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Techno-Economic Analysis of Increasing the Share of Renewable Energy Sources in Heat Generation Using the Example of a Medium-Sized City in Poland

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Abstract: In many countries located in Central–Eastern Europe, there is a need for heating in the autumn and winter seasons. In Poland, this has been met over the years, mainly through the development of centralized heating systems. The heat sources in such systems are based on fossil fuels like coal or gas. New regulations and climate concerns are forcing a transformation of existing systems towards green energy. The research presents two scenarios of such a change. The first focuses on maintaining centralized heat sources but increases the share of renewables in the heat supply. This can be realized by weather-independent, high-power sources such as biomass boilers and/or high-temperature heat pumps (HP) such as sewage heat pumps or ground source HP. The second scenario changes the location of the heat sources to more dispersed locations so that the unit power can be lower. In this case, renewable heat sources can be used at favorable locations in the system. Among the sources included in this scenario are solar panels, photovoltaic panels, micro wind turbines, and ground source heat pumps with local heat storage. These are characterized by low energy density. Their dispersion in the urban space can contribute to the desired energy generation, which would be impossible to achieve in the centralized scenario. Furthermore, the transmission losses are lower in this case, so lower heating medium temperatures are required. The existing district heating network can be used as a buffer or heat storage, contributing to stable system operation. The article presents a comparative analysis of these solutions.

Keywords: district heating; renewable heat sources; distributed heating system; centralized heating system; heat pumps; biomass; PV panels

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1. Introduction

Many European countries face the challenge of providing residents with an adequate heat supply while maximizing the share of renewable sources in its production. Over the years, the development of district heating has covered the energy efficiency increase, mainly by changing the district heating supply temperature to lower values, but also by renewable heating sources development [1]. Nowadays, the following renewable heat sources can be found in the literature: solar thermal (i.e., solar collectors), heat pump (driven by electricity from renewable electricity sources), geothermal heat, solid biomass (direct combustion, torrefaction, gasification or pyrolysis), liquid and gaseous biofuels, green hydrogen, or residual heat [2]. Currently, Germany is the EU leader in heat sales (Figure 1). Poland ranks second in this ranking, ahead of the Scandinavian countries Sweden, Finland, and Denmark. In 2022, the total amount of heat sold in the EU exceeded 2000 PJ. In each EU

country, different legal regulations and support mechanisms govern the operation of the district heating system. These primarily include property law, price regulation, metering, network connection, and environmental taxes [3].

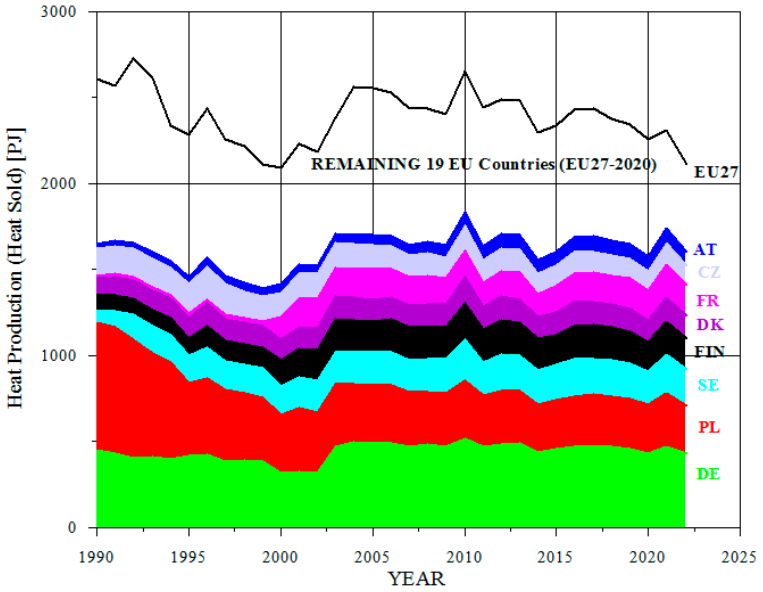


Figure 1. Heat production (sold) in EU countries 1990–2022. Source of the data: [4].

