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Sizing large-scale industrial heat pump for heat recovery from treated municipal sewage in coal-fired district heating system

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Abstract

Electrification of district heating and deep integration of sectors of national economies are fundamental elements of the future smart energy systems. This paper discusses the problem of optimal sizing of large-scale high-temperature heat pumps using treated sewage water as a heat source in a coal-fired district heating system. The study presents an approach to modelling of heat pump system that enables techno-economic analysis for investment decision making. Such analysis is enabled by a black-box-type identification model of the selected industrial heat pump. The model was developed based on the data generated by physical modelling of the heat pump using Ebsilon Professional software. In addition, it is proposed that the heat pump system is integrated with a dedicated photovoltaic power plant. The case study takes into consideration site-specific technical, economic, ecological, and legal constraints, weather conditions, hydraulic performance of the heating network, and variability of loads within the sewage and the district heating systems. The results revealed that the proposed modelling approach is effective regarding multiple simulations and system optimisation. In addition, it was found that large-scale heat pump projects can be technically feasible and profitable if the heat pump is appropriately sized and operated. In the given case, the optimum size of the heat pump for a city of around 180 000 inhabitants is around 12 MW under maximum winter load.

Keywords: District heating; Heat pumps; Sewage treatment plants; Sector integration; Renewable energy

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1. Introduction

The accelerating global climate change and the growing problem of the availability of primary energy resources have resulted in an unprecedented change in approach to energy supply planning and energy system development. According to major organisations [1–3], the ongoing energy transition is nowadays driven by digitalisation, decarbonisation, decentralisation, and disruption-as-usual. Renewable energy, energy efficiency, integration of sectors, and circular economy, as well as electrification of transport and district heating and cooling are key pillars of the future energy systems. According to IRENA's report [3], to limit the rise in global temperature to well below 2°C above pre-industrial levels, the annual energy-related CO_2 emissions should decline by 2050 by 70% below today's level. To achieve this, electricity should progressively become the central energy carrier. Its share in global final consumption should gradually increase to almost 50% by 2050, and 86% of electricity

Nomenclature

c – specific heat capacity, kJ/(kg K)
C – cost, EUR
CAPEX– capital expenditures, EUR
COP – coefficient of performance
DPB – discounted payback period, year
G – sewage load, m^3/day
h – specific enthalpy, kJ/kg
IRR – internal rate of return
L – residual value, EUR
$\dot{m}$ – mass flow rate, kg/s
N – economic lifetime, year
NPV – net present value, EUR
NPVR– net present value ratio
OC – sum of operational costs, EUR
p – pressure, kPa
P – electric power, kW
$\dot{Q}$ – heat flux, W
r – discounted cash flow rate
s – specific entropy, kJ/(kg K)
sc – specific energy cost, EUR/GJ
SPB – simple payback period, year
T – temperature, K
Tx – income tax, EUR
t – time, year

Greek symbols

Δ – difference
ε – pressure ratio
η – efficiency

Subscripts and Superscripts

aux – auxiliary equipment
av – average
B – boiler
CP – central heating plant
CHP – combined heat and power (cogeneration) unit
CSTP– central sewage treatment plant
d – daily
des – at design conditions
dhw – district heating network water
el – electricity, electrical
env – environmental
f – fuel
grid – power grid
HP – heat pump
i – isentropic
in – inlet conditions
lift – heat pump temperature lift
m – mechanical, materials
max – maximum
out – outlet conditions
sw – treated wastewater
s – after isentropic process
wf – working fluid
ref – reference value
t – time step

Abbreviations and Acronyms

CSTP– central sewage treatment plant
ETS – emissions trading system
HP – heat pump
M – electric motor
PV – photovoltaic

generation should be renewable, and 60% should come from solar and wind. The report also shows that by 2050 around 334 million heat pumps should be installed globally.

Regarding the energy supply and use patterns, energy harvesting, use of distributed resources, and distributed generation are envisioned as future backbones of the European energy system. Key topics of discussions that nowadays take place globally are related to the so-called smart energy systems [4], which among other components are considerably based on 4th generation district heating, electrification, electrofuels, and energy efficiency.

In the district heating sector, a faster rollout of energy transition must take place to meet energy and climate policy. Although the European Union (EU) strategy for making heating and cooling more efficient and sustainable was announced in 2016 [5], in some European regions little has been done in this area. On average, in the EU only about 25% of district heat is currently produced from renewable sources [6]. In countries like Poland, still, around 85% of primary energy input to district heating systems comes from fossil fuels, mainly coal, and diversification of primary energy sources used for heat production is progressing very slowly [7]. In addition to this, in cities, high-temperature district heating grids prevail. Overall, according to International Energy Agency (IEA) [6], decarbonisation potential of district heating is largely untapped, and decarbonisation efforts were not enough to curb associated emissions.

According to the *Project of strategy for district heating till 2030 with a perspective till 2040* [8], there is a political commitment to reorganisation, reconfiguration, and decarbonisation of the entire district heating sector in Poland. According to the policy targets, the share of renewable energy sources should increase from the current level of 9.5% to 28.4% in 2030, and 85% of district heating systems meet the Energy Efficiency Directive (EED) (EU/2023/1791) definition of an effective system. Regarding specific technologies, the strategy, among other ventures, recommends solar systems, geothermal plants, cogeneration plants fired with biogas and hydrogen, heat pumps driven by electricity from renewable sources, as well as lowering district heating network temperatures. The decomposition of district heating systems and the introduction of new tools to integrate distributed sources are also indicated in the document.

In the market, considerable activities focused on energy transition have been recently triggered by many district heating companies across the country. In many cases, investors take into consideration that future district heating infrastructures should be designed for the future system, and as recommended by Lund et al. [9,10] should enable the integration of district heating with the electricity sector. In this context, in the wide range of different projects in Poland, large-scale industrial heat pumps recovering heat from municipal sewages are frequently taken into consideration. The first project of this kind was carried out in 2020 by Veolia in Szlachęcin near Poznań [11]. In that project, the lower heat source for the heat pumps is treated wastewater being disposed to the Warta River. The minimum temperature of the sewage water in winter is 8°C and the flow is within the range of 50 m^3/h to 350 m^3/h. The water is directed to a 300 m^3 concrete tank and then pumped to the cascaded heat pump system of 1641 kW heating capacity, which delivers district heating water at 65°C.

Another example is the 12.5 MW heat pump ongoing project triggered by Fortum in Wrocław [12,13]. In this case, untreated sewage will be used as the heat source. The total cost of the project is estimated at PLN 82 million (around EUR 17.5 million). Large-scale heat pump projects were also triggered in 2022 by PGE Energia Ciepła in Cracow, by PGNiG Termika S.A. in Warsaw, and by PEC Gliwice Sp. z o.o. in Gliwice (*Przedsiębiorstwo Energetyki Cieplnej* – Heating Energy Company), and are considered by many other companies. In each case, projects are tailored taking into consideration local conditions for integration of sewage water treatment plant with district heating system. As in 2022, due to disruptions caused by the situation in Ukraine, which caused issues of limited coal availability, many projects of this type are focussed on the security of heat supply and resilience of the systems to market turmoil.

The use of large-scale industrial heat pumps, including high-temperature ones, for the decarbonisation of the district heating sector has gained the significant interest of many stakeholders, including industry, policymakers, and researchers globally. For example, Volkova et al. [14] claim that large-scale heat pumps are key future district heating technologies, which in the baseline scenario proposed will generate more than half of the heat for the Baltic states: Estonia, Latvia, and Lithuania in 2050. In Denmark, the total heat pump capacity in the district heating systems has increased in recent years, and experts expect this trend to continue as natural gas networks and coal are phased out [15]. Barco-Burgos et al. [16] have recently presented an extensive review paper focused on the integration of high-temperature heat pumps in district heating and cooling networks. According to their study, small district heating and cooling systems present the largest potential for heat pump use and significant reduction of consumption of fossil fuels, while, in medium and large systems this potential is lower.

David et al. [17] presented the results of the survey on the technical characteristics of 149 large-scale heat pumps in district heating systems with a total thermal heating output of 1.58 GW. The study revealed that with 54 examples in Norway, Sweden, Finland, and Switzerland and a total installed capacity of 891 MW, sewage water is the most common type of heat source. The average of the installed capacity was 17 MW per heat pump unit. Another interesting insight is that some of the heat pumps installed in the newest age group (2011–2016) were sized for the primary load and are operated continuously for 7000–8000 h/year, mainly to achieve a faster return rate of the investment. The annual operating hours of other heat pumps, especially the older ones, are in the range of 4000–7000 h.

Arpagaus et al. [18] presented an extensive review of the state-of-the-art and current research activities in the field of high-temperature heat pumps with heat sink temperatures in the range of 90°C to 160°C. They identified 13 manufacturers that can deliver heat at a sink temperature of at least 90°C, and the heating capacities range from about 20 kW to 20 MW. According to the study, most of the heat pumps examined use a single-stage thermodynamic cycle. They differ mainly in the type of refrigerant and compressor, and the coefficient of performance (COP) ranges from 2.4 to 5.8 at a temperature lift from 95°C to 40°C.

Bach et al. [19] analysed the technical and economic aspects of integrating large-capacity heat pumps in the Greater Copenhagen district heating system, which is, according to the authors, a state-of-the-art system with multiple heat sources. The results revealed that heat pumps connected to the distribution district heating networks can be operated for around 3500 full load hours and for approximately 4000 full load hours in a zero carbon-dioxide emission scenario expected in the year 2025. In the case heat pump is connected to the transmission network of an elevated temperature, the annual running time decreases to around 1000 full load hours. The main heat sources considered were drinking water, sewage water, and sea water, which resulted in average value of the COP at 3.1, 3.2, and 2.9, respectively, in the case heat pump is connected to the distribution network, and at 2.6, 2.6, and 2.5 in the case heat is delivered to the transmission network. The total heating capacity of heat pumps recovering heat from sewage water was estimated at 87 MW.

Popovski et al. [20] presented the results of a techno-economic analysis of different decarbonisation scenarios for an existing district heating network supplied by coal-fired combined heat and power plants in Germany. The main focus of the study was on large-scale heat pumps. Key conclusions of the study were that under the current regulatory and economic framework, large-scale heat pumps are not cost-competitive with the existing coal-fired cogeneration plants, and the European Union Emissions Trading System (EU ETS) CO_2 price will most likely not be a sufficient incentive in the short and medium term. To be cost-competitive, heat pumps should be operated for a significant number of hours per year, and the district heating supply temperature should be lowered.

