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# Approach to Modernizing Residential-Dominated District Heating Systems to Enhance Their Flexibility, Energy Efficiency, and Environmental Friendliness

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**Abstract:** The need to modernize existing district heating systems is due to increased requirements for their flexibility, energy efficiency, and environmental friendliness. The technical policy on district heating pursued in different countries centers on the listed goals and takes account of historical, climatic, and regional features of the resource, technology, and economic availability of various thermal energy sources. This study aims to analyze methods designed to improve the flexibility, energy efficiency, and environmental friendliness of district heating systems. The focus of the study is district heating system, which provides heating and hot water supply to consumers and consists of various types of thermal energy sources. The work shows the possibility for the heating system to transition from the third generation to the fourth one, which differ in their level of intellectualization. The establishment of an intelligent control system will ensure the interaction of various heat sources, but this is a separate strand of research. In this study, a model and a methodology were developed to optimize the structure of thermal energy sources and their operating conditions when covering the heat load curve of a territory with a predominance of household consumers. Gas-reciprocating and gas-turbine cogeneration plants are considered as the main thermal energy sources, whose efficiency is boosted through their joint operation with electric boilers, thermal energy storage systems, low-grade heat sources, and absorption chillers. The primary emphasis of the study is on the assessment of the environmental benefit to be gained by using cogeneration plants as a factor of enhancing the investment appeal of the district heating systems. The findings suggest that the transition of district heating systems to the next generation is impossible without changing the institutional environment, strengthening the role of active consumers, and introducing intelligent control for district heating systems.

**Keywords:** district heating system; flexibility; energy efficiency; environmental friendliness; cogeneration plant; residential consumer; electric boiler; heat pump; thermal energy storage; intelligent control system

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## 1. Introduction

The choice of a cost-effective way to modernize existing heating systems is an urgent social goal [1,2]. The reason for this is the need to supply thermal energy to the entities of the industrial and residential sectors in the needed quantities, while maintaining an acceptable cost and meeting the specified reliability standards [3,4].

In countries where the outdoor air temperature is below +10 °C for a long time during the year, it is necessary to have heating systems in buildings and premises for domestic purposes. It is also vital to provide hot water supply and ventilation [5,6]. In the period when heating is not required, it becomes essential to cool the internal air in these buildings and premises. The whole set of the objectives is to be accomplished by the heating systems and requires the use of various technologies for the production of thermal and cooling energy [7,8].

The advancement of technology has significantly broadened the range of options available, resulting in a great number of heating and cooling plants in the market with varying capital and operational costs. The mix of thermal energy sources and procedure for their use in a particular country are determined by climatic features, the availability of sufficient primary energy resources, and the requirement for a reliable and affordable heat supply for various consumers [9,10].

At present, the requirements for carbon neutrality of heating systems are coming to the fore, which has formed a steady trend towards the use of renewable energy resources incorporated into the heating systems [11–13]. Therefore, the ongoing projects give priority to heat pumps of various types and electric boilers that use an environmentally friendly energy resource, i.e., electricity, including that generated from renewable energy resources [14,15]. The thermal power of these sources reaches tens and hundreds of megawatts, which allows them to be used in district heating systems (DHSs). Cooling of the air is performed by various air conditioning and ventilation units, which also utilize electricity as a primary energy resource [16]. Sufficient research has been conducted on these technologies and their impact, particularly on the potential for boosting the efficiency of renewable energy sources through the use of thermal energy storage devices.

A significant part of electricity in many countries is produced at thermal power plants (TPPs) running on hydrocarbon fuels. In the last decade, power plants operating on solid household and industrial waste and utilizing secondary energy resources (landfill, coke, blast furnace, associated petroleum gas, and others) have become widespread [17–19]. These power plants are classified as more environmentally friendly sources of electrical and thermal energy but have a carbon footprint.

Until the entire volume of electricity necessary for the life of the population is produced from renewable energy resources, it is necessary to increase the beneficial use of fuel in the heat and electricity industry [20–22]. From this perspective, cogeneration technologies for the combined production of heat and electricity are the top priority. The issues of enhancing the efficiency of low-power cogeneration plants when combined with thermal storage devices, heat pumps, and electric boilers still remain inadequately investigated. The heating systems established on this basis can enhance the energy efficiency of heat production, create favorable conditions for the use of environmentally friendly sources of thermal energy, and reduce the share of heating boilers [23,24]. With the advent of various sources of thermal energy and their rise in numbers, the flexibility of heating systems increases [25,26].

This study aims to explore methods for boosting the flexibility and energy efficiency of heat supply to household consumers. By adopting this approach, it becomes possible not only to achieve environmental advantages from the production of heat and electricity but also an enhanced reliability and efficiency of the heat supply. The research focuses on DHSs and involves examining the methods of their transition from the third generation to the fourth one by expanding the variety of thermal energy sources in the structure of heating systems.

The scientific novelty of the study lies in the development of a calculation model and method that allow for optimizing the operation of thermal energy sources to cover the heat load curves of territories with a predominance of household consumers.

The structure of the paper is as follows. Section 2 shows the state of the art and prospects for the development of heating systems, highlighting the existing gaps in previous research. Section 3 presents a methodology for determining the annual operating conditions of a heating system consisting of various thermal energy sources. Section 4 focuses on a description of the results obtained and discusses the benefits to be gained from the use of district heating systems based on low-power CHP plants. The conclusion section provides the main findings and outlines the future research directions.

## 2. State of the Art

The structure of thermal energy consumers largely determines the strand of development for heating systems. Figure 1 shows an enlarged structure of thermal energy consumers in the heating systems of some countries. The investigations presented in [27,28] indicate that in countries and regions located above 45° north latitudes, the prevailing consumers of thermal energy are domestic households. This is due to the harsh climate and the significant role of heating systems in ensuring the life of the population and the functioning of service companies.

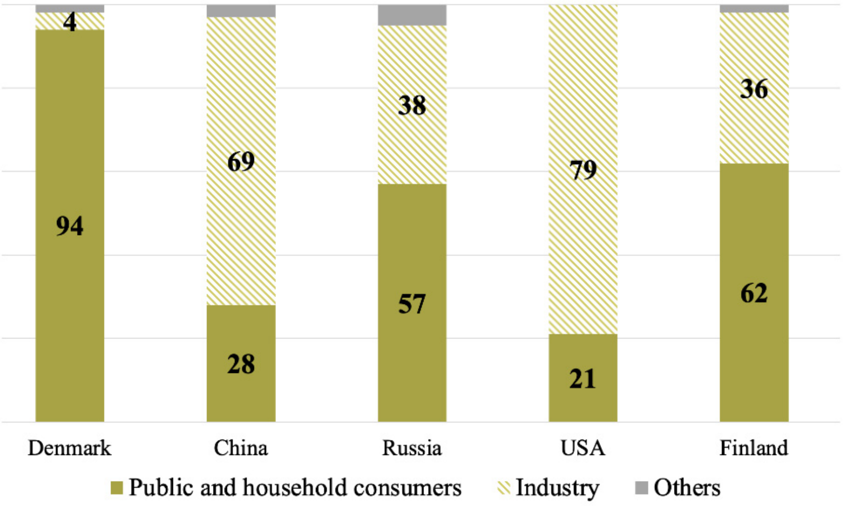

**Figure 1.** Structure of thermal energy consumers in some countries.

There are two ways to organize heat supply to the population, including household consumers: individual and centralized [29,30]. Their main function is the heating of public and residential buildings and premises during low-temperature periods. The performance of heating systems is assessed by the level of reliability, efficiency, and environmental friendliness of heat production [31,32].