Poland boasts one of the highest concentrations of district heating systems in Europe, with around twenty large district heating systems. In 2022, eight of these systems had an installed capacity in excess of 1000 MW each, which together accounted for around a third of the total possible capacity from all licensed sources. Warsaw, in particular, is home to the largest district heating system in the European Union, with the Siekierki CHP plant being the largest.

The cumulative installed capacity of licensed heat generators in 2022 exceeded 53 GW. Among them, small heat sources of up to 50 MW accounted for more than 43% of the total number of licensed facilities (220 out of 392). The district heating network system in Poland is extensive, with licensed companies managing district heating networks with a total length of more than 22,500 km by 2022. Cogeneration accounted for 62.1% of total heat production in the same year.

Despite diversification efforts, hard coal still dominates the fuel mix of district heating systems (Figure 2). Renewable energy sources accounted for 12.3% of the energy mix in 2022, with biomass being the main source [5]. Biogas had a much lower share (0.062%), while other sources, such as geothermal energy and solar thermal, were minimally represented at just 0.269%.

The predominance of biomass as the main energy source for licensed district heating companies is clearly visible in Figure 3. There has been an increase in the share of renewable energy sources compared to previous years, which can largely be attributed to biomass. It is worth noting that in the European Union, dry biomass (solid biofuels), mainly wood and straw, is the main renewable energy source. In Poland, biomass accounts for a significant 72% of final renewable energy consumption, compared to 40% in the European Union. Heating buildings with biomass in individual boilers is an easy way to meet renewable energy targets, but it is neither innovative nor transformative. It also contributes to smog and may lead to deforestation [6].

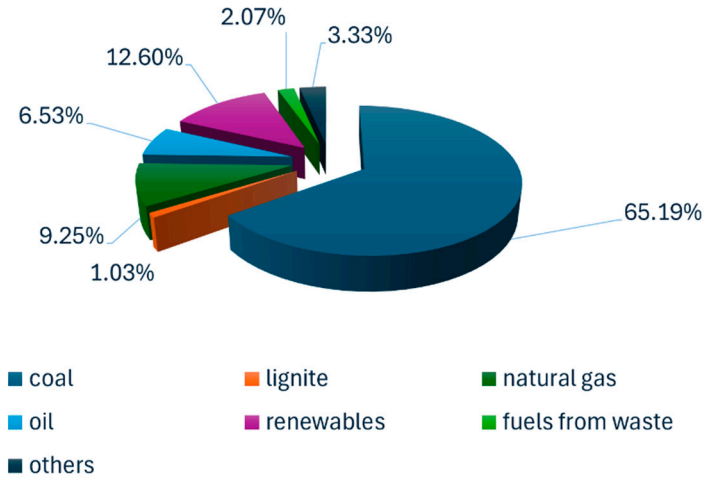


Figure 2. Shares of fuels used for heat production in 392 licensed district heating companies in Poland (2022). The energy delivered by fuels, 447 PJ. Data according to the Energy Regulatory Office (heat energy in numbers (2022)) [5]. Note: The fuel structure shown in the figure applies only to licensed district heating companies. Concessions cover companies with a source capacity of more than 5 MW.

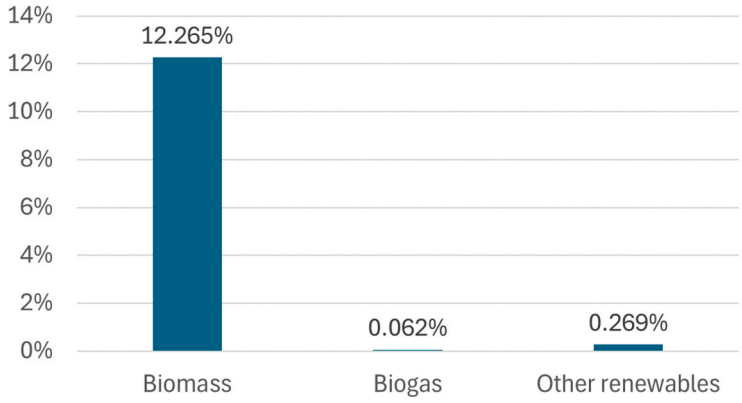


Figure 3. Shares of renewable energy sources in heat production in total heat from licensed sources.

