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What Can We Do in Bucharest? The Issues of Decarbonising Large District Heating Systems

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Abstract

District heating systems are central to Europe's decarbonisation efforts and its 2050 climate-neutrality target. However, given the deep embedding of district heating in the socio-economic system and built environment, meeting policy targets at the local level gives rise to a range of technical, infrastructural and socio-economic challenges. This is due to the high complexity and multidimensionality of the process, as well as the scarcity of local resources (e.g. land, surface waters, waste heat, etc.). In Bucharest, Romania, the largest district heating system in the European Union, the process of decarbonisation represents a particularly complex challenge. The system is characterised by high technical wear, heavy dependence on natural gas, significant heat losses and complex governance structures. This paper presents a strategic planning exercise for aligning the Bucharest system with the Energy Efficiency Directive 2023/1791. Drawing on system data, investment modelling and local resource mapping from the LIFE22-CET-SET_HEAT project, it evaluates scenarios for 2028 and 2035 that shift generation from natural gas to renewable, waste heat and high-efficiency sources. Options include large-scale heat pumps, waste-to-energy, geothermal and solar heat. Heat demand profiles and electricity price dynamics are used to evaluate economic feasibility and operational flexibility. The findings show that technical decarbonisation is possible, but financial viability hinges on phased investments, regulatory reforms and access to EU funding. The study concludes with recommendations for staged implementation, coordinated governance and socio-economic measures to safeguard affordability and reliability.

Keywords: district heating; energy transition; decarbonisation; renewable energy sources; waste heat; strategic planning; investment planning

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1. Introduction

Existing European district heating systems are undergoing a profound transformation to meet the EU's 2050 decarbonisation goals. The revised Energy Efficiency Directive (EED) [1] establishes that by 2028, DH systems must source at least 5% of heat from renewable sources (RES), and by 2035, 35% must be from either renewable or waste heat sources (WHS) and 80% in total renewable, waste, or high-efficiency cogeneration (CHP). By 2050, an efficient DH system must use only renewable energy, only waste heat, or only a combination of renewable energy and waste heat.

The focal point of this study is the strategic planning of the energy transition and decarbonization process for large DH systems. A growing body of literature nowadays investigates technological and strategic solutions for such systems. Lund et al. [2,3] introduced the fourth-generation district heating (4GDH) concept, promoting lower temperature operation and integration with renewable electricity. Volkova et al. [4] and Sihvonen et al. [5] highlighted large-scale heat pumps and sector coupling as key enablers of future heating systems. Pakere et al. [6] demonstrated that multi-source DH systems can achieve full decarbonisation by combining solar, biomass, and

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waste heat supported by seasonal storage. Pettersson et al. [7] and Pursiheimo et al. [8] emphasised the importance of integrated planning and compared heat pump and nuclear options for Nordic cities. Kubin et al. [9] presented DH transformation planning results, which confirmed that flexible sector coupling technologies form the backbone of the most economically efficient transition pathway. They highlighted the risks of rapid scale-up, especially regarding permitting, investment, and supply chain conditions.

Dzierzgowski and Cenian [10] proposed a decarbonisation methodology which focuses on substation modernisation and regulation, followed by the implementation of low-carbon heat sources (including waste heat) and the implementation of digital measures (monitoring and modelling). A large scale experiment performed in the DH system in Łomża, Poland, confirmed that the implemented methodology allowed a decrease in network supply temperature (from 121 to 96^{o}C) in the whole system, leading to lower heat losses, in turn reducing coal demand and CO_2 emissions (up to 30%), and increase of heat transfer efficiency in buildings, grid hydraulic stability and improvement in working condition of mixing systems in the CHP and heating Plant.

Kalina et al. [11] reveal that in such systems, decarbonisation is technically attainable, yet far more complex than often assumed. The transformation faces substantial technical barriers. The high operating temperatures of existing networks limit the performance of heat pumps during the heating season, and the large-scale seasonal storage required to balance intermittent sources exceeds what is realistically possible. Even when technically feasible, the transition introduces significant economic burdens. Under the study's financial modelling, the overall investment package leads to a negative net present value unless supported by substantial external funding. The study concludes that decarbonisation cannot be treated as a narrow technological upgrade. Instead, success depends on broader structural changes, including lowering network temperatures, improving building efficiency, enabling sector coupling, adjusting legal frameworks, and establishing new business models for cooperation with waste heat suppliers.

The announced strategies of such cities as Berlin, Amsterdam, Copenhagen, and Vienna revealed that, depending on local conditions, the future primary energy mix may be highly diversified and DH systems become very complex structures. Although these strategies differ in pace, resource availability and governance, a clear pattern emerges. Each of the considered cities envisions a future district heating system built on low-temperature networks, large-scale heat pumps, extensive waste-heat recovery and the systematic integration of renewable electricity.

Berlin's strategy reflects both the legacy of a large, historically fossil-fuelled heat system and growing political ambition [12]. Coal has already been phased out, and future supply is expected to rely heavily on industrial and data-centre waste heat, combined with large heat pumps powered by renewable electricity. Detailed Berlin's heat planning process is based on heat maps and zoning tools, which determine where district heating will expand, where buildings will shift to individual heat pumps and how existing networks will gradually be transformed. Lowering supply temperatures is essential to integrate low-temperature resources, while bans on new fossil installations and updated efficiency standards reinforce the shift at the regulatory level.

Amsterdam approaches decarbonisation from a different angle, which is a binding political decision to eliminate natural-gas use in buildings by 2040 [13]. Publicly released heat transition visions outline which districts will move to DH, all-electric solutions or hybrid systems. Amsterdam's plans emphasise rapid expansion of both high- and low-temperature networks and make unusually strong use of aquathermal energy (i.e., heat extracted from canals, rivers and wastewater) as well as large heat pumps and substantial geothermal potential where geological conditions allow. Waste heat from waste-to-energy plants and data centres serves as a further backbone of the system. The city pairs this technical rollout with a socially oriented governance framework that ensures affordability and transparency as gas networks are dismantled neighbourhood by neighbourhood.

Copenhagen, long considered a frontrunner in district heating, has articulated some of Europe's most detailed long-term strategies. The city's carbon-neutrality goal and the broader metropolitan "Heat Plan Copenhagen" [14] provide a system-wide blueprint that extends to mid-century. The plan foresees a marked reduction in network temperatures, enabling large heat pumps, geothermal installations and significant amounts of industrial and municipal waste heat to feed into the system. Copenhagen emphasises system optimisation through sector coupling, where district heating is positioned as a flexible component in a wider energy system dominated by wind and solar power. Large-scale thermal storage, including pit thermal energy storage, ensures that excess renewable electricity can be converted into heat and stored for later use. Remaining fossil or biomass-based CHP plants are expected to be gradually replaced or supplemented by carbon-neutral fuels and carbon-capture technologies. Power-to-X technologies and CO_2 capture installations are also taken into consideration.

Vienna's trajectory is influenced by its 2040 fossil-free heating target, one of the earliest and most ambitious in Europe. The city has developed a heat-planning approach that distinguishes areas best served by district heating from those suited to individual heat pumps [15,16]. As part of this strategy, district heating is expected to supply more than half of the city's heat demand by 2040, and the DH system itself must reach full climate neutrality by the same year. Large heat pumps powered by wastewater, river water and industrial waste heat form a central pillar. Deep geothermal energy, combined with heat pumps, is projected to deliver a substantial share of Vienna's future district heating production, around 4 TWh annually, allowing the gradual retirement of fossil-fuelled CHP plants. At the same time, existing waste-to-energy facilities are to be progressively decarbonised through more efficient operation and potentially carbon-capture technologies. Vienna complements these technological measures with broad renovation programmes and a citywide initiative "Raus aus Gas", which pilots alternatives to gas in municipal and social housing, ensuring that building-level interventions align with the transformation of the heat networks.

Malcher et al. [17] evaluated how different decarbonization strategies reduce emissions in national district heating systems by applying an integrated energy-and-emissions model combined with a derivative-based sensitivity analysis. Focusing on Sweden, France, Germany and Poland, they examined widely discussed measures such as increasing low-carbon heat sources, lowering supply temperatures, improving efficiency, deploying power-to-heat technologies, and modifying the role of CHP. Results show that the effectiveness of these strategies varies strongly by each country's energy mix and the extent to which CHP plants rely on fossil fuels. Expanding low-carbon heat sources is consistently the most impactful option. A 1% increase in their share can reduce emissions by 0.8–1.3 kg CO_2e/GJ of heat. In Sweden and France, where electricity is already largely low-carbon, heat pumps and electric boilers emerge as the next most effective measures. Conversely, in Germany and Poland, characterised by higher-carbon power, reducing heat demand and distribution losses delivers comparable emission cuts (0.7–1.3 kg CO_2e/GJ). Substantially lowering fossil-fuel-based CHP generation also achieves significant reductions, challenging policies that incentivise gas-fired CHP. Other options, including green hydrogen and CCS, offer noticeably smaller benefits.

