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Valorisation of Waste Heat in Existing and Future District Heating Systems

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Abstract: To recover thermal energy from different sources, its quality and possibilities for utilisation are essential. The wide range of engineering solutions includes a direct connection to the district heating (DH) system and the integration of low-quality heat using heat pumps to increase the temperature level of recoverable heat. Therefore, this article compares waste heat valorisation strategies for integration into existing DH networks, low-temperature DH, and ultra-low heat supply systems using the multi-criteria assessment method. In addition, a local scale assessment was performed to identify the waste heat role in existing RES-based DH systems. The results show that the highest waste heat valorisation rate could be reached when integrated into low-temperature DH systems due to high waste heat potential and suitable temperature conditions. However, a local scale assessment shows a significant impact on the already implemented solar technologies, as waste heat could cover around 70% of the summer heat load.

Keywords: district heating; waste heat; low-temperature heat sources

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1. Introduction

District heating (DH) systems are a necessity in northern and central European countries to move forward sustainable energy systems due to in-place infrastructure, which can be further transformed for integration of renewable energy sources (RESs) and thermal energy storage [1]. In addition, future energy systems require more efficient use of primary energy resources by recovering and utilising unused energy flows [2]. Therefore, DH networks that connect a great number of buildings in urban areas and provide heat for more than half of the city population have significant potential to integrate these recovered heat flows defined as surplus or waste heat [3].

Several studies have shown that integration into DH systems is one of the best solutions for waste heat utilisation [4]. The main reasons are improved efficiency of both the existing heat supply and the waste heat source, lower overall environmental impact due to reduced fuel consumption and avoided thermal flows, and reduced costs from primary energy savings. DH networks can also provide a more flexible heat demand for heat flow utilisation and alignment [5,6]. However, when there is no DH network available at an economically sound distance from the energy source, local heat supply solutions can be analysed by applying energy community solutions with local buildings [7].

1.1. Identification of Waste Heat Sources

The most common waste heat source is industrial objects. Industrial waste heat is divided into three sections based on its temperature—low, medium, and high temperature [8]. Very high-temperature waste heat (above 400 °C) usually arises from combustion processes. The utilisation potential of such very high-temperature heat flows is the highest as it can be used for power generation [9]. Waste heat with temperatures from 100 °C to 400 °C is considered medium-temperature waste heat, and it is part of the exhaust processes [5]. Such temperature levels are suitable for direct integration in DH systems to cover the heat demand. Low-temperature heat or waste heat with a temperature below 100 °C is mostly recovered from cooling processes in industries [10]. During the last decades, research has focused on the utilisation of ultra-low heat sources because innovative integration strategies and operational changes in existing heating networks are necessary to use these heat flows [11].

Heat recovery potential from different industries has been a highly researched strategy for reaching primary energy savings [12–14]. Jauhara et al. [15] reviewed the best practices for various waste heat recovery technologies such as recuperators, regenerators, passive air preheaters, regenerative and recuperative burners, plate heat exchangers and economisers in the steel and iron, food, and ceramic industries. In the research conducted by Denarie et al. [16], industrial waste heat is divided into different temperature levels—high temperature, low temperature, and steam. The authors conclude that in Italy, the main recoverable heat could come from energy production sites and different industrial enterprises. Kasmadakis concluded that the total potential for the implementation of industrial heat pumps (HPs) to recover unused heat flows is 28.37 TWh per year [17].

Boiler houses and combined heat and power plants are excellent waste heat sources for their high-temperature levels [18]. The source of waste heat for CHP plants and boiler houses is flue gases. When a flue gas condenser is not used, then the flue gas temperature can be more than 100 °C and therefore can be used directly with a heat exchanger in the DH network. Nevertheless, it is more useful to use a flue gas condenser for heat recovery in boiler houses and CHPs, especially when the used fuel has a high moisture content, for example, woodchips and biomass. In the case of biomass combustion, a flue gas condenser can increase the boiler efficiency by up to 20% (relating to the lowest heating value) depending on the biomass parameters, design of the boiler, and operating conditions [19].

When a flue gas condenser is used, the leaving flue gases are cooled down to the DH return temperature, which is normally 45–50 °C in the case of a high-temperature DH network. This heat can also be recovered using HPs, as the flue gases can be cooled to 20 °C [20]. This kind of solution is implemented in Tallinn at the Mustamäe CHP plant, where both a flue gas condenser and flue gas HP are installed to recover even more heat. The profitability of this kind of technical solution depends on the capacity of the boiler. Normally, additional heat recovery of the HP in this case can be 4–5% of the total heat.

One of the possible low-temperature waste heat sources is data centres that generate a remarkable amount of heat from electronic equipment—about 97% of that can be used internally or externally for heat load coverage. It is stated that data centres use about 3% of the world's energy consumption, and the used energy amount will only increase in the future [21]. Usually, these centres need constant cooling for proper maintenance, which is an energy-intensive process. Cooling technologies can be supplemented with heat recovery technology to recover the heat generated in these centres and use it internally for space heating or domestic hot water preparation or integrated into the DH network [22]. In this case, for heat recovery, HPs could be used so that all the excess heat would not be emitted into the atmosphere. In data centres, 30–40% of the used energy is from cooling processes, which is a significant amount of energy consumption and one of the criteria to consider using waste heat [23]. This energy in data centres in the liquid cooling system is usually at a temperature from 50 to 60 °C but from air cooling systems, it reaches about 25–35 °C [24]. Another benefit of recovering waste heat, particularly in data centres, is its stable working hours because the cooling system in data centres is needed all the time.

Using sewage water heat in DH with the help of large-scale HPs is an often-used practice, as sewage water is a very good heat source because its temperatures are high enough for HP integration. Normally, when sewage water first arrives at the water treatment plant, the flow temperatures are between 11 and 15 °C during the winter period and above 15 °C during the summer period, which would be excellent for use as a low-temperature heat source for HPs [25]. Still, the wastewater treatment process needs sufficient temperatures for the biological treatment process, so waste heat can be used after the treatment process when the flow temperature is around 9–10 °C.

Sewage water waste heat is highly available as water treatment plants are in most major cities and normally, they are not very far from DH networks [26]. For using treated sewage water as a heat source, the most important parameter in addition to the temperature level is the flow rate, which determines the amount of possible recoverable waste heat. Normally, there are no limiting factors for possible recoverable waste heat by the reservoir where purified sewage is led after treatment. For example, if purified sewage water is led toward the sea after the treatment process, then the purified sewage temperature should be close to the seawater temperature. During the heating period, sewage water temperature is always higher than the seawater temperature, and heat recovery for DH would have a good influence on the marine environment, as the sewage temperature is closer to the seawater temperature.

Although the amount of waste heat from sewage water can be enough to cover a small city's DH demand, this heat source cannot be the main heat source, as the demand and production curves do not match. Heat production from sewage water is quite constant with short periodical fluctuations, so there is not enough heat for the winter period, and a significant amount is left over during the summer period. This can be solved with thermal energy storage or using auxiliary heat sources.

There are many studies dedicated to other types of waste heat and their potential role in heat supply coverage. Escriva et al. [27] investigated heat recovery from refrigerated systems in supermarkets and concluded that useful heat recovered in a UK supermarket could range from 28.7% to 43.2%. A relatively small number of studies are dedicated to heat recovery from electric transformers, which could also be used as a heat source for individual heating or integrated into DH networks [28]. Petrovic et al. [29]. estimated that the theoretical amount of excess heat from power transformers available for DH in Denmark could reach 0.28 TWh per year.