The economic viability of district heating systems depends on meeting the conditions set out in the Directive [7]. Currently, by 31 December 2027, an efficient district heating and cooling system must use at least 50% renewable energy, 50% waste heat, 75% combined heat and power, or 50% combined such energy and heat.

Significant changes are to take place in the following years. From 1 January 2028, systems must meet criteria including the use of at least 50% renewable energy, 50% waste heat, 50% renewable energy and waste heat, 80% high-efficiency combined heat and power, or a combination thereof, with specified minimum shares of renewable energy and overall total energy.

From 1 January 2035, revised criteria will apply, with flexibility for systems meeting the specified renewable energy and waste heat thresholds.

From 1 January 2040, systems should use at least 75% renewable energy, 75% waste heat, or 75% renewable energy and waste heat, or at least 95% renewable energy, waste heat, and high-efficiency cogeneration, with specified minimum shares of renewable energy or waste heat. Subsequent changes to the definitions will mandate the efficient use of renewable energy and waste heat, culminating in the requirement for systems to rely solely on renewable energy, waste heat, or a combination thereof by 1 January 2050. The criteria are summarized in Table 1.

Table 1. Requirements for district heating in the near future.

	From 1 January 2028	From 1 January 2035	From 1 January 2040	From 1 January 2045	From 1 January 2050
Definition 1 *	50% renewable energy, 50% waste heat, 50% renewable energy and waste heat, 80% of high-efficiency cogeneration heat	50% renewable energy, 50% waste heat, 50% renewable energy and waste heat	75% renewable energy, 75% waste heat, 75% renewable energy and waste heat	75% renewable energy, 75% waste heat, 75% renewable energy	100% renewable energy, 100% waste heat, 100% combination of renewable energy and waste heat
Definition 2 *	The share of renewable energy is at least 5%, and the total share of renewable energy, waste heat, or high-efficiency cogenerated heat is at least 50%.	The total share of renewable energy, waste heat, or high-efficiency cogenerated heat is at least 80%, and the total share of renewable energy or waste heat is at least 35%.	A total share of 95% renewable energy, waste heat, and high-efficiency cogenerated heat, and in addition, the total share of renewable energy or waste heat is at least 35%.		

* The system can be classified according to definition 1 or 2, depending on preference.

Member States may alternatively adopt sustainability criteria based on greenhouse gases (GHG) emissions per unit of heat or cooling delivered to customers. The maximum emission thresholds decrease over time, aiming for zero emissions by 1 January 2050 (Figure 4). This means that by 2050, district heating systems should use 100% renewable energy sources [8].

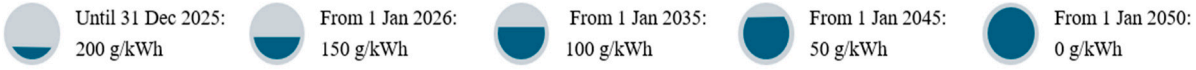


Figure 4. The roadmap for maximum emission thresholds decreases over time, aiming for zero emissions by 1 January 2050.

The Renewable Energy Directive [9] limits the use of biomass to meet 2030 targets, requiring the adoption of more innovative technologies. From 2026 onwards, biomass use must reduce CO_2 emissions by 80% (70% by 2025), including indirect emissions such as those from transport [6].

Given the challenges presented, there is a growing need to explore alternative heat technologies. In general, heat sources in such systems could be heat pumps, waste or biomass combined heat and power plants (CHP), biomass, geothermal energy, solar collectors (direct heat source), or photovoltaic (PV) panels as a source of electricity for electric or HP boilers [10]. Two systems are considered in modern heat supply scenarios: centralized and neighborhood-scale systems [11]. District heating systems tend to become low-temperature systems [12], which increases efficiency, especially for renewable energy sources such as electricity like HP [13], but requires investment costs not only on the system side but also on the internal household infrastructure [14]. To increase the efficiency of the heating system, special attention needs to be paid to the building infrastructure, such as insulation, internal heating systems, and metering infrastructure, which can contribute to energy savings [15].

In Poland, climatic conditions pose a challenge to the large-scale use of solar energy (both solar collectors and PV panels), and seasonal heat storage is associated with significant costs. This study analyses the cost-effectiveness of higher heat density heat sources, including heat pumps, energy from waste, and electric boilers. The study aims to compare two renewable heat supply scenarios: distributed and centralized.

