity prices varied significantly. Therefore, finally, in the step 7 of the methodology, sensitivity analyses were caried out by changing the following key parameters: operating hours, fuel (NG and B) prices, HP CAPEX, CO2e tax and loan rate for investment. The one-at-a-time method was used by varying the above parameters by +/- 30% [39]. Obtained results of sensitivity analysis are presented in Tornado diagrams.

### Model Assumptions

Energy carriers’ prices and other parameters used in the model are depicted in the Table 4.

**Table 4.** Cost of energy sources and other parameters for economic analysis.

|  |  |  |
| --- | --- | --- |
| Parameter | Riga | London |
| Network electricity price EUR/MWh | 142.70 [40] | 158.70 [41] |
| Natural gas price [42], EUR/MWh | 55 | 71.3 |
| Wood chip price [43], EUR/MWh | 30 | 30 |
| Value-added tax (VAT),% | 21 | 5 |
| Household income [44], EUR/year | 17275 | 37145 |
| Carbon quote price [45] | 90 | 90 |

Expenses for building additional heating lines connecting the WWSHP with the existing DH network were evaluated by considering the assumptions presented in Table 5.

**Table 5.** Heating network construction costs for economic analysis.

|  |  |  |
| --- | --- | --- |
| **Investment with asphalting works\*** | **Unit** | **Value** |
| Pipelines for connecting the WWSHP with the DH system (Riga -DN250) | EUR/m | 1100 |
| Pipelines for connecting the WWSHP with the DH system (London – DN200) | EUR/m | 1400 |

\*The preliminary costs for the construction of the pipeline have been estimated based on the previous experience of the DH companies [46].

Large-scale HP capital costs, operation and maintenance costs were obtained from Danish Energy Agency catalogue “Technology data. Generation of Electricity and District heating” [46], and all values were corrected to account for inflation [47], as shown in Table 6.

**Table 6.** Cost and technology inputs for economic analysis.

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Unit** | **Value** |
| CAPEX for HP | mln.EUR/MWth | 0.8285 |
| HP variable O&M | EUR/MWhth | 1.6 |
| HP fixed O&M | EUR/MWth/year | 2000 |
| HP variable O&M | EUR/MWhth | 1.2 |

Loan repayment period was assumed 10 years with weighted average cost of capital (WACC) 4.5%.

## CASE STUDY DESCRIPTION AND INITIAL ANALYSIS

### Initial feasibility assessment on reusing heat recovered from treated WW

In the first step, the initial conditions of the treated WW and its heat recovery potential were estimated. In Riga, the treated effluent is currently discharged into the Gulf of Riga. The average temperature of WW is stable around 10-11°C in the heating season and in the range of 12-20°C in the rest of the year (Fig.3). In London, average effluent temperature is slightly higher than in Riga, reaching +18°C during the heating season due to higher average outdoor temperature. These temperature levels indicate it is feasible to install a WWSHP for heat recovery. Climatic conditions in London are milder, which are more favourable to the operation of the HP, e.g. average outdoor temperature in the coldest five days is just +1.1°C, whereas in Riga temperatures can plunge to -20°C. Nevertheless, the average outdoor temperature in Riga during the heating period is +1.1°C, as shown in Table 7. Differences in outdoor temperature can also be expressed in terms of HDDs, which are 3684 and 1989 for Riga and London, respectively.