Trabert et al. [21] theoretically examined the economic performance of electricity price-driven heat production by a river water two-stage ammonia heat pump in district heating systems using the EnergyPRO software. The heat pump was integrated with an existing cogeneration plant and a heat storage tank. The electricity for the heat pump was assumed to be supplied by the cogeneration plant, and the electricity costs resulted only from the lost revenue from a potential sale of electricity at the spot market. Four values of heating capacity were tested in the heat pump sizing exercise, i.e. 4.70, 5.17, 5.64, and 6.11 MW, respectively. The annual average COP of the heat pump was in the range from 3.4 to 3.7 depending on the heat pump size, and the annual running hours were from 6354 h/a for the smallest heat pump to 4794 h/a for the largest one. The results revealed that the lowest levelized cost of heat (LCOH) was obtained for the heat pump of 4.70 MW heating capacity and the electricity-price driven operation was especially relevant for lower heating loads out of the heating season.

Fambri et al. [22] investigated the operation of large-scale heat pumps in district heating systems considering that the power-to-heat energy conversion process may provide flexibility for the electricity sector. They performed a case study for the city of Turin and created a potential scenario for heat pump operation based on the integration of the electric distribution system and the district heating distribution system. Results revealed that the installation of a 2.5 MW heat pump using groundwater of 15°C as a heat source and 250 m^3 heat storage tank may be profitable. The achieved simple payback period (SPB) of the project was in the range of 10.2 years with a potential reduction by 18% depending on flexibility provision incentives.

This work focuses on the heat recovery from municipal sewage water treatment plants. According to Volkova et al. [14], sewage water treatment plants are sources of heat with a high utilisation potential and are available all year round, ensuring relatively high values of COP. On the other hand, Ziemele and Dace [23] claim that usually located at a certain distance from the city, away from most heat consumers, and the full exploitation of their potential can be problematic. In their study for Riga, they sized heat pump for the heat demand of the adjacent heating area, which resulted in a much lower capacity (8 MW) than the total heat potential of the treated wastewater. This resulted in the waste water heat recovery share in annual heat production at the level of 2%.

In this paper, the techno-economic study of the integration of municipal sewage treatment system and district heating system through the installation of large-scale heat pump is performed under Polish 2022 market conditions. One of the challenges in such projects is to determine the optimal size of the equipment, which depends on several factors, such as the flow and temperature of treated wastewater, the desired district heating network water temperature, and the economic and environmental constraints of the project. In this paper, a general methodological framework for sizing industrial heat pumps for waste heat recovery from sewage treatment plants is presented. According to [16], only a few published works discuss the optimal and basic integration of heat pumps in district heating and cooling systems, while the optimal size of heat pumps for a given system widely depends on local conditions, and macroeconomic factors, such as electricity and fuel prices. The proposed methodology is analogous to the one used for sizing organic Rankine cycle (ORC) cogeneration systems in retrofitting projects of coal-fired district heating plants [24,25].

The case study was carried out for the city of Gliwice, where the share of coal in the energy mix for district heating is currently 100%. In addition, heat is produced in heat-only boilers. The main objectives of the work are:

i) to assess energy, environmental, and financial performance indicators of the heat pump implementation project,
ii) to optimally size the heat pump for the given system,
iii) to determine whether the integration of sectors through the heat pump is competitive in the district heating system,
iv) to identify key factors influencing the profitability.

Optimal selection of heat pump size, working fluids, parameters, and its integration with the existing district heating system are critical issues of the project. Considerable differences in energy, ecological, and economic results are observed for different heat pump cycle configurations and working fluids [18,26]. An important aspect of system design is also the hydraulic performance of a district heating network [27]. Regarding practical solutions, Barco-Burgos et al. [16] identified twelve generic configurations of heat pumps and how they can be integrated into district heating and cooling systems. The design task should also take into consideration an operational strategy and control of the heat pump unit under variable load and price conditions. An important problem of the optimisation task is also a selection of proper objective functions and constraints. The task must be properly formulated under the site-specific heating load profile, economic (including financial support mechanism) and legal conditions, including different strategies to supply electric energy to the heat pump plant. On the other hand, in practice, the final solution adopted for implementation is heavily dependent on the offers of heat pump manufacturers and engineering companies, as well as on the maturity of the market.

In Poland, according to the report [28], the district heating sector covers around 24% of the total demand for heat in the country, and the share of coal in heat production in the sector was 72.5% in 2018. District heating systems are responsible for more than 35 million tons of CO_2 emissions annually. In cities with a population in the range of 20–99 thousand people, the share of heat delivered from ineffective heating systems is 72.5% and in smaller cities, it is 86.2%. The heat pump market is emerging and nowadays there is only one reference system with a cascade of Mitsubishi heat pumps [11]. The heat pump was traditionally regarded as a non-competitive solution in Polish district heating systems. The reason for this was the relatively low price of coal. Moreover, according to the position of power transmission system operator (TSO) – PSE S.A., there will not be a sufficient amount of electricity available to electrify district heating in Poland in 20–30 years. The situation has dramatically changed in the year 2022 as coal prices increased several times. In addition, there has been a considerable increase in the number of European Union emission allowances (EUAs) processed under EU ETS. This together resulted in a significant increase of heat production costs. Additionally, emission limits resulting from the EU directives [29,30] force district heating companies to make strategic investment decisions.

The work presented concerns pre-feasibility study and predesign process of the heat pump plant for heat recovery from the central municipal sewage water treatment plant in the city of Gliwice. The scope of work covers the preparation and analysis of input data, heat pump modelling, system design and simulations, and financial analysis. The aim is to perform a quantitative assessment of the technical feasibility and cost-effectiveness of the project and to provide the information necessary to make an investment decision, proceed to further stages of design, and take steps to raise investment funds.

A single heat pump technology is considered for size optimisation. The main reason for this is the actual availability of appropriate heat pumps in the Polish market. Although the number of identified companies was considerable, only a few of them responded to inquiries on potential deliveries and their willingness to cooperate within the project. The technology preliminary evaluated for this study is the SHP-C600 heat pump system proposed by Siemens Energy [31,32].

2. Decarbonisation of Gliwice district heating system

The city of Gliwice is located in the southern part of the country, in the Silesia region, where also significant coal resources and active coal mines exist. The population of the city is around 180 thousand inhabitants. The city is located in the area of an accumulation plain cut by the Kłodnica River valley, which has a symmetrically developed network of side valleys in this area. Morphologically, the Gliwice region is poorly diversified. The average annual temperature varies between 7–8°C. The average monthly temperature in January is between –3°C and –2°C, while the average monthly temperature in July varies between 14°C and 16°C. Important factors influencing the climate of the city of Gliwice are high economic activity and the concentration of residential buildings. The significant degree of urbanisation results in the emissions of gaseous and particulate pollutants much higher than in other parts of the country.

The largest heat supplier and district heating network operator in the city is the municipal district heating company PEC Gliwice Sp. z o.o. (PEC), which operates in the field of heat generation, transmission, and distribution in accordance with the concessions granted by the President of the Energy Regulatory Authority of Poland. The main source of heat for the district heating network is the central heating plant equipped with 7 coal-fired boilers of total heating capacity of 360.5 MW, which is located in the western part of the city. The technological system of the heating plant includes a boiler house consisting of three WP-70 pulverised coal-fired water-tube boilers of 81.4 MW nominal heating capacity each and a boiler house in which four WR-25 coal-fired water-tube grate boilers of 29.2 MW nominal heating capacity are installed. The minimum allowable heating output of the WP-70 boiler is around 35 MW and that of the WR-25 boiler around 10–12 MW. The indicative thermal efficiency of boilers (ratio of thermal output to fuel LHV (lower calorific value) chemical energy input) in the 2021/22 heating season was $\eta_B = 0.84$ for WP-70 boilers and $\eta_B = 0.87$ for WR-25 boilers. Total annual coal consumption in the 2021/2022 heating season was 114 207.93 tonnes, and the average LHV (lower heating value) of coal was 21.4 MJ/kg. Apart from coal, the plant also uses significant amounts of quick lime, urea, and water in exhaust gas treatment systems to keep emissions below the current limits.

The total length of the district heating network is around 235 km. The network is the 2G (second generation) high-temperature water network with a maximum winter forward water temperature of 120°C. The network arrangement is of mixed radial and ring type, with several loops in the central region. The heat carrier is led out of the heating plant via 4 transmission pipelines: North-Western (2×DN600), New Western (2×DN700), Southern (2×DN500), and Northern (2×DN350). The total number of heating substations in the network is 1682 located in 6 heating zones. Figure 1 depicts the central heating plant output, while the temperature characteristics of the district heating network is depicted in Fig. 2.

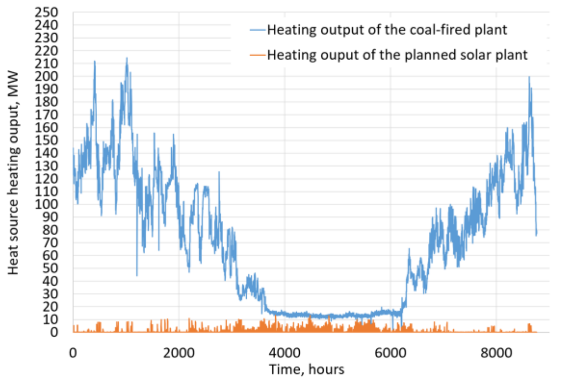

Fig. 1. Annual profile of heating plant thermal output (2022 data).

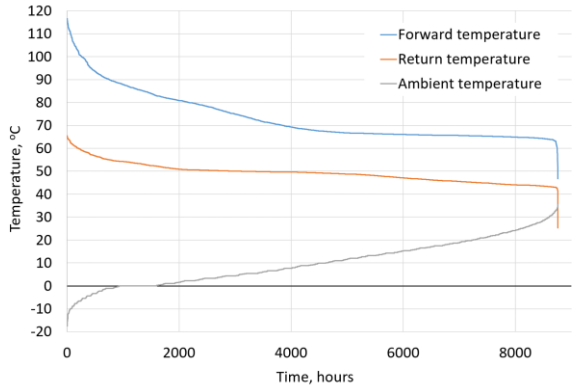

Fig. 2. Annual characteristic temperatures of the system.