2. Methods

In order to conduct analyses related to the operation of renewable sources, data determining the distribution of average hourly capacity factor (CF) values for photovoltaic (PV) panels were used. The data used for the analyses were obtained from the European Commission databases available for individual European Union countries on its website [16].

Having input data in the form of the hourly distribution of the CF values for PV panels and the distribution of heat demand of the reference city for a representative year, it is possible to prepare a balanced model allowing for the determination of aggregated and momentary indicators of the operation of the set: energy source, energy storage, and receiver.

A Microsoft Excel spreadsheet was used as a tool for building the model.

In addition to meteorological data, other input values were required during the model preparation:

- Nominal power of the PV installation [kW];
- Energy storage capacity and power [MWh];
- Filling level of the energy storage at time 0 [%].

For the presented set of input data in the prepared model, first of all, for each hour of the representative year, the hourly production of electricity from the PV installation is calculated.

Then, for each hour, an energy balance is calculated. Then, the following parameters are determined:

- Current storage level [kWh];
- Electricity from the generation system transferred to the heat pump system in a given hour [kWh/h];
- Energy from storage transferred to the heat pump system in a given hour [kWh/h];
- Excess electricity from the generation system, which is the difference between the energy generated by the generation system and the energy transferred to the heat pump system [kWh/h];
- Energy transferred to the energy storage [kWh/h];
- Electricity transferred to the grid [kWh/h].

3. Analyzed Scenarios

The climatic conditions in Poland make it difficult to easily and directly use renewable sources (especially weather-dependent sources) to meet heating needs. The basic sources of renewable energy, i.e., solar (PV panels for electricity and collectors for heat production) and wind energy (electricity), show high dynamics of load changes throughout the year. These dynamics can be observed both in short-term periods, e.g., daily, as well as in seasonal periods. Additionally, the supply of energy (both electricity and heat) from renewable sources is shifted in time with its demand [17].

Moreover, current heating systems were designed to cooperate with conventional heat sources, which practically means operation with high-temperature heat. To increase the efficiency of their operation, renewable sources perform better with low-temperature receivers.

The above circumstances create technological challenges that must be faced when designing modern systems. These challenges can therefore include the following:

- A time mismatch between the supply of energy from renewable energy sources and the demand for this energy for heat production;
- The preferred high temperature of current heating systems;
- The limited supply of land for the development of renewable energy sources in urban infrastructure conditions.

The challenges defined above require the configuration of a heating plant system composed of many components, thus having the features of a hybrid system. As part of this study, it is proposed to refer for further consideration to a system consisting of the following:

- Photovoltaic panels;
- Seasonal heat storage;
- Heat pumps;
- A ground heat exchanger;
- An electric boiler;
- a biomass boiler.

Further analysis was carried out with the assumption that peak heat demand for the example city equals 40 MW, which corresponds to 30,000 citizens. Two scenarios summarized in Table 2 were considered.

Table 2. Sources in analyzed scenarios.

Source	Scenario 1	Scenario 2
PV panels	850 × monocrystalline photovoltaic panels, single module power approx. 500 Wp, located on roofs	X
Coal boiler	X	WR 25 coal boiler, 29 MW (residual, peak source)
Biomass boiler	X	One unit, 25 MW
Electric boiler	4 × 50 kW (peak source)	X
Heat pumps	2 × 500 kW, with ground heat exchanger	Treated sludge heat pump installation with a capacity of 4.5 MW
Heat store	8 underground tanks of 1000 m^3 each (8000 m^3 in total), 380 MWh	X

3.1. Distributed Heating Scenario

One of the emerging concepts is the decentralization of heating by using many local low-power systems to meet heating needs, e.g., on the scale of a single housing estate. Such systems should make it possible to meet the needs for heat generated mostly from renewable sources (more than 80%).