**Fig.3.** Effluent temperature during the year

**Table 7.** Climate conditions in both cities considered in the investigation.

|  |  |  |
| --- | --- | --- |
| Parameters | Riga | London |
| Heating-degree days | 3684 | 1989 |
| Average outdoor temperature in the coldest five days, °C | -20 | +1.1 |
| Average outdoor temperature during the heating season, °C | +1.1 | +6.8 |

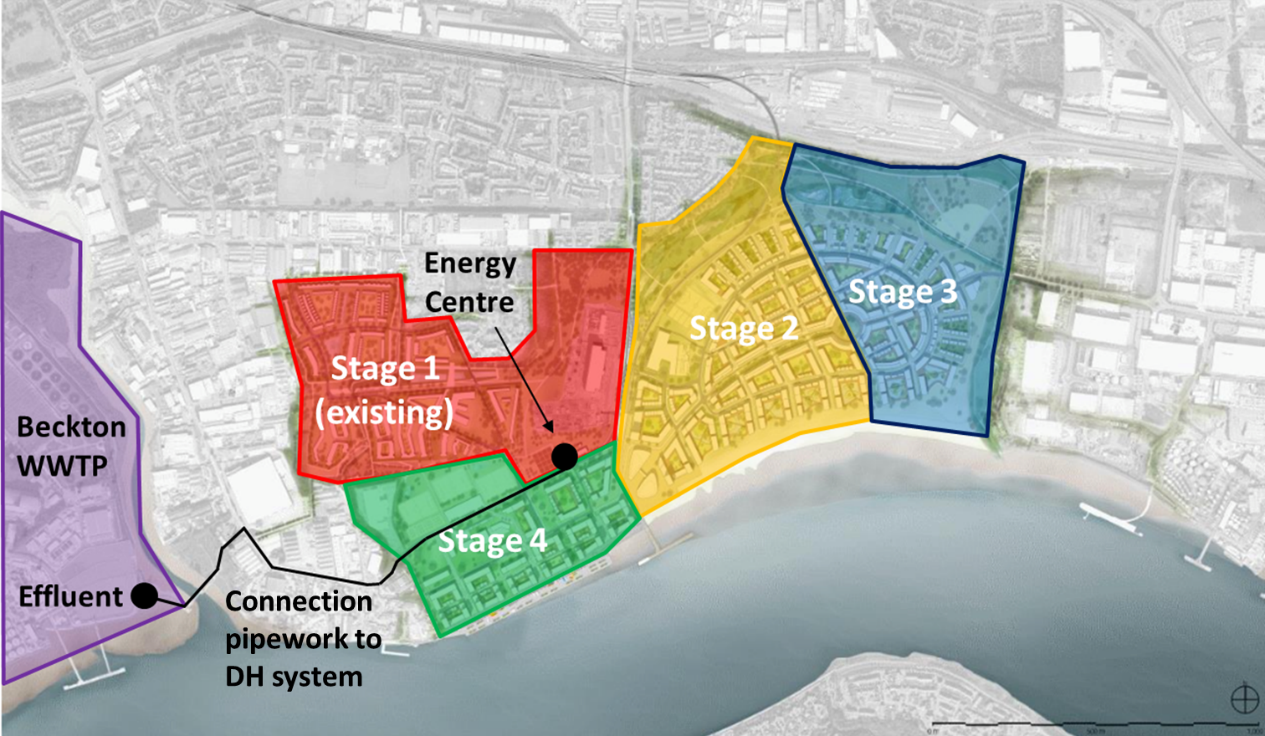
### Spatiotemporal analysis of WWSHP implementation and capacity optimisation

A spatiotemporal analysis involved overlaying the supply and demand profiles. Considering the temperature profile of treated WW, it fits very well for DH applications because of the continuity of treated WW flow and its high potential for recovery. The WWTP in Riga is located near two residential areas served by smaller DH networks, the location of which is far from the main DH network in the city (Fig.4). WWTP collects and treats wastewater from all over Riga and the suburbs. Approximately 3% of the total heat energy consumption in Riga is produced and consumed in both heat supply districts, a demand that could potentially be met with heat recovered from treated wastewater. In addition, it should be noted that the two local DH networks are not interconnected. The WWTP is relatively close to local DH networks - approximately 2.4 km away. The existing DH network, depicted as stage 1 in Figure 4, was used as a case study area in this research. The existing network is currently supplied with heat produced using biomass and natural gas boilers. Assuming that the temperature of the treated WW would be lowered by 5K when recovering heat, the extraction potential from the treated WW is 25 MW. Due to a mismatch between supply capacity and the demand of the nearby DH network, the case study would not be able to use all the waste heat available from Riga’s WWTP.