The current state of heating systems and future trajectory of their development are largely affected by historical features, traditions, the social structure of society, and other factors. In European countries, where the heating period is about 100 days a year, the focus is on individual heating systems and home boilers. The countries where this method of heating and hot water supply dominates in the domestic sector include England, France, Germany, Italy, the USA, and other countries in Europe and North America. This is usually due to the lack of inexpensive hydrocarbon fuel in these countries, which requires the population to limit their consumption of expensive thermal energy.

District heating systems are widely used in densely populated urban or industrial areas of regions and countries with a sharply continental climate. There are about 80 thousand of them in the world. The main proportion of DHSs is in Scandinavian countries, since the heating period in them lasts more than 200 days a year. In Australia, China, Mongolia, Poland, Russia, Belarus, and other countries, the energy policy is aimed at the development of district heating systems [33–35]. The process of urbanization in developing countries drives the advancement of DHSs that supply thermal energy to household consumers.

Orientation towards DHSs is normally accompanied by the improvement in market mechanisms that determine the rules and procedures for the production and consumption of thermal energy. According to statistics, the global district heating market in 2022 was estimated at $49.96 billion, and according to preliminary estimates, its value will be $56.05 billion by 2028 [36] (Figure 2).

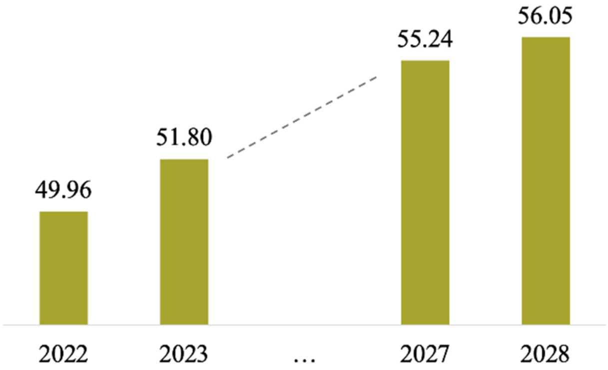

**Figure 2.** Projected growth of the global district heating market from 2022 to 2028 (billion USD).

To streamline the process of thermal energy production and consumption, it was necessary to develop and implement modern systems for metering thermal energy. To increase energy saving, measures are taken to improve market mechanisms and methods of technical regulation [37,38]. Improvement in market mechanisms and technical requirements is aimed at

- Stimulating the reduction in thermal pollution during thermal energy transmission and consumption;
- Boosting the DHS controllability to reduce harmful emissions into the environment from the thermal energy production.

The progressive development of DHSs in European countries is the result of implementing an integrated approach [39]. For example, the values of heat pipeline transmission losses achieved in the EU countries are at the level of 1–7%, against 35–40% in some other countries [40,41].

Existing DHSs are usually referred to one of five generations that differ in the level of energy efficiency [42,43]. About 50 years elapsed between the first and second generation of DHSs. With the advancement of technological progress, the rate of change in generations of heating systems has almost doubled. Let us give a brief description of the DHS generations:

- The first generation (1 GDH) is characterized by steam heating with a steam temperature of 100–200 °C and high thermal energy losses exceeding 30%. It is mainly used in steam boilers operating on solid fuels (coal, peat, etc.).
- The second generation (2 GDH) is characterized by water heating with a network water temperature above 100 °C at high pressure and high thermal energy losses (up to 30%). These DHSs mainly focus on providing heat to industrial consumers, while the surplus thermal energy is used to meet the needs of household consumers. They can include heat and electricity cogeneration plants operating mainly on solid fuels.
- The third generation (3 GDH) is characterized by water heating with a network water temperature of 70–100 °C for heat supply to domestic consumers. Energy saving measures are implemented to reduce thermal energy losses during the coolant transfer from the source to consumers (up to 18%) and to control harmful emissions from the combustion of hydrocarbon fuels. Thermal energy sources use solid and gaseous fuels [44]. Cogeneration technologies are widely used to generate heat and electricity. There is an insignificant share of generation (up to 10%) using renewable energy resources [45].
- The fourth generation (4 GDH) is characterized by a network water temperature of 50–70 °C, while heat losses do not exceed 6%. Secondary and renewable energy resources are massively used; heat storage, automation, and digitalization systems are introduced into the processes of thermal energy production and distribution [46,47]. Along with efficient cogeneration technologies, heat pumps, solar collectors, and other plants based on renewable energy resources are used to produce thermal energy.

Trigeneration technologies are utilized for the air conditioning of buildings, enhancing the capabilities of district heating systems.

- The fifth generation (5 GDHC) is characterized by a coolant temperature from 5 to 25 °C, while heat losses do not exceed 5%. Highly efficient thermal energy sources are utilized that make use of secondary energy resources such as solid industrial, agricultural, and domestic waste to minimize CO2 emissions. These district heating systems employ integrated automation systems as the basis for intelligent control systems to be created [48].

In [41,42,49], 5 GDHC systems do not relate to the evolutionary development of the previous four generations of heating systems, because there are significant disparities in the structure and composition of sources, where electric heat plays a major role. The latter creates additional loads on electrical networks and increases the risks of power supply disruption. The use of low-power cogeneration plants in close proximity to heat sources using electricity, however, makes it possible to eliminate this problem. Therefore, we believe that the 5 GDHC systems can be considered as a stage in the evolutionary development of DHS.

Figure 3 shows the process of district heating evolution, which reflects the key differences in all five generations of district heating systems.

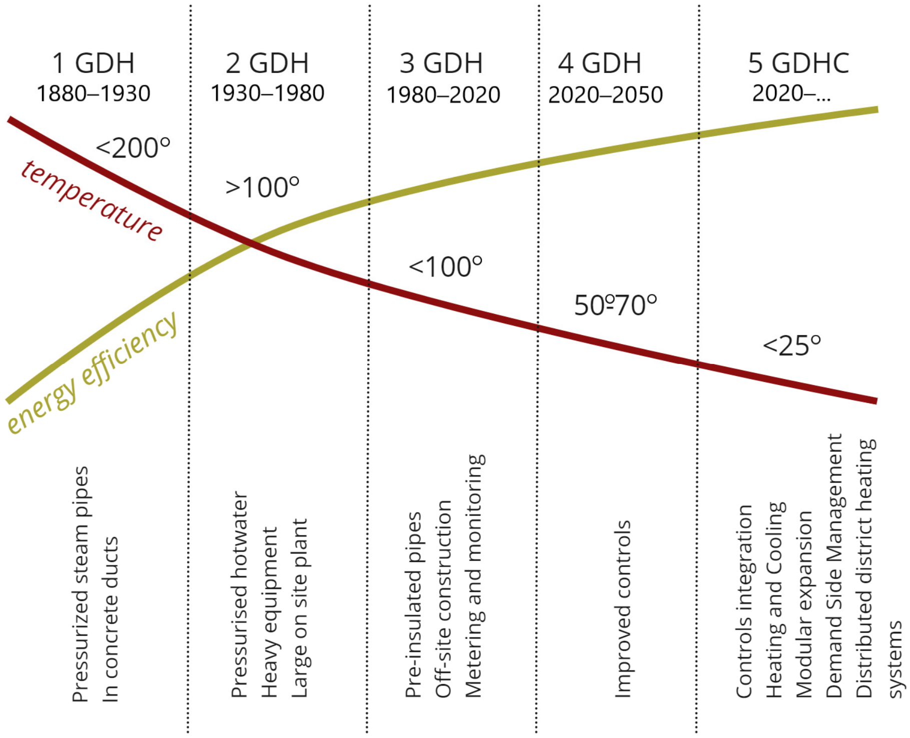

**Figure 3.** Generations of district heating systems.

The higher the district heating generation, the more diverse the set of energy resources used by heat sources. Modern district heating systems use heat sources focused on the use of primary energy resources, which can be divided into three groups:

- Hydrocarbon fuels, industrial, agricultural, and domestic solid waste (boilers, combined heat and power plants (CHPPs));
- Renewable energy resources (heat pumps, solar collectors, etc.);
- Electricity (electric boiler rooms, individual electric boilers) [50].