1.2. Methods Used for Waste Heat Potential Estimation

Waste heat integration into the DH system can be divided into indirect and direct integration, which depends on the waste heat temperature and operating temperature of the DH network. Direct waste heat means that it is possible to use it without increasing temperature with a heat exchanger, but when the heat source temperature is too low to use in DH systems, it is necessary to increase the temperature and integrate the heat source indirectly. Therefore, for low-temperature DH systems, HPs are essential elements for the broader integration of waste heat flows [30].

Previous research mostly used bottom-up (surveys) or top-down (estimation) approaches or a combination of both methods for estimating waste heat potential. The bottom-up approach reckons single case study reports and equalises them as a general result. The top-down approach uses general results through already-calculated waste heat potential factors for quantification of waste heat potential. Furthermore, waste heat potential itself is divided into three categories—theoretical, technical, and economical [31].

In the study conducted by Forman et al. [31], global waste heat potential is calculated using the top-down method. In their study, waste heat is part of three types of losses in energy conversion processes—exhaust, effluent, and other losses. The temperature range is also considered. The results show that the largest volume of waste heat is available in low-temperature levels (61% of exhausts and effluents) and most of the waste heat comes from electricity generation.

A study in Taiwan used bottom-up analysis to quantify industrial waste heat potential. In that study, only exhaust flue gas flows are considered [32]. Based on the calculations, the chemical industry has the largest waste heat potential, accounting for 66.5% of total theoretical waste heat potential and 45.8% of technical potential. Exhaust gases with temperatures between 100 and 150 °C have the highest potential in theoretical calculations.

1.3. Waste Heat Integration into DH Networks

Lower-temperature DH systems will allow for utilising low-temperature waste heat sources since those are the most widely available [33]. Previous authors have defined four generations of DH systems and an additional ultra-low DH system concept attributed as a type of fourth-generation DH (4GDH) system or a fifth-generation district heating and cooling (5GDHC) system in some studies [34,35]. The 4GDH system is based on a broader integration of different RES and operations with a low-temperature heat carrier—about 50–70 °C. It reduces the heating network heat losses, expands the energy efficiency of energy conversion technologies [36], and makes it easier to use waste heat in DH systems. The 5GDH concept uses a heat carrier with a temperature close to ambient temperature, which is increased individually at each heat consumer using HPs [37]. The fifth generation [38] DH system differs from others with its combination of heating and cooling systems. Considering, that this generation DH system is based on using different RES, it gives a lot of flexibility when it comes to heating supply—it is possible to use CHP, HPs, solar energy, electric boilers, and others [39]. These DH concepts are also considered smart energy systems that interact with power networks for more efficient use of intermittent RES power [40].

HPs are necessary for low-temperature DH systems and cross-sectoral integration as large electrically powered HPs are used in power-to-heat solutions [41]. What makes this system effective is that it allows for using more renewable energy instead of using fossil fuel, especially in the heat supply. Using HPs can help to smooth the uncontrollable RES electricity production peaks and therefore to stabilise the electricity price and market. Power-to-heat technologies, together with relatively cheaper thermal energy storage [42], allow DH systems to accommodate more intermittent renewable energy than alternatives. However, the whole system is more complicated, and there are more operation conditions that need to be considered, for instance, heat storage. In the event of a significant increase in electricity demand due to power-based heat production [43], additional investments are likely to be required to increase the capacity of the transmission and distribution network. Depending on the waste heat source and previous DH price for consumers, these kinds of investments can still reduce the price for consumers [43]. To make the investments more attractive to DH companies, investment support could be a good option.

1.4. Aim and Scope of This Study

While previous research has explored waste heat potential and the feasibility of heat load coverage, a research gap remains in understanding the conditions necessary for the broader utilisation of waste heat flows, particularly in the context of evolving fourth- and fifth-generation district heating (4GDH and 5GDH) systems and their integration into smart energy systems. Further studies on waste heat's role among different heat supply systems and its potential impact on existing heat supply are necessary. The innovation of this study lies in its pursuit of bridging this gap. The research sets out to explore waste heat's evolving role among various heat supply systems and its potential impact on existing heat supply structures.

Potential waste heat sources are valorised within this study using in-depth national potential assessment and technical simulation. In addition, a local scale waste heat assessment is provided to analyse the potential impact on the existing RES heat supply technologies. This localised analysis is crucial for understanding how waste heat utilisation can complement or potentially impact existing RES systems at the DH system level.

Therefore, this study includes multi-scale analyses by investigating waste heat valorisation for utilisation in DH systems in local and national contexts. Using this approach, the authors aim to provide a comprehensive framework for understanding the potential of waste heat utilisation, not only as an energy source but as a critical component of the evolving energy landscape.

2. Materials and Methods

Within this study, the authors use two approaches for waste heat valorisation assessment—a top-down approach on a national scale and a bottom-up approach for a local urban area. The main steps of the research are shown in Figure 1. A detailed dataset of available waste heat sources and DH networks is collected to perform top-down waste heat potential assessment for utilisation in different types of DH systems. The gathered information is compiled within the main technical parameters of both waste heat sources and integration technologies, for example, temperature regimes of waste heat and heat carriers in DH networks, the necessary amount of power for heat pumps and availability periods, etc. In addition, a multi-criteria assessment method is used to evaluate various impacts on the operation conditions of existing heat supply systems.

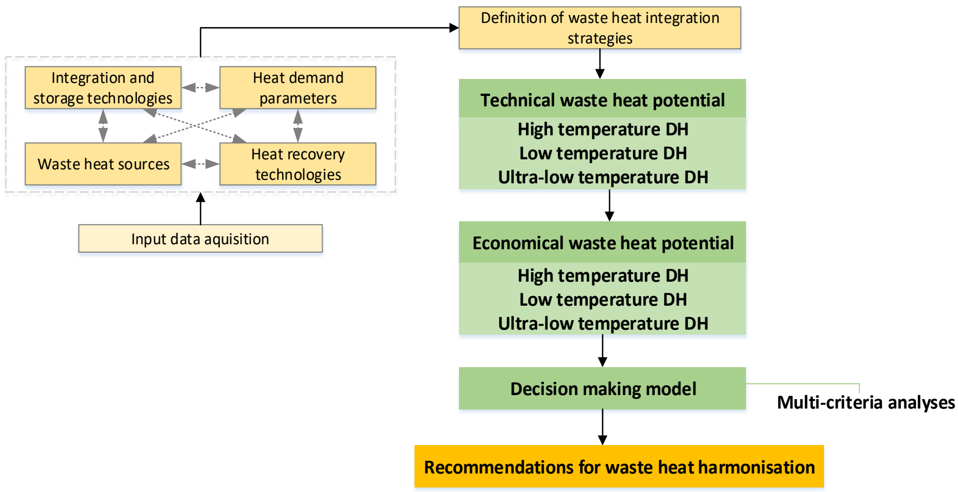

Figure 1. Main research steps.

Further, local-scale waste heat potential analyses are performed to develop a decision-making model for the integration of waste heat sources. Several criteria, including primary energy savings and specific investment costs, are gathered in the decision-making model to compare different waste heat sources from the perspective of the DH operator.

2.1. Top-Down Approach for Waste Heat Valorisation

This study includes the main waste heat sources indicated in Figure 2 and analyses their possible integration into different DH system types. The analysed waste heat sources include existing power and heat generation units (CHP and boiler houses), industrial enterprises, data centres, the largest retail centres, electric transformers, and wastewater treatment plants. Future studies could also include a waste heat assessment from cooling and refrigeration processes in cold warehouses and other service and residential buildings. Also, metro stations are not included as potential heat sources because such infrastructure does not exist in Latvia.

