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Comparative assessment of heat recovery from treated wastewater in the district heating systems of the three capitals of the Baltic countries

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ABSTRACT

Urban cities have a great potential for the sewage wastewater (WW) and treated WW but this heat resource is still underutilised in many European cities, including the three Baltic capitals of Tallinn, Riga, and Vilnius. The aim of this paper was to evaluate the integration of waste heat (WH) into a district heating (DH) system via absorption heat pumps by using key performance indicators (KPIs) in the fields of energy, environment, economy and social sphere in the three Baltic capitals. The paper presents a three-step methodology that develops an innovative multi-dimensional approach to energy poverty analysis and includes the three main drivers of energy poverty: fuel prices, household income, and energy efficiency. The paper shows that the integration of WH is economically feasible from the consumer's point of view and reduces energy poverty, especially when the price of fuel increases.

1. Introduction

The member states of the European Union (EU) have committed to implement the European Green Deal policy and to make the EU the first carbon-neutral continent by 2050 [1]. The revised Energy Efficiency Directive emphasises that the effective water management can make a substantial contribution to energy savings, especially for an efficient district heating (DH) [2]. The utilisation of waste/excess heat can help to decarbonise the DH system [3], while also lowering DH costs by approximately 15% [4], and ensuring the DH transition to low temperature 4th generation DH (4GDH) [5]. Heat from sewage wastewater (WW) and treated WW from wastewater treatment plants (WWTP) has an underutilised potential that could be integrated into DH. Several studies have assessed WW heat potential by using economic indicators such as payback period, avoided CO2 emissions, and primary energy consumption in different countries: Serbia [6], Hungary [7], and Denmark [8]. The introduction of urban waste heat (WH) into city energy systems was also described in Ref. [9]. Sandvall A. et al. Investigated the economic aspects of WH recovery in four European cities: Berlin, Brunswick, Madrid, and Nice [10]. The introduction of WH directly affects the costs of the DH system and the heat tariff. The heat tariff also serves for a social purpose in climatic conditions when the population needs to be supplied by the sufficient heat for the population's survival [11]. Therefore, inadequately high heating costs can lead to social problems and energy poverty for the elderly, single mothers with children, and others vulnerable groups of consumers in developed countries. While several studies have focused on various aspects of heat recovery from treated WW, there have been few studies linking the economic aspects of integrating recovered heat into a DH system with social issues and energy poverty.

The aim of this study was to evaluate the integration of recovered WH from treated WW into the DH system by using key performance indicators (KPIs) in the fields of energy, environment, economy and social sphere in the three Baltic capitals. Additionally, the study assesses how recovered WH from WWTP affects energy affordability and energy poverty in selected case study areas.

2. Overview of Kpis for WW heat recovery and sustainable energy transition

2.1. Energy, environmental and economic assessment of WWTP heat recovery

Given that WW is now officially recognised as a RES, an increasing

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number of DH producers are considering the possibility of integrating recovered heat into the DH system. Energy, environmental, and economic indicators are frequently used to assess the heat.

The International Performance Measurement and Verification Protocol was used by Andres et al. [12] to evaluate urban WH recovery solutions, including WW heating. The following KPIs were used for the evaluation: energy - PE savings, useful energy demand (heating and cooling), final energy demand (fuel and electricity), RES share, SCOP of HPs (heating and cooling), total useful energy, and electric consumption ratio; economic - cost avoidance, total costs, CAPEX, OPEX, costs, payback period, RoI, IRR, NPV, job creation; environmental - GHG emission reduction and total GHG emissions; social – the proportion of people who have a positive attitude towards this project, the degree of people's satisfaction, the average comfort perception level, and presence on social media.

To evaluate heat recovery in WWTPs, Spriet et al. [13] used a combination of energy analysis at WWTPs and spatiotemporal analysis. The energy analysis evaluates the heat demand and the available WH potential based on the WW temperature, flow rate, and COP. Spatiotemporal analysis makes it possible to determine the areas where a WW heat recovery solution is most feasible.

A study by Živković and Ivezić [6] used three groups of KPIs to analyse the WW heat potential in all DH systems in Serbia: energy performance, the security of energy supply, and environmental impact. Average KPI values for DH systems were calculated, as well as individual KPIs for the largest Serbian DH system. The KPIs for the current situation are compared with the case of WW heat pump (HP) implementation.

Another paper presented an analysis of demos in Cologne (Germany: Wahn and Mülheim) that used an innovative heat pump system to extract heat from sewage, resulting in lower primary energy consumption and CO_2 emissions [14]. Various KPIs were used to evaluate and compare the demos, including total energy consumption, total heat supplied, seasonal coefficient of performance, gas boiler efficiency, system energy efficiency, heat recovered from sewage, share of heat supplied via HPs, primary energy consumption and primary energy savings, carbon dioxide emissions and carbon dioxide savings, emissions per heat supplied, total cost per primary energy saved, and total cost per tonne of energy saved.

Huang R et al. [15] proposed a framework for evaluating WWTP performance and energy efficiency in terms of energy neutrality. Two KPIs have been established: the energy self-sufficiency indicator, which reflects the offset degree of energy recovery, and the water–energy efficiency indicator, which characterises the efficiency of water–energy conversion.

Furthermore, there is a growing interest in local WW heat recovery units of various configurations, such as pre-heating domestic hot water using WW with direct heat exchange or using a local heat pump. The following KPIs were used for comparative analysis: annual heat recovered per square metre of heat transfer area, average heat recovery rate per metre of heat exchanger, degree of coverage, heat recovery ratio (heat recovered compared to total available heat in WW), and average heat exchanger efficiency [16].

There are also non-technical limitations for heat recovery from WW plants, as well as drivers for its implementation, such as government subsidies, tax incentives, and municipal participation in its promotion [17].

The transition from the high temperature DH system to the low temperature 4GDH cannot be fully represented by focusing solely on technical and economic aspects. The price of DH directly affects the income and savings of final consumers. One of the most recent examples is the sharp increase in the price of natural gas in Europe and consequently the increase in the price of DH for consumers. Arrears on utility bills are associated with high energy costs and/or low household income and thus the inability to pay on time due to financial difficulties. Energy poverty is defined as a scenario in which consumers spend a significant proportion of their income on energy bills [18]. As a result, consumers' ability to cover other living costs is affected. Moreover, the low income of households is not the only criterion associated with energy poverty. Highly energy-inefficient multi-apartment buildings that require a considerable amount of thermal energy is a major issue, particularly in the Baltic states [19]. Energy poverty is measured by using social indicators such as the inability to provide adequate heating in the home, arrears on utility bills, low absolute energy expenditure, and the high share of energy expenditure in income. Energy poverty is a multidimensional concept, therefore three main attributes (dimensions) of energy poverty such as fuel prices, household income, and energy efficiency can be used for the evaluation of energy poverty. Multidimensional energy poverty index [20] was used for the energy poverty in developed countries on the example of Japan in 2000–2011. However, none of the studies has evaluated energy poverty in relation with the integration of recovered heat from treated WW into the DH system in the three Baltic capitals.

3. Background information

In 2015, the Nord Pool was appointed as the nominated operator of the electricity market in the three Baltic countries. As a result, Estonia, Latvia, and Lithuania are currently participating in a joint power market with several European countries, including Finland, Sweden, Denmark, and Norway.