When choosing the direction of DHS development, special attention is paid to enhancing their reliability and reducing heat transmission losses. Since 1986, no major accidents have been registered in the Danish DHS (4 GDH) [51,52]. To this end, thermography of heat networks is performed once every 2 years to identify leaks and heat losses at the most significant nodes. The diagnostics are carried out along with the reconstruction of the pipeline DHS. The energy saving measures have halved the consumption of thermal energy for heating 1 $m^2$ of living space over the past 30 years. Losses of thermal energy from the source to consumers do not currently exceed 3–5% in the main heat networks [53].

In Finland, where the DHS corresponds to 3 GDH, losses in heat networks also do not exceed 1%, and there is 100% heat network redundancy even between neighboring cities. This can be achieved when the distances between cities are small [54,55].

Not all the countries with district heating have the systems corresponding to 3 GDH. In China and Russia, accidents in the DHS, namely in heat networks, are more frequent. There are examples of pipeline breaks in heat networks, accompanied by human casualties [56]. As the DHS transitions to a more advanced generation, the frequency of accidents goes down, with a decline in the heat transmission losses and a reduction in the specific thermal energy consumption for heating. A high accident rate is observed in DHSs with worn-out and extended heat networks, especially during peak heat loads, when heat networks operate to the limit.

The need to combat global climate change and address environmental degradation demands effective ways to reduce the consumption of various forms of energy derived from hydrocarbon fuels. The transformation of electric power and heating systems is greatly influenced by these factors, which in turn are reflected in the ESG standards [57]. These standards play a crucial role in determining the investment attractiveness of energy companies, which encourages the use of appropriate technical solutions when designing strategies for the long-term development of the companies.

The distribution diagram of CO2 emissions in different regions of the world (Figure 4) shows the dynamics of their changes over a more than 30-year period [58]. Between 2019 and 2022, the countries of Europe and North America saw a reduction in emissions by 1–2%, which was achieved, in particular, through the measures aimed at enhancing energy efficiency in production and energy conservation in the thermal energy transmission and consumption.

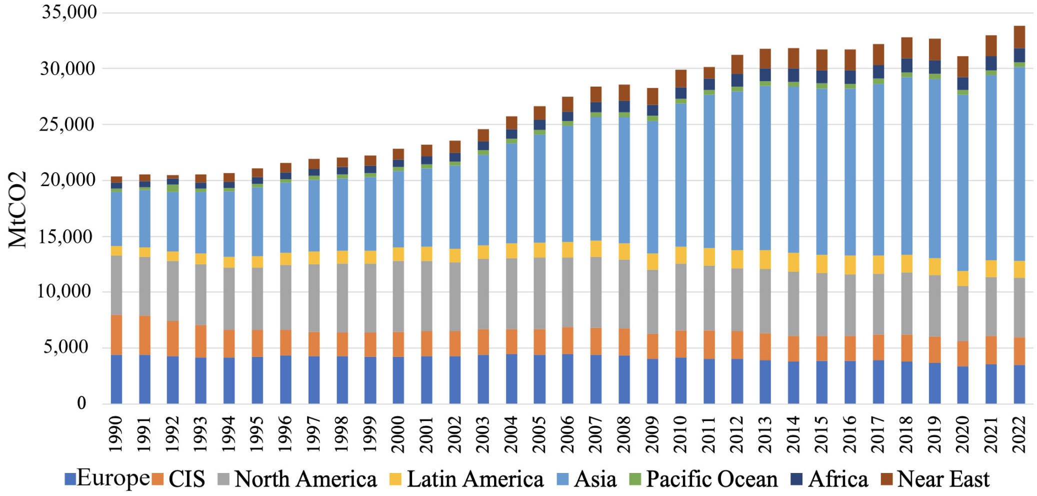

**Figure 4.** Dynamics of changes in CO2 emissions from 1990 to 2022.

There are two ways to boost the energy efficiency of heating systems. These are the introduction of technologies increasing the efficiency of hydrocarbon fuels and the involvement of renewable energy resources in the production of thermal energy [59,60]. These technologies can reduce the carbon footprint and can serve as a basis for the expansion planning of heating systems [42,61].

Various types of heat pumps are widely used to enhance the energy efficiency of heat production. Back in the 1980s, the Empire State Building in New York was equipped with a heat pump. Heat pumps are energy-efficient devices for heating and cooling buildings. These pumps utilize renewable energy resources, i.e., heat from soil, water, and air. This solution is a promising avenue to effectively combat global climate change. In the United States, Japan, and some other countries, reversible air-to-air heat pumps are widely used for heating and air conditioning. Europe predominantly uses water-to-water and water-to-air heat pumps. Millions of heat pumps are currently operating in the Unites States, of which more than half are installed for domestic consumers [62,63]. In Scandinavian countries, large-scale heat pumps are widely used in DHSs. Heating systems for residential and public buildings with low- and high-level ground-water heat sources are developing rapidly [64].

Sweden's experience serves as a clear example, with heat pumps generating around 50% of thermal energy. As a result, it is possible to reduce the amount of hydrocarbon fuel combustion emissions into the atmosphere by almost 400 thousand tons/year. The most powerful (320 MW) Stockholm heat pump utilizes the water of the Baltic Sea as a source of low-grade heat. This heat pump is located on barges moored to the shore and can cool the seawater from 4 to 2 °C in winter. The cost of thermal energy production from this heat pump is 20% lower than the cost of its production from heating boilers [65,66].

It is important to emphasize that this technology is quite expensive, and therefore, the mass introduction of heat pump systems needs appropriate measures of financial support. The main incentives for the use of heat pumps in many countries are an effective system of penalties for CO2 emissions from hydrocarbon fuel combustion and rewards for the use of low-grade heat sources for heating purposes [67,68].

Thermal energy storage units play a special role in improving the energy efficiency of DHSs [64]. What makes them so appealing is their ability to shift the processes of thermal energy generation and consumption in time [69,70]. This feature enables the storage of thermal energy across various time spans from hours to weeks or longer periods. Thermal energy storage enables the integration of stochastic renewable energy resources into heating systems, resulting in the production of environmentally friendly heat [71,72]. To date, the total energy capacity of thermal storage units installed in the world has reached 199 GWh. According to expert estimates, by 2030, the thermal storage market may grow several times, reaching more than 800 GWh [64,73].

DHSs account for the major share of the installed capacity of thermal energy storage. In 49% of DHSs, where this technology has been introduced (Europe, Canada, China), thermal energy storage serves as the interseasonal energy storage (Figure 5) [64].