**Fig.4**. Riga case study.

As for London, the case study selected consisted of a new housing development in Barking, East London, which is being constructed at the time of writing. The construction is being carried out in 4 different stages, as illustrated in Figure 5, and the development will consist of 10,800 households and more than 65,000 m2 of commercial space once completed. For this investigation, a total heat demand of 31,405 MWh was considered, which is projected for 2025, when stages 1 and 2 will be completed, and is similar in size to the Riga case study. The reason this case study was selected is due to its privileged location, which is in the vicinity of the Beckton Sewage Treatment Works, the largest WWTP in Europe, with a capacity in population equivalent (PE) of ca. 3 million as of 2018 [48]. With an approximate dry flow rate of 5 m3/s, the waste heat recovery potential from Beckton would be of 105 MW, considering the same heat extraction rate of 5 K.



**Fig. 5.** London case study.

Heat load duration curves for the studied areas in Riga and London are presented in Figure 6. The main planning challenge that this study faces is related to optimising costs. Figure 6 shows that the peak load (14.8 MW) in Riga increases rapidly due to the considerably lower minimum outdoor temperature compared to London, as indicated in Table 7. It is worth noting that the end of the heating season in Riga is more distinct than in London, and this is due to the historical practice of turning off the heating as soon as the average outdoor temperature reaches +7°C during the day.

**Fig.6.** Heat load duration curves for Riga and London.

The optimisation algorithm described in Section 3 "Methodology" (Equations 1-2) is used to determine the thermal capacity of the HP (, in MW). The calculated values were of 6.3 MW in Riga and 5.8 MW in London, showing a relatively high potential of recovered heat from treated WW that could be integrated into DH systems in these two cities, which aligns with the proposed hypothesis. The optimisation was performed to achieve the minimum LCOH possible for the WWSHP system, including costs of connection to the DH systems. The WWSHPs in Riga and London can operate for 5200 and 5100 hours respectively. This ensures the equipment's high economic feasibility and follows the assumptions provided in section 3 of the methodology.

## RESULTS AND DISCUSSION: MULTI-FACTORIAL ASSESSMENT OF THE POTENTIAL OF TREATED WASTEWATER HEAT

### Energy and economic impacts of WWSHP implementation

Figure 7 shows the results of the LCOH calculations for heat recovery using WWSHP, which were of 69.4 EUR/MWh and 71.2 EUR/MWh for Riga and London, respectively. In both cases, they are lower compared to the cost of heat using existing combustion-based technologies (see Tables 8 and 9).

**Fig.7.** Levelised cost of heat for heat production by using WWSHP

**Table 8.** Economic feasibility results for implementation of a WWSHP in Riga.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Scenarios | Sc1/0/R | Sc1/30/R | Sc1/50/R | Sc1/70/R | Sc1/90/R |
| LCOH for Sc1, EUR/MWh | 136.97 | 126.53 | 116.09 | 105.66 | 95.22 |
| Cost benefit of WWSHP EUR/MWh | 67.57 | 57.13 | 46.69 | 36.25 | 25.82 |
| Scenarios | **Sc2/10/R** | **Sc2/30/R** | **Sc2/50/R** | **Sc2/70/R** | **Sc2/90/R** |
| LCOH for Sc2, EUR/MWh | 137.61 | 129.70 | 121.78 | 113.87 | 105.96 |
| Cost benefit of WWSHP EUR/MW) | 68.22 | 60.31 | 52.39 | 44.48 | 36.57 |