The three Baltic countries, Estonia, Latvia, and Lithuania have historically had well-developed DH systems that cover approximately 65–70% of total heat demand. The main challenges of the three Baltic countries in the DH sector are currently related to the decarbonisation of the heat supply. WH recovery is increasingly used as one of the directions in a decarbonisation strategy and a transition from combustion to non-combustion heat generation in several European countries, including Denmark [21]. WW is the most common and steady heat source used for HPs. High-capacity HPs have been installed in the capitals of several Nordic countries, and the heat produced is fed into the following DH systems: Stockholm (230 MW), Helsinki (90 MW), and Oslo (40 MW) [22]. This practice might be adopted by the Baltic countries of Estonia, Latvia, and Lithuania, and similar solutions could be implemented to benefit DH systems aiming to reduce the proportion of combustion-based heat generation. In their study on the potential of large-scale HPs for DH systems, Volkova et al. determined that large-scale HPs in the Baltic countries can produce up to 25% of thermal energy in 2050 [23].

The capitals (Tallinn, Riga, and Vilnius) have well-developed heating networks, but cooling is handled by local units. Currently, centralised cooling systems are only in the planning stages. Since the Soviet era, Latvia, Lithuania, and, to a lesser extent, Estonia have primarily produced heat using Russian natural gas. In 2014, a liquefied gas terminal was built in Klaipeda (Lithuania), which partially solved the problem of natural gas competition in the primary energy market. As a result of the changing geopolitical situation, Estonia has begun the construction of a liquefied gas terminal in Paldiski, whereas Latvia is only planning to build one. Because biomass wood chips are available in all three countries, they are the renewable energy resource used for heat production using boilers and combined heat and power (CHP) technologies. The transition towards 4GDH systems allows for more efficient use of WH, including heat recovery from treated WW. Therefore, this issue is relevant for the three Baltic countries.

The DH companies in Tallinn, Riga, and Vilnius are the leading heating and hot water providers in their respective countries. The main advantages of DH companies in capitals, which allow for the integration of the significant potential of WH from WW into the DH system, are related to high building density, well-developed DH networks with the possibility of expansion even in historic centres [24], orientation towards innovations, and low-temperature DH [25]. The opportunity to be leaders in introducing innovative solutions by replicating this technology in other Baltic cities is a major argument for evaluating the implementation of this technology in the capitals.

3.1. Description of structure of DH companies and WWTPs in the three baltic capitals

3.1.1. Tallinn case study description

Tallinn, Estonia's capital, has the country's largest district heating system. The energy company Utilitas OÜ runs the DHN, which supplies heat to over 4000 buildings. The current large Tallinn DHN was formed by connecting the East and West Tallinn DHNs ten years ago [26]. Over the last three years, the share of heat produced by CHP biomass has increased to 53% (Fig. 1). The system also has five natural gas boilers providing peak load, which produced 26% on average in the same period. Utilitas, the district heating operator, is a private company. Heat is produced at CHPs and boilers owned by Utilitas. The waste incineration plant is owned by another company, Enefit Green, and provides 21% on average of the heat production.

The idea of incorporating large heat pumps into the Tallinn DH network was investigated. For example, in Ref. [27], the possibilities of integrating various low-temperature heat sources were studied. WW was analysed as one of the sources along with atmospheric air, lakes, rivers, seawater, and groundwater. According to the results, the use of sewage water for heat pumps has the greatest potential and can cover about 38% (46 MW) of the maximum heat load covered by HPs.

3.1.2. Riga case study description

Riga, the capital of Latvia has a well-developed DH system, which is serviced by Rigas Siltums Joint Stock Company (JSC). The Daugava River splits Riga into two parts. The DH system on the left bank is operated by the DH company Rigas Siltums, which has a monopoly in this heating area. On the right bank of the river, heat is supplied by seven heat and electricity producers, the largest of which is Latvenergo JSC, as well as six other heat producers, including Rigas Siltums JSC. The company manages and distributes 76% of the thermal energy in Riga. Heating and hot water for residential buildings consume 70% of thermal energy, whereas other consumers utilise 30%. The company produces up to 30% of the heat supplied to consumers. Fig. 1 depicts the share of produced heat over the last three years in Rigas Siltums JSC, clearly demonstrating that two types of fuel dominated the DH system over the last three heating seasons: natural gas (62% on average) and biomass (38% on average). Natural gas-based heat production has been on the decline during the last three heating seasons. The addition of new boiler houses in 2022 will allow for a significant increase in the generation of heat from biomass chips.

The Daugavgrva WWTP collects approximately 130,000 m^3 of WW per day from the city of Riga and a part of the city of Jurmala. This treated WW, with a temperature of 10 °C in the winter and 20 °C in the summer, is discharged into the Gulf of Riga at about 2.4 km from the coast and to a depth of 15 m after treatment. The heat created by HP absorption can be fed into the DH system, which is around 2.4 km away

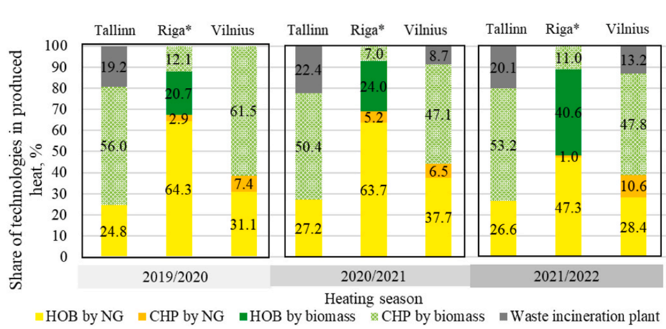

Fig. 1. Share of different heat production technologies in the total amount of heat produced in the three Baltic capitals (the heating season for DH companies starts in October and ends in September of the following year).

from the WWTP. The pre-project study showed that two HPs with a maximum total thermal power on the generator side of 8 MW could be installed.

3.1.3. Vilnius case study description

The Vilnius DH system, which is owned by the Vilnius City Municipality, was established in 1958 and is Lithuania's leading provider of heating and hot water. Vilniaus Silumos Tinklai JSC currently supplies heat to over 210,000 households and businesses in the city.

Over the past two decades, historically significant changes have been made to Vilnius DH. From 2002 to 2017, Vilnius DH was leased to Veolia, a French group of companies. The private company reorganised Vilnius DH, changed the management structure, streamlined the company's functions, and invested in information systems. One of the most significant accomplishments was the reduction of DH network losses from 24% to 12%. In 2017, the ownership of Vilnius DH was transferred to Vilnius City Municipality.

The Lithuanian DH supply model is based on competition and is one-of-a-kind in Europe. Each month, different DH suppliers compete in price levels at auctions. Thus, the Vilnius DH company produces about 60–70% of the annual DH energy. In Vilnius DH, the share of natural gas has decreased from 80% to 40% over the last five heating seasons, with the rest of the heat produced using biomass. The sharp increase in natural gas prices towards the end of 2022 has had a significant impact on Vilnius DH.

The new Vilnius waste incineration plant aims to reduce municipal waste disposal in landfills by developing a rational utilisation of waste energy resources. A waste-to-energy cogeneration plant uses waste that cannot be recycled but still has energy value after processing. It is projected that after the waste incineration plant is completely up and running, it will be able to produce around 40% of the annual heat supply in Vilnius DH by the end of 2023. The waste incineration plant provided 13.2% of the heat production in the 2021/2022 heating season (Fig. 1).

Every day, the Vilnius City WWTP Vilniaus Vandenys collects and treats around 110,000 m^3 of WW. The feasibility of installing absorption HPs (AHP) with a 22.2 MW thermal capacity (sum capacity of condenser and absorber) was determined as a result of pre-project study conducted by Vilniaus Silumos Tinklai JSC.

3.2. Comparative assessment of DH system performance in Tallinn, Riga, and Vilnius

When comparing the DH systems of the three Baltic capitals, it should be noted that the DH system in Riga is larger in absolute terms than the other two. As a result, it is more developed because it provides 1.65 and 1.49 times more heat than the DH systems in Tallinn and Vilnius, respectively (see Table 1).