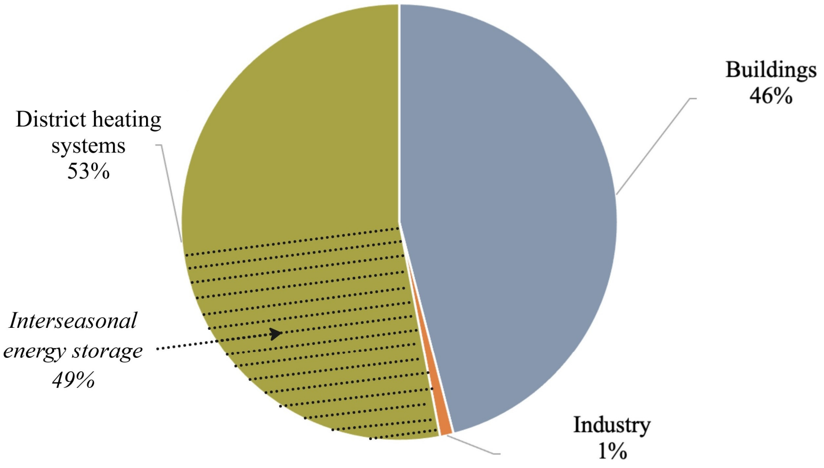

**Figure 5.** The use of thermal energy storage in district heating systems.

The use of thermal energy storage contributes to the decarbonization of the thermal power industry. For example, Finland has put into service a large sand-based thermal energy storage that converts wind energy into thermal energy. An integrated system with heat pumps, electric boilers, and a thermal energy storage unit reduced CO2 emissions by

30% through the replacement of natural gas-fired boilers. At the same time, the issue of storing surplus electricity generated by wind and solar power plants is addressed. With an increase in the share of stochastic generation in the energy balance, the use of thermal energy storage devices in the electrical-to-thermal energy conversion system enables an elimination (minimization) of limitations on electricity generation from renewable energy resources. A study of the Pennsylvania–New Jersey–Maryland energy market in the USA suggests that the use of hydrocarbon fuels can be reduced by 50–90% through the utilization of either heat pumps with thermal energy storage or resistance heaters with thermal energy storage [63].

Heating systems for domestic consumers started using thermal energy storage in the early 2000s. For example, one of the thermal energy storage units in the UK receives thermal energy from solar collectors for its subsequent storage in eighteen 100 m boreholes to use it for heating in the winter [74].

In Canada, in 2007, a system of solar collectors was installed on the roofs of garages to generate thermal energy and store it in a grid of 35 m wide and 35 m deep boreholes for heating during the cold season [75].

In the city of Braedstrup (Denmark), about 8000 m$^2$ of solar collectors are used to generate up to 4 million kWh of thermal energy per year and store it in an extensive network of 50 m boreholes for later use [76].

Siemens-Gamesa has built a basalt-based thermal energy storage facility with a temperature of 750 °C, a capacity of 1.5 MW, and an energy capacity of 130 MWh near the city of Hamburg (Germany) [77]. A similar thermal energy storage facility operates in the city of Sorø (Denmark), which returns 41–58% of the stored 18 MWh to the city's DHS in the form of thermal energy, with 30–41% used to generate electricity [78].

Figure 6 demonstrates thermal energy storage facilities based on various technologies, which are widely used in DHSs [64]. The technologies used in the heating systems of domestic consumers provide off-season storage of thermal energy for its subsequent use. The advancement of thermal energy storage technologies significantly expands the ranges of capacities and speeds with which thermal energy can be collected and distributed to consumers. These features are determined by the choice of storage technology and the design of thermal energy storage.

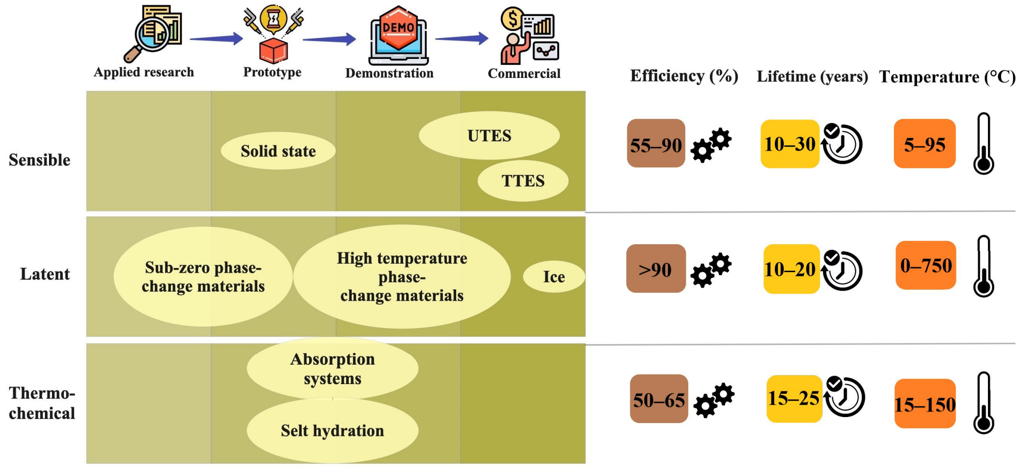

**Figure 6.** Thermal energy storage technologies and prospects for their development.

Table 1 shows the main technical characteristics of some types of thermal energy storage units used by household consumers [64].

**Table 1.** Technical characteristics of thermal energy storage units.

| Type of Thermal Energy Storage | Technology | Capacity | Power | Operating Temperature, °C | Efficiency, % | Storage Time | Lifetime |
|---|---|---|---|---|---|---|---|
| Sensible | WTTES * | 1 kWh–1 GWh | 1 kW–10 MW | 10–90 | 50–90 | Hours–months | 15–40 years |
| | UTES ** | MWh–GWh | 1–100 MW | 5–95 | >90 | Weeks–months | 50 years |
| | Solid state | 10 kWh–GWh | 1 kW–100 MW | 160–1300 | >90 | Hours–months | 5000 cycles |
| Latent | Low-temperature PCM *** | 1 kWh–100 kWh | 1–10 kW | >120 | >90 | Hours | 300–3000 cycles |
| | High-temperature PCM **** | 10 kWh–1 GWh | 10 kW–100 MW | >1000 | >90 | Hours–days | 5000 cycles |
| Thermo-chemical | Salt hydration | 10 kWh–100 kWh | – | 30–200 | 50–60 | Months | 20 years |

* WTTES—water tank thermal energy storage. ** UTES—underground thermal energy storage. *** Low-temperature PCM—low-temperature phase-change material. **** High-temperature PCM—high-temperature composite phase-change material.

The use of electric boilers utilizing electricity to generate thermal energy is a promising solution for DHSs. However, this requires the availability of a sufficient amount of inexpensive electricity produced primarily from renewable energy resources. Electricity is also required in air conditioning and ventilation systems to cool buildings and premises, although absorption chillers that consume thermal energy are also widely used for these purposes.

Despite the achievements of technical progress in the field of heating technology, heating systems in the Netherlands, France, Finland, Germany, Italy, China, and other countries still belong to the third generation. This is not so much because of the sufficient hydrocarbon fuels, which is typical of China and Russia, but because of a lack of economic incentives and technical requirements aimed at increasing the energy efficiency of heating systems.

These countries make energy conservation a priority in order to reduce thermal energy consumption and minimize losses during its transmission to consumers. This strategy has beneficial effects, including environmental ones, with a decrease in the volume of combustion of hydrocarbon fuels. While the focus on this strand of energy policy is indeed important, it is crucial to recognize the significant impact that can be achieved by simultaneously improving the energy efficiency of thermal energy production. By doing so, it is possible to magnify the positive environmental effects even further. To this end, attention should be paid to the wider use of cogeneration and trigeneration technologies in DHSs of the residential sector.

The flexibility of heating systems refers to the interchangeability of primary energy resources utilized to generate thermal energy, types of energy converted into thermal energy, and thermal energy sources that produce and supply thermal energy to the DHS [79–82].

The introduction of electric boilers, heat pumps [83], and thermal energy storage units has significantly enhanced flexibility of DHSs. Previously, boiler houses and CHPPs running on various types of hydrocarbon fuels were used as sources of thermal energy. The use of seasonal thermal energy storage devices during the non-heating period with a low heat load for residential consumers allows for increasing not only the flexibility of the DHS but also the efficiency of the CHPP operation [84,85].

This is due to the unique features of CHPPs where the fuel efficiency factor declines significantly and the specific fuel consumption for electricity production increases without the heat cogeneration [86,87]. The use of thermal energy storage devices enables the production of affordable electricity from CHPPs all year round, which is economically feasible to use for the generation of thermal energy in electric boilers or for power supply to heat pumps.