This paper focuses on Bucharest, Romania, where the DH system is the largest in the European Union. According to the IEA DHC definition [18], this is a second-generation system with a water network operating forward temperature ranging from 80 to 110 °C. The district heating network (DHN) has a total length of 3847 km and delivers heat to more than 500,000 individual households, 3611 industrial and 1122 other consumers. The current peak demand for heat approaches 2.0 GW, and the annual amount of heat delivered to the network is around 4500 GWh/year. The heating network covers around 72 % of the heating demand of the Municipality of Bucharest. The remaining 28 % is heat produced in various individual heating units.

The input energy mix is not diversified, and the system is almost entirely based on the combustion of natural gas. As for 2024, it experiences severe losses and frequent breakdowns. The key system components, i.e. production plants and networks, are worn out and in bad technical condition. Since the system has been underinvested for many years, the scale of the required renovation is enormous. A potential action plan is presented in this study, which examines possibilities to integrate different technological solutions.

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2. Materials and Methods

This study was performed under the Life Programme co-founded LIFE22-CET-SET_HEAT project framework. It builds on analyses conducted within joint development and design activities from October 1st 2023, to March 14th 2025, of the project, including a series of the project's co-creation workshops in Croatia, Lithuania, Poland, and Romania, which took place in 2024 and 2025. During the workshops, the Project Partners and invited guests worked together to identify potential technology solutions and other measures, which would help targeted DH systems meet the status of efficient ones as defined in the revised Energy Efficiency Directive [1].

The main problem in this study is to assess the technically feasible scenarios for the decarbonisation of the large fossil-fuel-fired DH system in Bucharest in a way that would meet the criteria of an efficient district heating system (EDHS) given in the EED [1]. The objective is to meet the criteria of an efficient DH system from 1 January 2028, by ensuring that the share of heat from RES in the total amount of heat fed into the DHN is at least 5% and the total share of RES, WHS or CHP is at least 50%. From 1 January 2035, the target is to ensure a minimum of 35% RES and WHS, and a minimum of 80% total share of these sources and CHP. This constitutes the following constraints for the strategic planning:

$$u_{RES,2028} = \frac{\sum_t \sum_i Q_{i,\mathrm{RES},t}}{\sum_t \sum_i Q_{i,t}} \geq 0.05 \cup u_{RES+WHS+CHP,2028} = \frac{\sum_t \sum_i Q_{i,\mathrm{RES+CHP},t}}{\sum_t \sum_i Q_{i,t}} \geq 0.50, \quad (1)$$

$$u_{RES+WHS,2035} = \frac{\sum_t \sum_i Q_{i,\mathrm{RES+WHS},t}}{\sum_t \sum_i Q_{i,t}} = 0.35 \cup u_{RES+WHS+CHP,2035} = \frac{\sum_t \sum_i Q_{i,\mathrm{RES+WHS+CHP},t}}{\sum_t \sum_i Q_{i,t}} \geq 0.80, \quad (2)$$

where u is the share of heat from particular types of heat sources in the total heat delivered to DHN, Q_i is the heat delivered from specific source i at hour t.

The research and planning methodology integrated making inventories of existing infrastructure, system diagnostics, system and energy mapping, scenario development, investment modelling and assessment, and hourly system simulations based on actual weather, load and market data. The adopted methodological approach was broadly discussed in [11]. In the case of Bucharest, however, greater attention was paid to spatial planning and the location of individual heat sources in the dense urban area. Several web tools and public data sources [19–23] were used for data collection, and the energyPRO™ software [24] was used for system simulations. The operation of particular production units was optimised using Mixed Integer Linear Programming Technique (MILP) and the open source HiGHS solver integrated in the software tool. Costing and financial calculations were made using the MS Excel spreadsheet software.

The Bucharest DH network comprises 6 heating areas, so-called sectors, and 8 main production plants, namely Sud, Progresul, Grozăvești, Vest, Vest Energo, and Grivița, Titan and Casa Presei, with a combined installed heating capacity exceeding 1.73 GW_{th}. Forward temperatures range from 80 to 110 °C, with returns of 40–55 °C, characteristic of second-generation DH systems. The system boundary and location of heating plants are depicted in Figure 1. In addition, there are more than 46 local gas boiler plants of the total installed capacity of 257 MW, which are not delivering heat to the DH network but directly to buildings. The total heat demand density is depicted in Figure 2.

The DHN, which supplies heat to approximately 8,200 apartment blocks, 320 buildings, and around 4,900 institutions, is operated by Compania Municipală Termoenergetica București S.A. (CMTEB). It has a total length of 3847 km, of which 884 km form the so-called primary transmission network, and the remaining 2963 km form the secondary distribution network, to which buildings are connected. An important components of the network infrastructure are around 1027 so-called Thermal Points, which are heat exchanger stations between primary and secondary networks. The location of these stations around the city is depicted in Figure 3.

Nowadays, around 92% of DHN input heat is purchased from external suppliers. In total, approximately 74% of purchased heat is produced in old-fashioned steam cycle cogeneration units, and the remaining 26% is produced in boilers. All in-house production of CMTEB is done in boilers. Figure 4 depicts an annual DHN heat supply profile, and Figure 5 shows the primary network regulation curves. Figure 4 also shows an indicative level of newly installed (continuous) heating capacity to satisfy the requirements of EED for an efficient DH system.

Although the system currently meets the criteria of an efficient district heating system set in EED, its current technical condition is not satisfactory regarding the heat sources, networks and installations in buildings. The thermal plants were put into operation between 1955 and 1982. Around 65% of the primary network and 46% of the secondary network are pipelines older than 25 years. The biggest problem with the network is the high corrosion of the pipes. Many parts of the network are damaged, causing major operational problems and low availability of the system, which currently ranges from 75 to 85% due to numerous failures. The annual number of emergency interventions exceeds 1250. The risk of system collapse is high. Annual heat losses from the DHN amount to 30 – 40%. With the priorities: 1) reliability and security of heat supply, 2) heat affordability, 3) heat greening, significant local resources must be engaged and large investments secured to carry out the system retrofitting and transition simultaneously.

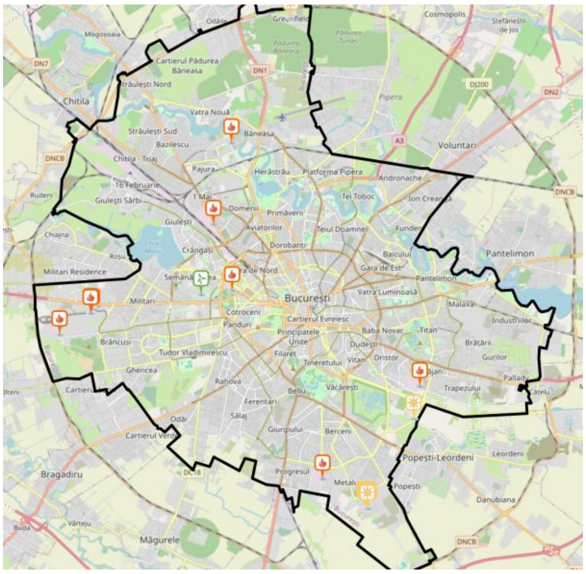

Figure 1. This is a figure. Schemes follow the same formatting [19].

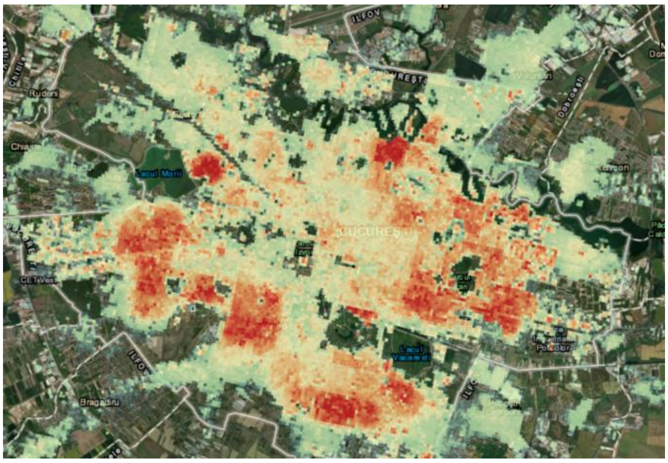

Figure 2. Total heat demand density in Bucharest [23].