Riga also has the longest heating network, stretching for 830 km. The Riga heating network has the lowest specific heat loss (11.8%), indicating that it is in great technical condition and has appropriate

Table 1
Characteristics of DH systems in Tallinn, Riga, and Vilnius.

Parameters	Tallinn	Riga	Vilnius
Population (2021)	449,000	615,000	540,000
DH pipeline trench length, km	449	830	748
Relative heat losses, % (2019–2022)	14.1	11.8	13.9
Heat consumed, GWh	1638	2700	1816
Types of installed capacities	CHP biomass Heat only boiler (HOB) by natural gas (NG) Waste incineration	CHP (NG and biomass) HOB (NG and biomass)	CHP (NG and biomass) HOB (NG and biomass) Waste incineration

temperature regulation.

Fig. 1 depicts the contribution of various heat production technologies to the total amount of heat produced in Tallinn, Riga, and Vilnius. As shown in Fig. 1, Tallinn's DH system has produced 53% of heat using biomass CHP technology over the last three heating seasons. Rigas Siltums JSC, on the other hand, uses biomass CHP to produce 10% of its heat, while the Vilnius DH system uses the same technology to produce 52% of heat. Over the last three years, the Tallinn DH system has produced an average of 26% of its heat via NG boilers. During the same period, natural gas boilers were used 58% of the time in Riga and 32% of the time in Vilnius. Vilnius had the highest share of NG CHP technology use (8% over the last three heating seasons).

All three Baltic capitals are working hard to increase the use of renewable energy sources (RES) and integrate WH into their DH systems. Another issue that DH companies must address is how to overcome existing barriers to integrating WH into DH systems, given that the WWTPs are not owned by DH companies. Tallinn is an exception, as Utilitas also manages the WWTP.

4. Methodology

4.1. Methodology algorithm

The analysis of treated WW heat integration into the DH network provided in this paper aims to assess the effect of integrating WH into a DH system on energy poverty in the three Baltic capital cities. The study used a three-stage methodology (Fig. 2): (1) a spatiotemporal analysis of supply and demand in potential consumption areas; (2) a comprehensive analysis of heat recovery by comparing energy, environmental, and economic KPIs and comparing possible future scenarios at various energy prices; and (3) an innovative multi-dimensional approach to energy poverty analysis applied to assess changes in energy availability due to the integration of WH.

The first step of the spatiotemporal analysis leads to the selection of the AHP capacity and evaluation of the evaporator's capacity (recovered heat from WW) and generator. AHP was chosen as a technology for the recovery of WH from treated WW since the additional heat required for AHP operation is currently cheaper than the electricity required for the operation of compression HPs in all three Baltic countries.

4.2. Energy performance indicators

The first step of the study was to evaluate the temporal matching of supply and demand. The recoverable heat from treated WW was estimated based on the flow and temperature of the WW. However, the heat demand of the consumers adjacent to the WWTP must correspond to the recovered heat.

The thermal capacity of the heat recovered from treated WW (Q_{ww} , MW) was calculated as follows [6]:

$$Q_{ww} = m_{ww} \cdot c \cdot \Delta t \quad (1)$$

where m_{ww} is the treated WW mass flow rate, kg/s; c is the specific thermal capacity of treated WW, MJ/kgK; Δt is the temperature difference of treated WW in the inlet and outlet of AHH evaporator; H is the operating hours of the AHP.

The thermal capacity of heat produced at the AHP (Q_{ahp} , MW) was calculated as follows:

$$Q_{ahp} = Q_{ww} \cdot COP / (COP - 1) \quad (2)$$

where COP is the annual performance factor of the AHP used in this study, which is 1.7.

The basis of the spatial analysis is the distance from WWTP to the nearest point of connection to the heating networks, as well as the diameter of these heating networks, which would allow this connection to be made. The diameter of the heating networks (d, m) connecting the WWTP to the existing heating networks was calculated as follows:

$$d = \sqrt{4m_h / \rho \cdot \pi \cdot v_h} \quad (3)$$

where m_h is the mass flow rate of the heat carrier from the AHP (condenser and absorber), kg/s; ρ is the density of water, kg/m3; v_h is the heat carrier velocity, m/s. At maximum capacity, the optimal velocity of the heat carrier should be in the range of 1 m/s to 3 m/s.

According to the "EU Strategy for the Integration of Energy Systems" [28] the primary energy factor (PEF) is an important indicator that shows the utilisation rate of renewable energy sources while also determining the efficiency of the DH system. The PEF was calculated using the overall energy balance (Fig. 3). Heat from waste incineration was assumed to come from somewhere other than the DH system (purchased heat). The PEF was calculated in accordance with the ISO 5200–1:2007 [29] using the primary resource factors given in Table 2:

$$PEF = \left(\sum_j F_j \cdot f_{nren,j} + \sum_j F_j \cdot f_{ren,j} + Q_{wi} \cdot f_{nren,w} / \eta_{wi} + Q_{wi} \cdot f_{ren,w} / \eta_{wi} - Q_{EE} \cdot f_{nren,EE} - Q_{EE} \cdot f_{ren,EE} \right) / Q_{con} \quad (4)$$

where F_j is the fuel consumption in the DH system, MWh per year; $f_{nren,j}$ is the primary resource factor of non-renewable energy of jth sources; $f_{ren,j}$ is the primary resource factor of renewable energy of jth resources; Q_{wi} is the heat purchased from the waste incineration plant, MWh per year; η_{wi} is the coefficient of performance of the waste incineration plant; $f_{nren,w}$ and $f_{ren,w}$ are the primary resource factor of non-renewable and renewable heat from the waste incineration plant; Q_{EE} is the amount of power supplied to the power grid and generated at the CHP, MWh per year; $f_{nren,EE}$ and $f_{nren,EE}$ are the primary resource factor of non-renewable and renewable power supplied to the power grid; Q_{con} is the amount of

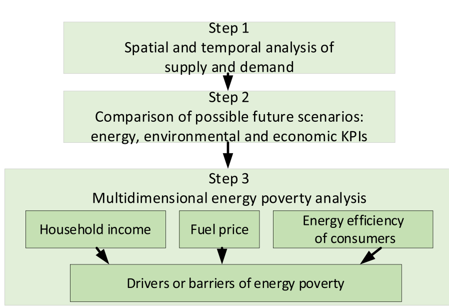

Fig. 2. Methodology algorithm.

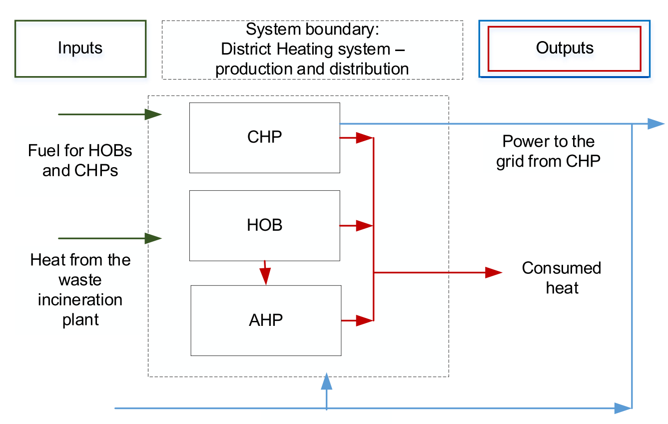

Fig. 3. DH system boundary for PEF calculation.

Table 2
Primary resource factors[a] [29].

Energy carrier	Primary resource factor of non-renewable energy, $f_{nren,j}$	Primary resource factor of renewable energy, $f_{ren,j}$	Total primary resource factor, $f_{tot,j}$
Natural gas	1.1	0	1.1
Wood chips	0.2	1	1.2
Electricity	2.3	0.2	2.5
Waste incineration[b]	0.65	0	0.65

[a] The study uses the primary resource factors according to ISO 52000–1:2017 because of the variety of definitions of their numbers in the national legislation.
[b] The coefficient of performance of the waste incineration plant (η_{wi}) is 0.8, according to Tallinn's waste incineration plant data.

heat consumed, MWh per year.