For the national scale assessment, three different types of existing and future DH systems are analysed as heat sinks for waste heat utilisation. First, the waste heat integration into existing heat supply systems (defined as a high-temperature DH system) is investigated. In addition, two future development heat supply systems are compared—low-temperature DH and ultra-low DH systems (representing the 5GDHC concept). The main assumed parameters for the heat supply systems are shown in Figure 2.

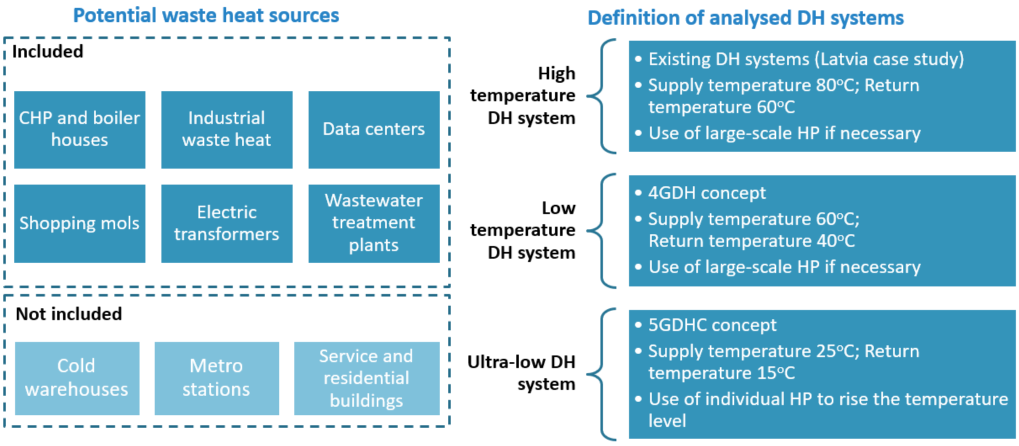

Figure 2. Research boundaries.

Table 1 lists the potential heat recovery technologies assumed for waste heat integration—direct heat recovery using heat exchangers and flue gas condensers and indirect heat recovery with air or water HPs. Direct heat recovery would be possible only for high-temperature waste heat from industrial sites and energy facilities.

Table 1. Overview of analysed waste heat sources [44].

Waste Heat Source	Process for Recovery	Temperature Level	Existing DH Network	Low-Temperature DH	Ultra-Low DH System
CHP and boiler houses	Heat recovery from flue gases	70–100 °C	Flue gas condenser	Heat exchanger	Not suitable
	Deep cooling of flue gases	40–70 °C	HP	Heat exchanger	Heat exchanger
Industrial waste heat	Rejected heat from industrial processes	70–100 °C	Heat exchanger	Heat exchanger	Not suitable
	Rejected heat from refrigeration and compressed air systems, ventilation exhaust air	30–40 °C	Air-to-water HP	Air-to-water HP	Air-to-water HP
Data centres	Server room cooling, central cooling devices	25–35 °C	Air-to-water HP	Air-to-water HP	Air-to-water HP
Shopping malls	Rejected heat from refrigeration systems	30–50 °C	Air-to-water HP	Air-to-water HP	Air-to-water HP
Wastewater treatment	Post-treatment sewage water	8–15 °C	Not suitable	Water-to-water HP	Water-to-water HP
Electric transformers	Transformer air cooling system	25–30 °C	Not suitable	Air-to-water HP	Air-to-water HP

2.1.1. Estimating National Waste Heat Potential

The general approach for waste heat potential quantification is derived from previous studies in the field. Table 2 shows the overall input data used to quantify the heat recovery potential. The derived input parameters are multiplied by a waste heat factor that differs among the considered heat sources and their temperatures. The estimations of waste heat factors are described further in this section.

Table 2. Waste heat potential determination on a national scale.

Waste Heat Source	Input Data	Waste Heat Recovery Factor	Temperature Levels		
			<30 °C	30–60 °C	>60 °C
			Ultra-Low DH System	Low-Temperature DH	Existing DH Network
Biomass boiler houses and CHP	PEC *	Share of PEC	n/a	25%	20%
Other boiler houses and CHP	PEC	Share of PEC	n/a	15%	10%
Industrial facilities					
Chemical industry	PEC	Share of PEC	n/a	7%	15%
Iron and steel	PEC	Share of PEC	n/a	18%	11%
Food, drink, and tobacco	PEC	Share of PEC	n/a	21%	6%
Non-ferrous metals	PEC	Share of PEC	n/a	9%	10%
Non-metallic minerals	PEC	Share of PEC	n/a	13%	11%
Paper and printing	PEC	Share of PEC	n/a	0%	13%
Wood and wood products	PEC	Share of PEC	n/a	20%	6%
Other waste heat sources					
Data centres	Total power consumption	Share from power consumption	44%	30%	n/a
Electric substations	Number of substations	Amount per substation	560 MWh/year	n/a	n/a
Retail stores	Retail store area	kWh/m^2	30	20	n/a
Wastewater treatment plants	Volume of wastewater	kWh/m^3 of wastewater	6.97	n/a	n/a

* PEC—Primary energy consumption.

The waste heat factor for the heat recovery from flue gases in boiler houses and CHP in this study assumes that 20% of heat could be recovered by integrating flue gas condensers in biomass-based facilities [19]. An additional 5% of heat could be recovered in the case of a low-temperature DH system using additional deep cooling of flue gases by integrating a heat pump. The heat recovery potential is lower for natural gas-fired energy plants due to lower latent heat content in flue gases. Therefore, the authors assume a waste heat recovery factor of 10 to 15%.

The industrial waste heat recovery factors are derived from previous research [16,45–47] that analysed industrial processes and their temperature levels. Some authors previously estimated the waste heat potential from the industrial sector in Latvia [48]. However, the potential was not divided into different temperature levels depending on the DH system requirements. Therefore, the primary energy consumption (PEC) in each industrial sector is multiplied by the estimated waste heat factor (see Table 2) to estimate the waste heat potential with low and high-temperature levels.

The waste heat potential in data centres depends on the total power consumption of the equipment—servers, networks, and power coordination equipment. Based on research by Luo [49], the power consumption of IT equipment accounts for 44% of the total power consumption of data centres. An alternative method [50] for calculating data centre equipment using the data centre's total electricity consumption is to use the power usage effectiveness factor, which indicates the ratio of total power consumption and consumption of equipment. If detailed technical information is available, electricity consumption can be calculated according to the methodology developed by Chung and Wang [51], using the number of different cells in the data centre, operating speed, and frequencies. However, there are very limited input data available on data centres in Latvia. In the preliminary assessment, the 20 largest data centres have been identified and their power consumption surveyed. The waste heat factor for heat recovery and integration into ultra-low temperature DH systems has been estimated to reach 44% of the total power consumption, but for the low-temperature DH system level, it is assumed that this potential would be lower at 30% due to the necessity to increase waste heat temperature.