The largest part of the LCOH is the cost of electricity for HP operation (58.9% and 58.2% for Riga and London, respectively). These strongly similar results are determined by the fact that technology costs are the same on the European market and the HP CAPEX is 24.2% and 25.3% of the total costs in Riga and London, respectively. Relatively cheaper electricity in Riga (142.7 EUR/MWh vs. 158 EUR/MWh for London) does not make the use of this technology much more profitable, as this is compensated by the lower COP values obtained for Riga. The results fit well with previous published studies. Ozcan H.G. et.al. [49] notes that the lower limit of the cost of produced heat by using WWSHP is 80.1 EUR/MWh and depends on the effluent temperature. Considering the relatively high temperature of the effluents and possible high their decrease after recovery (ΔT 5K), both case studies achieve high economic efficiency of heat production. The study shows that in all cases the installation of WWSHP is economically justified, which is also noted by Kontu K. et.al. [50].

**Table 9.** Economic feasibility results for implementation of a WWSHP in London.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Scenarios | Sc1/0/L | Sc1/30/L | Sc1/50/L | Sc1/70/L | Sc1/90/L |
| LCOH for Sc1, EUR/MWh | 141.73 | 130.24 | 118.74 | 107.24 | 95.75 |
| Cost benefit of WWSHP EUR/MWh | 70.53 | 59.03 | 47.54 | 36.04 | 24.54 |
| Scenarios | **Sc2/10/L** | **Sc2/30/L** | **Sc2/50/L** | **Sc2/70/L** | **Sc2/90/L** |
| LCOH for Sc2, EUR/MWh | 141.94 | 133.92 | 125.90 | 117.89 | 109.87 |
| Cost benefit of WWSHP EUR/MW) | 70.75 | 62.74 | 54.72 | 46.70 | 38.68 |

The LCOH were calculated for each scenario according to Eqs. 3 and 4 of section 3 (“Methodology”). The trends both in the assessment of existing levelised costs of heat and in the calculation of benefits from the implementation of WWSHP are the same for both cities. In general, the cost-effectiveness is higher for Sc2, as more expensive fossil fuels are replaced by waste heat from the WWTP. In most cases, London provides greater savings compared to Riga due to higher initial LCOH (EUR/MWh) for the incumbent technology. For instance, when replacing heat recovered from WW in a DH system that uses a combination of 50% biomass and 50% natural gas HOB technology, the levelised savings are 0.85 EUR/MWh higher in London (47.54 EUR/MWh) than in Riga (46.69 EUR/MWh). In addition, it should be noted that if the structure of the DH system has a larger share of CHP technology or biomass-based HOBs, then the economic benefit decreases because of lower LCOH for both replaced technologies. In the case of biomass HOB technologies, economic benefit falls on average 2.7 times vs. natural gas HOBs, and in the case of CHP technologies, 1.8 times.

### Environmental impacts of WWSHP installation

The high environmental performance of the DH system with integrated recovered heat from treated WW effluent, as well as the above-mentioned economic performance, significantly decreases if the technology displaced is biomass HOBs. Figure 8 presents an analysis of annual avoided CO2e emissions for different shares of biomass HOB technology in the initial DH fuel mix. If the DH system is based on NG HOB technology, the avoided CO2e emission could reach 77.1% or 72.5% in the Riga and London case studies, respectively. However, in a DH system where only half of the heat is produced with NG HOB technology, these indicators are reduced to 61.2% and 53.3% for Riga and London, respectively. The reason for the greater reduction in CO2e emissions savings in London compared to Riga is that the CO2e emission factor assumed for electricity in London is higher than that of Riga (0.109 tCO2e/MWh in Riga compared to 0.193 tCO2e/MWh in London, as listed in Table 3).

**Fig.8.** CO2e emission saving before and after WWSHP installation by HOB based DH system (Sc1).

**Fig.9.** CO2e emission saving before and after WWSHP installation by scenario 2 with different share of CHP technology by NG in technologies mix (Sc2).