Specific changes in PEF (PEF_s,%) show an increase in DH system efficiency and facilitate the decarbonisation of the DH system by recovering heat from WW using AHP. It can be calculated as follows:

$$PEF_s = \left(PEF_{init} - PEF_{fin}\right)\cdot 100\% / PEF_{init} \tag{5}$$

PEF_{init} is the initial primary energy factor; PEF_{fin} is the primary energy factor after AHP installation.

Additional heat loss from the pipeline connecting the AHP wastewater treatment plant to the heating networks of the DH system, which depends on pipeline length and diameter, insulation, ground temperature, and temperature mode in the heating network, is calculated as follows [30]:

$$Q_{los} = t_h \cdot 10^{-3} \sum_k^z q_{lk} L_k \tag{6}$$

$$q_{lk} = (T_s + T_r - 2T_{so}) \,/\, (R_{ins} + R_{so} + R_c) \tag{7}$$

where t_h is the system's operating time, h/year; q_{lk} is the linear heat losses, W/m; L_k is the length of the heating network section m; z is the total number of sections in the network; k is the pipe network section; T_s is the supply temperature, °C; T_r is the return temperature, °C; T_{so} is the ground temperature, °C; R_{ins} is the insulation material's linear heat resistance, (m·K/W); R_{so} is the ground's linear heat resistance, (m·K/W); R_c is the additional linear heat resistance from the overlap of supply and return pipe temperature fields, (m·K/W).

4.3. Environmental impact indicators

As mentioned above, heat recovery from treated WW facilitates the decarbonisation of the DH system. The share of avoided emissions (S_{CO2}, %) are used to assess the degree of decarbonisation and are calculated as follows:

$$S_{CO2} = \left(E_{CO2_{init}} - E_{CO2_{fin}}\right)\cdot 100\% / E_{CO2_{init}} \tag{8}$$

$$E_{CO2} = \sum_j F_j \cdot e_j + Q_{wi} \cdot e_{wi} / \eta_{wi} \tag{9}$$

where $E_{CO2_{init}}$ is the initial amount of CO_2 emissions, t_{CO2}/yr; $E_{CO2_{fin}}$ is the amount of CO_2 emissions after AHP installation, t_{CO2}/yr; e_j is the CO_2 emission factor for jth resources; e_{wi} is the CO_2 emission factor for waste incineration.

The CO_2 emission factors were chosen based on each country's national data (Table 3). Table 3 shows the CO_2 emission factors.

The most significant difference from ISO 52000–1:2017 [29] is the CO_2 emission factor for electricity, as each country uses its own fuel mix to generate electricity. This factor is especially different in Estonia, where a portion of the electricity is generated using oil shale, a local energy source with high CO_2 emission factors. The CO_2 emission factors for the Vilnius DH system are the average for the EU and equal to ISO 52000–1:2007 "Energy performance of buildings – Overarching EPB assessment – Part 1: General framework and procedures" [29] because the Lithuanian energy system is the most integrated in the common market of the EU due to the use of liquefied gas from Klaipeda and the import of a larger part of electricity.

Table 3
CO_2 emission factors.

Energy resource	CO_2 emission factors, tCO_2/MWh			
	Tallinn [31]	Riga [32]	Vilnius [33]	ISO 52000–1:2017 [29]
Natural gas	0.202	0.202	0.220	0.220
Wood chips	0.040	0.040	0.040	0.040
Electrical power	0.687	0.109	0.420	0.420
Waste incineration	0.213	–	–	–

4.4. Economic indicators as part of multidimensional poverty analysis

The main purpose of the DH system is to supply residents with quality heat at an affordable price. At the same time, from the consumer's perspective, the most essential factor is how much they have to pay to keep their house warm and use hot water. The annual heating costs in the scenario i with t technologies mix $A_{t,i}$ (EUR/year) for an apartment with area S (m^2) was calculated using the following equation:

$$A_{t,i} = T_{tot,i} \cdot (1 + VAT_i) \cdot q_i \cdot S \tag{10}$$

where $T_{tot,i}$ is the end user tariff, EUR/MWh; VAT_i is the value-added tax; q_i is the specific heat consumption, MWh/m^2 per year; S is the area of an average family apartment (60 m^2 was adopted for all countries).

The heat tariff structure is the similar in all three Baltic countries and includes the costs of production, transmission, and sale of heat:

$$T_{tot,i} = \sum T_{prod,t,i} \cdot \varphi_{t,i} + T_{oth,i} \tag{11}$$

where $T_{tot,i}$ is the total heat tariff (for end users) in scenario i, EUR/MWh; $T_{prod,t,i}$ is the production tariff for technology t, EUR/MWh; $\varphi_{t,i}$ is the share of technology t; $T_{oth,i}$ represents other costs that include transmission and sale, EUR/MWh.

The study identified the heat production tariff for heat produced by the AHP, which replaced the amount of heat produced by natural gas boilers.

The production tariff for technology t consists of two components: fixed costs $VC_{t,i}$ (EUR/year) and variable costs $FC_{t,i}$ (EUR/year), and it is calculated as follows:

$$T_{prod,t,i} = \left(VC_{prod,t,i} + FC_{prod,t,i}\right) / Q_{prod,t,i} \tag{12}$$

where $Q_{prodt,i}$ is the amount of heat produced using technology t, MWh/yr.

The variable costs of the production tariff are determined as follows:

$$VC_{prod,t,i} = Q_{prod,t,i} \cdot \left(\frac{C_{fuel,t,i}}{\eta_{t,i}} + C_{tax,t,i} + C_{ee,t,i} \cdot Q_{ee,t,i} + C_{oth,t,i}\right) \tag{13}$$

$C_{fuel,t,i}$ is the fuel price, EUR/MWh; $\eta_{t,i}$ is technological efficiency;

$C_{tax,t,i}$ represents taxes, EUR/MWh; $C_{el,t,i}$ is the electricity price, EUR/MWh$_{el}$; $Q_{ee,t,i}$ is the power consumed for the production, MWh$_{el}$/MWh, $C_{oth,t,i}$ represents other costs, EUR/MWh.

The fixed costs $FC_{prodt,i}$ (EUR/MWh) of the production tariff are calculated as follows:

$$FC_{prod,t,i} = Q_{prod,t,i} \cdot C_{O\&M,t,i} + C_{inv,t,i} \cdot N_{t,i} \cdot \left(1/\tau_{t,i} + P_{t,i}\right) \tag{14}$$

where $C_{O\&M,t,i}$ represents operation and maintenance costs for technology t in scenario i, EUR/MWh; $C_{inv,t,i}$ represents technology t investment costs, EUR/MW; $N_{t,i}$ is the installed capacity of technology t, MW; $\tau_{t,i}$ is the loan repayment term (assumed to be 25 years); $P_{t,i}$ is the weighted average cost of capital (assumed to be 8.51%), %/year.

Additional heating network that will connect the WWTP with the main heating network need to be built by installing an AHP. In the case of transmission costs, the investment in installed equipment ($C_{inv,t,i} \cdot N_{t,i}$) in equation (14) is replaced by investment in the heating network ($C_{inv,net} \cdot m$): where $C_{inv,net}$ is the cost of connection to the heating network, EUR/m; m is the distance to the main network.

The result of multi-dimensional energy poverty can be expressed as a quantitative indicator – the share of heating costs in household income (AP_i, %) [6,34]. This indicator will describe the social impact as it includes the impact of WH integration, value-added tax, and specific heat consumption in each scenario for each country:

$$AP_{t,i} = \frac{A_{t,i} \cdot 100\%}{I_i} \tag{15}$$

where I_i is the household income in scenario i with t technologies mix, EUR/year.