Another ultra-low-temperature heat source is wastewater treatment plants. The most important parameters for using treated sewage water waste heat are temperature level and flow rate. These parameters determine the possible amount of heat Q_s that can be recovered according to (1).

$$Q_s = G \cdot c_p \cdot \rho (t_1 - t_2), \tag{1}$$

where G (m^3) is the annual amount of purified sewage, t_1 (°C) is the sewage temperature before heat recovery, and t_2 (°C) is the sewage temperature after heat recovery. C_p (kJ/(kg·K)) refers to the specific heat of the flow and ρ is the average density of the sewage water. In previous studies [52], it has been estimated that if the potential temperature drop for sewage water is around 5 °C, the annual waste heat recovery potential could be around 6.97 kWh/m^3 wastewater.

The heat recovery potential from retail stores is determined by combining the methodology used in the ReUseHeat project provided by Persson [53] and information from retail building energy-efficiency certificates regarding the cooling system energy consumption. Within the national scale assessment, only waste heat potential from the largest retail stores (floor area above 1000 m^2) has been analysed. The data on the total area were collected from large retail chain stores.

Previous research [54] shows that the waste heat potential from electric transformers can be obtained by knowing the voltage and the nominal power of the electric substation. By adjusting the results of Petrovic et al. [29], it has been assumed that a 330 kV transformer can produce 18,400 MWh per year and a 110 kV transformer can produce 560 MWh per year. The main parameters of electric substations in Latvia have been provided by the national transmission operator.

2.1.2. Comparison of Waste Heat Utilisation Strategies Using a Multi-Criteria Assessment

Waste heat potential utilisation strategies are compared using a multi-criteria assessment method by identifying the main impacting aspects when integrated into the DH systems with different temperature levels. Nine criteria were identified to assess the waste heat future role in existing, low-temperature, and ultra-low-temperature DH systems. Table 3 summarises the identified criteria, among which there are both qualitative and quantitative criteria. The section below describes the methodology for the determination of each of them.

First, the technical waste heat potential under different temperature levels is calculated using the quantification methodology described in Section 2.1.1. Within the assessment, detailed spatial analyses are included since the exact location of future ultra-low temperature DH systems is unknown. However, based on previous research, the spatial factor is attributed based on the mapping of existing DH systems and waste heat locations. In previous studies, authors have assumed that 86% of the high-temperature waste heat is in DH areas. For low-temperature DH systems, the waste heat potential spatial location and availability have been assumed to be slightly higher (90%), as the identified heat sources are mainly urban excess heat [48].

Table 3. Overview of identified criteria for comparison of different waste heat utilisation strategies.

Criterion	Unit	Criteria Type	Source	Desired Condition
Waste heat technical potential	GWh	Quantitative	Described in Section 2.1.1	Max
Necessary power input	kWh/MWh	Quantitative	[20,55]	Min
Heat supply share	Estimated % of national heat demand	Quantitative	[56]	Max
Optimal heat density for new connections	MWh/m	Quantitative	[57,58]	Min
Average heat losses of the network	% of heat production	Quantitative	[48]	Min
Exergy utilisation rate	n/a	Quantitative	[59]	Min
Necessary investment costs	n/a	Qualitative	[60]	Min
Impact on existing RES-based heat supply equipment	n/a	Qualitative	[61]	Min
CO_2 reduction potential	n/a	Qualitative	[62,63]	Max

Another important aspect of waste heat valorisation is the operation of HPs to ensure the necessary temperature levels to provide space heating and domestic hot water preparation in buildings. Therefore, the approximate level of HP efficiency is calculated. To find the average COP of the HP based on the DH supply and return levels, the following formula is used [55]

$$COP_{off} = COP_d + a(T_{source,i} - T_{source,i,d}) + b(T_{DH,s} - T_{DH,s,d}) + c(T_{DH,r} - T_{DH,\,r,d}), \quad (2)$$

where COP_{off} is the COP for off-design operation; COP_d is the COP for design conditions; $T_{source,i}$ is the heat source inlet temperature for off-design operation of heat source i (K); $T_{source,i,d}$ is the heat source inlet temperature for design operation of heat source i (K); $T_{DH,s}$ is the DH supply temperature for off-design conditions (K); $T_{DH,s,d}$ is the DH supply temperature for design conditions (K); $T_{DH,r}$ is the DH return temperature for off-design conditions (K); $T_{DH,r,d}$ is the DH return temperature for design conditions (K); and a, b, and c are coefficients based on linear regression [20].

The constants and coefficients in formula (2) depend on the temperature level of the DH systems where an HP is used and are given in Table 4 (see [20,55]).

Table 4. Parameters for off-design COP calculations.

Parameter	High-Temperature DH Network	Low-Temperature DH Network	Ultra-Low-Temperature DH Network
COP_d	2.91	3.75	3.75
$T_{source,i,d}$	7 °C	7 °C	7 °C
$T_{DH,s,d}$	90 °C	60 °C	20 °C
$T_{DH,r,d}$	60 °C	30 °C	10 °C
A	0.0286	0.0562	0.0562
B	−0.013	0.0290	0.0290
c	−0.013	0	0

According to the classical COP definition in thermodynamics (3), the amount of heat given to the network should decrease when COP is higher. The Lorenz efficiency factor

η_{Lorenz}, which is the ratio between actual HP COP and ideal COP, is estimated to be the same for high and low-temperature DH networks.

$$\mathrm{COP} = \frac{Q_n}{Q_n - Q_s} \cdot \eta_{Lorenz} \tag{3}$$

From the estimated average COP values, the necessary power consumption for waste heat integration using the HP application is determined and included within the multi-criteria assessment.

Another criterion describes the overall heat supply share of each DH system type attributed to the existing situation and future potential. For the existing DH systems, the actual statistical data on connected buildings are used. The heat supply potential for low-temperature and ultra-low-temperature heat supply systems is assumed from analyses in the literature by considering the potential barriers to wide-scale implementation.

The main benefit of lower heat supply system implementation is attributed to lower DH network losses and the possibility of implementing DH in low-density areas. Therefore, two criteria based on analyses in the literature are included to represent these aspects. In addition, the exergy utilisation rate considers different temperature levels of heat supply temperatures of analysed DH systems as well as consumer requirements for necessary space heating and domestic hot water temperatures. The methodology for exergy utilisation rate calculations is described by Gong & Werner [59].

Finally, three qualitative criteria are added to the multi-criteria assessment due to their project-specific nature; therefore, the impact scale is used for evaluation. The necessary investment costs are scaled from 1 (low necessary investment costs for waste heat integration) to 3 (high necessary investment costs). The impact on already-implemented RES technologies is rated as 1—no impact on the operation of existing heat supply and 3—high impact on existing RES technologies. This criterion is included since there are many biomass-based DH systems with installed new equipment and recent investments that have not yet paid off. Finally, the last qualitative criterion is the CO_2 reduction potential from the waste heat utilisation, which is evaluated as high (3 points) for the existing DH systems, which are either fossil fuel-based or biomass-based with fossil fuel peak load boilers covering the part of heat demand. The potential is lower (1 point) for both low-temperature DH systems, which are assumed to be already RES-based.

Further, the multi-criteria assessment method is used to compare the analysed waste heat integration strategies. The TOPSIS decision-making method chooses the shortest distance from the ideal solution and the most significant distance from the perfect negative solution [64]. The criteria values are normalised to transform the assigned values into non-dimensional attributes, allowing comparisons across measures. Within this assessment, it is assumed that all criteria are equally significant. The positive ideal solution (4) and the negative ideal solution (5) are calculated using the normalised decision-making matrix.

$$d_a^+ = \sqrt{\sum_i \left(V_i^+ - V_{ai}\right)^2}, a = 1, \ldots, \mathrm{m} \tag{4}$$

$$d_a^- = \sqrt{\sum_i \left(V_i^- - V_{ai}\right)^2}, a = 1, \ldots, \mathrm{m} \tag{5}$$

where V_{ai} is the normalised criterion and V_i^+ and V_i^- are the ideal positive and negative weighted solutions for each criterion, respectively.