The situation where an initial DH system consists of both CHP and HOB technologies is significantly different. The implementation of WWSHP technologies allows the reduction of avoided carbon emissions from 76.5% to 69.7% in Riga and from 70.5% to 63.4% in London, which demonstrates the higher environmental efficiency of these scenarios compared to Sc1. This means that the benefits of waste heat are better exploited when displacing heating technologies that rely on fossil fuels such as natural gas, which is in line with the proposed hypothesis.

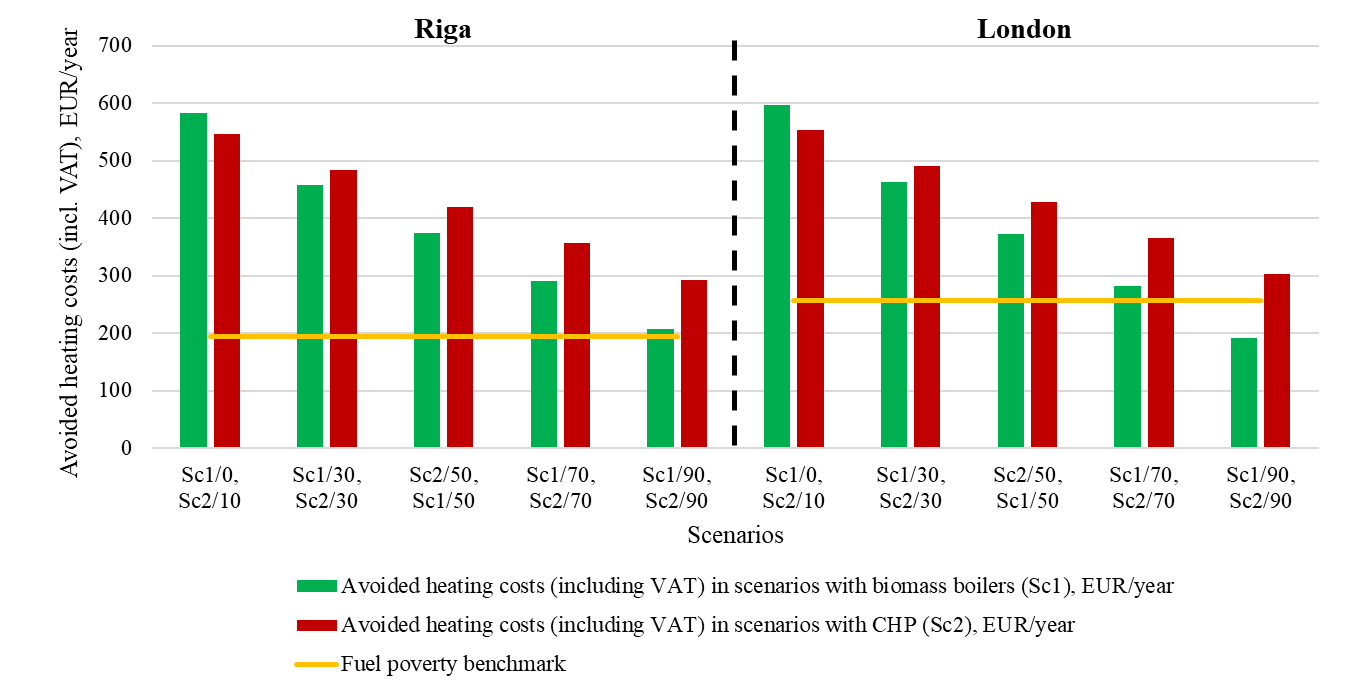
Determining the cost of avoided emissions allows combining economic and environmental efficiencies of the WWSHP system. Figure 10 presents the cost of avoided emissions (Eq. 11, , EUR/tCO2e) versus the share of technology in different scenarios (Sc1 - share of HOB technology by biomass in technologies mix, Sc2 - share of CHP technology by NG in technologies mix). In order to determine the economic and environmental efficiency limit, a benchmark indicating the average price of carbon quotes in 2023 was introduced, which is equivalent to 90 EUR/tCO2e. Figure 10 indicates how the cost of avoided carbon emissions increases rapidly if the share of biomass in the fuel is greater than 50%. It enables concluding that the installation of WWSHP would be justified from environmental and economic perspectives in the studied DH system with a biomass HOB technology proportion of up to 30%, at the current emission price of 90 EUR/tCO2e. The cost savings from avoided carbon emissions in DH systems that utilise CHP technologies are steadily increasing over time. However, if the share of CHP heat generation is greater than 45% of the overall DH demand, then the avoided carbon emission costs will exceed the existing carbon quota prices in both cities. This indicates how, in cases with large DH systems with a large share of cogeneration from natural gas, decision-makers will have to look for additional justification to install WWSHP. As noted by Konti et.al. [50] in their study, in medium and large DH systems with economically feasible CHP production, the potential for WWSHPs is lower. However, WWSHPs are still installed in these conditions due to a clear understanding of the possibility of utilising heat that would otherwise be wasted [51].