In order to keep buildings and premises cool during the non-heating period, electricity is primarily consumed by air conditioning and ventilation systems [88,89]. The cost of electricity produced by CHPPs remains cheaper than that produced using renewable energy resources. By directing this electricity to power household air conditioners and ventilation systems of public buildings, their operating efficiency can be increased. The use of absorption chillers, however, is even more effective, since they can utilize the thermal energy produced from the CHPP. The use of trigeneration helps boost the DHS efficiency.

The use of thermal energy storage devices, heat pumps, and electric boilers and the transition to trigeneration enhance the flexibility of DHSs [90,91]. At the same time, conditions are created to improve the CHPP efficiency during the non-heating period, which increases the capacity factor, i.e., enables the generation of a larger volume of affordable thermal and electrical energy [92,93].

The presence of a large number of various thermal energy sources also augments the flexibility of the DHS [94–96]. Figure 7 shows a DHS scheme where along with the CHPP and heating boiler houses, there are electric boilers and heat pumps that generate thermal energy. Furthermore, to increase the efficiency of electricity production, thermal energy storage facilities, and absorption chillers are used together with the CHPP.

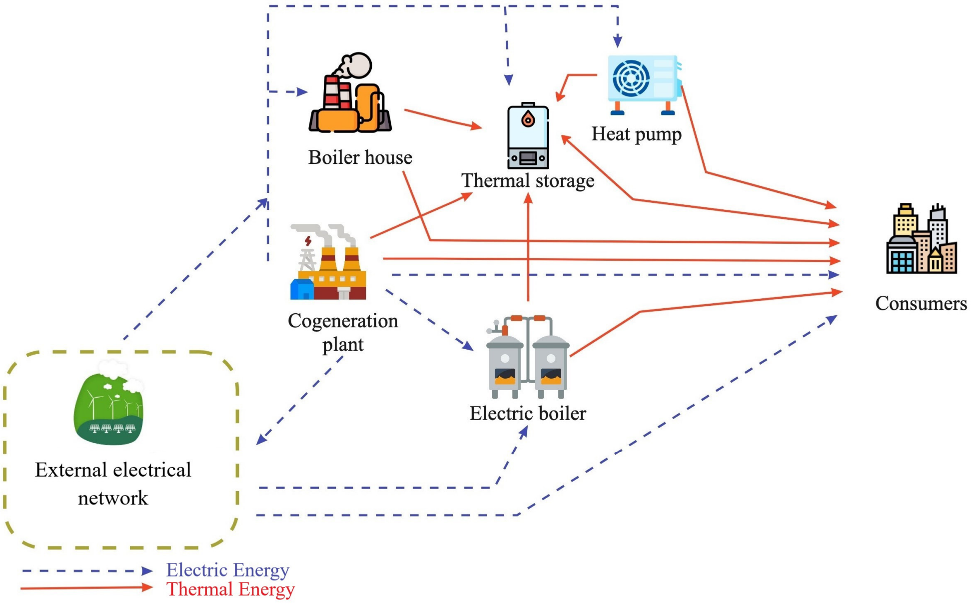

**Figure 7.** Scheme of a DHS with various sources of thermal energy.

The dotted lines in Figure 7 show the electric power system within the DHS, indicating the directions of power flows. In addition, the figure indicates the connection of the electric power system with the external electrical network, which receives the surplus electricity produced by the CHPP, and which delivers electricity in the event of its undersupply [97,98].

The DHS illustrated in Figure 7 is highly environmentally friendly, which is crucial in the current context. This factor enhances the appeal of DHSs for investment and fosters a positive perception of their development within society. According to the classification, the system in Figure 7 corresponds to generation four of DHSs. Nowadays, many countries have the necessary resources, technological capabilities, and economic potential to transition from current DHSs, providing heat to households, to more advanced fourth generation of the systems.

## 3. Materials and Methods

The more electricity generated by CHPPs, the greater their energy efficiency tends to be. Modern CHPPs have a high fuel utilization factor, which, when the consumed fuel is distributed in proportion to the generated volumes of electrical and thermal energy, makes them the most efficient sources of electricity. As a source of thermal energy, CHPPs are inferior to modern boiler plants, which have a fuel utilization factor of about 92–95%, since they require more fuel to produce the same volume of thermal energy. When boiler plants function as a backup source of thermal energy and as a source to meet peak thermal loads, their role changes. Efficient electric boiler systems can reduce and even eliminate the need for boiler facilities that leave a significant carbon footprint.

The main reduction in fuel consumption when using CHPPs occurs due to the displacement of outdated thermal power plants from the balance of electrical energy and power with steam power units (SPUs) running on hydrocarbon fuel. The advantages of CHPPs over SPUs with electrical efficiency no higher than 35% are obvious. The magnitude of the fuel effect depends on the amount of electricity generated by CHPPs, the electrical efficiency of which depends on the thermal load, which varies throughout the year. Given that the fuel and environmental effects depend on the volume of electricity produced by CHPPs, to increase the efficiency and capacity factor, it is advisable to implement measures aimed at increasing the heat cogeneration [99].

The main characteristic of DHSs is the annual heat load curve, known as the load duration curve (Rossander graph). It can be built for any region or country as a whole, considering their climatic characteristics. The Rossander graph allows selecting a mix of thermal power and energy sources, as well as the degree of their participation in supplying the heat load. By utilizing this method, it becomes possible to assess the capacity factor of thermal energy sources and, knowing the level of their efficiency, calculate the quantity of energy resources required to produce the needed volume of thermal energy [100].

For example, gas reciprocating CHPPs have a direct relationship between the production of electrical ($P^G$, $E_G$) and thermal ($Q^G$, $W_G$) power and energy, which is reflected by cogeneration factor ($k$):

$$Q^G = P^G \cdot k, \tag{1}$$

$$W_G = E_G \cdot k. \tag{2}$$

The thermal energy generated by gas reciprocating plants and gas turbine units is a by-product of electricity production, which, however, affects their economic efficiency. The efficiency of CHPPs depends on the use of generated thermal energy in the DHS. The greater the share of cogenerated thermal energy, the lower the fuel component in the cost structure of electricity generated by the CHPP.

Knowing the calorific value of gas ($q$) used in the gas reciprocating plant, the fuel utilization factor ($\eta^G$), and the capacity factor ($T_G$), we can calculate the volume of the fuel used:

$$B^G = (P^G + Q^G) \cdot T_G \ / \ (\eta^G \cdot q). \tag{3}$$

When using all the thermal energy generated by the gas reciprocating plant in the DHS, the fuel consumption ($B^G$) should be distributed in proportion to the thermal and electrical energy produced from the CHPP:

$$B^Q / B^P = k, \tag{4}$$

In this case, we obtain:

$$B^Q = B^G \cdot k / (k+1), \tag{5}$$

$$B^P = B^G / (k+1). \tag{6}$$

Based on expressions (4)–(6), with a proportional distribution of fuel for the production of thermal and electrical energy, the calculated values of electrical and thermal efficiency will be equal to the fuel utilization factor of the gas reciprocating plant:

$$\eta^Q = \eta^G = \eta^P, \tag{7}$$

Based on this conclusion, an objective function can be formulated as follows: maximize electricity generation, provided that all cogenerated thermal energy is supplied to the DHS.

This condition has a significant impact on the operating conditions of the CHPP during the non-heating period. The efficiency of the CHPP can be increased by switching to trigeneration by means of an absorption chiller, while reducing the heat load. In this case, the absorption chiller consumes surplus thermal energy generated by the CHPP, which allows it to highly efficiently generate electricity to power electric boilers and heat pumps. The surplus thermal energy from the CHPP can be effectively used by integrating seasonal low-temperature thermal energy storage units into the DHS. Thus, it becomes possible to transfer part of the generated thermal energy between heating periods. There is an option of using water-heating boilers running on hydrocarbon fuel to cover peak loads, as shown in Figure 8.