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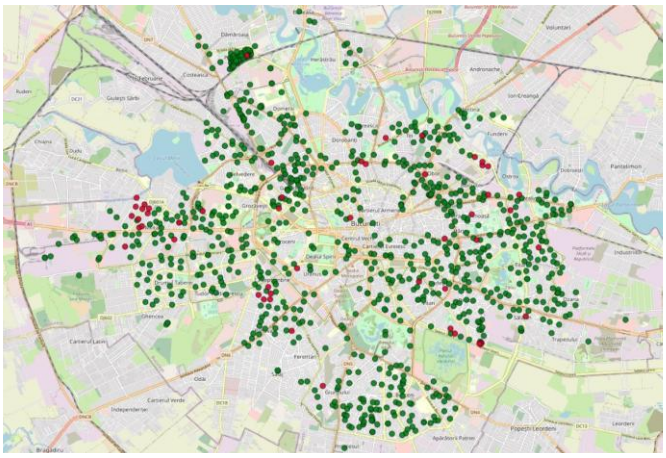

Figure 3. Distribution of thermal points around Bucharest.

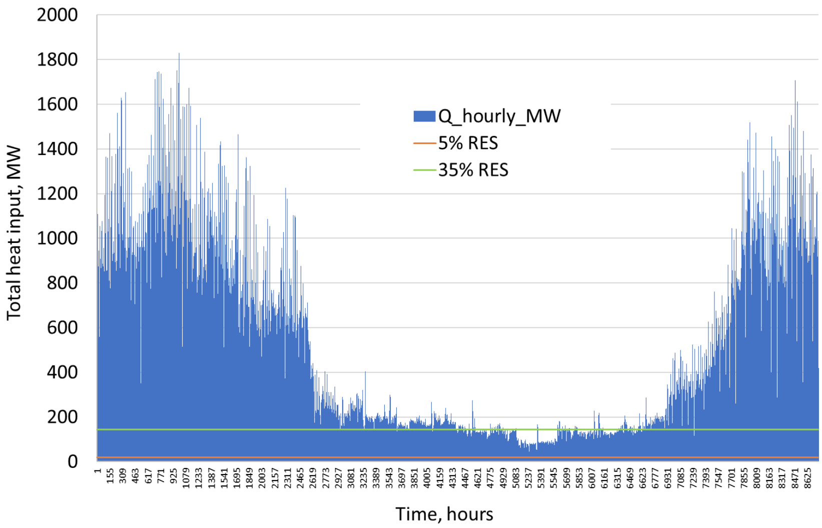

Figure 4. Annual DHN heat supply profile (assumed reduction of heat losses to 15%).

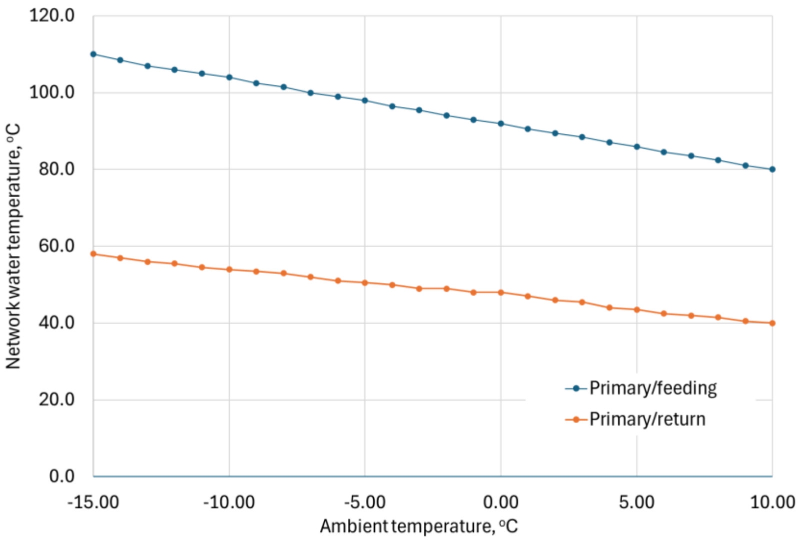

Figure 5. DHN forward and return temperature curves.

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The LIFE22-CET-SET_HEAT project activities focused on heat mapping revealed almost no waste heat, and limited resources to harness renewable energy. The main identified waste heat sources are a potential municipal waste incineration plant, a wastewater treatment plant in Glina, warm ventilation air from metro tunnels, data centres, and shopping malls. The identified renewable energy sources include solar rooftop plants (total potential depicted in Figure 6), air source heat pumps, lake water heat pumps, geothermal heating plants, and biogas CHP plants using agricultural biomass and separated organic fraction of municipal solid wastes. A waste-to-energy plant incinerating what remains from waste sorting is also a strong option. In total, the newly installed heating capacity potential was estimated at around 367 MW_{th}, which only allows for meeting the EED's criteria of an effective DH system until 2039. The results of heat mapping are depicted in Figure 7. The total number of identified new renewable and waste heat sources is 223, out of which 200 are the rooftops of thermal points. Further decarbonisation of the system requires effective engagement with external stakeholders and appropriate coordination of the planning activities between national and municipal authorities, utility companies, residents, and the private sector. To effectively address the DH decarbonisation challenge, local actors should consider the MultiD approach, which simultaneously takes into consideration such aspects as DH system territorial expansion, decomposition, reconfiguration, multiple distributed and intermittent heat sources, alternative decarbonised fuel-fired cogeneration, heat storage, digitisation, low-temperature heating networks, electrification and sector integration, adjustments of heat sink installations, improved energy efficiency in buildings, large-scale investments in municipal energy infrastructure, active consumers, optimisation, flexibility, resilience, integrated businesses and value stacking, democratisation, and disruption as a usual factor.

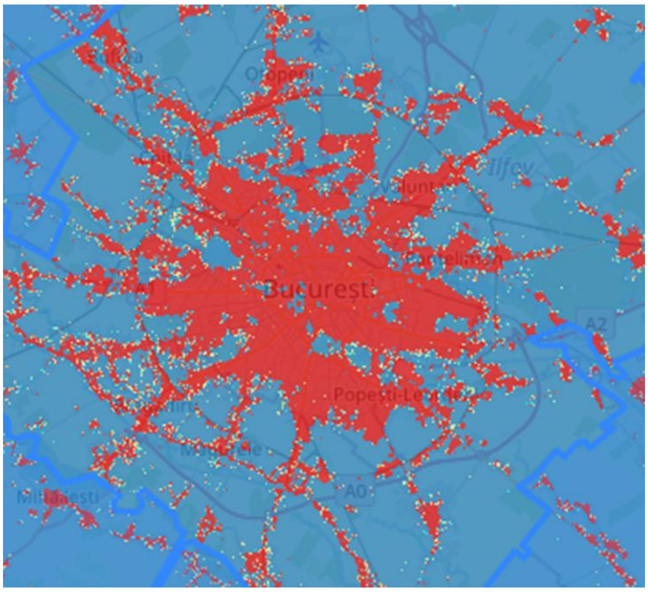

Figure 6. Potential for solar collectors located on building rooftops [23].

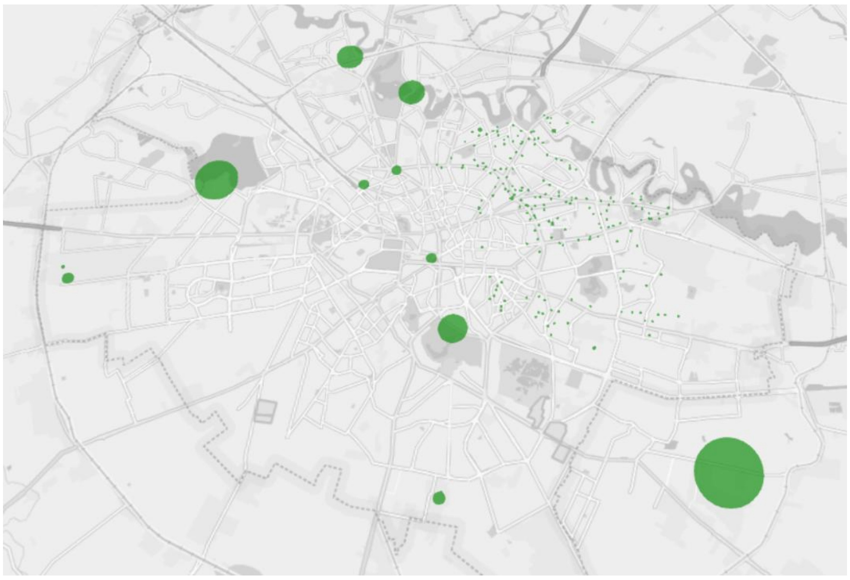

Figure 7. Results of Bucharest heat mapping (note: circle diameter represents annual energy potential in MWh).