The share of avoided heating costs SAE_i (%) is calculated as follows:

$$SAE_i = \left(A_{wAHP,i} - A_{AHP,i}\right) \cdot 100\% / A_{wAHP,i} \tag{16}$$

where $A_{wAHP,i}$ and $A_{AHP,i}$ are the annual heating costs for scenario i with and without AHP installation, EUR/year; $(A_{wAHP,i} - A_{AHP,i})$ present avoided heating costs, EUR/year.

4.5. Scenario Description and model assumptions

Given the rapidly changing fuel price situation since the end of 2021, the study considered three different scenarios.

- Scenario 1 (Sc1): heat tariffs, as well as fuel and electricity prices are at the average level for 2018–2019 that was the last stable price period in near past (used average historical data);
- Scenario 2 (Sc2): heat tariffs, as well as fuel and electricity prices are average for the period from September to December 2021;
- Scenario 3 (Sc3): heat tariffs, as well as fuel and electricity prices are 30% higher than in the period from September to December 2021. These are our price forecasts after the restructuring of the fuel supply chain, as well as the transition of the DH system of the three Baltic capitals to biomass as the basic fuel, which has been implemented over the last year due to a new geopolitical situation in the region.

The initial PEF (PEF_{init}) and amount of CO_2 emissions ($E_{CO2_{init}}$) were calculated using the average operating parameters of DH systems from 2018 to 2020 years.

Table 4 presents energy prices, heat tariffs and other parameters for a multi-dimensional energy poverty analysis.

Technology investment costs were included in the model, considering the AHP projects already implemented in the Baltic states (Table 5).

All costs presented in Table 5 were increased by 10% and 20% in the Sc2 and Sc3 cases respectively which represents a forecast of an increase in all expenses. Additional assumption: the heat recovered from the treated WW will replace the heat produced by the NG boiler technology.

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

Parameter	**Sc1(Sc0[a]) historical Tallinn/Riga/Vilnius**	**Sc2 historical Tallinn/Riga/Vilnius**	**Sc3 assumed** Tallinn/Riga/Vilnius
Network electricity price [35,36], **EUR/MWh**	91.21/86.04/90.27	182.21/180.43/187.38	223.27/222.63/230.35
Natural gas price [37], **EUR/MWh**	33.03/30.92/31.95	89.21/90.62/89.97	112.55/113.96/113.31
Wood chip price [38], **EUR/MWh**	16.40/17.47/16.40	17,47/19.47/21.84	22.71/25.31/28.39
Heat tariff, EUR/MWh	50.25/46.37/45.05	65.00/62.02/77.25	84.50/80.63/100.43
Value-added tax (VAT),%	20/21/9	20/21/9	20/21/9
Household income [39], **EUR/year**	17,275/15,501/19,257	18,879/17,234/18,845	19,567/17,918/19,529
CO_2 quote price [40], **EUR/t_{CO2}**	15	70	91

[a] Sc0 – same conditions as Sc1, but without AHP installation.

Table 5
Cost and technology inputs for economic analysis.

Parameter	Unit	Value
CAPEX for AHP (mln.EUR per MW of heating capacity of AHP)	mln.EUR/MW$_{th}$	0.528
Absorption HP variable O&M	EUR/MWh$_{th}$	1.3
HP fixed O&M	EUR/MW$_{th}$/year	2000
HP variable O&M	EUR/MWh$_{th}$	1

4.6. Description of the proposed scheme for introducing WW heat into the DH network using AHP

Fig. 4 depicts a possible scheme for connecting AHP to a DH network.

Because of the large number of independent heat producers (IHP), it makes more sense to use the heat carrier from the heating network as a primary heat source by utilising an absorption heat pump (AHP) for heat recovery.

The AHP unit, as is well-known, consists of four key components: a generator, a condenser, an evaporator, and an absorber. This means that an AHP's entire lifecycle begins with a generator. The generator is powered by the primary energy source, high-temperature hot water (T = 100 °C) from IHP. The temperature difference between the generator's inlet and outlet water flows should be around 30 °C.

Another important component of the AHP unit is the evaporator, which extracts heat from WW. In the selected scheme, the temperature difference between the treated WW entering the evaporator and the treated WW exiting the evaporator should be about 4 °C. The actual useable treated WW flow has been determined to be about 2000 m^3/h (as per Vilnius case study). At a temperature difference of 4 °C, such a flow can generate up to 9.3 MW of thermal power.

The remaining components of the AHP, the absorber and the condenser, heat the network return water. The return network water is heated from 45 °C to 63 °C and mixed with the water flow after the AHP generator. The absorber and condenser transfer the heat obtained from the AHP generator and evaporator. It should be noted that such a scheme necessitates the construction of a three-pipe system: a supply pipe from the existing DH network and two pipes connecting the return pipe from the existing DH and returning it to the heating networks. The heated water enters the absorber and mixes with the AHP generator's water flow in the condenser. Therefore, the AHP capacity (22.2 MW in the case of Vilnius) is supplemented with heat from the AHP generator's inlet

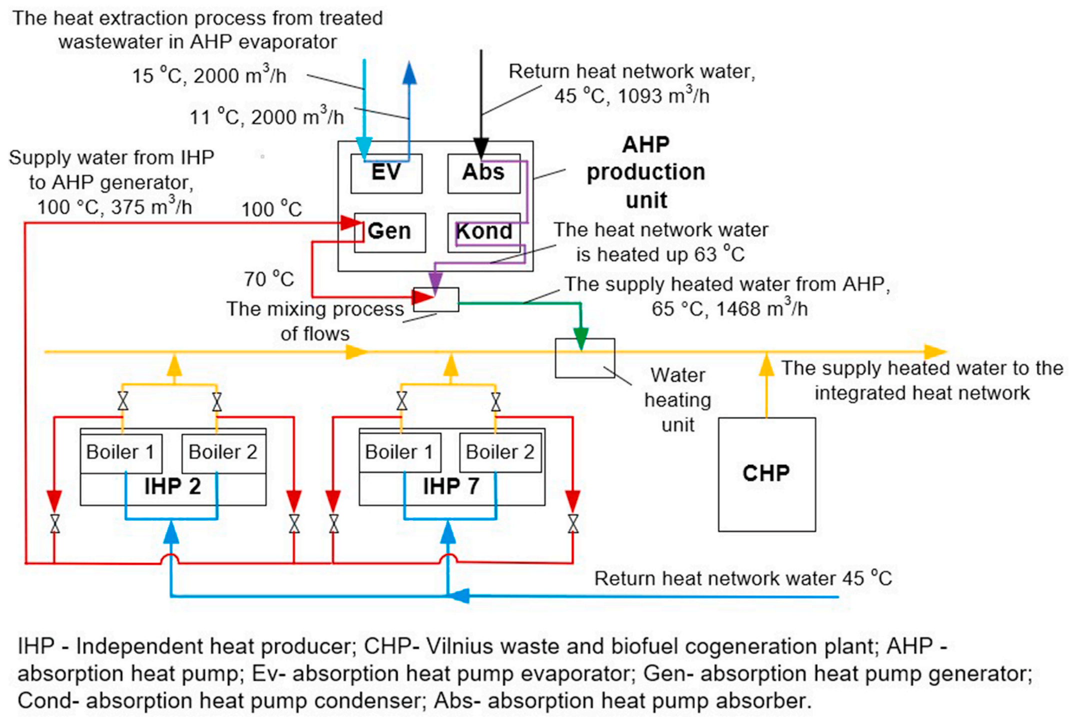

Fig. 4. Possible scheme for connecting AHP to the DH network in Vilnius.

flow, reaching 33.3 MW. When heat for the AHP is supplied by a boiler house located in the WWTP area, the amount of heat supplied from the AHP to the DH network corresponds to the capacity of the AHP condenser and absorber. In this case, only two pipes must be constructed: the return pipe from the existing DH must be connected to the AHP absorber and the AHP condenser outlet must be connected to the supply pipe of the existing heating networks.