As a result of the ongoing local programme of emission reduction from distributed domestic boilers and intensive development of new residential, retail, and office areas in Gliwice, the number of connected consumers and the ordered heating power are constantly increasing. For example, the heating power of facilities connected to the district heating network in the 2018/2019 season amounted to 15.65 MW, of which 5.47 MW were newly built buildings.

Recently, several new investment projects have been triggered aiming at obtaining the status of an efficient district heating system as defined by the revised EED [33]. Those include the implementation of a cogeneration plant fired with biomass and waste-derived fuels, a solar heating plant with a peak capacity of 13.3 MWp and heat storage. The investment project was publicly announced at [34]. The simulated heat output of the solar plant is already depicted in Fig. 1. In addition to this, several projects have been triggered in the field of waste heat recovery from distributed sources, including the Gliwice Central Sewage Treatment Plant. The key existing infrastructure for the project includes equipment and installations located at the heat pump and sewage treatment plant, and the district heating network.

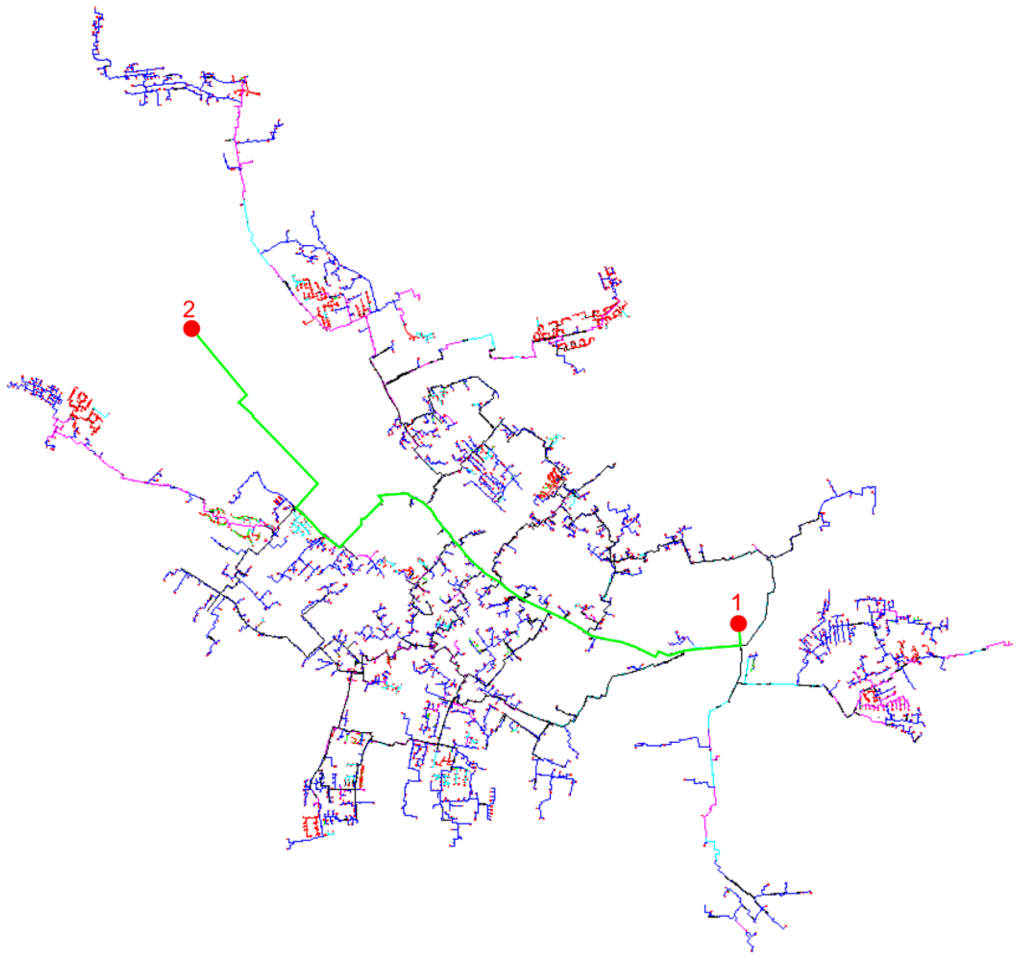

Fig. 3. Locations of the heating plant (1) and the sewage treatment plant (2) in the Gliwice district heating network.

Fig. 4. Central Sewage Treatment Plant of Gliwice (source: Google Earth).

Locations of the heating plant and the sewage treatment plant in the heating network are depicted in Fig. 3.

3. Heating potential of treated sewage water

The sewage treatment plant in Gliwice is presented in Fig. 4. It treats the city's sewage before discharging it into the Kłodnica River. The plant was designed for the maximum sewage treatment capacity of $G_{d,max}$ = 84 000 m^3/day, and daily average flow of $G_{d,av}$ = 40 000 m^3/day. Sewage treatment technology is based on mechanical and biological processes, with the possibility of chemical support. Before discharge into the river, the treated wastewater flows through a measuring station, where the flow and temperature are determined.

At the first stage of project development, the potential of treated sewage water for heat recovery was assessed. This was done by adopting flow rate and temperature measurements available from the plant's SCADA (supervisory control and data acquisition) system, and using the following formula:

$$\dot{Q}_{HP,in} = \dot{m}_{sw} c_{sw} \Delta T_{sw}. \tag{1}$$

Based on available measurement data, the annual flow and temperature models were developed with hourly resolution. Figure 5 depicts the flow of wastewater. Characteristic morning and evening peaks can be observed, as well as the night valleys, which typically occur between 2:00 and 7:00 am. Temperature of the wastewater is depicted in Fig. 6. The highest value measured is 22.9°C and the lowest one is 10.7°C. According to the acquired measurement data, the maximum thermal power that can be recovered from the treated wastewater at the temperature drop of ΔT = 5 K is 31.5 MW and the minimum is 2.7 MW. The annual average value is 8.1 MW. It was found that the peak flows occur on summer days in the time of heavy rains. The lowest heat recovery potential is in winter. The highest heat recovery potential is in July while the lowest one is in March. Figure 7 depicts the duration curve of the heat recovery potential. It can be concluded that very high recovery potential lasts for a relatively short time, and throughout most of the annual time the potential is close to average.

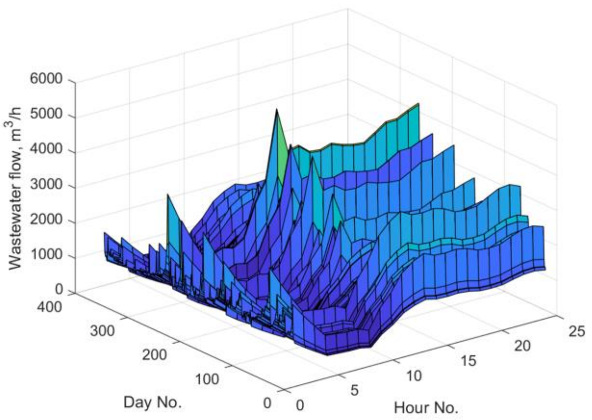

Fig. 5. Annual wastewater flow profile.

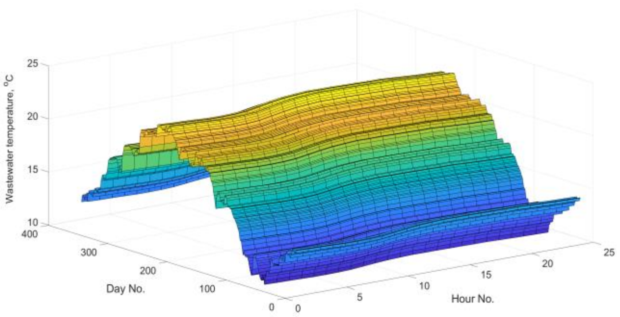

Fig. 6. Annual wastewater temperature profile.

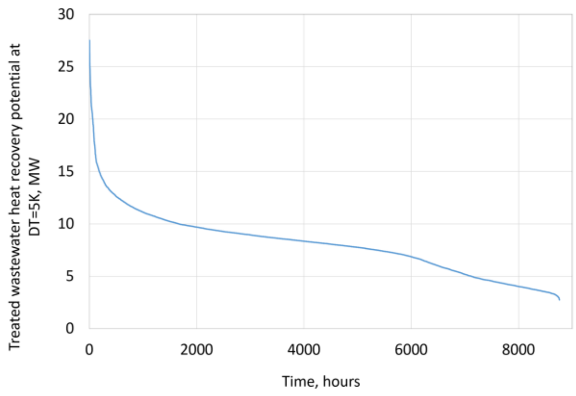

Fig. 7. Annual wastewater heat recovery potential duration curve.

There are two important features of the sewage treatment plant in Gliwice. The first one is that there are running two biogas-fired cogeneration modules of 365 kW and 210 kW installed electric power, respectively. The second favourable feature of the location is that there is available more than 20 000 m^2 of land for a photovoltaic (PV) power plant. Therefore it was decided that the PV system would be collocated with the heat pump. The realistic peak power output of the plant was assessed at around 1200 kW. The PV generation model is based on the measurements from a nearby PV plant located at the Gliwice campus of the Silesian University of Technology. The annual PV generation profile in kW is depicted in Fig. 8.

4. Materials and methods

Heat pumps are a major technology for integrating low-temperature heat sources with high-temperature district heating systems. The proposed methodology for optimal sizing of the heat pump and its integration with both the technological system of the sewage treatment plant and the district heating network is based on the following key steps:

a) acquisition of input data;
b) equipment availability assessment and selection of heat pump technology;
c) identification of key performance parameters of the heat pump system through physical modelling;
d) development of the heat pump identification model based on black-box type correlation;

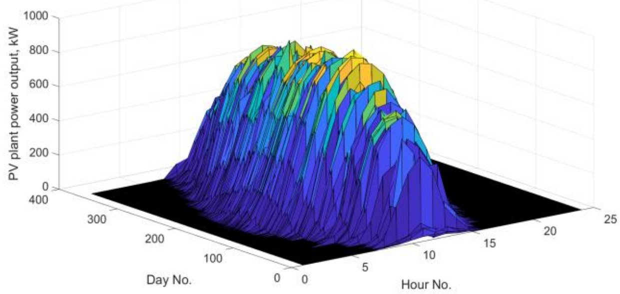

Fig. 8. Modelled annual power output of the PV plant.

e) hydraulic interconnection design for the integration of heat pump with the district heating system;
f) construction of a simulation model enabling multiple calculations and system optimisation;
g) annual system simulations with different values of decision variables, and determination of key items of the annual substance and energy balance;
h) estimation of investment expenditures for different heat pump heating capacities;
i) determination of the level of profitability of the project in the individual variants,
j) sensitivity analysis.