The EU Life Programme co-founded the LIFE22-CET-SET_HEAT project aims to accelerate the energy transition and decarbonization of district heating in four targeted Eastern European countries, through triggering strategic investment programmes and a significant number of tangible projects in the field of integration of low-grade renewable energy and waste heat into 2nd generation DHNs. The tactics to achieve a real change on a large scale are based on a coordinated approach to the transition planning that prioritises collaboration, knowledge exchange, and implementation of replicable technical and non-technical solutions. Replication and standardisation are pivotal to the process; they can streamline planning, reduce costs, improve quality, facilitate communication, and ultimately accelerate investment decisions and projects' implementation.

The central concept of the project was to develop a set of replicable model investment projects that could be adapted and implemented in various locations with minimal modifications. Based on a multi-criteria parametric assessment, 8 so-called model investment projects were defined, namely:
SET_HEAT_SEWAGE, which focuses on heat recovery from treated sewage;
SET_HEAT_RETAIL, which focuses on heat recovery from supermarkets;
SET_HEAT_RIVER, which focuses on a river water industrial heat pump;
SET_HEAT_LAKE, which focuses on a lake water industrial heat pump;
SET_HEAT_AIR, which focuses on an air source industrial heat pump;
SET_HEAT_SOLAR, which focuses on a solar plant as a distributed heat source;
SET_HEAT_PTES, which focuses on a remote seasonal PTES facility;
SET_HEAT_CHP, which focuses on waste heat recovery from low-temperature cooling circuits of existing gas engine cogeneration units.

The identified types of projects were addressed with extensive pre-feasibility studies and other ready-made documentation that aimed to facilitate the development process, implementation and replication. Public versions of the prefeasibility studies are available at the LIFE-CET-SET_HEAT project's website [25].

The choice of investment strategy for Bucharest depends on the availability of primary energy sources, the physical feasibility of locating new technologies and integrating them into the network, and the investment and operating costs. It should also be borne in mind that, in accordance with EED requirements [1], by 2028, the share of renewable energy in total heat going into the network is at least 5 % and the total share of renewable energy, waste heat or high-efficiency cogenerated heat is at least 50 %. By 2035, an efficient district heating system should be using 50 % renewable energy and waste heat, or 35 % of either renewable energy or waste heat, assuming that at least 55% of heat will be from high-efficiency cogeneration units. These thresholds are critical for selecting investment projects. Therefore, assuming that after DHN health restoration, the annual heat consumption will be approximately 3,576,594 MWh, 5% RES share requires at least 178830 MWh of heat from such sources. In 2035, at least 1,251,808 MWh will be required to satisfy a 35% RES share in the system.

After many discussions, it was found that technically it is possible to meet the criteria of the efficient system in 2028 and 2035. Two alternative scenarios were defined based on different energy inputs. However, taking into account the typical duration of project development, permitting implementation and procurement procedures is, in most cases, assessed at 4 to 7 years, it was concluded that regarding the starting point and the investment objectives in Bucharest, it may be difficult to meet the targets on time. Nevertheless, the pathway toward the thresholds for the efficient system set for 2035 is realistic.

Scenario 1 assumes that the key element of the transition will be a waste-to-energy project based on a waste incineration technology. The plant will be using a Refuse-Derived Fuel (RDF), which is a processed fuel made from municipal solid waste (MSW) after removing recyclables and inert materials. According to measurements the typical calorific value of RDF is 15–22 MJ/kg and 40–65% by weight are biogenic contents [26]. By defining as biomass also waste and residues of biological origin, RED/RED III [27] permits energy (heat, electricity) produced by burning the biodegradable (biogenic) fraction of waste to count as "renewable energy", provided that the waste/fuel meets the directive's sustainability and emissions criteria. It must be noted that since the heat from waste-to-energy plants does not meet the criterion of a by-product, in this work, according to [28], it is not counted as a waste heat.

In 2019 the General Council of Bucharest Municipality adopted the city's "Master Plan for Waste Management," which included a provision to build a large municipal waste-to-energy incinerator. As of 2025, the authorities are still in planning/preparation mode and there is no operational decision or go-ahead for construction. Therefore, realistically, it should be assumed that the waste-to-energy plant will not be commissioned before 2030. Similarly, projects assuming lake water and treated wastewater require long planning and implementation process. Therefore, the share of 5% RES in 2028 can be achieved by implementing solar thermal projects and air-source heat pumps (ASHPs). Eventually, the assumptions for Scenario 1 are:

Phase I:

1. Firstly, 200 selected thermal points will be equipped with rooftop solar thermal plants. Each system will consist of 80 m² of collector aperture area which gives around 14.1 MW of peak installed heating capacity and approximately 19,240 MWh of heat annually (It must be noted that first 2 rooftop solar thermal plants are being implemented and further will be deployed after confirming positive operational results);
2. Secondly, Industrial ASHPs of the total installed capacity of 29 MW will be implemented. Assuming that the ASHPs will be run for 5500 hours a year, the annual heat production will be approximately 159,500 MWh.

Phase II:

3. Waste-to-energy plant of 235,000 tonnes/year RDF processing capacity will be deployed before 2035. Assuming 8000 h of the annual operation time, the RDF chemical energy input will be approximately 135 MW. Taking into account benchmark figures, the expected electric output will be 47.1 MW and heating output will be 67.3 MW. The annual heat generation will be approximately 538,542 MWh. Assuming (with safety margin) that 30% of RDF mass input will the biomass fraction, approximately 161,563 MWh of hear should be regarded as renewable. In addition, it was assumed that RDF price is negative (EUR -0.13/kg), which represents the cost of wastes utilisation.
4. Lake water-source industrial heat pump of 50 MW heating capacity will be installed to harvest heat from Lake Morii.
5. Geothermal heating plants of the total heating capacity of 2 MW will be installed.

6. 90 MW_{th} wastewater-source heat pump will be integrated with Glina sewage treatment plant (3 x 30 MW_{th} modular design). It is assumed that a heat pump's output is can treated as renewable if its seasonal performance factor (SPF) will meets a required minimum threshold.
7. Municipal biogas cogeneration plant will be built of 10 MW_{th} heating output.
8. Seasonal Pit Thermal Energy Storage (PTES) will be implemented. The total storage volume will be 1.2 million m^3 (6 facilities of 200,000 m^3). The storage will be integrated with the DHN without additional heat pumps, and operating temperatures of hot and cold water will be 90 °C and 60 °CC.

Initially assessed contribution to DHN heat input from renewable energy sources is presented in Table 1. These assumptions are used for building system model in energyPRO software. As a result of simulations the demand for heat storage capacity will be additionally determined.

Scenario 2 is solely based on solar thermal plants (distributed on rooftops and free parcels), water and air source heat pumps. Phase I of this scenario is the same as in the previous case. In Phase II, however, the waste-to-energy plant is replaced by additional 14.1 MW_{peak} distributed solar thermal plants, and ASHPs of the total installed heating output of 14 MW_{th}. Providing that heat generated by a heat pump should be counted under [1] as renewable energy provided that the heat pump meets the minimum efficiency criteria [29], there will be also installed three ASHPs of total capacity of 7.2 MW to recover heat from Bucharest metro (at Unirii Station, Victoriei Station and Gara de Nord). Furthermore, two water-source heat pumps (WSHPs) of the total heating output of 1.2 MW_{th} will be installed to recover heat from data centres. Additionally, the total PTES storage volume was enlarged to 1.5 million m^3. Initially assessed contribution to DHN heat input from renewable energy sources in Scenario 2 is presented in Table 2. Actual contribution of heat sources to the total production was identified after system simulations.

Table 1. Assumed technical specification of the investment programme in Scenario 1.

Project	Installed capacity, MW_{th}	Annual running hours	Annual heat production, MWh	Contribution to the required annual heat from RES in 2035
Waste-to-energy plant	67.3 (30% bio)	8000	538542 (161,563 bio)	12.9%
Distributed solar plants	14.1 (peak)	3000	19240	1.5%
Lake heat pump	50.0	6000	300,000	24.0%
ASHPs	29	5500	159,500	12.7%
Geothermal plants	2.0	8000	16,000	1.3%
Wastewater heat pump	90.0	6000	540,000	43.1%
Municipal biogas CHP plant	10.0	7000	70,000	5.6%
TOTAL RES	215.3	-	1,703,282	101%*

* Calculated as relative to the required RES contribution of 1,251,808 MWh.

Table 2. Assumed technical specification of the investment programme in Scenario 2.