The preliminary costs for the construction of the pipeline have been estimated based on the previous experience of the DH companies (Table 6).

4.7. Sensitivity analysis

Considering that the aim of the study was to determine how recovered WH from the WWTP affects energy affordability. The parameters that most affect it according to previous studies [7,41] were chosen.

- Fuel price (NG and biomass);
- Technology costs (AHP technology and connection pipeline costs to main DH network);
- operation hours of AHP;
- loan rate for investment.

Sensitivity analysis was performed using the one-at-a-time (OET) method, varying the above parameters by ± 30% [42]. Obtained results of sensitivity analysis are presented by Tornado diagrams.

Table 6
Heating network construction costs for economic analysis.

Investment with asphalting works[a]	Unit	Value
Pipelines for powering the AHP (Tallinn – DN300)	EUR/m	1100
Pipelines for connecting the AHP with the DH system (Tallinn – DN600)	EUR/m	1800
Pipelines for powering the AHP (Riga -DN125)	EUR/m	600
Pipelines for connecting the AHP with the DH system (Riga -DN250)	EUR/m	900
Pipelines for powering AHP (Vilnius – DN200)	EUR/m	850
Pipelines for connecting the AHP with the DH system (Vilnius – DN400)	EUR/m	1400

[a] Three-pipe connection to the existing DH system.

5. Results and discussion

5.1. Evaluation of the impact on DH system performance due to the use of thermal energy recovered from treated WW

The evaluation began with an integrated matching potential analysis, which determined the amount of heat recovered from treated WW, as well as the heat demand in the DH system. Fig. 5 depicts the average temperature of treated WW throughout the year. Fig. 5 clearly shows that this temperature is sufficient to be able to increase its potential and, as a result, to introduce DH into the networks. The average temperature during the heating season is approximately 10 °C (minimum 7.3 °C). The heat potential was calculated as part of the first phase of the study (Fig. 5) on the assumption that the temperature of the treated WW would decrease by 4 °C, which is consistent with other scientists' findings [7]. An additional advantage of WW heat recovery is the fact that this heat is available 24 h a day, as the WW treatment process takes place continuously. Annual operating hours at maximum HP capacity were assumed to be 6000 h per year.

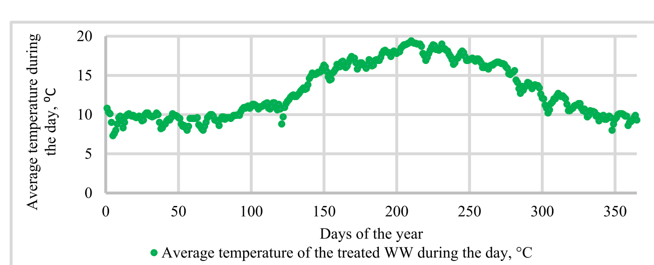

Fig. 5. Average temperature of treated WW.

To sum up, the temperature profile of the treated WW as well as the heat's continuous availability over time are the driving forces that promote the use of this heat in the DH system. Other authors came to the same conclusions using temporal analysis [8,13].

One of the most important aspects of the assessment is the location of the WWTP in regard to the heating networks and the heating demand in the heating area. The distance to the main heating networks and pipeline diameter will determine the investment necessary for the construction of the connection network and the operating costs to compensate for heat loss in the network. Table 7 displays the calculation results (Eq.(1) and (2)) and the DH system performance indicators.

The distance to the heating networks of all three Baltic capitals is relatively short: 2.5 km (Tallinn), 2.4 km (Riga), and 2 km (Vilnius), making it economically feasible to integrate the treated WW heat into the DH system. Previous research [46] has found that the economic feasibility of introducing heat from treated WW into the DH system depends on the distance from the main DH network. This distance can be both a driving force and a barrier to using this heat.

However, the spatial analysis revealed that the WW plant is in Riga, in the Daugavgriva suburb, a considerable distance from the main heating area of Riga, and thus the potential capacity of the AHP is limited due to the heat demand in this particular DH area. Therefore, heat can be used to cover only a portion of the heat demand in that suburb. Although Riga has a similar potential thermal capacity of AHP (61.4 MW) to Tallinn (66.1 MW) and Vilnius (51.9 MW) (Fig. 6), it cannot be utilised as extensively. Thus, the discrepancy between heat demand and the capacity of treated WW can also be a limiting factor.

Tallinn and Vilnius have better locations for WWTP. Tallinn has the most ambitious plans out of the three Baltic capitals and plans to implement a 46 MW AHP (Fig. 6).

On the one hand, the recovery of WH from treated WW improves energy efficiency by utilising the fuel's full potential after combustion and generation of heat. On the other hand, heat production using AHP increases the share of RES in the produced heat, especially when natural gas combustion technologies are replaced. Tallinn, Riga, and Vilnius, for example, boost their RES share in the produced heat to 8.6%, 2.7%, and 3.9%, respectively (Fig. 6).

The PEF analysis provides a more in-depth assessment of the current situation in terms of RES use while also determining the efficiency of the DH system (Fig. 7).

Tallinn's DH system used significantly more RES than the other two Baltic capitals prior to AHP installation. Even after AHP is installed,

Table 7
Data from completed treated WW heat recovery projects.

No.	Parameter	Unit	Tallinn	Riga	Vilnius
1.	Average treated WW flow rate	m^3/day mln. m^3/year	140,000 51.75	130,000 48.53	110,000 42
2.	Potential heat capacity of treated WW	MW	27	25	21
3.	Projected amount of heat produced by the AHP	GWh/year	276	48	133
4.	Total amount of heat produced in the DH system (on average in 2018–2020)	GWh/year	1906	3380 (1050)[a]	2672
5.	Distance to the DH network	km	2.5	2.4	2.0
6.	Specific heat losses in the existing system	%	14.3	11.8	10.7
7.	Specific heat consumption (including hot water)	kWh/m^2 per year	170 [43]	147 [44]	201 [45]
8.	Current share of RES in the fuel mix (on average in 2018–2020)	%	64.2	22.9	24.6

[a] Heat produced by Rigas Siltums JSC.

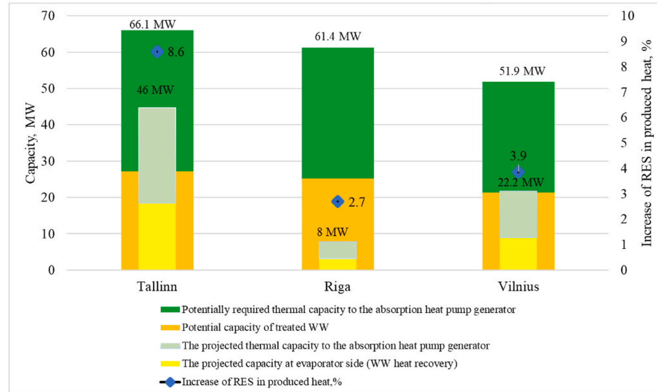

Fig. 6. Potential and projected thermal capacity of the AHP from both the generator and the evaporator.

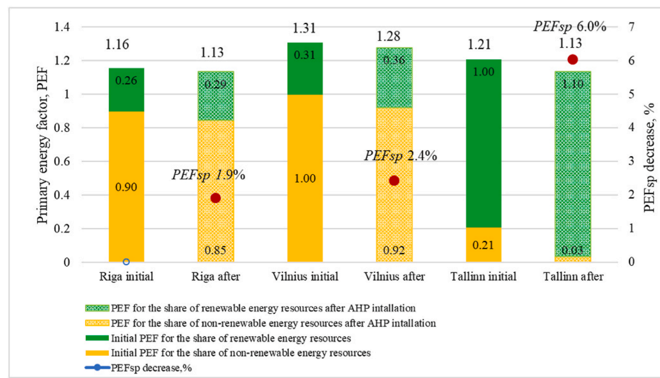

Fig. 7. Change in primary energy factor due to AHP introduction.