The proposed distributed heating system is based on multipliable heating modules dedicated to an estate with an ordered thermal power of 1000 kW, which corresponds to approximately 12,000 m^2 of usable area. The scheme of one module is shown in Figure 5. The installation consists of:

- 850 monocrystalline photovoltaic panels, with a single module power of approx. 500 Wp, located on the roof, at an angle of 35°;
- Heat storage—eight underground Tank Thermal Energy Storage units (TTES) with a capacity of 1000 m^3 each (8000 m^3 in total), ΔT = 40 °C, T_{max} = 85 °C. The maximum amount of energy that can be stored in a seasonal store is 380 MWh. The overall efficiency of a seasonal water heat storage system depends on various factors, including the design and location of the installation, the type of technologies used, the effectiveness of the insulation, the ambient temperature, and how the stored energy is utilized. Typically, seasonal efficiency of TTES is considered to be in the range 70–87% [18], or 66%, as reported by another study [19]. Heat losses were calculated for each hour of the storage operation by balancing losses to the ground (heat flux penetrating through the walls of the storage), taking into account changes in the temperature of the bed

and the ground. The result was available discharge heat equaling 270 MWh (efficiency of nearly 70%, which is in the range presented in the literature). Heat storage in the form of tanks should be located underground in undeveloped areas (e.g., parking lots) or under lightweight buildings, e.g., garages; application examples in the considered scale are presented in [20];

- Heat pumps—two compressor heat pumps. The thermal power of a single pump is approximately 500 kW, the maximal supply temperature is T_{max} = 85 °C, and COP is in the range of 3.0–3.5 as a function of lift temperature, as in [21,22], with 3.2 as an average, located in a separate building, cooperating with the local grid;
- Ground exchanger—120 wells at a depth of 150 m each; boreholes constituting the lower heat source for the heat pump should be located in undeveloped areas, e.g., green areas; the possible heat exchange from the ground probes is 40 W/m;
- Electric boiler—to ensure maximum self-consumption and for the use of energy peaks from the PV, four boilers with a capacity of approximately 50 kW each will be used; the recommended location is the heat pump building.

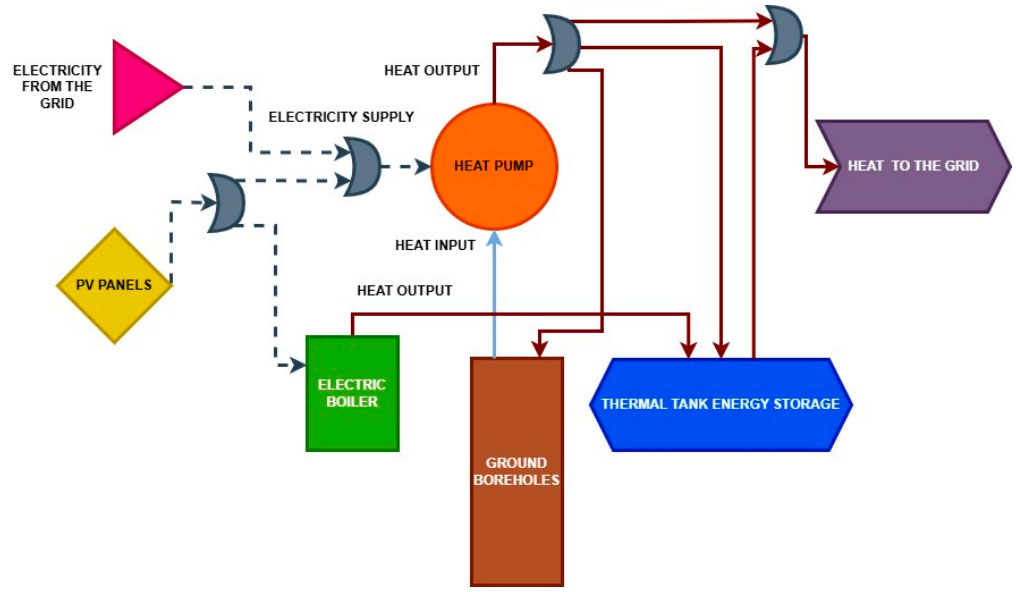


Figure 5. Distributed heating scenario: scheme of one module.

The main principles of distributed heating cells assume the following:

- In the summer season, the heat produced by heat pumps is first directed to the heating node, then to the seasonal heat storage, and finally to the ground;
- During the winter season, the electricity is purchased from external suppliers;
- During the winter season, the electric boiler remains turned off;
- During the winter season first source of heat is TTES;
- After unloading the seasonal heat storage, the boreholes are the lower heat source for heat pump.