Project	Installed capacity, MW_{th}	Annual running hours	Annual heat production, MWh	Contribution to the required annual heat from RES in 2035
Distributed solar plants	28.2 (peak)	3000	38,480	3.1%
Lake heat pump	50.0	6000	300,000	24.0%
ASHPs (independent)	43	5500	236,500	18.9%
ASHPs (metro stations)	7.2	7000	50,400	4.0%
WSHPs (data centres)	1.2	7000	8,400	0.7%
Geothermal plants	2.0	8000	16,000	1.3%

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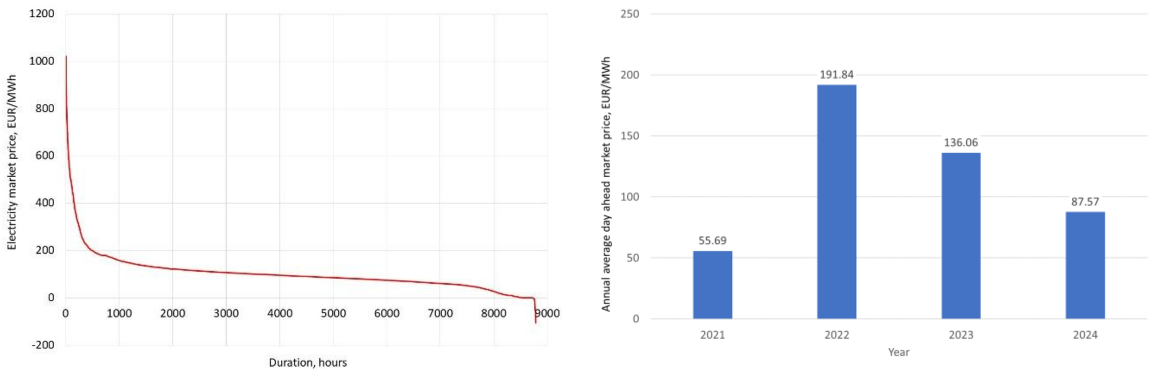
Wastewater heat pump	90.0	6000	540,000	43.1%
Municipal biogas CHP plant	10.0	7000	70,000	5.6%
TOTAL RES	231.6	-	1,259,780	101%*

* Calculated as relative to the required RES contribution of 1,251,808 MWh.

In both scenarios, it was also assumed that 3 existing gas-fired cogeneration plants will be modernised by 2035. Since, within the framework of the LIFE22-CET-SET_HEAT project significant exchange of knowledge and expertise has taken place, including study visits, it was decided that new combined-cycle gas and steam turbine plants (CCGT), as recently built in Zagreb, Croatia [30], can be replicated in Bucharest. Therefore, EL-TO Zagreb CCGT plant data were used for system modelling. Furthermore, it was assumed that by 2035, the DHN in Bucharest will be revitalised and its health restored.

Investment and operational simulations were performed for two milestone years, 2028 and 2035, corresponding to EED compliance thresholds. Each scenario was assessed under technical feasibility, financial sustainability, and environmental performance criteria. Hourly load data for 2024 were analysed alongside weather data and Romania's day-ahead electricity market prices to evaluate the operational feasibility of industrial heat pumps. The baseline scenario is the current state of the system regarding the production assets and an assumed healthy DHN. In the cases of assumed reduced heat losses, the load duration curve analysis confirmed a peak load of 1,829 MW and an average of 480 MW, corresponding to a load factor of 0.22.

As presented in [11], the transition of existing DH systems depends on the required capital expenditures (CAPEX) as well as on the market prices of fuels, electricity, and European CO_2 emission allowances (EUA). To reach acceptance, the transition plans must be financially feasible. In [11], the future market prices were anticipated until 2050. However, actual market data from subsequent years indicates that this approach may be overly optimistic. For example, EUA prices have fallen rather than risen as expected. Therefore, in this study, a simplified approach is adopted that considers constant prices as recorded in 2024. For example, Figure 8 depicts day-ahead electricity market prices in Romania in 2024 and their annual average value changes from 2021 to 2024.



(**a**) (**b**)

Figure 8. Day-ahead electricity market prices in Romania: (**a**) Duration curve of hourly prices; (**b**) Annual average price.

The initial profitability assessment of the proposed scenarios was performed in terms of net present value (NPV), internal rate of return (IRR), and simple and discounted payback. The profitability in terms of the net present value of the project is:

$$NPV = \sum_{y=1}^{N} \frac{\Delta CF_y}{(1+r)^y} - CAPEX, \tag{3}$$

In terms of IRR, it is:

$$\sum_{y=1}^{N} \frac{\Delta CF_y}{(1+IRR)^y} - CAPEX = 0, \quad (4)$$

where *CAPEX* stands for the total capital expenditures, ΔCF_y is the differential cash flow in the year y relative to the reference scenario, r is the discounted cash flow rate, and N is the calculation horizon (economic lifetime).

The financial analysis of the project will be presented in a differential approach in relation to the current situation. Under the assumption that no additional incomes are generated from selling heat to final users, achieving cost-effectiveness in the decarbonisation programme hinges on a reduction in the variable cost of heat production compared to a scenario where no action is taken. Generating operating cost savings will then enable the capital expenditure (CAPEX) to be recouped.

The key component of the objective function is the differential annual cash flow ΔCF_y resulting from cash flows after and before the project:

$$\Delta CF_y = CF_y' - CF_y = -\Delta \sum_t C_{q,var,t} - \Delta Tx_y + \Delta L_y, \quad (5)$$

where CF'_y is the cash flow in the year y after the implementation of a given scenario and CF_y is the cash flow in the year y in the refence scanario, $\Delta C_{q,var,t}$ is the variable heat production cost reduction, ΔTx_y is the annual change in tax paid in the year y, and ΔL_y is the change of residual value of production assets in the year y.

The differential cash flow is calculated against the reference "no action" scenario, which assumes no changes in heat sources but only the revitalisation of the network. The analysis was performed for the integrated system encompassing DHN and heat sources. Since this approach combines together production and network assets, which are in practice owned by different companies, the analysis does not take into consideration the cash flows between the heat producers and the network operator. An example of the Bucharest DH system modelled using the energyPRO v. 4.9 software is depicted in Figure 9.

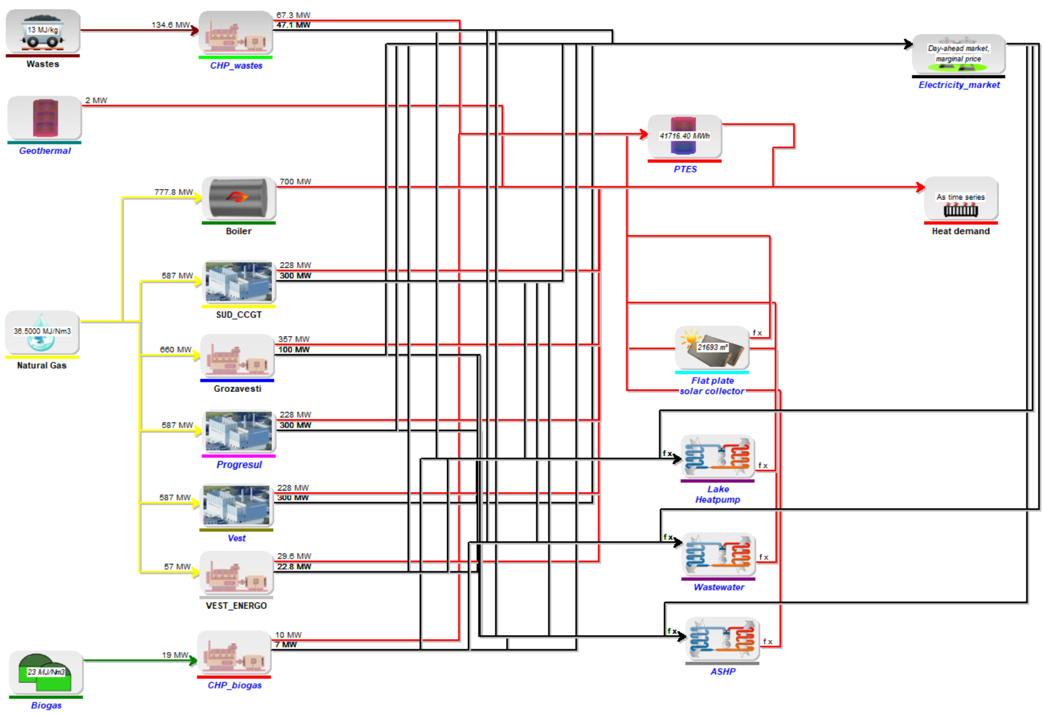


Figure 9. EnergyPRO diagram of the Bucharest DH system in Scenario 1, Phase 2.