In the first step, relevant valid measurement data on the operation of both the district heating system and the sewage treatment plant system were acquired and analysed. Based on this, daily variation profiles of the individual parameters were determined and an annual data set was compiled for the simulation calculations of the heat pump system.

The heat pump selection for the project should take into consideration criteria such as the design temperature lift, coefficient of performance (COP), capital and operating costs, reliability, maintenance, and environmental impact. In this study, the equipment market was screened for the availability of heat pumps, as well as the available reference projects were examined. Overall, two types of approaches were identified in the field of waste heat recovery from sewage treatment plants. The first is based on cascaded systems and a larger number of heat pumps like in the case of Szlachęcin project [11]. In the second approach, large-scale industrial heat pumps are used. As there is no need to reserve heating capacity due to the possibility of supplying from the existing heating plant, the second approach was selected. It was preliminary considered to adopt for further studies the SHP-C600 industrial heat pump produced by Siemens Energy [31,32,35,36]. According to Siemens Energy publicly available data, the solution has been proven, implemented, and improved since 1981, and there are currently more than 50 units of this type in operation with a single pump heating capacity ranging between 5 MW and 30 MW. So far, the technology has proven high availability and flexibility of operation. According to the obtained information, the heat pump can potentially run for 8700 hours per year and the minimum allowable heating load of the heat pump is 30% of maximum power. This enables flexible cooperation with the heating plant, as well as with the future sources of heat in the district heating system. The single heat pump unit arrangement of the wastewater heat recovery system is also focused on minimisation of the service costs.

The heat pump can be built in a heating capacity variant from 5 MW to 70 MW. The auxiliary equipment will be supplied with 0.4 kV. Although, according to Siemens, heat sink temperature up to 150°C is possible [36], it is planned to build a typical unit, reaching a hot water temperature of up to 99ºC at the outlet to the grid. The time of occurrence of the network supply water temperatures higher than 99ºC was approximately 314 hours in the 2021/2022 season. After taking into consideration the point of heat pump interconnection, network water flows, and heated areas of the system, it was concluded that the temperatures higher than 99ºC will be required throughout around 283 hours per year.

The heat pump consists of an evaporator, a condenser with a subcooler, expansion valves, a flash tank, and a two-stage radial turbo compressor with inlet guide vanes at both compressor stages. The compressor will be driven by an electric motor (alternating current (AC) machine) with a supply voltage of 10.5 kV. A schematic diagram of the heat pump is depicted in Fig. 9. An advantageous feature of the proposed system is the direct heat exchange between heat pump working fluid and the treated wastewater, which will eliminate the demand for an intermediate heat exchanger, which would cause unfavourable temperature differences and exergy losses.

4.1. Heat pump physical model

The physical model of the heat pump is built using equations that describe the thermodynamic processes that make up the heat pump cycle. The working fluid is trans-1,3,3,3-tetrafluoropropene, which is also named refrigerant R-1234ze(E). It is used by

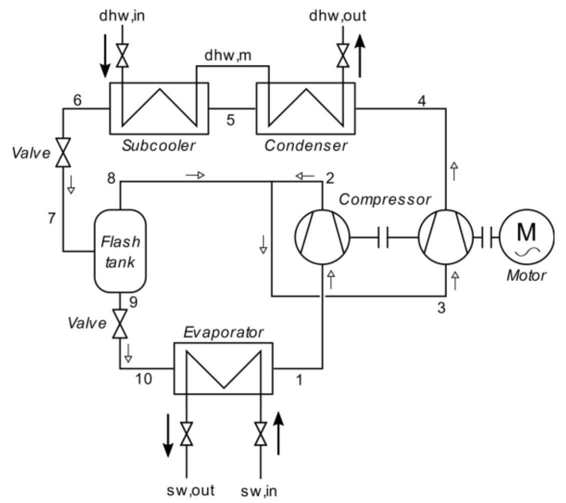

Fig. 9. Schematic diagram of the industrial heat pump.

several high-temperature heat pump manufacturers, including Siemens. The critical pressure of this fluid is 3634.90 kPa and critical temperature is 382.51 K.

The key performance parameters of heat pumps are heating capacity $\dot{Q}_{out}$, cooling capacity (or heat absorbed from the sink) $\dot{Q}_{in}$, temperature lift ΔT_{lift}, and coefficient of performance COP.

The heating output of the heat pump is the sum of heat extracted from the working fluid in the condenser and subcooler. Taking into account the specific points of the thermodynamic cycle defined in Fig. 9, the heat output can be presented as

$$\dot{Q}_{HP,out} = \dot{m}_{wf,4}\left(h_{wf,4} - h_{wf,6}\right). \qquad (2)$$

Heat losses from the heat exchangers were neglected due to the relatively low process temperature. The values of specific enthalpy of the working fluid in points 4, 5 and 6 result from the saturation conditions at the given pressure. The pressure setpoint results from the district heating network water temperatures at the heat pump outlet $T_{dhw,out}$. The temperature after the subcooler, and thus the enthalpy $h_{wf,6}$ result from the network water temperature at the heat pump inlet $T_{dhw,in}$.

After the subcooler, the working fluid pressure is throttled to the intermediate pressure, which results from the outlet pressure of the first compressor stage:

$$p_7 = p_2. \tag{3}$$

The throttling process occurs at constant enthalpy. Thus, equations for the two respective throttle valves are:

$$h_{wf,6} = h_{wf,7}, \tag{4}$$

$$h_{wf,9} = h_{wf,10}. \tag{5}$$

The mass and energy balances of the phase separator (flash tank) take the form

$$\dot{m}_{wf,7} = \dot{m}_{wf,8} + \dot{m}_{wf,9}, \tag{6}$$

$$\dot{m}_{wf,7}h_{wf,7} = \dot{m}_{wf,8}h_{wf,8} + \dot{m}_{wf,9}h_{wf,8}, \tag{7}$$

where specific enthalpies $h_{wf,8}$ and $h_{wf,9}$ are saturation enthalpies for liquid and vapour phase, respectively.

Heat delivered to the working fluid in the evaporator is

$$\dot{Q}_{HP,in} = \dot{m}_{wf,10}(h_{wf,1} - h_{wf,10}). \tag{8}$$

Again, the specific enthalpies of $h_{wf,1}$ and $h_{wf,10}$ results from the pressure setpoint, which depends on the treated wastewater temperature at the heat pump outlet ($T_{sw,out}$).

The most important component of the heat pump system is the compressor. In the SHP-C600, a two stage compressor is used. The respective pressure ratios of the particular stages are:

$$\varepsilon_1 = \frac{p_2}{p_1}, \tag{9}$$

$$\varepsilon_2 = \frac{p_4}{p_2}. \tag{10}$$

The entropy of the working fluid after the isentropic compression process is

$$s_2|_{p_2} = s_1|_{p_1}. \tag{11}$$

From the value of entropy s_2, the value of enthalpy $h_{2,s}$ after the isentropic compression is determined. Then the isentropic efficiency is used to calculate the enthalpy after the actual compression process:

$$h_{wf,2} = \eta_i(h_{wf,2,s} - h_{wf,1}) + h_{wf,1}. \tag{12}$$

Electrical power delivered to the electric motor driving the compressor first stage is

$$P_{el,in,1} = \frac{\dot{m}_{wf,1}(h_{wf,2} - h_{wf,1})}{\eta_m \eta_{el}}. \tag{13}$$

The power deliver to the second stage is

$$P_{el,in,2} = \frac{\dot{m}_{wf,3}(h_{wf,4} - h_{wf,3})}{\eta_m \eta_{el}}. \tag{14}$$

Finally, the coefficient of performance is

$$\mathrm{COP} = \frac{\dot{Q}_{HP,out}}{P_{el,in,1} + P_{el,in,2}}. \tag{15}$$

The temperature lift is defined as

$$\Delta T_{lift} = T_{dhw,out} - T_{sw,in}. \tag{16}$$

In actual operating conditions, the heat pump runs at variable parameters. The key independent parameters selected for the heat pump model are: treated sewage water temperature at the evaporator inlet ($T_{sw,in}$); water temperature at the inlet and outlet of the condenser ($T_{dhw,in}$, $T_{dhw,out}$); and heating capacity ($\dot{Q}_{HP,out}$), which can be lower than the maximum achievable at given temperatures (part load conditions). To appropriately assess annual energy balance of the system, time series simulation is required with hourly resolution. District heating network and treated sewage water parameters are known from measurements. Parameters of the heat pump must be determined from the model for each time step (t).

The heat pump cycle is depicted in the temperature – entropy (T-s) diagram in Fig. 10. Because the measurements of relevant heat pump performance parameters were not available, the relevant model was built using Ebsilon Professional simulation software [37], and calibrated with publicly available data given in [31,32,35]. The model is shown in Fig. 11. The most important issue of the modelling is the unknown pressure-flow characteristics of the compressor. In the study the Ebsilon built-in characteristics was used. Table 1 presents a comparison of results obtained by the model with parameters initially presented by Siemens Energy in [35]. The heat pump was simulated in design and off-design modes respectively, and a number of data points were generated. Those data were then used to develop regression models of key performance parameters, which were later used

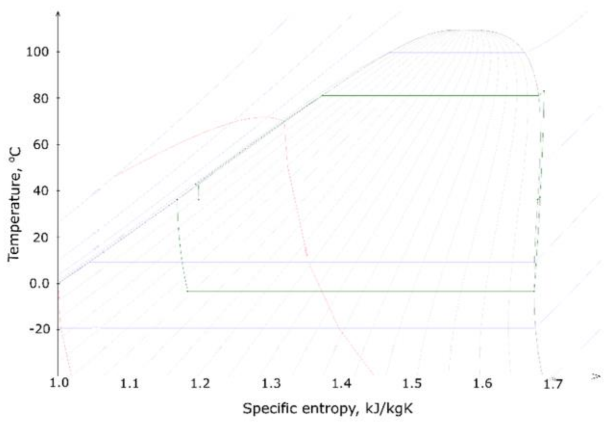

Fig. 10. Simulated heat pump cycle in T-s diagram.