The main barriers that may hinder the implementation of technology include the following:

- Property rights in the context of the construction of PV installations;
- Ownership rights to land on which wells are to be drilled as the lower heat source for the heat pump;
- The possibility of drawing electrical power from the grid and the limitations of connecting the generating installation to the grid;

- Restrictions resulting from local spatial development plans, which may introduce restrictions, e.g., on the maximum allowable power of PV installations, or eliminate certain technologies, e.g., wind turbines.
- The operation of a decentralized system is based on the following principles: whenever possible, the electricity supply for the HP derives from the PV panels; electricity from the grid is taken only when there is no other possibility (no electricity from PV, insufficient heat in the store).
- The lower heat source for the heat pump is the ground heat exchanger (always).
- Heat produced in the heat pump supplies the local heating grid. In case of no heat demand in the grid, the heat goes to the store (only with PV supply). When the store is full, ground heat exchanger regeneration with the heat from the heat pump occurs (only with a PV supply).
- Surplus electricity from PV panels can be utilized in the electric boiler, which supplies heat to the store or is sold to the grid when the store is full.

3.2. Centralized Heating System

Numerous cities in Central–Eastern Europe can use the heating grid, which is already built and, in numerous cases, modernized. This means that it can be utilized without any—or with very small—investment costs. To switch the centralized heat generation to renewables, the energy generation sources should be replaced. In the proposed scenario (min. 80% renewables in annual heat production), the following heat sources are considered:

- Treated sludge heat pump installation with a capacity of 4.5 MW;
- Biomass boiler with a nominal power of 25 MW;
- WR 25 coal boiler with a nominal power of 29 MW, treated as a peak source.

4. Results

This section presents the results of the mathematical modeling in terms of heat production by source in each hour of the example year. Both scenarios produced heat from renewable sources at around 80% of supply.

4.1. Distributed Heating Scenario

In the distributed heat supply scenario, heat storage plays a key role, as the heat sources are not fully controllable. In the winter months, all PV production feeds the heat pump and the electric boiler. In the summer, there are times when surplus PV electricity can be sold to the grid. The heat storage is recharged in the summer when heat demand is lower due to weather conditions. Heat pumps first use electricity from PV, and then electricity from the grid. Heat production by sources and energy flows in the distributed scenario are shown in Figures 6 and 7. In total:

- Number of modules in the system—59;
- Heat production per module—1734.83 MWh/year;
- Electricity demand from the grid for heat production—180.1 MWh/year/module.

4.2. Centralized Heating Scenario

In the centralized scenario, the heat sources are easier to control. During the summer months, almost the entire heat demand is covered by the heat pump. In autumn and spring, the HP is supported by a biomass boiler. The coal boiler is used as a peak source for less than 900 h/year (Figure 8). The total heat production by source is shown in Table 3.

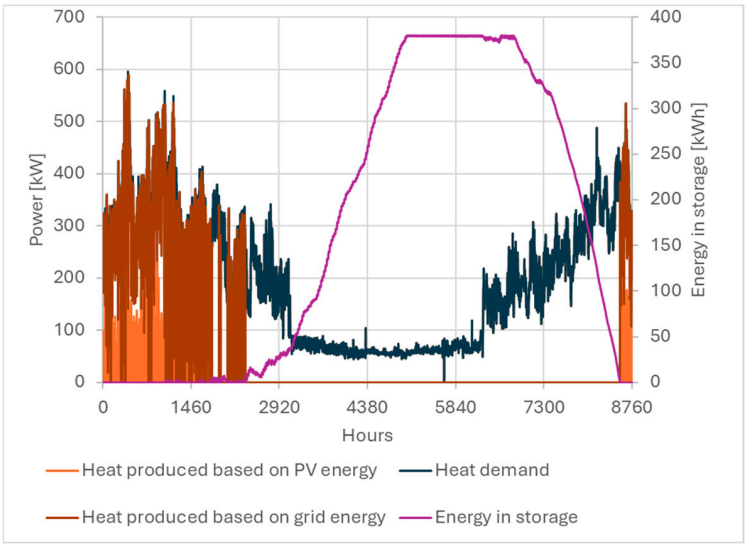


Figure 6. Heat produced by source, and heat stored in the distributed scenario during the year.