**Fig.10.** Annual cost of avoided emissions vs share of technologies mixes in initial DH system.

### Energy poverty and social impacts of WWSHP implementation

The analysis of energy poverty impacts follows the methodology described in section 3.1, which evaluates how the avoided heating costs (Eq. 11, , EUR/tCO2e) resulting from the WWSHP system could support vulnerable households in Riga and London. In both cases, the results from the social KPI (avoided heating cost) were compared to two different benchmarks for fuel poverty in Riga (€194 per household) and London (€257 per household), and this is illustrated in Figure 11. As it can be observed, the savings achieved by the WWSHP system is generally higher than the fuel poverty benchmark across all scenarios where the system would be predominantly replacing natural gas boilers, with lower shares of CHP and biomass (0 to 50%).

The highest value of avoided heating cost was obtained for Sc1/0, where the WWSHP technology would only displace gas boilers and achieve annual savings per connected dwelling of €583 (46%) in Riga and €597 (49%) in London. In these cases, the share of avoided heating cost, in relation to the average household income (Eq. 7, , %), would be of 3.26% in Riga and 1.64% in London. The greater shares obtained for Riga can be explained by its lower average household income when compared to London. However, London achieved greater annual savings in energy bills (EUR/year), which can be explained by a higher share of demand being met by the WWSHP (94% as opposed to 90% for Riga), and a lower VAT (5% vs. 21%) and a higher natural gas tariff (147.5 EUR/MWh vs. 142.2 EUR/MWh). By considering the benchmark energy poverty values selected, it can be observed that the benefit in Riga would be three times the value of the housing support payments that could be claimed by a typical household. In total, the energy cost savings achieved by the WWSHP system when compared to natural gas HOB would be equivalent to providing housing support to 13,409 average-sized dwellings in Riga. As for London, energy cost savings per household would be over twice the value of the current fuel poverty gap, and overall cost savings would be enough to lift 8,725 homes out of fuel poverty.