Tallinn's DH system will use the most RES, and the PEF will decrease by 6%. However, in terms of overall DH system efficiency, Riga has the most efficient heat production because the overall PEF was in the previous period was the lowest at 1.16. This fact can be explained by the widespread use of condensing economizers, which improve energy efficiency. If Tallinn succeeds in recovering WW and producing heat via an AHP with a total capacity of 46 MW, the efficiency of heat production in both cities will remain the same - 1.13. Nevertheless, even after the incorporation of AHP, Riga will retain the lowest share of RES, as the Vilnius DH system will produce the second-best results.

To evaluate the avoided CO_2 emissions in the analysed systems, the amount of avoided CO_2 emissions was calculated (Eq. (9)) before and after the installation of the AHP, along with the share of avoided CO_2 emissions (Fig. 8). Tallinn, Riga, and Vilnius have specific CO_2 emissions

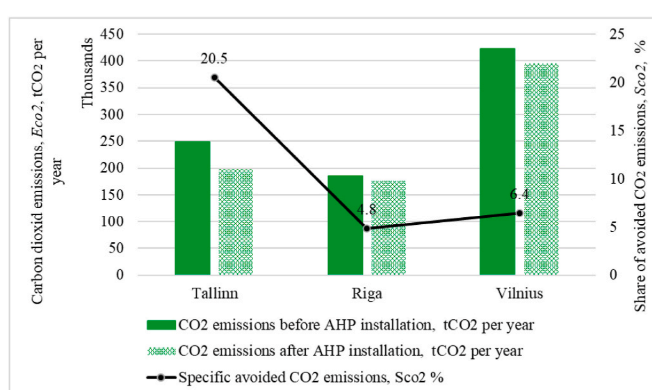

Fig. 8. Change in carbon dioxide emissions due to AHP incorporation.

of 20.5%, 4.9%, and 6.4%, respectively. Tallinn's relatively higher percentage of specific avoided CO_2 emissions is explained by the fact that the initial amount of CO_2 emissions in Tallinn's DH is lower than in Riga and Vilnius, as well as heat is produced in cogeneration using biomass wood chips with a low CO_2 emission coefficient. The analysis also demonstrates that WW heat recovery contributes to the decarbonisation of the DH system, which is the driving force behind such a project.

5.2. Evaluation of the impact of thermal energy recovered from treated WW on energy poverty

Tariffs for heat generation were calculated to evaluate the impact of recovered WW heat on energy poverty. A three-pipe heating network will be constructed to connect the AHP to the existing DH system (see Chapter 4.7).

The annual heating costs for each scenario with and without the AHP were calculated using Equation (10). The results of the calculation are given in Table 8.

When planning the integration of WH into the DH system, it is important to consider how it would benefit society. Many authors emphasize that public acceptance and usability of new technologies in society are often used as social indicators in the energy model that studies the energy transition to the decarbonisation of the DH system [34]. When it comes to economic benefits, introducing new technologies (WW heat recovery is an innovation for the Baltic States) is the most effective way to reach out to residents. The methodology presented in this study (Fig. 2) involves at least three components that ultimately affect the share of household expenses spent on heating: household income, fuel prices, and energy efficiency. Another factor that can affect the results is the technology's efficiency. The higher the annual COP of the AHP, the less money will have to be spent on additional heat supplied to the AHP generator. As a result, heat recovered from treated WW will be more affordable.

Fig. 9 shows the expenses indicator, i.e. the share of income spent on heating (AP_i, %) (Eq. (15)). This indicator shows that heating costs in the three Baltic capitals were roughly the same during the 2018–2019 period of financial stability (3.56, 3.19, and 3.08 in Tallinn, Riga, and Vilnius, respectively). In scenarios Sc2 and Sc3, the share of income spent on heating increases due to rising fuel costs. Furthermore, it should be noted that it is growing even faster in Vilnius due to a lower energy efficiency indicator: specific heat consumption in buildings (201 kWh/m^2 per year; see Table 7). The share of heat produced by the AHP in Tallinn, Riga, and Vilnius is 13.88%, 4.54%, and 6.49%, respectively.

The recovery of heat from treated WW and its utilisation in the DH system in Sc1 reduces the proportion of income spent on heating by 2.91% in Tallinn and 1.10% in Vilnius (Fig. 9). Unfortunately, an increase of 0.28% was recorded in Riga.

Even though the proportion of income spent on heating increases in scenarios 2 and 3 (Fig. 10), the integration of heat recovered from WW into the DH system allows it to be reduced. In scenario 2, for example, avoided heating costs ($A_{wAHP,i} - A_{AHP,i}$) are 13.41%, 3.76%, and 4.96% in Tallinn, Riga, and Vilnius, respectively. Moreover, despite the rise in fuel prices, even AHPs with relatively small capacities, such as those in Riga,

Table 8
Annual heating costs for each scenario before and after AHP installation.

Scenario	Heat produced by using	Tallinn	Riga	Vilnius
		Heat costs per household, EUR per year		
Sc1	natural gas	549.9	448.8	571.2
	AHP	420.8	479.6	470.5
Sc2	natural gas	1237.5	1086.0	1333.9
	AHP	468.8	537.6	558.4
Sc3	natural gas	1873.5	1654.0	2025.7
	AHP	563.2	640.7	700.5

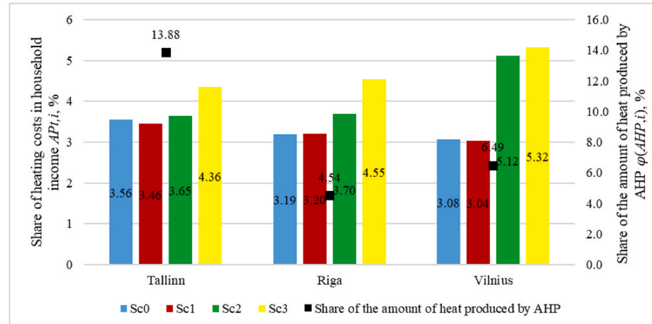

Fig. 9. Share of household income spent on heating and amount of heat produced by AHP.

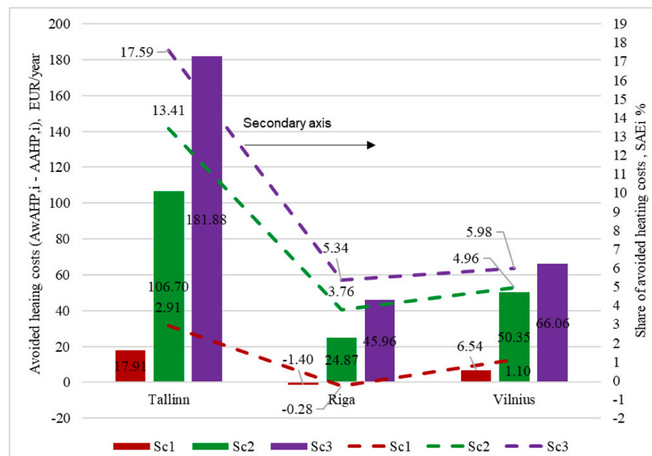

Fig. 10. Heating costs avoided in scenario *i* without AHP for heat recovery from treated WW.

remain economically beneficial to consumers (Sc2 and Sc3), which is driving the adoption of this technology.