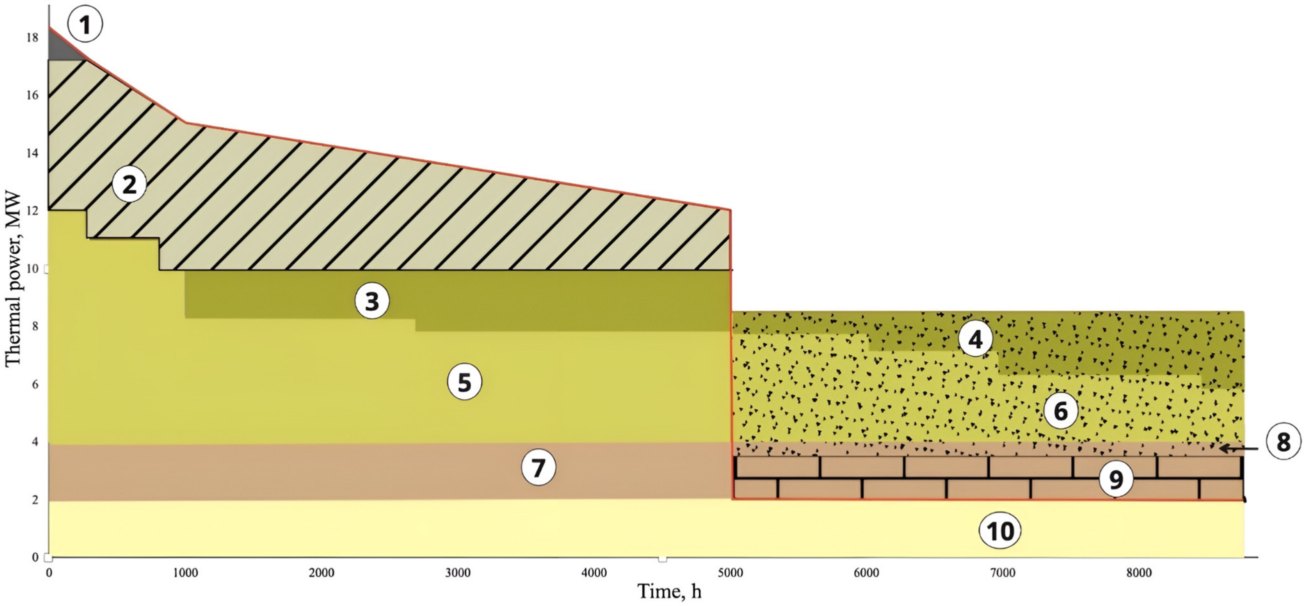

**Figure 8.** Graphic model of the Rossander graph filled with various thermal energy sources. 1—Heat supply from gas boilers and electric boilers; 2—heat delivered by thermal energy storage devices; 3—heat supply from CHPPs with their electricity delivered to external electrical network; 4—CHPP heat stored by thermal energy storage devices with CHPP electricity supplied to external electrical network; 5—heat supply from CHPP providing electricity to consumers in DHS; 6—CHPP heat stored by a thermal energy storage with CHPP electricity supplied to consumers in DHS; 7—heat supply from CHPPs powering electric boilers and heat pumps; 8—CHPP heat stored by thermal energy storage devices with CHPP electricity supplied to electric boilers and heat pumps; 9—heat supply from CHPP to absorption chillers; 10—heat supply from electric boilers and heat pumps.

The presented graphical model of filling the Rossander graph (Figure 8) allows the use of other thermal energy sources as well. These include low-potential heat pumps, ground-source energy facilities, solar collectors, and other plants for the production of thermal energy from renewable energy resources.

Below is a methodology for determining a mix of thermal energy sources in DHS, including CHPP, heating boiler houses, thermal energy storage devices, and electric boilers, which cover the annual heat load curve. The heating system has high inertia, which makes it resistant to various disturbances. This property is factored in and allows the proposed model to be considered robust when ensuring power and energy balances.

The total production of thermal energy can be represented by the sum of thermal energies generated by various sources:

$$W = W'_G + W_K + W_E + W_S, \tag{8}$$

where $W$ is the thermal energy required to cover the load duration curve throughout the year, MWh; $W'_G$ is the thermal energy generated from the CHPP to cover the heat load curve except for the energy intended for charging the thermal energy storage ($W_{ch}$) and operation of trigeneration ($W_t$), MWh; $W_K$ is the thermal energy produced by heating boiler plants, MWh; $W_E$ is the thermal energy generated by electric boilers, MWh; and $W_S$ is the thermal energy supplied by thermal energy storage devices to the DHS, MWh.

$W'_G$ is calculated using expression (9):

$$W'_G = W_G - W_t - W_{ch}, \tag{9}$$

where $W_G$ is the thermal energy generated by the CHPP to meet the heat load.

The thermal energy supplied by thermal energy storage devices is calculated based on the stored thermal energy ($W_{ch}$) and efficiency of the thermal energy storage ($\eta^s$):

$$W_S = \eta^s \cdot W_{ch}. \tag{10}$$

For electric boilers, the production of thermal energy is calculated by the amount of electrical energy consumed ($E_E$) and efficiency ($\eta^e$):

$$W_E = \eta^e \cdot E_E. \tag{11}$$

The equipment capacity necessary for the heating boiler plant is determined based on the requirement to ensure a balance of thermal power. For the studied DHS, the objective function has the form:

$$\begin{gathered} E_G = (E_E + E_c + E_r + E_t) \to max : \\ at \begin{cases} W_G = W + W_t + W_{ch} - W_K - W_E - W_S \\ \quad Q \geq (Q_G + Q_s + Q_K + Q_E) \\ \quad\quad T_G \leq T'_G \end{cases}, \end{gathered} \tag{12}$$

where $E_E$ is electrical energy generated by the CHPP to power electric boilers, MWh; $E_c$ is electrical energy generated by the CHPP to meet the load of consumers in the DHS service area, MWh; $E_r$ is the electrical energy generated by the CHPP to supply it to the external electrical network, MWh; $E_t$ is the electrical energy generated by the CHPP for auxiliaries, including the electrical energy for trigeneration, MWh; $Q$ is the thermal power of consumers served by the DHS, MW; $Q_s$ is the thermal power of the thermal energy storage, MW; $Q_K$ is the thermal power of the equipment at the heating boiler plant, MW; $Q_E$ is the thermal power of electrical boilers, MW; $T'_G$ is the maximum possible capacity factor of the CHPP, depending on its type and design, %; and $T_G$ is the actual capacity factor of the chosen CHPPs, %.

Knowing the amount of thermal energy generated by CHPPs, it is possible to calculate their capacity factor and the volume of electricity produced by them, which depends on the value of the cogeneration coefficient ($k$) for the selected technology.

The electricity generation from the CHPP will lead to a reduction in the electricity output of TPPs, which allows for calculating the magnitude of the CO2 emission reduction ($\Delta E_{\text{CO2}}$). The maximum environmental effect is achieved by reducing the utilization of steam coal at TPPs:

$$\Delta E_{\text{CO2}} = E_{\text{CO2}}{}^{coal} - E_{\text{CO2}}{}^{G}, \tag{13}$$

where $E_{\text{CO2}}{}^{coal}$ is CO2 emissions from electricity generation in the amount of $E_G$ at coal-fired TPPs; $E_{\text{CO2}}{}^{G}$ is CO2 emissions from electricity generation in the amount of $E_G$ at the CHPP.