In each hour t, the heat balance of the system must be satisfied:

$$\sum_i Q_{i,t} \pm Q_{PTES,t} - Q_{loss} = Q_{DHN,in}, \quad (6)$$

where Q_{PTES} is the amount of heat charged to or discharged from storage, Q_{loss} is the heat lost from storage, and Q_{DHN} is the heat fed into DHN.

Operating windows of heat production devices are taken into consideration:

$$\dot{Q}_{i,min} \leq \dot{Q}_{i,t} \leq \dot{Q}_{i,max}, \quad (7)$$

where *min* and *max* stand for *the* minimum and maximum allowable heat output of the device *i*.

The variable part of the heat production cost takes into account changes in costs of electricity, fuel costs, and maintenance and environmental costs related to particular heat sources. In the energyPRO, the variable cost of heat is calculated based on the user-specified cost and price vectors for each hour t of a given year using the formula:

$$C_{q,var,t} = \sum_i \left(C_{f,i} + C_{el,i} + C_{om,i} + C_{env,i} + C_{ETS,i} - S_{el,chp,i}\right)_t, \quad (8)$$

where C_f is the cost of fuel, C_{el} is the cost of electricity, C_{om} is the cost of operation and maintenance, C_{env} is the cost of using the environment, C_{ETS} is the cost of EU EUA and $S_{el,chp}$ is the revenue from selling cogenerated electricity.

In each scenario, costs $C_{q,var,t}$ is calculated for the given set of production units. The cost of fuel for boilers and CHPs results from heating output, energy efficiency and fuel price:

$$C_{f,t} = \frac{Q_t}{\eta_t} p_{f,t}, \quad (9)$$

where η is the energy efficiency (in the case of CHP related to heat production), p_f is the fuel price per energy unit.

Electricity costs C_{el} are calculated assuming the purchase at variable electricity market price and transmission and distribution costs of 50 EUR/MWh paid to the local distribution system operator (DSO). In case of heat pumps, the cost of electricity imports results from the heating output, heat pump coefficient of performance (COP), electricity market price and electricity distribution costs:

$$C_{el,HP,t} = \frac{Q_t}{COP_t}(p_{el,t} + dc_{el}), \quad (10)$$

where p_{el} is the electricity market price, and dc_{el} is the electricity distribution cost.

Equipment operation and maintenance cost for each production unit C_{om} is calculated using cost data from [31]. The cost of CO_2 emissions allowances C_{ETS} is calculated for natural gas and RDF using the heating values LHV_{RDF} = 21.33 MJ/kg, LHV_{gas} = 36.54 MJ/Nm^3, and emission indices: $CO_{2,ETS,RDF}$ = 91.7 kg/GJ, $CO_{2,ETS,gas}$ = 55.42 kg/GJ given in the legal regulations related to carbon balancing in the EU ETS system.

In the case of cogeneration units, the income from sales of exported electricity is assessed using the formula:

$$S_{el,CHP,t} = \sum_{CHP} Q_{CHP,t}\sigma_t(1-\alpha)p_{el,t}, \quad (11)$$

where σ is the power to heat ratio of the CHP unit, and α is the auxiliary electricity consumption of the unit.

In case CHP units and heat pumps work together, the electric energy is balanced within the system and costs and revenues are determined only for net imported and exported amounts.

Key assumptions made for the study were as follows:

The amount of heat is constant in the following years (this assumption in practice means that all heat consumption reductions will be compensated by new connections; this trend is currently observed in other LIFE22-CET-SET_HEAT project countries);

Capital expenditures for DHN revitalisation and thermal insulation of building stock are not taken into consideration since these costs must be incurred in all scenarios.

All financial calculations in this study were performed in constant value of money (the base year is 2024);

Time horizon for NPV calculations is 23 years (until 2027 - 2050), and the constant nominal cash flow is used based on the 2024 data;

VAT is not included;
During the investment project, operation of the DH network continues uninterrupted;
No any form of financial support for investments is taken into account in the base financing scenario;
As the basic financing option, the investment is financed 25% from equity and 75% from a bank loan;
The interest rate on the bank loan was assumed to be 9.0% per annum (for corporate investments in Romania);
The repayment period for the bank loan was set to 10 years;
Company income tax rate (CIT) for Romania is 16% of the tax base;
The average annual inflation rate is projected to be 8.6% (as of October 2025 EU harmonised value);
The financial discount rate for the basic analysis was set at 10.0%, which accounts for a higher risk premium;
The investment will not result in an increase in personnel and general administrative costs(there will be no increase in the number of jobs, and the new equipment will be operated using existing human resources);
The straight-line method was used to determine the depreciation rate for fixed assets;
Due to the lack of relevant data to build a model of the system services market, the calculations assumed that no such activity existed.

To assess the required capital investment costs (CAPEX), a catalogue of district heating technologies was developed [32]. Key costing curves from the catalogue are depicted in [11]. In addition, data were used from [31], from local vendors, and in some cases from engineering companies. The data from different years were indexed using the Chemical Engineering Plant Cost Index (CEPCI). It must be noted that since all of the planned energy conversion facilities will be located at the own sites of either CMTEB or partner companies, the land purchase costs were not taken into consideration. Furthermore, it was assumed that the CAPEX related to the DHN revitalisation process will be incurred anyway, and it does not influence the investments in heat sources. The summary of capital cost estimates is given in Tables 3 and 4. In phase two, in addition to the proposed heat sources, the seasonal heat storage is taken into consideration, which enables the constraints set by equation (2) to be satisfied. Without storage, it would be necessary to significantly increase the installed capacity of particular technologies, while in summer, most of the units would be idling. In addition, it should be noted that

Table 3. Anticipated capital expenditures (CAPEX) in Scenario 1.

Technology	Phase 1, million EUR	Phase 2, million EUR
Conversion of existing CHPs into modern CCGT plants	150 – 200 (1 plant)	300 – 400 (2 plants)
Waste-to-energy plant	0	300 - 400
Distributed solar plants	12.7	0
Lake heat pump	0	66.7
ASHPs	43,6	0
Geothermal plants	0	25.0
Wastewater heat pump	0	88.4
Municipal biogas CHP plant	0	40.0
Seasonal PTES (1,200,000 m^3)		84.0
TOTAL estimated including 10% contingency	**281.9**	**1214.5**

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Table 4. Anticipated capital expenditures (CAPEX) in Scenario 2.

Technology	Phase 1, EUR	Phase 2, EUR
Conversion of existing CHPs into modern CCGT plants	150 – 200 (1 plant)	300 – 400 (2 plants)
Distributed solar plants	12.7	12.7
Lake heat pump	0	66.7
ASHPs (independent)	43,6	21.2
ASHPs (metro stations)	0	11.5
WSHPs (data centres)	0	4.2
Geothermal plants	0	25.0
Wastewater heat pump	0	88.4
Municipal biogas CHP plant	0	40.0
Seasonal PTES (1,500,000 m^3)	0	105
TOTAL estimated including 10% contingency	**281.9**	**852.2**

3. Results

The two proposed scenarios were examined in terms of system operability, energy and financial performances. Achieving appropriate ratios for the share of heat from individual sources in total heat depends both on the installed capacity of individual sources and on how they are controlled. Figure 10 depicts an example of the energyPRO simulated new production profile for scenario 1, phase 2 of the project. In the first run, the simulation was performed with the objective of minimum variable heat cost (8). Therefore, the waste-to-energy plant was positioned as a base load unit (due to negative fuel cost), which is shown in Figure 10. The annual results revealed that in such a case, the thresholds (1) and (2) are not met under the given fuel and energy prices. Therefore, multiple simulations had to be run in an iterative way to meet the required share of RES in the total heat delivered to DHN. Ensuring adequate shares of heat from RES required forcing heat pumps to operate at times when cogeneration or gas boilers were actually a cheaper option. Key annual figures are presented in Table 5. Significantly increased electricity generation can be noticed, which is the result of the conversion of cogeneration technology into modern CCGT blocks of much higher electricity-to-heat ratio. This enabled net heat production costs to be reduced compared to the reference scenario. However, although the threshold for RES contribution was satisfied, the system appeared not to be effective since the share of high-efficiency CHP was too small, and the share of boilers was still considerable. Therefore, in the last run, the priority for boiler operation was set to low, which practically shifted heat production to CHP, even if electricity prices were not favourable. As a result, electricity production, gas consumption and total CO_2 emissions increased considerably. The financial effects of the decarbonisation programme also deteriorated, which is presented in Table 7.