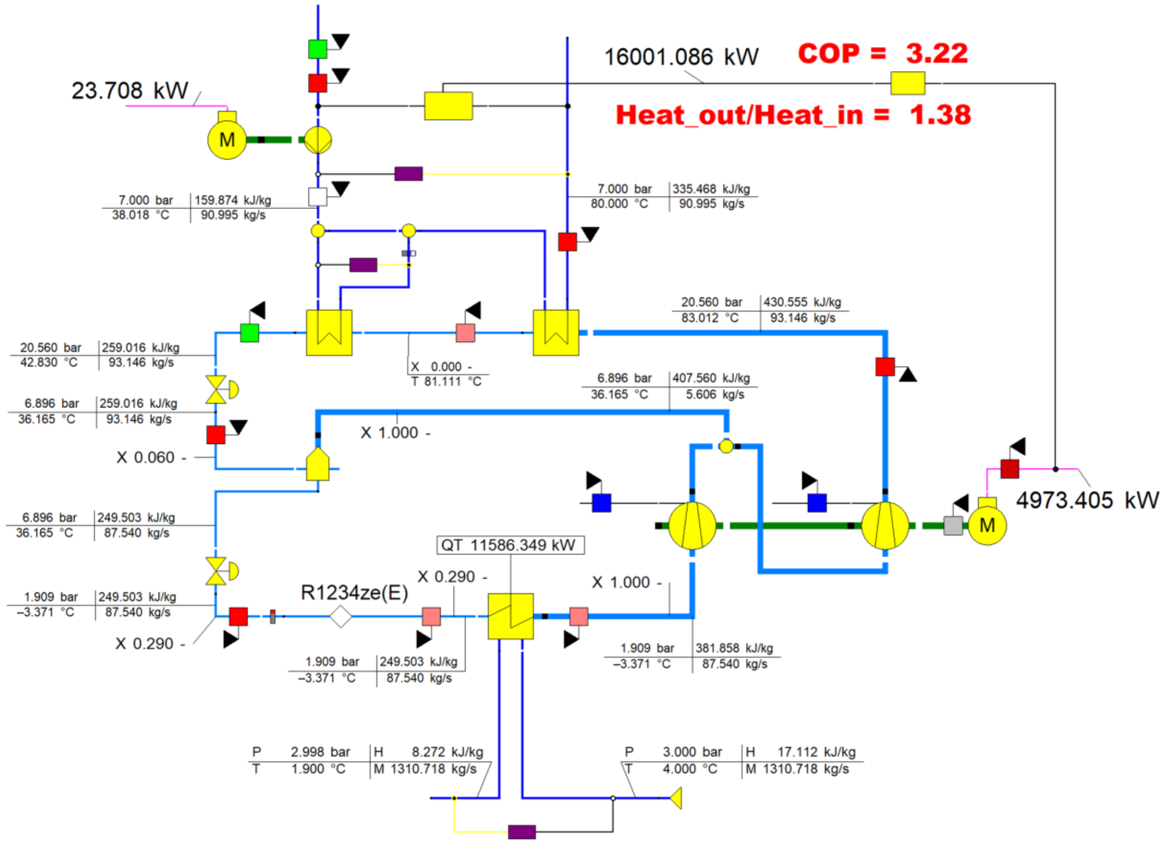

Fig. 11. Ebsilon Professional physical model of the Siemens SHP-C600 heat pump; M – electric motor, M – mass flow, H – enthalpy, P – pressure; T – temperature; QT – heat transferred, X – vapour quality.

for an annual simulation of the system's operation. Such an approach was previously demonstrated in [24,25,38].

The highest capacity and COP values are achievable in the summer when the wastewater temperature is high and the network water temperature is low. In winter, both heating output and COP decrease. Hence, the average annual efficiency of the system is influenced by the utilisation strategy of the unit and the duration of operation under winter and summer conditions respectively.

4.2. Heat pump black-box identification model

Although physical equation based modelling of heat pump performance gives relatively good predictions of the key performance parameters, it is not effective regarding multiple time series simulations required for system optimisation. The problem is long calculation times and convergence problems at some set points. For this reason, a black-box parametric model was developed that enabled multiple trouble-free simulations.

The highest assumed heating capacity of the heat pump model under winter conditions was 18 970 kW at a wastewater temperature of 14°C and a district heating network water temperature of 99°C. This value has been set as the reference one $\dot{Q}^{ref}_{HP,out,des}$. The heating capacity $\dot{Q}_{HP,out,des}$ was then used as the scaling and sizing design parameter. The Matlab software was used to fit appropriate correlations which enabled multiple annual simulations of the heat pump operation with hourly resolution. The relative achievable full load heating output under given thermal conditions, which was obtained from Ebsilon simulations, is

Table 1. Comparison of modelling results with data declared by the HP manufacturer.

Parameter	Unit	Declared data [35]	Modelling result	Relative difference
Heat source water mass flow	kg/s	1333.0	1310.72	-1.67%
Heat sink water mass flow	kg/s	94.0	90.99	-3.20%
Working fluid mass flow through the evaporator	kg/s	87.5	87.54	0.05%
Working fluid mass flow through the condenser	kg/s	93.0	93.15	0.16%
Heating capacity	kW	16510.0	16001.09	-3.08%
Cooling capacity (heat input)	kW	11563.0	11586.35	0.20%
Electric power input	kW	5124.0	4973.41	-2.94%

$$\frac{\dot{Q}_{HP,out,max}}{\dot{Q}_{HP,out,des}} = \left[-a + bT_{sw,in} + c\Delta T_{lift} - dT_{sw,in}\Delta T_{lift} - e\left(\Delta T_{lift}\right)^2\right], \quad (17)$$

where the values of coefficients are: $a = 5.9340$, $b = 0.2129$, $c = 0.1386$, $d = 0.0021$, $e = 0.0007$. The coefficient of determination for this correlation is $R^2 = 0.9999$. The results of curve fitting are depicted in Fig. 12.

The maximum value of COP achievable under given temperature conditions is

$$\mathrm{COP}_{max} = \left[a + bT_{HP,out} - cT_{sw,in} - d\left(T_{HP,out}\right)^2 + eT_{HP,out}T_{sw,in} + f\left(T_{sw,in}\right)^2\right], \quad (18)$$

where the values of coefficients are: $a = 2.8150$, $b = 0.0368$, $c = 0.0597$, $d = 0.0004$, $e = 0.0003$, $f = 0.0014$. The coefficient of determination for this correlation is $R^2 = 0.9966$.

Under real operating conditions, the heating capacity of the heat pump is frequently limited by the heat balance of the district heating network. Therefore, the actual COP at given time step is calculated using the following formula:

$$\mathrm{COP} = \left[-a + b\frac{\dot{Q}_{HP,out}}{\dot{Q}_{HP,out,max}} + cT_{sw,in} - d\left(\frac{\dot{Q}_{HP,out}}{\dot{Q}_{HP,out,max}}\right)^2 - e\frac{\dot{Q}_{HP,out}}{\dot{Q}_{HP,out,max}}T_{sw,in}\right], \quad (19)$$

where the values of coefficients are: $a = 0.126$, $b = 2.047$, $c = 0.03105$, $d = 0.9205$, $e = 0.03109$. The coefficient of determination for this correlation is $R^2 = 0.999$.

In the next step, hydraulic and thermal simulations of the district heating network were performed to determine the interconnecting pipe diameter and the effects of the network operation

4.3. Hydraulic integration

It was proposed to directly integrate the heat pump with the treated wastewater duct and the district heating grid. The approach is based on the construction of a concrete overflow buffer tank for the treated wastewater pumping station and a concrete heating chamber equipped with appropriate shut-off fittings, which will provide two modes of operation for the heat pump system:

- mode 1 – in parallel with the central heating plant –plugging into the supply and return pipelines;
- mode 2 – in series with the central heating plant – connection to the return pipeline only for preheating of return water.

The second mode will be applied at the lowest ambient temperatures when the heat pump will contribute only to around 5% of the total heat demand of the district heating system. A schematic diagram of the heat pump hydraulic integration is presented in Fig. 13.

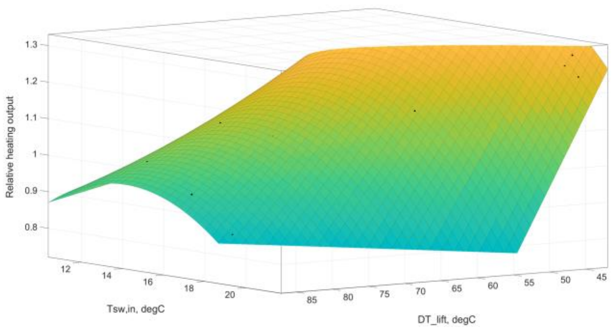

Fig. 12. Curve fitting to Ebsilon Professional simulation results.