Given that the Baltic countries do not currently use AHPs to recover heat from WW, it is reasonable to conclude that there is a lack of awareness of the benefits of this technology. In other cases, such as Riga (Sc1), state subsidies and tax incentives should be implemented to develop technology [17] that allows for increased overall DH system efficiency through the use of WH, reducing PEF and CO_2 emissions.

Tallinn has the highest avoided heating costs (Sc2 – 106.7, Sc3 – 181.88 EUR/year) and the highest proportion (Sc2 – 13.41%, Sc3 – 17.59%) of the three Baltic capitals (Fig. 10). Because heating costs are affected by three key parameters (fuel price, heat tariff, and specific hear consumption) the avoided heating costs and their proportion increase more dramatically in Sc3 for Tallinn than for Vilnius (see Tables 4 and 8). These parameters are relatively greater in Vilnius than in Tallinn, for example: Sc3 heat tariff – 84.5 EUR/MWh in Tallinn vs. 100.43 EUR/MWh in Vilnius; specific heat consumption of 170 kWh/m2 per year in Tallinn vs. 201 kWh/m2 per year in Vilnius. As a result, Tallinn's avoided heating costs and their proportion increased more significantly. The multidimensional approach used in this study allows for a comprehensive analysis of WW heat recovery and quantifies its impact on energy poverty by calculating the proportion of avoided costs in household income.

5.3. Sensitivity analysis

Given the multidimensional approach presented in this study, it should be noted that many of the indicators evaluated in this study affect avoided heating costs. A sensitivity analysis was performed based on four key uncertainty factors: the price of NG and biomass; technology costs (the cost of the AHP technology and the cost of connection to the main DH network); AHP operating hours; and the interest rate of the investment loan. The results of the sensitivity analysis show similar trends for all three scenarios. Consequently, only Sc2 results are discussed in depth.

The future fuel price uncertainty was included in the sensitivity analysis and was discovered that this parameter has the greatest impact on the final result in all cities. A 30% increase or decrease in fuel prices changes the proportion of avoided heating expenses by ± 40%, 49%, and 42% in Tallinn, Riga, and Vilnius, respectively (Fig. 11). Given that heat recovered from WW replaces heat produced by NG boilers, an increase in the NG price raises the avoided heating costs, EUR/year) in Sc2 from 106 EUR/year to 149 EUR/year, increasing the share of avoided heating costs (SAE_i, %). The results of the study indicate that rising NG prices will make the use of WW heat more economically feasible, as argued by Somogyi V. et al. In Ref. [30].

Another factor that makes using WH extremely profitable is the increase in operating hours. A 30% increase in operating hours (from 6000 to 7800) allows Tallinn, Riga, and Vilnius to increase the proportion of avoided heating costs by 39%, 47%, and 40%, respectively.

The proportion of avoided heating costs is more flexible than the other two sensitivity analysis parameters: technology costs (costs related to the AHP and connection to the main DH network) and investment loan interest rate. An increase in either parameter reduces the appeal of using WW heat. In Tallinn, Riga, and Vilnius, technology costs increase or decrease the proportion of avoided heating costs by 8%, 15%, and 9%, respectively. The sensitivity analysis also revealed that lower-capacity AHPs (for example, in Riga) are more sensitive to changes in technology costs, indicating economies of scale. The investment loan interest rate has the least impact on consumer benefits from integrating WW heat into the DH system in order to increase the proportion of avoided heating costs.

6. Conclusions

This study provides a comprehensive assessment of energy poverty in the context of multidimensional poverty that evaluates the integration of recovered heat from treated WW into the DH system in the three Baltic capitals. The approach presented here is more suitable for developed countries. The implemented three-stage methodology's spatiotemporal analysis allows for the assessment of the AHP's potential and design capacity for WH utilisation in Tallinn, Riga, and Vilnius. Tallinn (27 MW), Riga (25 MW), and Vilnius (21 MW) were found to have similar WW heat potential. Riga has the least opportunity to utilise this potential due to the location of the WWTP in relation to the heat demand of the surrounding heating area. Tallinn, Riga, and Vilnius have a potential share of AHP heat production of 13.88%, 4.54%, and 6.49%, respectively.

As fuel prices rise from low in Sc1 to high in Sc3, the integration of WH becomes more appealing to consumers, which will be the driving factor behind their integration into the DH system.

Public support and a socially robust policy are necessary to ensure the integration of WH into the DH system, aimed at achieving a low-carbon society. The study assessed the economic benefits of incorporating WW heat into the DH system using the energy poverty indicator (proportion of income spent on heating). The proposed multidimensional approach identified three components affecting the proportion of avoided heating costs: household income, fuel prices, and energy efficiency. This multidimensional indicator demonstrates how incorporating heat recovered from treated WW into the DH system benefits society, which can be a significant factor in the development of this technology. The study shows that avoided heating costs are highest in Tallinn (Sc1 – 17.91, Sc2 – 106.70, Sc3 – 181.88 EUR/year), followed by Vilnius (Sc1 – 6.54, Sc2 – 50,35, Sc3 – 66.06 EUR/year). Low fuel prices do not incentivise WH integration into the DH system, which is one of the major barriers to WH integration into the DH system. Even a low-capacity AHP can contribute to avoided heating costs when fuel prices rise (avoided heating costs in Riga are Sc2 – 24.87, Sc3 – 45.96 EUR/year). But at low fuel prices, the development of this technology must be supported by a policy - government subsidies, tax relief.

According to the sensitivity analysis, avoided heating costs are sensitive to increases in fuel price and AHP operating hours, but more flexible to technology costs (costs related to the AHP and connection to the main DH network) and investment loan interest rate.

The proposed research methodology can be used to assess other WH sources introduced into the DH system and their impact on energy poverty.

Credit author statement

Jelena Ziemele – conceptualization, methodology, data curation and analysis, modelling, writing – original draft, review & editing, visualization, funding acquisition, supervision. Anna Volkova – data curation, conceptualization, writing – original draft, review & editing, supervision. Eduard Latõšov – data curation, conceptualization. Lina Murauskaitė – data curation, conceptualization, writing – original draft, review & editing. Vytautas Džiuvė – data curation, conceptualization, writing – original draft, review & editing, visualization.

All authors have read and agreed to the published version of the manuscript.

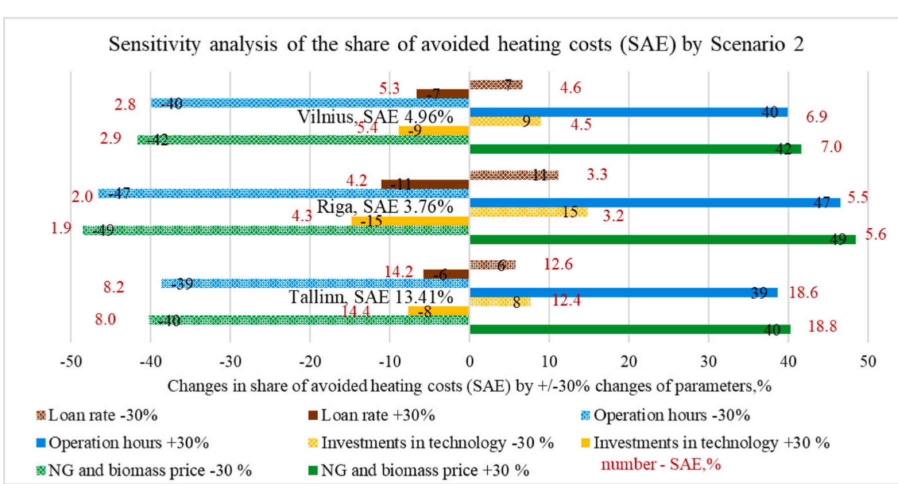

Fig. 11. Tornado diagram for the sensitivity analysis of the share of avoided heating costs (SAE) for Scenario 2.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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