It is vital to acknowledge the pivotal function of seasonal heat storage in meeting the requirements of the European Energy Efficiency Directive (EED). During the initial phase of system transition, all newly constructed production units were equipped to cover base heating loads alone, thus negating the necessity for storage. However, commencing from the year 2035, the storage will facilitate the transfer of heat from the summer period to the heating season. The operational dynamics of the storage are illustrated in Figure 11 for the designated transition scenarios. It is discernible that, in scenario 1, the storage's functionality within the system is more akin to seasonal storage, while in scenario 2, its role is more oriented towards system balancing.

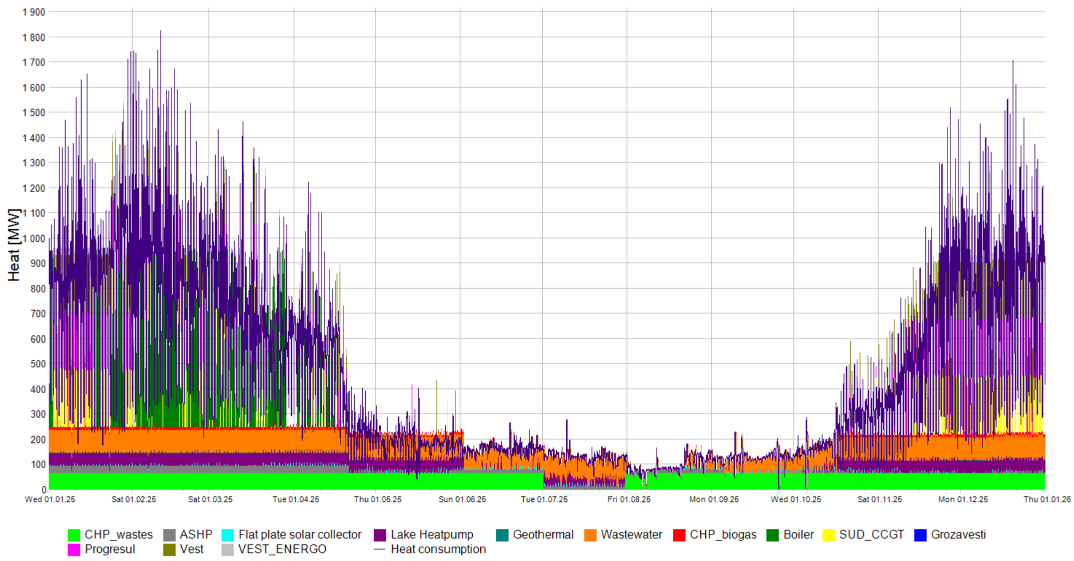

Figure 10. EnergyPRO generated a heat production profile for Scenario 1, Phase 2.

Table 5. Bucharest DH system annual mass and energy balance results.

Title 1	n 2028 to 2034 (Phase 1)	From 2035 to 2039 Scenario 1	From 2028 to 2034 Scenario 2
Total annual heat supplied to DHN, MWh	3,576,851	3,576,851	3,576,851
Heat supplied by geothermal plants, MWh	0	7,207 (0.2%)***	12,644 (0.4%)***
Heat supplied by solar plants, MWh	17,321 (0.5%)	15,483** (0.4%)***	35,330** (1.0%)***
Heat supplied by ASHPs, MWh	162,563 (4.5%)	123,494** (3.5%)***	245,340** (6.8%)***
Heat supplied by WSHPs, MWh	0	895,152** (25.0%)***	900,718** (25,2%)***
Heat supplied by biogas CHP, MWh	0	56,933** (1.6%)***	86,726** (2.4%)***
Heat supplied by waste-to-energy plant, MWh	0	522,859** (RES 4,4%)***	0
Heat supplied by high-efficiency CHPs, MWh	1,927,752	1,245,934	1,542,093
Heat supplied by other CHPs, MWh	68,677	9,768	44,890
Share of RES in heat supplied	5,0%	35,1%	35,5
Share of high-efficiency CHPs in heat supplied	53.9%	34.8%	43,1
Heat supplied by gas boilers, MWh	1,400,538	703,457	720.264
Heat losses from PTES, MWh	0	10,490	11,187
Total electricity generated, MWh	2,071,150	2,020,284	2,072,346
Total electricity consumed, MWh	45,830	278,030	325,864
Net electricity balance change*, MWh	+771,156	+488,091	+492,318
Electricity exported, MWh	2,037,574	1,764,897	1,907,377
Electricity imported, MWh	12,254	22,643	160,895
Total gas consumption, MWh	6,292,586	3,974,213	4,817,819
Gas consumption change*, MWh	+405,761	-1,912,612	-1,069,006
RDF consumption, MWh	0	1,045,852	0
Change of CO_2 emissions*, tones/a	+80,954	-36,332	-213,280

* Calculated versus the reference scenario. ** Net value after consideration of heat losses from storage. *** Values in brackets are RES contributions to the total heat input to DHN.

In relation to the reference scenario, electricity generation increased. This is the result of the conversion of old CHP plants into new CCGT blocs. In the reference scenario, due to unfavourable performance indicators, for many hours, gas boilers were prioritised over CHPs. After retrofitting and a technology change, CCGTs became key contributors to heat generation, and the operation of gas boilers was largely eliminated.

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Although in phase 2 of both scenarios, more than 35% of heat fed into the DHN is from RES, the total share of high-efficiency CHP, RES and WHS is below the required 80%.

Table 6. Key financial operating results.

Investment scenario	Total Operating Expenditures, EUR	Revenues – Sales of electricity, EUR	**Net differential operating cash flow, EUR**
Reference scenario	325,341,051	175366522	**-**
Scenarios 1 and 2, Phase 1	366,218,187	269815460	**-53,571,803**
Scenario 1, Phase 2	259,283,456	243731733	**-134,422,807**
Scenario 1, Phase 2, EED satisfied	318,458,194	291715609	**-123,231,945**
Scenario 2, Phase 2	339,458,678	272275872	**-82,791,724**
Scenario 2, Phase 2, EED satisfied	397,914,280	318607991	**-70,668,240**

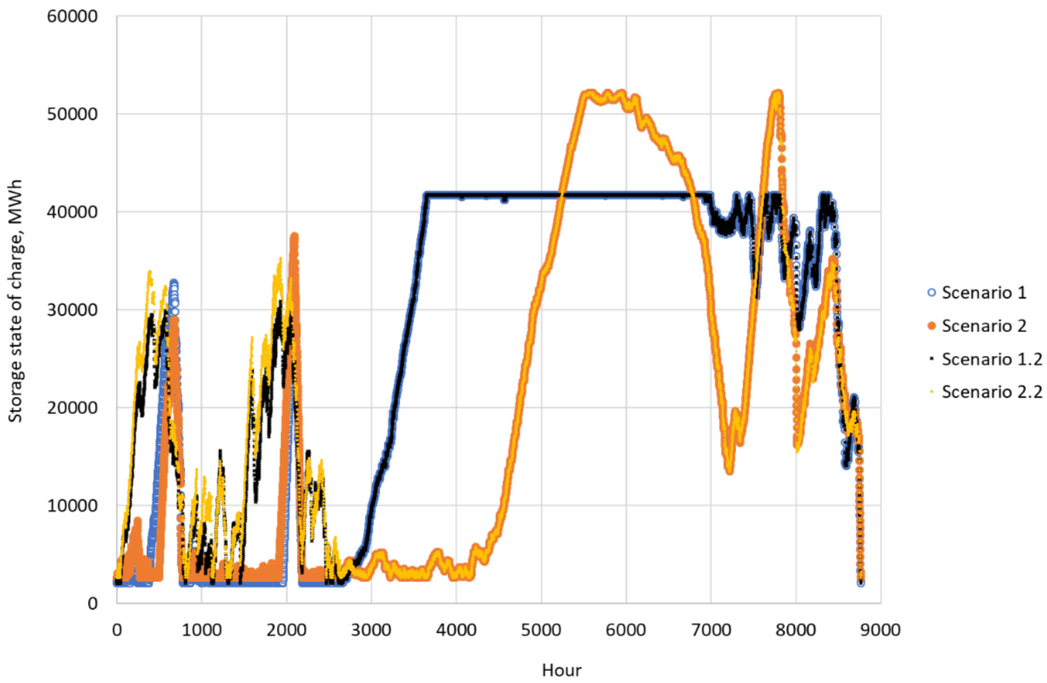

Figure 11. State of seasonal PTES charge (note: Scenarios 1.2 and 2.2 are those with forced operation of heating units to fully meet the EED requirements).

Table 7. Estimated values of profitability indices.