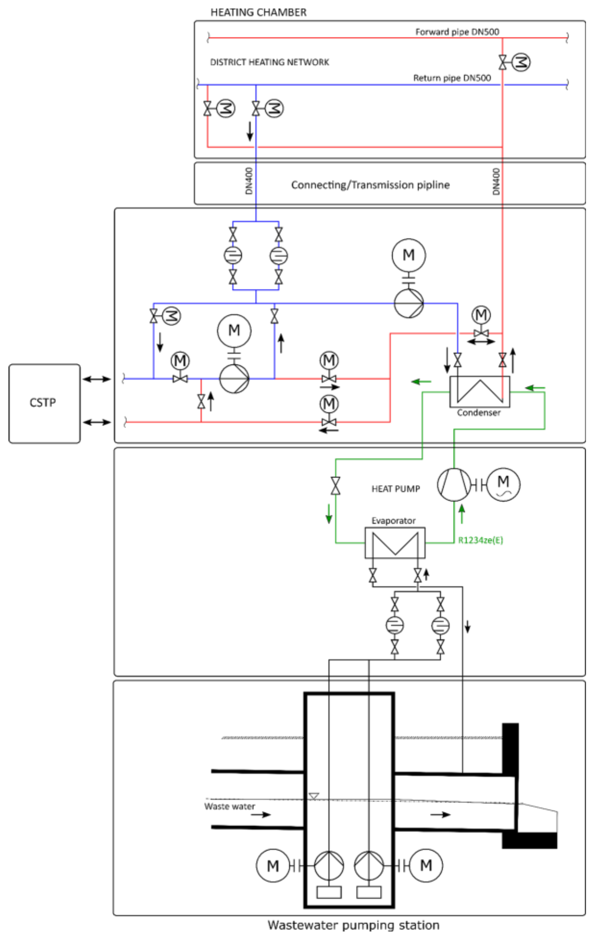

Fig. 13. Schematic diagram of the heat pump hydraulic integration.

with multiple heat sources. As it is presented in Fig. 3, the central heating plant and heat pump are located in different parts of the city and the distance between them is around 7 228 m. The district heating network model was built using the NetSim software [39] and detailed network data available in the Municipal Spatial Information System – Systemic Heat Portal (https://msip.gliwice.eu/geoportale). In particular, the routes and diameters of the pipelines were taken from the portal. The model was calibrated with measurement data for selected states of the district heating network provided by the district heating company. In the study, three pipe diameters were taken into consideration: DN200, DN400, and DN500 respectively. Sample results are depicted in Figs. 14 and 15.

It was found that the DN200 diameter of the interconnecting pipe results in high values of differential pressure at the heat pump system, thus the cost of water pumping increases. A change in pipeline diameter from DN200 to DN400 leads to a significant reduction in the required differential pressure and thus in the electrical drive power requirement of the network water pumps. The pipeline diameter is further increased to DN500, and the reduction in the required differential pressure is relatively small. Eventually, the DN400 pre-insulated pipeline was selected.

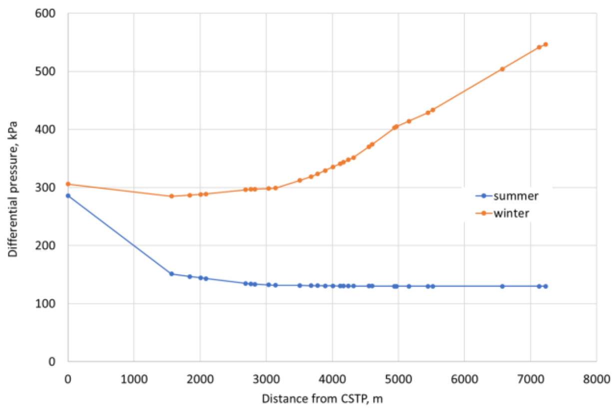

Fig. 14. Estimated distribution of differential pressure in the section connecting the heating and sewage treatment plants for a heat pump with a heating capacity of 13 MW and a transmission pipeline diameter of DN400.

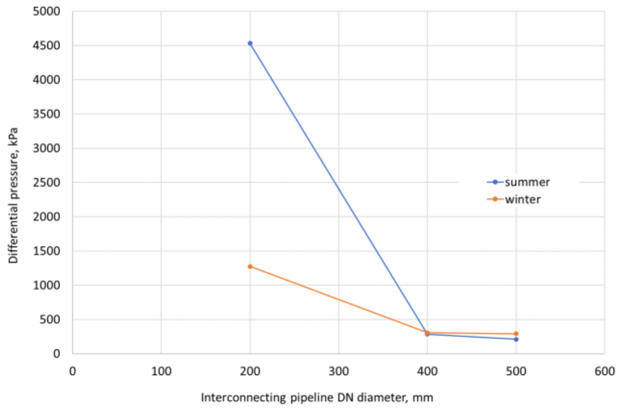

Fig. 15. Required differential pressure at the point of incorporation of a heat pump with a heating capacity of 13 MW, depending on the diameter of the transmission pipeline.

The obtained results confirmed the possibility of cooperation between the existing central heating plant and the heat pump located on the premises of the sewage treatment plant. The respective heat sources will run in parallel and supply heat to different areas of the district heating system. It was also confirmed that, under summer load conditions, it is possible to switch off the central heating plant and deliver heat to consumers from the heat pump only.

4.4. Economic model

The final step was to evaluate the feasibility and profitability of installing an industrial heat pump for waste heat recovery from sewage treatment plants. This was done by comparing the financial benefits and costs of the project over the assumed lifetime of 15 years. According to market producers estimations, the specific capital investment costs for the installed system without integration are 250 to 800 EUR/kWth, and depend mainly on heating capacity, temperature lift and scope of supply [36]. The investment costs are studied in depth in [40–42]. According to different data sources, the expected value for 10 MWth heat pump is between 350 and 500 EUR/kWth. After consulting different engineering offices and potential vendors, investment cost data were acquired. Available data from other projects were also taken into consideration. As the total capital investment costs (total CAPEX) are always site-specific and significantly influenced by system integration costs, this study uses engineering evaluation methods based on the scope of the project, which includes:

- heat pump;
- container transformer station with 20 kV input voltage with 10.5 kV outputs (heat pump) and 0.4 kV (internal installations and drives);
- connection to the external electricity grid and power supply to the transformer station (cable line of estimated length of 1500 m);
- construction of a concrete overflow buffer tank for the wastewater pumping station with an estimated volume of 125 m^3;
- installation of a system of submersible pumps for the treated wastewater to the heat pump, together with an intake filter to prevent the coarse fraction (plants, dead birds) from entering the pumps;
- variable-speed drives for treated wastewater pumps;
- machinery house building of 12 m× 35 m and height of 9 m on a floodplain, soundproofed, equipped with overhead crane and social space, including fabrication;
- machinery house building electrical, HVAC (heating, ventilation, air conditioning), and sanitary installations;
- photovoltaic plant with a peak capacity of 1.17 MWp;
- electrical installation integrating sewage treatment plant, PV, and heat pump systems;
- pre-insulated pipe DN400 district heating network transmission section, 1700 m long (complete supply, works and acceptance in the thermal-technological sector);
- concrete heating chamber at the point of connection of the system to the district heating network;
- hydraulic system and fittings of a district heating chamber ensuring change of supply modes of a district heating network;

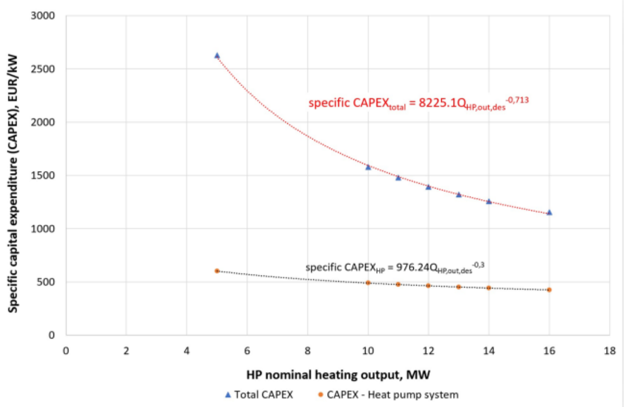

Fig. 16. Investment cost estimations.

- electrical installation of the heating chamber and power supply;
- district heating network water pumping station;
- hydraulic system to integrate the sewage treatment plant with the heat pump system and the district heating network (auxiliary equipment, fittings, pipework – complete supply, works and commissioning of the heat-technology branch);
- control system, field measurements, and telemetry for PEC (complete supply, works, and commissioning in the field of instrumentation and control engineering).

The costing curves elaborated for CAPEX estimations are depicted in Fig. 16. The investment costs for the interconnecting pipeline strongly depends on the pipe diameter, which is shown in Fig. 17. The obtained values of the estimated capital expenditures are overall in line with the literature data taking into account recent increases in costs in the construction sector. It can be also concluded that the specific scope of the project and site-specific requirements, such as hydraulic and electric interconnections, and the collocated PV plant, significantly influence the total CAPEX. Therefore, the specific total CAPEX gets very high values for the smallest heat pump option. The higher is the design heating capacity $\dot{Q}_{HP,out,des}$ the lower is the total specific CAPEX.

The optimisation problem is to select the size of the heat pump to achieve the best value of a selected quality indicator (objective function) under given constraints. The task is solved from the local financial perspective. Therefore, the net present value (NPV) calculated for the economic lifetime of the project was selected as the main objective function:

$$\max \mathrm{NPV}, \tag{20}$$

where

$$\mathrm{NPV} = \sum_{t=1}^{N} \frac{\Delta \mathrm{CF}_t}{(1+r)^t} - \mathrm{CAPEX}. \tag{21}$$

Other financial indicators such as net present value ratio (NPVR), internal rate of return (IRR), simple payback period (SPB), discounted payback period (DPB) were also calculated where it was possible.

The key component of the objective function is the differential cash flow $\Delta \mathrm{CF}_t$ resulting from cash flows after and before the project. Assuming that the project does not generate new incomes as the market for heat remains the same after the project, the differential cash flow results mainly from the changes in costs:

$$\Delta \mathrm{CF}_t = \mathrm{CF}'_t - \mathrm{CF}_t = -\Delta \mathrm{OC}_t - \Delta \mathrm{Tx}_t + \Delta L_t, \tag{22}$$

where the residual value L is calculated only for $t = 15$. The differential operational costs take into account mainly changes in costs of electricity, fuel costs, and maintenance and environmental costs related to heat sources:

$$\Delta \mathrm{OC}_t = C_{HP,t} + \Delta C_{CP,t} = \left(C_{el,HP} + C_{m,HP} + \Delta C_{f,CP} + \Delta C_{el,CP} + \Delta C_{m,CP} + \Delta C_{env,CP}\right)_t. \tag{23}$$

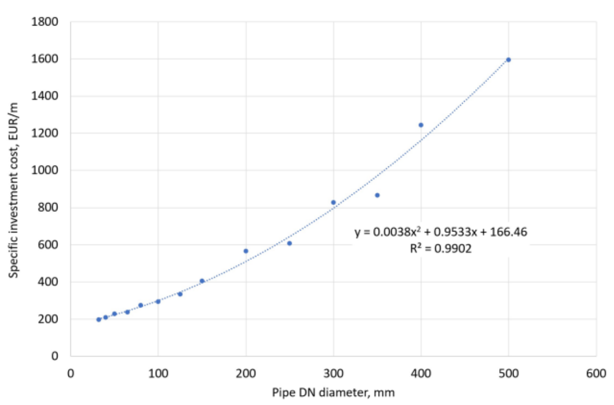

Fig. 17. Specific investment costs for the interconnecting pipeline as a function of diameter (Poland, 2022 prices, pre-insulated pipes in reinforced trench).