The last step within the TOPSIS method is the determination of the closeness to the perfect solution (6), which allows ranking waste heat valorisation strategies.

$$\mathrm{C_a} = \frac{d_a^-}{d_a^+ + d_a^-} \tag{6}$$

2.2. Bottom-Up Approach for DH Operator Decision-Making

The waste heat potential and integration into the existing heat supply system have been validated for the small-scale urban area in Salaspils, which is considered one of the most innovative DH systems in the Baltic States [65]. The heat is supplied using a large-scale solar thermal field in the summer period and biomass boilers in the high heat demand period from September to April. In addition, natural gas boilers are used for peak demand coverage (see Figure 3). A thermal storage tank of 8000 m^3 is used to accumulate solar energy [66]. However, the capacity would not be suitable to store additional heat amount from waste heat sources. The heat supply temperature level of the analysed DH system varies from 90 °C in the heating season to 65 °C in the summer period; therefore, it can be considered a high-temperature DH system.

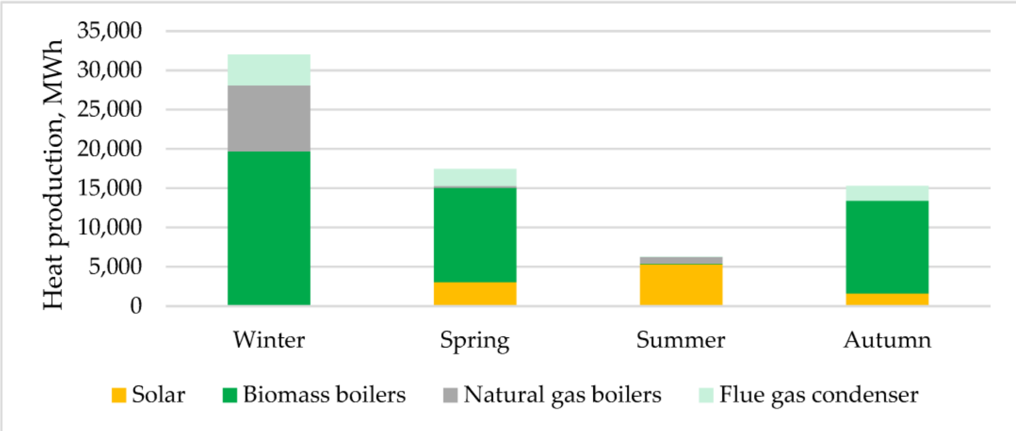

Figure 3. Distribution of heat production divided by fuel type for the analysed DH system in 2021.

Sources of excess heat in the city of Salaspils were initially selected according to their type of business, area, and location. Within the preliminary assessment, 25 different waste heat sources were identified within the urban area. The municipal buildings such as educational institutions, the city council building, the swimming pool, and others, were not considered in the further assessment due to the relatively small amount of heat recovery potential compared with other waste heat sources.

The next selection criterion for waste heat assessment was the location for which the spatial analyses were used (see Figure 4). When the selected enterprises were compiled and the approximate distance from the heating networks was determined, the estimation of waste heat potential and data collection took place. A survey regarding the main technical parameters and energy consumption was used to determine the necessary data for waste heat assessment. The data collection was carried out by surveying companies via e-mail and phone and on-site visits. In addition, the information was gathered using publicly available permits for polluting activities.

After the preliminary assessment and spatial analyses, 12 different waste heat sources were selected for further evaluation. The potential waste heat sources include 5 retail stores, 5 industrial objects (metal and wood processing enterprises), one wastewater treatment plant, and one electric transformer. The main characteristics and input data used for the assessment are summarised in Table 5.

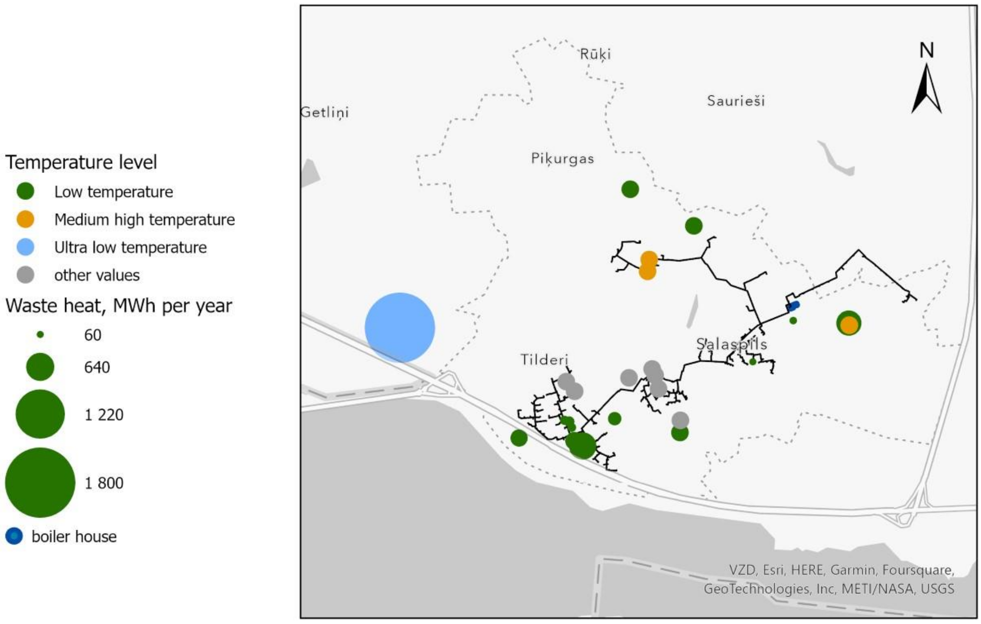

Figure 4. Preliminary assessment of available waste heat sources in Salaspils.

Table 5. Review on identified retail stores as waste heat sources.

Name	Type	Building Area or Other Describing Parameters	Heat Source	Power Consumption, MWh/y	Heat Consumption, MWh/y
RS 1	Retail store	918 m^2	HP	603	0
RS 2	Retail store	524 m^2	DH	191	78.6
RS 3	Retail store	3639 m^2	Gas boiler, solar collectors	1019	435
RS 4	Retail store	2410 m^2	HP	n/d	n/d
RS 5	Retail store	3457 m^2	n/d	n/d	n/d
MP 1	Metal processing	7049 m^2	DH	1106	342
MP 2	Metal processing	4359 m^2	DH	n/d	n/d
MP 3	Metal processing	2370 m^2	Gas boiler	n/d	48
MP 4	Metal processing	1324 m^2	Gas boiler	n/d	624
WP	Wood processing	2366 m^2	Biomass boiler	n/d	1102
WWTP	Wastewater treatment plant	982 thousand m^3/y	n/a	n/d	n/a
ET	Electric transformer	223 MVA/330 kV	n/a	n/d	n/a

Within the analysed area, there are four different metal processing enterprises. However, only one of the surveyed companies (see MP 1 in Table 5) was ready to share more detailed information on technological processes and data on energy consumption. The company has an approximate production capacity of 1200 t/year for metal products. The metal heating processes are carried out in five furnaces that are powered by electricity (total power consumption of 80 MWh per year). The mechanised painting line consists of a product painting preparation plant, a drying machine, and a painting chamber. The installed power of the painting line is 180 kW and, on average, the electricity consumption per month is 15 MWh. To ensure technological processes, two compressors with a capacity of 36 kW and 16 kW are installed at the enterprise. Total electricity consumption at the enterprise is 1106 MWh/year. Total heat consumption for space heating and hot water preparation is 343 MWh/year. Heat is obtained from the DH network.