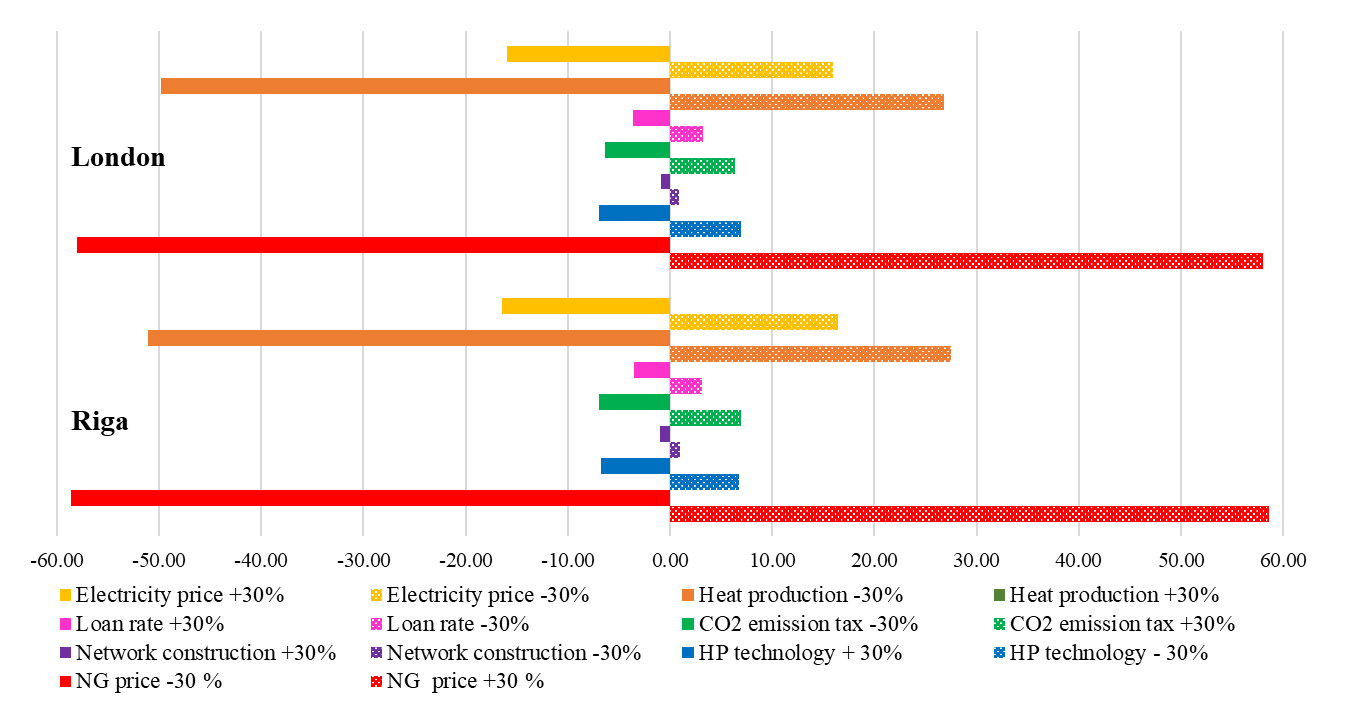
**Fig.11.** Annual avoided heating costs compared to fuel poverty benchmarks

in Riga and London.

However, the benefits of integrating WW heat into DH are lower when the displaced technology is either biomass boilers or gas-fired CHPs. As shown in Figure 11, displacing a scenario with 90% biomass (Sc1/90) would achieve avoided heating costs of €207 per household annually in Riga, which is only 7% higher than the housing support offered to households in Latvia. As for London, where CHP technologies are commonly deployed in DH systems, displacing a heat demand that is 90% met with CHP (Sc2/90) would lead to a reduction in household energy bills of 192 EUR per annum, which is equivalent to approximately 75% of the current fuel poverty gap. These results strongly contrast the expected social impacts of heat pumps reported in [18], which estimated the transition from typical gas boilers to air-source heat pumps to increase household heating costs in London by £20-40 (€23-47), considering 2019 energy prices.

### Sensitivity analysis and impacts on avoided heating costs

Given the multidimensional element of the methodology applied in this study, it must be noted that many different factors can influence the social impacts of waste heat, which has been analysed based on the social KPI of avoided heating costs. This is highlighted in Figure 12, which compares how changing different inputs by ±30% may affect the shares of avoided heating costs. As it can be observed, the parameters tested include the CAPEX for both DH and WWSHP, the amount of heat produced by the system, gas and electricity prices, as well as the value of the carbon tax and the loan interest rate. The sensitivity analysis was only carried out for Sc1/0, where the WWSHP system would displace natural gas boilers.