For tax calculations also the changes in depreciation and financial costs are taken into consideration. It must be emphasised that the cost of heat recovered from the treated wastewater was set to 0.

The key assumptions for financial calculations are as follows:

- The project is a standalone unit of analysis.
- The project's economic lifetime is 15 years.
- Construction time is 2 years.
- Discounted cash flow rate is $r = 0.03$.
- Two funding options were considered: with no subsidy (only equity and loan) and with a subsidy of 30% of the total investment cost. In the first option, the share of equity is 25%.
- Prices are valid for the year 2022.
- Coal price: 195 EUR/tonne (at LHV = 21.40 MJ/kg).
- Utility grid electricity price: 195 EUR/MWh (constant price based on current contract).
- Price of CO_2 emission allowance in EU ETS: 84 EUR/tonne.

- Heat pump service and maintenance cost (including reserves for overhauls): 2.5% of the direct investment expenditures (i.e. related to the productive assets).

The objective function is subject to both equality and inequality constraints, which result from heat load profile, heat recovery potential from the treated wastewater, parameters of district heating water, energy and substance balances, heat pump and coal-fired heat only boilers characteristics including COP and efficiency variations, range of allowable loads, etc. The basis for the sizing of the heat pump and the analyses of the quantitative effects of the project is the reference hourly distribution model of key parameters in terms of substance and energy balances. Calculations were carried out using an hour-by-hour simulation method. In the heating season, the heat pump system is covering the base heating load of the district heating system. During the off-season operation, heat for the district heating network is generated exclusively by heat pump systems and a solar thermal plant. Coal-fired boiler plants are not in operation. The heat pump works under part load conditions to enable full consumption of the solar heat.

The municipal district heating network balance takes into consideration heat supplies from different heat sources. Assuming that at each hour the heat generation by solar plant, as well as heat consumption and losses from the grid remain unchanged after the project, the differential heating power balance results in reduced heating output of coal-fired boilers:

$$-\Delta\dot{Q}_B = \dot{Q}_{HP,out} + \dot{Q}_{CHP} - \dot{Q}_{CSTP}. \tag{24}$$

Electric power balance of the heat pump system takes into account electricity from the grid and generated on-site:

$$\frac{\dot{Q}_{HP,out}}{\mathrm{COP}} + P_{aux} = P_{grid} + P_{PV} + P_{CHP} + -P_{PV,CSTP} + \Delta P_{CP}. \tag{25}$$

In the base case scenario, a year-round operation of the heat pump unit was assumed (8000 hours), with two shutdowns at the beginning and end of the heating season. The assumed shutdowns aim to ensure a technical minimum for the coal-fired boilers being dispatched. An alternative operating strategy can be oriented towards minimising the cost of heat generation and dependent on the instantaneous price of electricity. Typically, this approach to pump control is used for energy purchases on the Commodity Exchange. In this study, however, constant electricity price was assumed as the electricity for PEC is procured through a tendering procedure. Therefore, the alternative strategy taken into consideration assumes shutdowns of the heat pump whenever performance parameters do not justify the momentary costs of heat production.

5. Results and discussion

Detailed annual simulations were carried out for 6 variants of the heat pump size expressed by the maximum heating power in winter conditions. In each variant, this power is: variant HP_16 – 16 MW, variant HP_14 – 14 MW, variant HP_13 – 13 MW, variant HP_12 – 12 MW, variant HP_11 – 11 MW, variant HP_10 – 10 MW, and variant HP_5 – 5 MW.

It was found that variability of treated wastewater flow and temperature, district heating network heat demand, and temperatures result in high variability of the heat pump performance parameters, such as the achievable heating capacity and COP. Depending on the heat pump design heating capacity (size), the fraction of annual time where the heat pump works under part load conditions is different. The simulated annual variations of heat pump relative heating capacity and COP in the base case operation scenario for the heat pump_12 variant are depicted in Figs. 18 and 19, respectively. It can be concluded that the highest values of COP occur in summer. However, in summer the

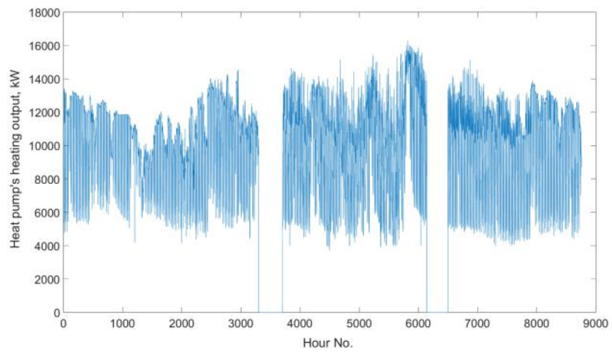

Fig. 18. Simulated annual variations of a 12 MW heat pump's heating output.

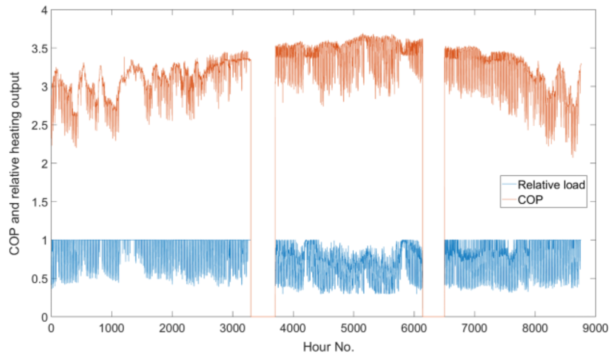

Fig. 19. Simulated annual variations of relative heating output and COP of a 12 MW heat pump.

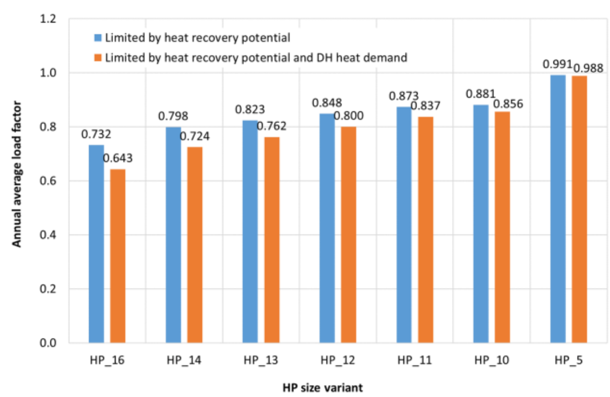

Fig. 20. Annual average load factor.

heating output is significantly reduced due to both low heating demand and parallel operation with the solar plant. On the other

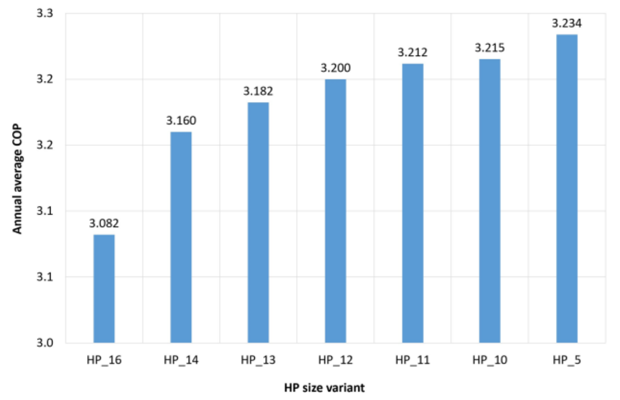

Fig. 21. Annual average COP.

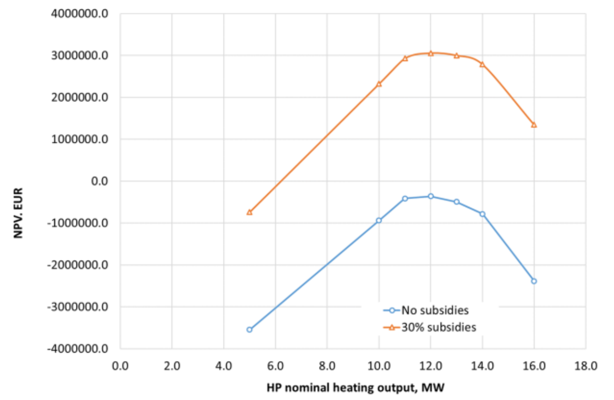

Fig. 23. NPV for different heat pump size variants.

hand, in the winter the heat pump runs closer to full load conditions, however, the achievable heating output and COP vary due to the availability of heat recovery potential.

Figures 20 to 24 summarise the key simulation results for the individual heat pump capacity variants. Figure 20 depicts the annual average load factor (defined as the ratio of the actual heating capacity to the achievable capacity under given thermal conditions) for different heat pump size options. As the installed capacity of the heat pump increases, the value of the annual average load factor decreases. It can be concluded that only the smallest heat pump can operate close to full load conditions. The larger the heat pump the actual load is limited by both the availability of the heat recovery potential and the heat demand in the district heating network. The influence of those limitations on COP is shown in Fig. 21.

Figure 22 depicts potential direct reductions in coal consumption at heating plant and related CO_2 emissions. The presented values are valid only if the electricity to drive the heat pump is supplied from renewable energy sources. In the case electricity is from coal-fired power plants, the systemic effects will be lower as the heat pump operation will result in additional fuel consumption at utility power plant.

Figures 23 and 25 present values of the objective function (NPV) for different heat pump size variants. It was found that the best option under the given assumptions is the HP_12 variant. However, the NPV curve is quite flat in the area of optimal solutions. Therefore, the potential range of heat pump design heating capacities that should be considered for the project is 11–14 MW. This gives the manufacturer a flexibility margin. Another important finding is that under given prices and operational strategy the project is not profitable without subsidies. The final value of NPV index is slightly negative for all the variants within the range of optimal solutions. The value of discounted payback period (DPB) is higher than 15 years and the value of SPB is in the range of 12 years, as depicted in Fig. 24.