The premises of the enterprise have high energy-efficiency improvement potential through building insulation. Therefore, some of the recovered heat flows could be used internally. Several options for waste heat recovery have been identified. Additional heat recovery from compressed air systems could be introduced. The excess heat could also be collected from the mechanised painting line and returned into production or utilised via the DH network.

Five retail stores were identified as potential waste heat sources in Salaspils city. The main characteristics of the identified retail stores are described in Table 5. The main input data for waste heat potential determination is the electricity consumption of the stores shown in Figure 5. In all stores, electricity is mainly consumed for indoor climate equipment, refrigeration and cooling systems and lighting. RS 2 has already implemented heat recovery from the regeneration system with a thermal capacity of 64 kW. The recovered heat is used to provide hot water in the store. Also, RS 3 is recovering thermal energy from cooling systems. In this store, solar collectors are also installed on the roof of the store for the preparation of hot water. The energy consumption data were available only for 3 retail stores (see Figure 5); therefore, the average values were used for the stores without data available.

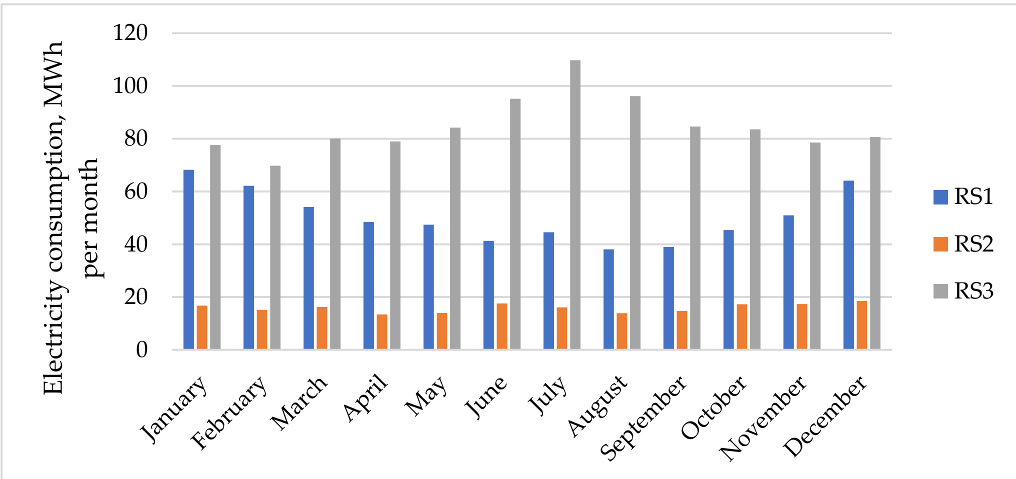

Figure 5. Distribution of total electricity consumption in analysed retail stores.

In addition to the waste heat sources described above, the 223 MVA electric transformer station for high-voltage direct current (330 kV) conversion to low-voltage altering current (110 kV) was identified as a potential waste heat source. The heat that is transferred from transformer oil to air is considered a source of waste heat since it is discharged into the environment at relatively high temperatures. The temperature of the oil and, therefore, the air depends on the ambient temperature and losses, which depend on the power load. According to Jarmen et al.'s case study, the 240 MVA/400 kV autotransformers could generate 1025 kW of waste heat at 60% load [67]. A similar amount of waste heat potential has been estimated for the Salaspils case study.

Additional waste heat flows could be recovered from the city wastewater treatment plant, which is located around 2 km from the DH heating network. Data on wastewater flow rates and monthly average temperatures were obtained from the wastewater treatment plant. Therefore, the total amount of waste heat from wastewater could reach 6392 MWh per year.

After quantification of waste heat potential, the authors further develop the decision-making model, which aims to compare the identified waste heat sources from different integration aspects. Table 6 shows the identified criteria for the decision-making model, which slightly differ from those used for the national scale assessment. For the analysed DH system, additional criteria include the heat load alignment coefficient, which considers the seasonal mismatch of recovered waste heat and heat demand. It is calculated as the ratio of the average surpluses and shortages of waste heat and the total integrated waste heat amount. For the fuel-saving calculation, the actual heat production rates of the analysed DH system are used and compared with the waste heat potential from each source (see Figure 3). The waste heat recovery distribution among analysed seasons is based on the obtained data or assumptions derived from the research of Sendwall et al. [68].

Table 6. Overview of identified criteria for comparison of different waste heat sources.

Criterion	Unit	Desired Condition
Waste heat technical potential	MWh per year	Max
Linear heat density	MWh/m	Max
Power consumption for waste heat integration	kWh/MWh	Min
Share in total heat production	%	Max
Load alignment coefficient	n/a	Max
Reduced solar energy utilisation	MWh	Min
Primary energy savings	MWh	Max
Specific investment cost	EUR/MWh	Min

More detailed assessments are included regarding the impact on the existing heat generation units. The reduced solar energy utilisation factor considers how the integration of waste heat would impact the share of solar thermal energy. Therefore, the priority would be attributed to the waste heat sources that are available during periods with lower solar intensity. In addition, the primary energy savings are calculated as the waste heat integration would allow avoiding the use of biomass and natural gas for heat production. Finally, the specific investments are included as criteria by analysing the investment costs for new network pipelines and heat recovery equipment based on the temperature level of waste heat sources [30].

Further, the criteria values are normalised and compared following the same multi-criteria assessment steps as described in Section 2.1.1.

3. Results

The section presents the results for both top-down and bottom-up waste heat analysis frameworks. The national scale waste heat potential and the valorisation in different types of heat supply systems are presented in Section 3.1. The results of the decision-making model, which are used to determine which identified waste heat sources would be most suitable for the analysed DH system, are presented in Section 3.2.

3.1. Waste Heat Valorisation Model

The first step of the research was to identify and quantify the total available waste heat potential at different temperature levels (see Figure 6). The theoretical high-temperature waste heat potential for Latvia could reach around 1834 GWh per year, but the determined low-temperature waste heat is 3408 GWh per year. For comparison, the total heat production rates in DH systems in 2020 in Latvia accounted for 7514 GWh. The total ultra-low temperature recovered heat amount could reach 732 GWh per year.