Index	**Scenario 1**	**Scenario 2**
NPV, million EUR	-195.1	-201.9
IRR	0.056	0.036
SPB, years	16.2	18.3
DPB, years	Not found within the given time horizon	Not found within the given time horizon

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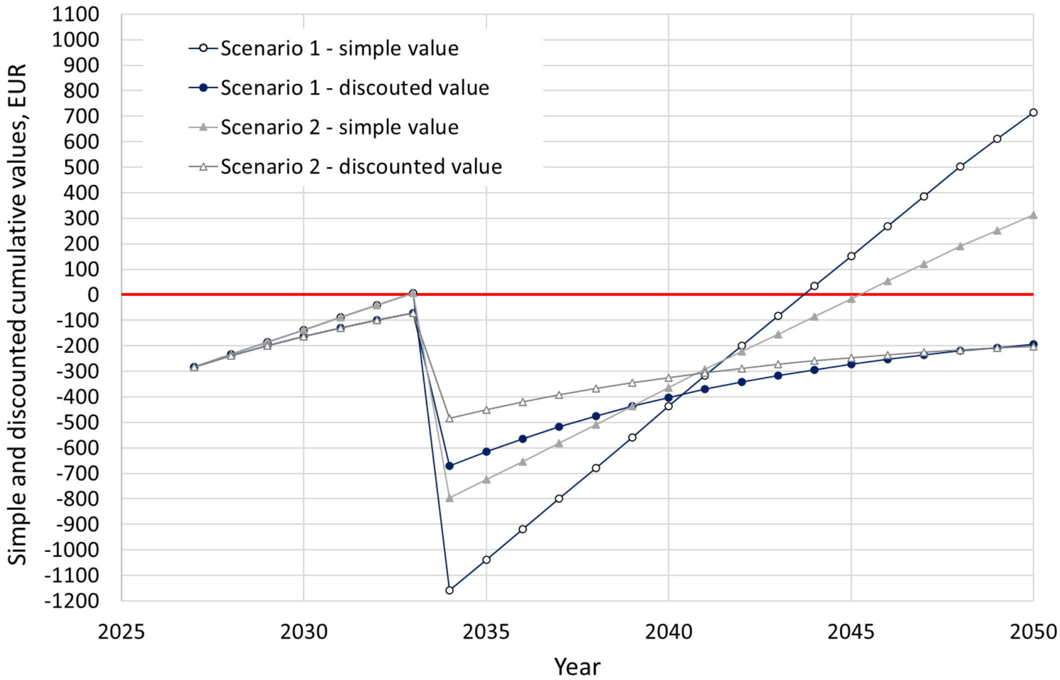

Figure 12. Projected **s**imple and discounted values of the DH system transition programme.

4. Discussion

The analysis confirms that achieving compliance with the Energy Efficiency Directive (EED) targets for 2028 and 2035 in the Bucharest district heating (DH) system is technically feasible, yet highly constrained by system characteristics and local boundary conditions. The system's second-generation design, high supply temperatures, extensive heat losses, and limited availability of local renewable and waste heat resources within the city boundaries significantly restrict the range of effective decarbonisation options.

A central finding is the strong sensitivity of EED compliance to operational strategy. When heat production is dispatched solely on the basis of minimum variable costs, the proposed system configurations fail to meet the required RES shares. Conversely, enforcing compliance through forced operation of heat pumps and CHP units leads to higher operating costs, increased electricity consumption, and higher CO_2 emissions. This demonstrates a fundamental trade-off between economic optimisation and regulatory compliance in large legacy DH systems.

Seasonal thermal energy storage plays a pivotal role after 2035 by enabling the temporal shift of renewable heat from summer to the heating season. However, the required storage volumes are substantial, and realistic deployment is limited by land availability, investment costs, and integration complexity in a dense metropolitan context. As a result, dispatchable low-carbon heat sources remain indispensable for maintaining system reliability during peak demand.

The comparison of scenarios indicates that the waste-to-energy-based pathway offers greater operational stability and lower variable costs, but depends on long lead times, permitting processes, and waste policy decisions beyond the control of the DH operator. The alternative pathway relying exclusively on heat pumps and solar thermal increases exposure to electricity price volatility and requires larger storage capacities.

From a financial perspective, both scenarios yield negative net present values under conservative assumptions without external support. This confirms that deep decarbonisation of large, capital-intensive DH systems cannot be financed solely through operational savings.

From a policy perspective, the study underlines that Bucharest's transition requires a coordinated governance model integrating all relevant stakeholders, including municipal authorities and policymakers. Institutional fragmentation remains a critical bottleneck, delaying investment implementation since the decarbonisation of Bucharest's DH system requires appropriate policy instruments, unprecedented levels of investment and effective coordination. The study highlights that without EU-level financial support and tariff reforms, achieving cost-effective decarbonisation remains unlikely.

5. Conclusions

The EED poses a serious challenge to large DH systems in terms of decarbonisation. This study presents a strategic, system-level assessment of decarbonisation pathways for the Bucharest district heating system and provides insights applicable to other large, fossil-fuel-dependent, second-generation DH systems. The results show that compliance with the EED criteria for 2028 and 2035 is achievable in principle, but only under restrictive technical and economic conditions.

The main conclusions are as follows:

- Compliance with EED targets is not equivalent to system efficiency and may require operational compromises that increase costs or emissions.
- Dispatchable low-carbon heat sources are essential to ensure security of supply and limit overreliance on electricity-driven technologies.
- Seasonal thermal energy storage is a key enabler, but its feasible scale is limited in dense urban environments.
- Modernised CHP plants remain critical transitional assets, supporting flexibility and mitigating electricity market risks.
- Financial viability cannot be achieved without external support, underscoring the necessity of EU funding, regulatory incentives, and risk-sharing mechanisms.

Although the analysis shows that compliance with the EED requirements for 2035 can be achieved with relative ease through a targeted portfolio of renewable energy, waste heat, and high-efficiency cogeneration technologies, the results also indicate that further progress toward deep decarbonisation becomes significantly more challenging beyond this milestone. As the most accessible and dispatchable low-carbon resources are exhausted, additional emission reductions increasingly depend on complex system reconfiguration, large-scale energy storage, electrification, and extensive coordination across sectors and stakeholders. This confirms that incremental, technology-by-technology approaches are insufficient and that multidimensional, holistic strategic planning is indispensable. Such planning must simultaneously address network transformation, heat demand reduction, market integration, governance structures, and social acceptance. A common feature emerging from both this study and comparable transition strategies is the growing emphasis on energy harvesting, systematic recovery of low-grade renewable and waste heat dispersed across the urban environment, which increasingly defines the backbone of long-term district heating decarbonisation pathways.

In addition to the modernisation of existing production facilities and networks, and the integration of multiple distributed heat sources, it is recommended that future activities concentrate on transitioning to fourth-generation (4GDH) standards and gradually reducing the temperature in the DHN. Network performance studies indicate that Bucharest has considerable potential for this transition, given the oversized pipeline diameters and the temperature difference of 30-40 K between the primary and secondary networks. This has, however, not been addressed in this study and left for future work.

The socio-economic dimension is equally critical. Residential heat tariffs are heavily subsidised, creating a fiscal burden on the municipality but protecting low-income consumers. This policy complicates investment cost recovery and discourages energy efficiency. At the same time, heat affordability remains politically sensitive, making social dialogue essential for a just transition.

Overall, the decarbonisation of large DH systems should be understood as a multidimensional socio-technical transition rather than a purely technological upgrade. Effective transition strategies must integrate infrastructure renewal, system flexibility, spatial planning, governance coordination, and long-term policy alignment.

Future work will focus on uncertainty and sensitivity analyses of energy and CO_2 price trajectories, detailed modelling of network temperature reduction and building-side adaptations, assessment of business models for waste heat integration, and broader environmental and social impact evaluations. Further research will also examine the replicability of the proposed methodological framework across other metropolitan DH systems in Central and Eastern Europe.

Author Contributions: Conceptualisation, methodology, project administration, funding acquisition and supervision, Jacek Kalina; validation, formal analysis, investigation, resources, Wiktoria Pohl, Wojciech Kostowski, Andrzej Sachajdak.; data curation, Celino Craiciu, Lucian Vișcoțel; writing—original draft preparation, writing—review and editing; visualisation, Wiktoria Pohl, Jacek Kalina. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

ASHP	Air-source heat pump
CAPEX	Capital expenditures
CCGT	Combined-cycle gas and steam turbine plant
CHP	Combined heat and power production
CMTEB	Compania Municipală Termoenergetica București S.A.
DH	District heating
DHN	District heating network
EDHS	Efficient district heating system
EED	Energy Efficiency Directive
EUA	European CO_2 emission allowance
IRR	Internal rate of return
MILP	Mixed Integer Linear Programming Technique
NPV	Net present value
RES	Renewable energy sources
PTES	Pit thermal energy storage
RDF	Refuse-derived fuel
WHS	Waste heat sources
WSHP	Water-source heat pump
4GDH	Fourth-generation district heating

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