As a result of the analyses carried out, the most favourable technical solution was found to be a heat pump variant with a design heating capacity of 12 MW under maximum winter load conditions. The baseline operational strategy assumed heat pump operation within 8000 hours per year. It results in an average annual heat pump load factor of 0.80 and an average annual COP of 3.20. Its implementation leads to a reduction in coal consumption at the central heating plant of approximately 15987 tonnes/year and a reduction in CO_2 emissions of approximately 34694 tonnes/year. The estimated total investment outlay (CAPEX) is at the level of EUR 14 759 183, which results in a specific investment cost of 1230 EUR/kW. The profitability indices without subsidies are slightly negative: NPV = –360070.4 EUR, NPVR = –0.025, IRR = 0.027,

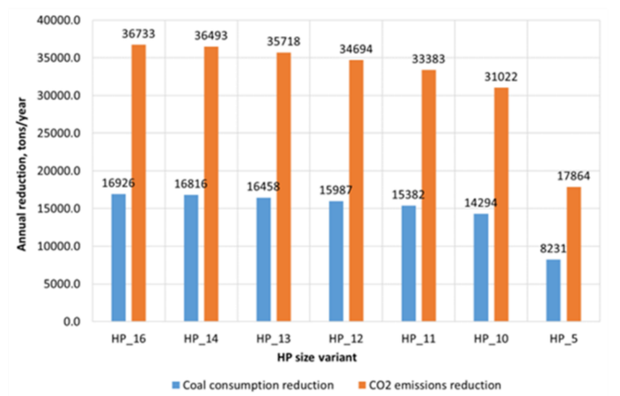

Fig. 22. Annual reduction of coal consumption and related CO_2 emissions from coal-fired boilers.

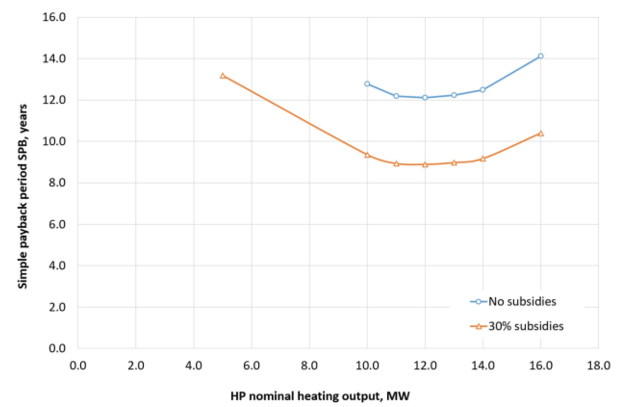

Fig. 24. SPB for different heat pump size variants.

SPB = 12.12 years, and DPB >15 years. The change in the project's value over the years is depicted in Fig. 25. Figure 26 depicts the project's sensitivity to critical financial parameters.

If the project is subsidised at 30% of CAPEX, the profitability indicators take on the values: NPV = 3,056,658.3 EUR, NPVR = 0.21, IRR = 0.068, SPB = 8.88 years, DPB = 10.73 years. Those are values typically accepted in the district heating sector.

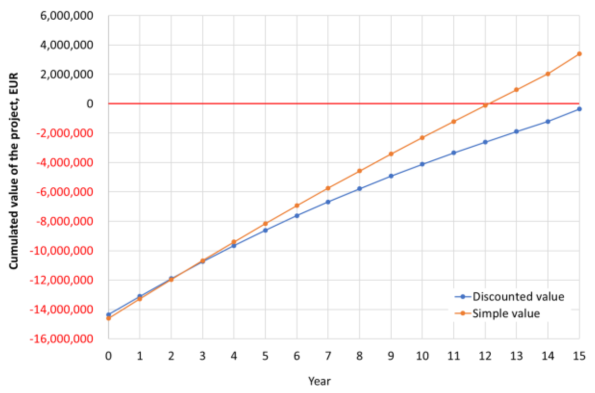

Fig. 25. Simple and discounted value of the project for HP_12 size variant.

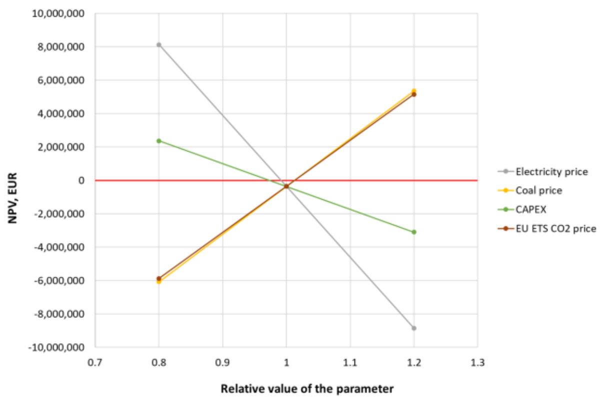

Fig. 26. Sensitivity analysis for HP_12 size variant.

The profitability of the project is highly sensitive to the variability of the critical project parameters, which include the electricity purchase price, the coal purchase price, the CO_2 emission allowance (EUA) price, and the total capital expenditure (CAPEX). The project shows the greatest sensitivity in relation to the electricity purchase price, and then to coal and EUA prices. The project is much less sensitive to CAPEX, which means operational effects are of critical importance for profitability.

After considering the specific contribution of each project effect to the final financial value, it was found that, relative to the results presented, there is a potential for improvement in energy and financial performance. This, however, requires the development of a suitable strategy for operating the heat pump.

Given that the cost-effectiveness of heat pump operation in the district heating system with coal-fired boilers is determined by the ratio of the cost of driving energy, which is the ratio of electricity cost to the sum of the costs of coal and CO_2 emissions, a potential for improving the financial effects exists in reducing the annual operating time of the heat pump to the period during which the following precondition is met:

$$\frac{sc_{el}}{\mathrm{COP}} < \frac{sc_f}{\eta_B}. \tag{26}$$

Given that the average efficiency of a coal-fired boiler at heating plant is around 0.85 and the COP is 3.2 for average annual conditions and 2.6 for winter conditions, the ratio of electricity cost to fuel cost should be below 3.76 for average annual conditions and 3.06 in the winter. The assumed prices result in a ratio of 3.11, which means that winter operation of the heat pump with low COP generates financial losses. Taking the heat pump periodically out of operation at the lowest achievable COP values will lead to reduced losses and therefore an improved annual result. Therefore, in additional simulation, it was assumed that the heat pump is taken out of service when the COP falls below 3.0. The values of the profitability indices obtained for the financing variant without financing improved (see Fig. 27), resulted in NPV = 728 508 EUR, NPVR = 0.05, IRR = 0.037, SPB = 11.15 years, and DPB = 14.19 years. The annual operating time of the heat pump in this control scenario was 6986 hours per year. The simulations also revealed that setting the COP criterion too high leads to a further reduction in operating time, which leads to a reduction in cost-effectiveness. It is therefore recommended that an algorithm be developed to control the use of the heat pump depending on the achievable COP and the actual energy cost ratio.

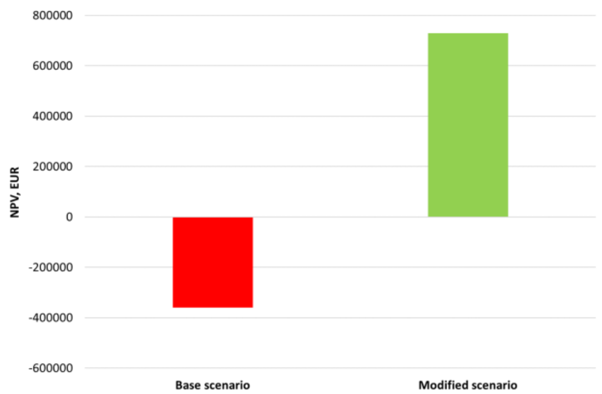

Fig. 27. Impact of operational strategy on NPV.

6. Conclusions

Using physical modelling to develop a black-box-type identification model of the industrial heat pump system appeared to be effective modelling approach that enabled multiple system simulations and techno-economic optimisation. Models of such type can deliver useful information regarding investment decision making and production planning. Heat pumps are thermodynamic systems that can be modelled relatively fast using available software tools. However, such model require calibration using measurement data form existing plants. Better accuracy of the models can be achieved if larger collections of measurement data is available.

An important conclusion from the study is that the projects of implementation of large industrial heat pumps in Polish district heating systems may be nowadays profitable. Although the expected payback periods are quite long, the profitability indices are overall positive if the heat pump is appropriately sized and runs under given price conditions. The profitability is highly influenced by the energy performance of the system, which mainly results from the sizing of the heat pump, load conditions, and achievable COP. In the presented case study, the project of integration of sewage treatment plant and heating plant with the heat pump system is on the verge of profitability, and therefore even small changes in technical performance may significantly influence the objective function.

It was also concluded that the profitability of the project is strongly dependent on the size of the heat pump and the optimal solution exists. For the given potential for heat recovery from the treated wastewater, which is between the summer maximum of 31.5 MW and the winter minimum of 2.7 MW, the optimal size of the heat pump (regarded as maximum heating capacity under winter conditions) is 12 MWth. Such a heat pump unit ensures an annual average heat recovery rate of around 7 MW, which is slightly below the annual average heat recovery potential (7.9 MW). Smaller heat pumps are less cost-effective as a significant increase in the total CAPEX occurs once the heat pump size is reduced. The profitability of larger heat pumps is significantly influenced by part load conditions, which result in COP reductions.

As the project's profitability is very sensitive to the technical performance of the system, and considering that due to the heat pump integration with high-temperature heating grid the resulting COP is relatively low, the recommended strategy for heat pump operation is to control the momentary cost of heat generation resulting from thermal conditions, COP, electricity and fuel prices and environmental costs. Relevant algorithms and software should be implemented to assist system operators in making well-informed operational decisions.

The market trends in Poland have recently revealed a considerable decrease in electricity prices while coal and CO_2 prices remained close to the values assumed for the study. This is the result of a significant increase in power generation by PV and wind plants recently commissioned in Poland. In addition, major energy companies in Poland have recently announced strategies indicating the withdrawal of coal assets and significant investments in renewable energy sources. In June 2023, for the first time in history, negative prices of electricity occurred in the national commodity energy exchange. In the light of the obtained results of this study, it can be concluded that the profitability of projects assuming the implementation of large-scale heat pumps in the district heating sector in Poland will improve shortly and a considerable number of new projects should be expected to be triggered.

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