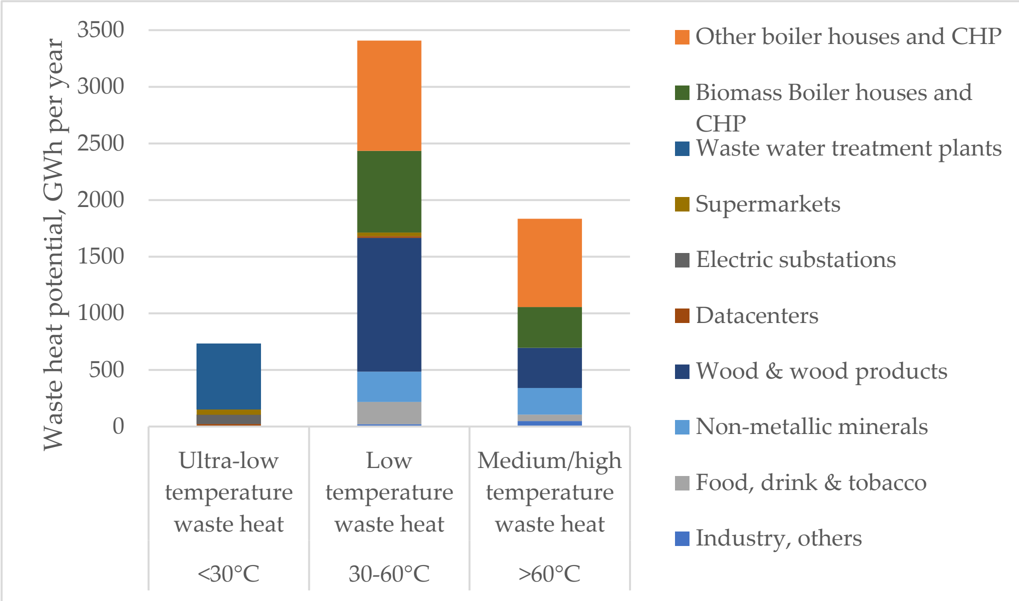

Figure 6. Total available waste heat potential assessment results for different temperature levels.

The highest identified heat recovery potential in the Latvia case study was identified for the energy sector facilities. With additional flue gas cooling technologies and direct heat recovery, it would be possible to recover around 1140 GWh of heat, but by integrating the HP and deep cooling of flue gases, this potential can be increased to 1695 GWh per year. A significant amount of low-temperature waste heat potential (1181 GWh) is identified in the wood industry, which is the main economic sector in Latvia. As can be seen in Figure 6, the determined waste heat amount from the data centres, retail stores, and electric transformers comprises only 20% of the identified ultra-low temperature waste heat potential, and the main part could be delivered from the threatened sewage water.

To further analyse the valorisation strategies for the identified waste heat potential, several criteria were calculated (see Table 7). The technical waste heat potential was determined by considering the approximate location of the waste heat objects from the previous research. The necessary specific power consumption is higher for ultra-low DH systems, which consider increasing the temperature at each consumer by implementing individual HP. In the case of existing DH systems and low-temperature DH systems, it is assumed that part of the waste heat could be integrated through direct heat exchange without HP application due to suitable temperature levels. From the statistical data, it is found that the existing DH systems provide heat supply to 70% of buildings. Due to the necessity to adjust the existing consumers to lower supply temperature levels, it is assumed that only around 40% of the necessary heat supply could be provided by low-temperature systems in the near future.

The ultra-low heat supply system concept requires more technical changes in the existing infrastructure. Therefore, it is assumed that such a system would be better developed as a new DH system for specific locations and would supply around 10% of necessary heat in the future. The lowest optimal heat density for connecting new consumers could be around 1 MWh/m in the case of the ultra-low heat supply concept, which would also result in the lowest heat losses in the distribution network, assumed to be around 5%.

Table 7. Obtained criteria value comparison among different waste heat valorisation strategies.

Criteria	Existing DH	Low-Temperature DH	Ultra-Low Temperature DH
Technical potential, GWh	1578	3068	659
Necessary power input, kWh/MWh	167	133	200
Heat supply share, %	70%	40%	10%
Optimal heat density for new connections, MWh/m	3.0	2.0	1.0
Average heat losses of the network [%]	15%	10%	5%
Exergy utilisation rate	5%	7%	15%
Necessary investment costs	1	2	3
Impact on existing RES-based heat supply equipment	3	2	1
CO_2 reduction potential	3	2	1

The calculated exergy utilisation rates based on supply, return, and consumed temperature levels range from 5% in high-temperature heat supply systems to 15% in the ultra-low DH system. This criterion shows the relation between the exergy demands of the consumer's final heat demands and the exergy supplied into the heat distribution network from the heat supply units. Future research could also include the estimation of exergy losses due to HP integration.

In addition, three qualitative criteria were used, for which the evaluation points are attributed based on the conclusions of previous research. The highest necessary investments for the integration of waste heat are assumed for the ultra-low temperature DH due to investments in individual HP. The integration of waste heat into existing DH systems could cause the highest impact due to the reduced operation time of already installed RES equipment. The highest CO_2 reduction potential is assumed for the existing DH systems due to the use of fossil fuels and biomass as main heat sources.

The determined criteria results were normalised and ranked according to the TOPSIS method. Figure 7 shows the ranking results for the waste heat integration, from which it can be concluded that the low-temperature DH system has the highest potential for waste heat valorisation due to high waste heat potential, relatively smaller investment costs, and increased transmission efficiency.

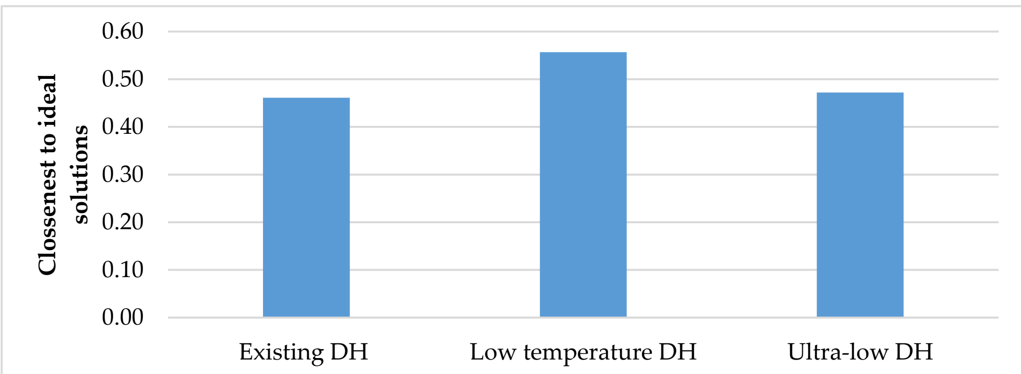

Figure 7. Waste heat valorisation potential comparison under different heat supply conditions.

3.2. Local-Scale Decision-Making Model

The authors estimated the heat recovery potential for the urban area of Salaspils for a further assessment of waste heat valorisation. Following the methodology of national scale waste heat potential assessments supplemented with more precise consumption data for some of the potential heat sources, it was determined that the waste heat potential in Salaspils could reach around 13.3 GWh per year. The heat sources with the highest waste heat potential are the electric transformer and sewage water. When analysing the waste heat potential among different seasons (see Figure 8), the highest share of waste heat potential occurs in the summer period, when it could cover around 72% of total DH heat demand, compared with only 7% in the winter period, when there are low outdoor temperatures and high heat demand.

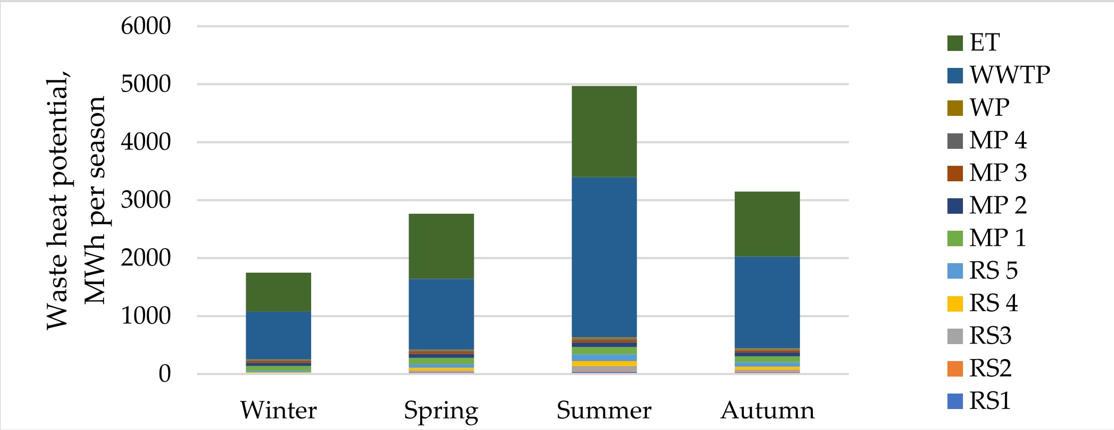

Figure 8. Waste heat potential distribution among seasons.