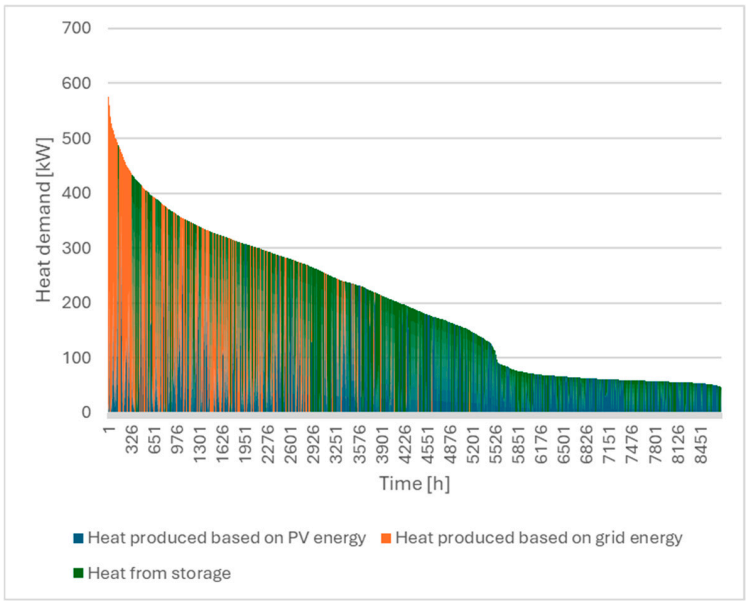


Figure 7. Heat demand covered by the energy source: distributed scenario, ordered chart.

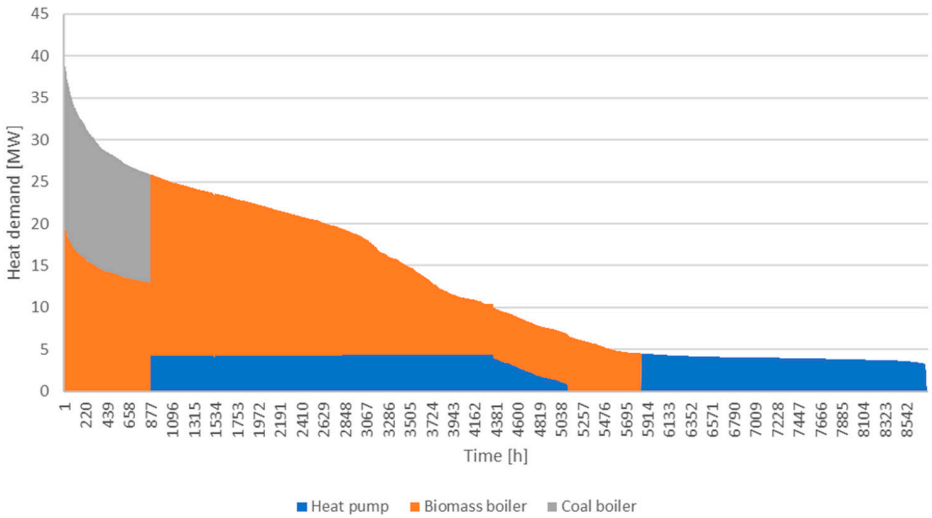


Figure 8. Heat produced by source in the centralized scenario over the year.

Table 3. Annual heat production by source, centralized scenario.

No.	Source	Unit	Value	Share [%]
1	Coal boiler	MWh/year	12,944.07	11.4
2	Biomass boiler	MWh/year	72,382.77	63.7
3	Heat pump	MWh/year	28,231.73	24.9

5. Economic Analysis

The economic analysis aimed to compare the scenarios. The LCOH (*Levelized Cost of Heat*) was chosen as the parameter. This factor allows an evaluation of the economic aspects of both scenarios, due to the inclusion of all costs incurred during the lifecycle of the installations [23].

$$LCOH = \frac{\sum_{i=0}^{N} \frac{I_i + M_i}{(1+r)^i}}{\sum_{i=0}^{N} \frac{Q_i}{(1+r)^i}} \quad (1)$$

where:

$LCOH$—unit average cost of heat production in the life cycle [EUR/MWh],
I_i—investment costs in the I year [EUR],
M_i—operational costs in the i year [EUR],
Q_i—heat production in the I year [MWh],
r—discount rate,
N—lifetime [years].