**Fig.12.** Impacts of changing key parameters on avoided heating costs (%).

As it can be observed, the factors that most affected the share of avoided heating costs were the gas price and heat production, followed by the electricity price to a lower extent. A 30% increase in the amount of heat produced by the WWSHP system would cause avoided heating costs to rise by approximately 27% in both locations. On the other hand, a 30% reduction in heat generation would lead to a decrease of around 50% in savings. The reason for this significant impact is a reduction in heat output from the WWSHP without affecting the required capita investment for the entire system. Gas prices were also a key factor affecting the avoided heating costs. A ±30% would cause a change of ±58% in the savings obtain in both cities, showing how the social impacts of waste heat are significantly affected by energy market conditions, as also shown by the impacts of varying electricity prices (approximately ±16% in avoided heating costs). The carbon tax is still not high enough to make a significant impact on avoided heating costs, and as costs associated with CAPEX are annualised, their influence on energy bills is reduced, particularly for the DH network infrastructure, which was assumed to have a design life of 50 years. Overall, the sensitivity analysis highlighted how the WWSHP should generate as much heat as possible to justify its high capital investment. Furthermore, the uncertainty around future fuel prices can significantly affect the savings achieved by the system and should always be considered in feasibility studies.

## CONCLUSIONS

This investigation provided a comprehensive multi-factorial assessment on the potential for integrating waste heat from a WWTP into district heating, considering several KPIs related to economic, environmental and social spheres. The analysis of the factors researched in this study can support decision-making regarding the implementation of WH recovery technologies considering the DH conditions and structures of the city.

All hypotheses raised in the study were proved. For example, in environmental terms, significant carbon emissions can be obtained when the main energy source being displaced is natural gas, whether it is used for HOB or CHP systems. Additionally, when compared to biomass boilers, the carbon savings of WWSHP are much lower and depend on the carbon intensity of the electricity that is used to power the heat pump. As the electricity carbon factor in Riga is lower, the achieved carbon savings were generally higher than in London. Therefore, for a DH system with an initial technology mix based on natural gas and biomass, the avoided CO2e emission reduction in Riga varied from 12.2% to 77.1%. In London, this variation was between 6.6% and 72.5%. Both results reflect the savings obtained by increasing the use of biomass from 90% to 0 in the technology mix. The study shows that DH systems conditions and structures (share of different heat production technologies and used fuel) as well as the impact of carbon prices require additional research and justification for the installation of WWSHP. carbon

In the social sphere, this investigation has shown how waste heat can strongly support the reduction of energy bills for consumers, and this was observed across all analysed scenarios, supporting the hypothesis of this research. A novelty of this study has been to analyse the social impacts of waste heat when compared to different displaced technologies, namely HOB (NG and biomass) and gas-fired CHP systems, using energy poverty metrics as an indicator. Results showed how social benefit diminished when the replaced technology is biomass or CHP, as the latter has a lower cost per unit of energy than NG, whilst the latter can achieve lower operating costs due to the export of generated electricity. The analysis also showed how waste heat can be a powerful resource to mitigate energy poverty. In London, the energy cost savings achieved by waste heat would be enough to cover the fuel poverty gap for all connected households in all CHP scenarios, and in Riga, the avoided heating costs are higher than the existing value of housing support in all analysed scenarios.

Finally, a sensitivity analysis was carried out to investigate the most influential factors when it comes to affecting the social benefits that can be achieved with waste heat. Overall, the most impactful external factor observed was the cost of energy. In a scenario with a 30% increase in gas prices, the social impact of the WWSHP system increased by 58%, indicating how waste heat can play an important role in improving energy security. The proposed research methodology could be applied to other DH systems and other WH sources when the effects of integration of WH into the DH system need to be assessed concerning the transition towards the 4GDH system and carbon neutrality as well as their impact on energy poverty.

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**Credit author statement**

Henrique Lagoeiro – conceptualization, methodology, data curation and analysis, modelling, writing – original draft, writing – original draft, writing – review & editing, visualization.

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**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 the paper.

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