Table 8 shows the overall results for the other analysed criteria for the identified waste heat sources. The highest linear density value is obtained for the enterprises that are already connected to the DH system (MP 1, MP 2, RS 2) and for the electric transformer, which is located close to the heating network and has relatively high waste heat potential compared to other waste heat sources.

The lowest load mismatch coefficient is obtained for metal processing plant MP1, which has high production rates and power consumption in the winter period that could result in higher waste heat potential. The lowest specific power consumption is determined for industrial sites that have higher temperature levels for waste heat; therefore, lower necessary power for temperature lift is consumed by the HP. The highest share of total heat delivered to the DH network and highest primary energy savings are attributed to those waste heat sources that have the highest heat recovery potential—wastewater treatment plants, electric transformers, and metal processing sites (MP 1). Finally, the lowest specific investments are determined for the metal processing site, which is already connected to the DH network and therefore does not require additional investments for new pipelines.

The analysed waste heat sources are further ranked using the multi-criteria assessment method. Figure 9 shows that the highest rate is obtained for the integration of electric transformers due to relatively high identified waste heat potential, a small distance from the existing network, and enough waste heat occurring during the heating season. However, integration of this waste heat source would result in lower heat demand for the already operating solar thermal field. The decision-making model indicates that the waste heat flows could also be utilised and valorised from the wastewater treatment plant, one of the metal processing plants (MP 1), and the retail store (RS 2) that obtained a relatively higher score.

Table 8. Obtained criteria value comparison among different waste heat sources in Salaspils.

	Waste Heat Source											
Criterion	**RS 1**	**RS 2**	**RS 3**	**RS 4**	**RS 5**	**MP 1**	**MP 2**	**MP 3**	**MP 4**	**WP**	**WWTP**	**ET**
Waste heat potential, MWh/y	91	57	143	199	285	435	269	146	82	66	7035	4490
Linear heat density, MWh/m	1.82	5.73	2.85	0.74	1.06	86.94	13.44	0.58	0.16	0.26	3.52	14.97
Share from total heat production, %	0.1%	0.1%	0.2%	0.3%	0.4%	0.6%	0.4%	0.2%	0.1%	0.0%	9.9%	6.3%
Load mismatch coefficient, %	23%	10%	28%	20%	20%	25%	25%	25%	25%	25%	19%	15%
Power consumption, kWh/MWh	222	222	222	222	222	200	200	200	200	200	333	213
Primary energy savings, MWh	46	39	49	102	146	262	170	92	52	42	3247	2604
Reduced solar energy share, %	1%	0%	2%	2%	2%	2%	1%	1%	1%	0%	52%	29%
Specific investment cost, EUR/MWh	276	163	216	518	395	103	122	613	1937	1234	252	111

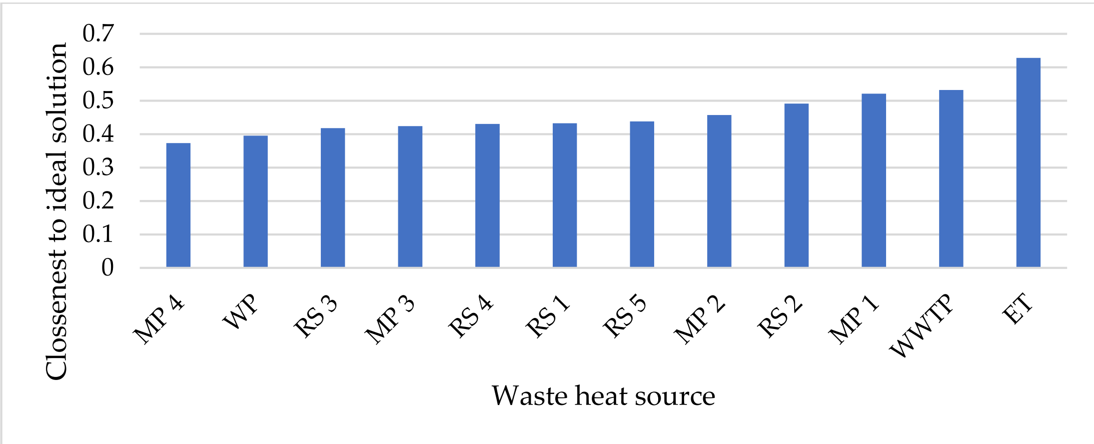

Figure 9. Decision-making results for ranking identified waste heat sources.

4. Conclusions and Discussion

This study analyses various waste heat integration and valorisation strategies in future heat supply systems by comparing the waste heat potential for existing high-temperature DH and future low and ultra-low heat supply systems.

The methodology is developed for assessing waste heat potential under different waste heat valorisation strategies by merging top-down and bottom-up approaches. The theoretical high-temperature waste heat potential for Latvia could reach around 1834 GWh per year and cover around 24% of the existing DH supply. The determined low-temperature waste heat reached 3408 GWh per year. The highest waste heat potential in Latvia could be recovered from the existing energy facilities—biomass-based CHP and boiler houses—by implementing flue gas condensers and the deep cooling of flue gases with HPs. The energy facilities, together with waste heat from the wood processing industry, would serve the highest share of the low-temperature waste heat potential. The determined waste heat amount from the data centres, retail stores, and electric transformers comprises only 20% of the identified ultra-low temperature waste heat potential. However, high uncertainty remains about the future role of ultra-low heat supply systems in countries with well-developed DH infrastructure, such as Latvia.

The local DH analyses show that the most beneficial waste heat sources are the electric transformer and wastewater treatment plant, which also have the highest waste heat potential. However, within the DH system, the utilisation of waste heat would impact the already operating solar thermal system because the heat recovery could cover around 70% of heat demand in the summer period.

The local scale assessment identified several waste heat sources with relatively small waste heat potential (small industrial sites and retail stores), which does not show the feasibility of being recovered under the existing heat supply conditions. However, such small-scale sources could be beneficial for low-temperature DH areas where there are no other already implemented RES heat generation technologies.

However, it is crucial to acknowledge certain limitations inherent to this study. One prominent limitation is the variation in technical parameters of DH systems across different countries. Different countries have distinct energy pricing structures and unique DH system configurations, which can significantly impact the feasibility and economic viability of waste heat integration and valorisation. Therefore, the insights and conclusions drawn from this study are specific to the context of Latvia and may not directly apply to other regions with distinct energy landscapes and DH infrastructures.

This study has highlighted the dynamic landscape of waste heat integration and valorisation in future heat supply systems, emphasising the importance of context-specific approaches. While substantial potential exists, realising it requires careful consideration of existing infrastructure, local conditions, and the evolving role of alternative heat supply systems. Future research should continue to explore these nuances and refine strategies for sustainable waste heat utilisation and integration of heat pumps.

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