The volume of CO2 emissions, considering all types of fuel used for electricity production, will be calculated using the expression:

$$E_{CO2} = \sum_{1}^{j} \left( EF_{CO2,j} \cdot B_j \cdot b_j \cdot 29308 \right) / 1000, \tag{14}$$

where $E_{CO2}$ is CO2 emissions from fuel combustion for the period, tons; $EF_{CO2,j}$ is CO2 emission factor for the combustion of fuel $j$, ton CO2/GJ; $j$ is the type of fuel used; $b_j$ is the conversion coefficient of fuel $j$ into the standard fuel; and $B_j$ is the consumption of fuel $j$ in physical terms, ton.

## 4. Results and Discussion

### *4.1. Modeling Example*

As an example, we consider a DHS with a maximum thermal load of consumers of 18 MW, an electrical load of 8 MW, and a heating period of 6000 h. Based on the optimization performed using a genetic algorithm in the MathLAB/Simulink 10.3 (Load Frequency Control) software, a graphical model of thermal energy source operation was obtained (Figure 9) [101–103].

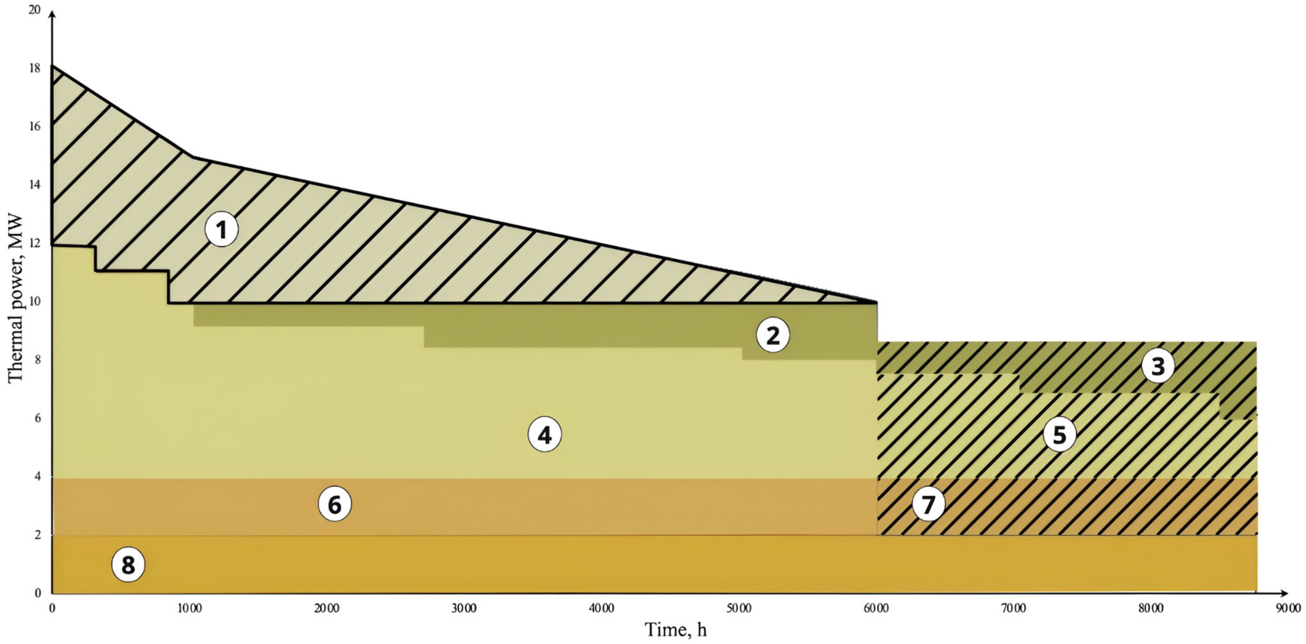

**Figure 9.** Graphic model of the Rossander graph for the selected DHS. 1—Heat delivered by thermal energy storage devices; 2—heat supply from CHPPs with their electricity transmitted to external electrical network; 3—CHPP heat stored by thermal energy storage devices with CHPP electricity supplied to external electrical network; 4—heat supply from CHPP providing electricity to consumers in DHS; 5—CHPP heat stored by thermal energy storage devices with CHP electricity supplied to consumers in DHS; 6—heat supply from CHPPs powering electric boilers; 7—CHPP heat stored by thermal energy storage devices with CHPP electricity supplied to electric boilers; 8—heat supply from electric boilers.

The mix of the equipment selected for the considered DHS, the installed capacity of each type of thermal energy source and the volumes of consumed energy resources are presented in Table 2.

Based on the calculation findings, the capacity factor of the CHPP increased to 76%, and with the value of the cogeneration coefficient ($k$) close to unity, the amount of electricity generated by the CHPP was more than 67,000 MWh. Part of this electricity was used to power electric boilers that provide hot water. CHPP electricity generation on the basis of gas reciprocating plants is accompanied by CO2 emissions equal to 31.3 thousand tons.

**Table 2.** Equipment for the considered DHS.

| Type of Energy Source | Capacity, MW | Energy Resource | Resource Volume |
|---|---|---|---|
| CHPP | 10 | Natural gas | 17,000 thousand $m^3$ |
| Electrical boilers | 2 | Electrical energy | 17,500 MWh |
| Thermal energy storage | 6 | Thermal energy from CHPP | 18,000 MWh |

A reduction in the electricity output of the TPP by 67,000 MWh, with a specific fuel consumption of 300 g.c.e./kWh, will save burned fuel by 26.2 thousand tons of coal in physical terms and cut down CO2 emissions by 70.8 thousand tons. Thus, the environmental benefit from reducing greenhouse gas emissions will be 39.5 thousand tons. A similar decrease in CO2 emissions can be achieved by generating electricity from a photovoltaic power plant with a capacity of about 27 MW, operating with a capacity factor of 16%.

In addition to the above-discussed main benefits to be gained from the modernization of the DHS of residential consumers, there are additional benefits to be derived with further upgrading of the systems.

### 4.2. Enhancing the Energy Efficiency of Thermal Energy Production

Based on its key features, the analyzed DHS, which primarily serves household consumers and encompasses a range of thermal energy sources, can be classified as a fourth-generation system (4 GDH). However, this DHS has great potential to transition to the advanced fifth generation (5 GDH).

The DHS at issue relies on low-power CHP units (up to 5 MW), which serve as cost-effective sources of both electrical and thermal energy. The presence of the CHPP as part of the DHS makes it possible to partially or completely satisfy the demand for electricity of consumers located in the DHS service area and distribute the surplus to the external electrical network [104,105].

The increase in the environmental friendliness of the DHS allows us to simultaneously address the challenges of enhancing the technical reliability and economic accessibility of thermal and electrical energy.

In large cities with a high share of household consumers, the thermal energy supply from large TPPs reaches 80%. For example, in Copenhagen, Odense, and other cities in Denmark, this figure is 98%. The share of cogeneration heat production in large cities in Finland is close to 95%.

The main potential for increasing the energy efficiency of electric and thermal energy production from the CHPP is concentrated in medium and small towns and populated localities. The main reason for this is the existence of various gas boiler houses of different sizes in these areas. These boiler houses serve as the primary sources of thermal energy in DHSs. The introduction of low-power CHPPs in these cities will improve the technical reliability and economic accessibility of the heat supply.

### 4.3. Boosting the DHS Technical Reliability

In the studied DHS, where thermal energy is produced using electric boilers, it becomes possible to bring the peak source of thermal energy closer to the consumer [106,107]. This will help to facilitate the operation of heat networks, reduce losses during thermal energy transmission, and lower the number of accidents in heat networks. The listed issues are most relevant for DHSs with worn-out and extensive heat networks.

Heat networks are more vulnerable during peak-load periods when the temperature or volume of the coolant rises. This vulnerability causes a decline in their technical reliability. With the peak heat source transferred directly to the consumer, heat networks will operate with no increase in the temperature and volume of the coolant when the outside air temperature drops. Calculations show that the technical reliability of heat networks in this case increases by more than 25% [108,109].