In this study, investment costs were present only in year 0. The calculational lifetime of the installations was assumed to be 20 years. The discount rate in the present analysis was 5.85% [24].

5.1. Distributed Heat Scenario

In the distributed heat scenario, the system is assumed to consist of multiple installations of 1 MW, called modules. The investment costs for one module are shown in Table 4. A total of 59 district heating modules are needed to provide the heat supply for the city under consideration in this scenario. The operating costs are shown in Table 5.

Table 4. CAPEX for sources in the distributed scenario, one module of 1 MW.

Source	Price [EUR]
PV panels with inverters, supporting structure, necessary electrical installation, and assembly of the whole	520,000 [25]
Seasonal heat storage, including earthworks, construction of tanks, insulation, and reconstruction works	1,600,000 [26]
Vertical drilling	1,260,000 [27]
Main engine room, including heat pumps, circulation pumps, heat exchangers, hydraulic and electrical installations, fittings, and installation service	1,500,000 [28]
Electric boilers	16,000 [29]
Reserve	250,000
TOTAL	**5,146,000**

Table 5. OPEX for sources in the distributed scenario, one module of 1 MW.

Position	Price
Costs of ongoing maintenance and inspections of the system	50,000 [EUR/year]
Cost of staff salaries (approximately 10 h per week)	10,000 [EUR/year]
The cost of servicing the units located in the main engine room (mainly HP) after 15 years of system operation	260,000 [EUR]

5.2. Centralized Heating System

The investment costs for sources in scenario two (centralized) are shown in Table 6. It is assumed that, as in many cities in Poland, there is an existing coal-fired boiler that can be successfully operated as a peak source without investment costs.

Table 6. CAPEX for sources in the centralized scenario.

Source	Price [EUR]
Heat pumps	4,700,000
Biomass boiler	16,000,000
Reserve	300,000
TOTAL	**21,000,000**

The operating costs were assumed to be 3.5% of the investment costs for the heat pump and 1% for the biomass and coal boilers per year. In addition, a network operating cost level of 5 EUR/GJ was assumed. The electricity price was set as 200 EUR/MWh (based on data from [30]).

The levelized cost of heat (LCOH) in the centralized scenario is 74.66 EUR/MWh, while in the distributed scenario, it is 308.7 EUR/MWh. When comparing the results with data from Helsinki [31], where heat prices vary from 40.6 EUR/MWh (in summer) to 121.75 EUR/MWh (in winter), it can be concluded that the result from the centralized scenario remains in this scope. The price for heat in the distributed scenario is much higher, so it cannot be economically reliable in the assumed conditions.

6. CO_2 Emissions

The analyzed scenarios were compared in the frame of CO_2 emissions. The carbon dioxide emission for hard coal was assumed as 94.83 kg/GJ (chemical energy of fuel) [32]. The average emissions for electricity from the grid in Poland equals 666 g/kWh$_e$ [33]. For the centralized scenario, emissions are related to coal burning and electricity for the HP supply. In this scenario, total annual emission equals 10,838.9 t/year, which corresponds to unit emissions of 26.5 kg/GJ of useful heat. In the distributed scenario, the only emission derives from electricity generation for the HP supply. The emissivity in this system is 19.2 kg/GJ of useful heat. In comparison with the old system based on hard coal boilers, the reduction of CO_2 emissions in the case of the centralized scenario is 85.0 kg/GJ, while in case of the distributed scenario is 92.4 kg/GJ.

7. Outcomes

The aim of this study was to compare two district heating system development scenarios under the conditions of a typical city of 30,000 inhabitants in the weather conditions of Central–Eastern Europe. Two scenarios were considered: a centralized one, with an existing district heating network and coal-fired boiler, and a distributed one, consisting of 1 MW heating modules. A mathematical balance model was built for each. As a result, the

heat production and storage for each hour of a typical year were calculated. An economic analysis was carried out for the entire scenario assessment. The LCOH was compared as a parameter. For economic reasons, the centralized scenario appears to be the more cost-effective solution. This is because the investment costs in the distributed scenario are almost four times higher than in the centralized scenario, which can use the existing infrastructure of coal-fired boilers and the district heating network.

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