### *4.4. Increasing the DHS Cost-Effectiveness*

The rise in the number and variety of thermal energy sources and options for their placement in DHSs enhances their overall efficiency. For example, the high economic efficiency of electric boilers when used for hot water supply to consumers is due to the production of inexpensive electricity at the CHPP [110,111]. The cost of electricity generated by the CHPP is less than the cost of electricity supplied to residential consumers from the retail electricity market. The proximity of the CHPP to electrical loads, their high capacity factor, and electrical efficiency determine their cost-effectiveness. This approach significantly enhances the appeal of investing in CHPPs and ensures their payback in about 3–5 years, also guaranteeing a supply of resources for a minimum of 10–15 years.

The availability of inexpensive thermal and electrical energy from CHPPs helps to attract private investment in the construction of electric boilers, heat pumps, and thermal energy storage systems, as well as their integration with CHPPs within the district heating and cooling systems [112].

### *4.5. Establishment of Intelligent Control Systems for DHSs*

Along with the increase in the energy efficiency of thermal energy production, it is crucial to pay special attention to energy saving. This involves equipping DHSs with an appropriate intelligent control system. When dealing with this issue, it is important to consider the specificities and variations in consumer requirements within the public utility industry across various countries.

The level of energy saving can be determined by the comfortable temperature maintained in apartments. It is imperative to highlight that in countries with higher levels of gross domestic product (GDP) per capita, the temperature maintained in apartments is lower. Figure 10 shows the active participation of household consumers in energy conservation [113].

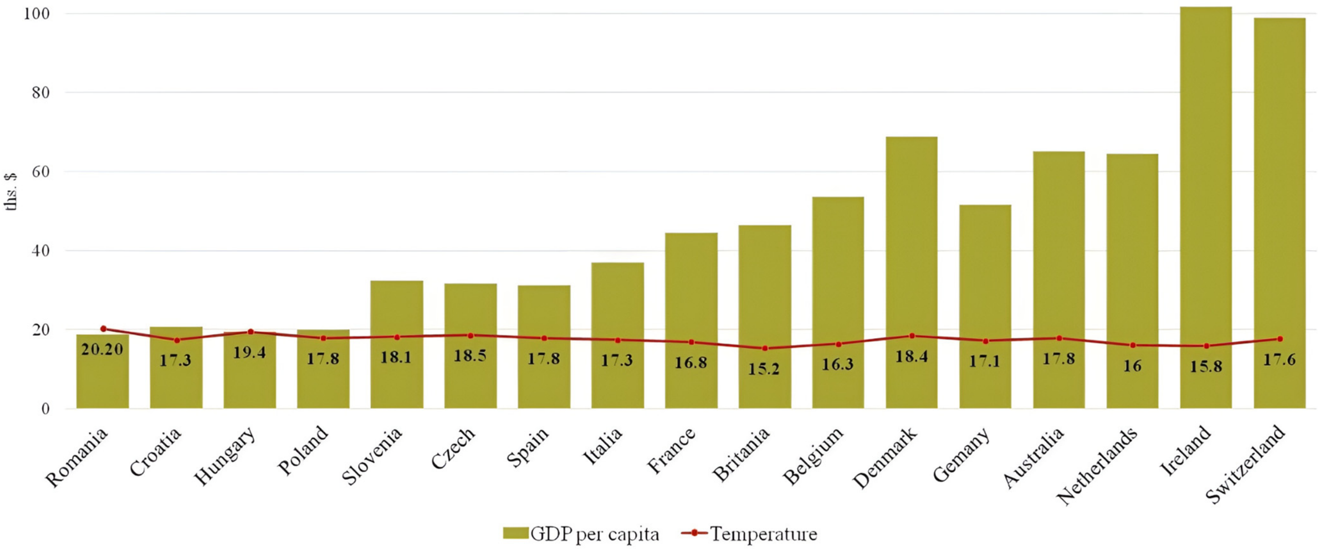

**Figure 10.** The relationship between GDP per capita and temperature in apartments by country.

Decrease in thermal energy consumption for heating apartments is achieved through the use of control devices in individual heating systems. In DHS, there can be a combination of system-wide and individual approaches to managing thermal energy consumption, but this requires the modernization of DHSs and their control systems.

The primary focus of modernizing DHS control systems lies in their digitalization and intelligentization. Without intelligent control systems for the production and consumption of thermal energy, it is difficult to ensure optimal coordination of the interests of producers, suppliers, and consumers of thermal energy. An efficient technological interaction between various sources of thermal energy and heat receivers is crucial for a successful transition of DHSs to the level of 4 GDH and 5 GDH. If consumers are not provided with the opportunity to actively and equally participate in the thermal energy market, and if they are not encouraged to use their sources of thermal energy for supply to the DHS, then ensuring the development of DHSs in the domestic sector will be a challenging task.

Global climate change associated with global warming heightens the need for a cooling supply to consumers in many countries, which requires the adaptation of DHSs to new challenges. The possibility of expanding the DHS functions into the area of cooling supply to consumers should be considered to enhance its economic viability.

The creation of a flexible and efficient DHS that integrates a host of different sources of thermal energy using various energy resources, including renewable ones, allows the DHS to transition to a more energy-efficient generation [114,115]. To ensure the transition of the DHS to 4 GDH and 5 GDH level, it is recommended to commence it in regions and countries that offer favorable preconditions for the development of integrated energy systems based on a low-power CHPP for household consumers.

## 5. Conclusions

The study focuses on the use of low-power CHPPs that generate inexpensive electrical and thermal energy. The findings have demonstrated that the efficiency of CHPPs depends on the ratio of the thermal and electrical load curves they cover. The maximum CHPP efficiency is achieved when all generated thermal energy is supplied to the DHS. With the pronounced seasonality of the heat load curve of residential consumers during the non-heating period, it is important to use thermal energy storage devices. This solution will enhance the efficiency of electricity generated from the CHPP when part of it is supplied to power thermal energy sources, including heat pumps and electric boilers. The use of a CHPP makes it possible to create heating systems that harness the benefits of both individual and district systems; however, the implementation of intelligent control systems is necessary for this to become a reality.

We have developed a methodology that enables us to identify the optimal mix of thermal energy sources to cover a given annual heat load duration curve. The objective function during optimization is to maximize the electricity generation from the CHPP, subject to the useful supply of all generated thermal energy to the DHS.

A significant positive impact on the environment is achieved by replacing outdated coal-fired thermal power plants with CHPPs, which ensures a better balance of electrical energy and power, and a reduction in the amount of thermal coal burned. The modeling results show that the district heating system with a low-power CHPP can reduce CO2 emissions by cutting down energy production from a coal-fired power plant. A similar effect is obtained with a solar power plant, the power of which is almost three times higher than that of the CHPP.

The study indicates that the proposed methodology can provide prerequisites for the transition of the district heating system from the third generation to the fourthone, and there are promising prospects for a future transition to the fifth generation. Such a system will be highly flexible since it allows the interchangeability of various thermal energy sources. Inexpensive electricity from CHPPs can be used to produce thermal energy in electric boilers. In addition, the DHS functions are expanding with cooling supply provided to buildings and premises of residential consumers, thus boosting the economic efficiency of the DHS.

### *Future Research Directions*

The implementation of the proposed approach to the modernization of existing district heating systems requires the incorporation of intelligent control systems for managing the production and consumption of thermal energy. It is crucial to identify the boundary conditions that determine the investment attractiveness of incorporating certain sources in the district heating system. In addition, changes and updates to the institutional framework are essential to increase competition in the thermal energy market and bolster the appeal of the DHS to attract potential investors.

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