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A First of a kind Hub for circularity demonstrator for Attica and peripheral regions

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Publishable summary

Deliverable 6.1, titled "RES Technologies", was developed within the framework of WP 6 "Energy Symbiotic Flows" and focuses on the integration of innovative Renewable Energy Sources (RES) into District Heating (DH) systems. Specifically, it explores a range of RES technologies suitable for DH applications—including solar thermal systems, biomass boilers, geothermal heat pumps, and wind power—alongside the potential use of alternative fuels such as hydrogen and the injection of biogas into the natural gas network.

Particular emphasis is placed on the role of energy storage technologies in enhancing system flexibility and efficiency. Furthermore, the deliverable presents potential hybrid configurations that could offer improved operational performance.

The final section of the report centres on the Energy Pilot Site of Ptolemaida, evaluating its potential for integrating renewable energy solutions into the existing district heating infrastructure, with the aim of supporting its transition toward a greener energy model.

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Contents

1 Abstract 12
2 Introduction 13
3 RES technologies to DH 14
3.1 Solar Thermal Systems 14
3.1.1 Technology description 14
3.1.2 Benefits 16
3.1.3 Obstacle and Barriers 16
3.1.4 Replicability issues 17
3.2 Biomass Boilers 17
3.2.1 Technology description 17
3.2.2 Benefits 18
3.2.3 Obstacle and Barriers 18
3.2.4 Replicability issues 19
3.3 Geothermal Heat Pumps 19
3.3.1 Technology description 19
3.3.2 Benefits 20
3.3.3 Obstacle and Barriers 21
3.3.4 Replicability issues 21
3.4 Wind Power 22
3.4.1 Technology description 22
3.4.2 Benefits 23
3.4.3 Obstacle and Barriers 24
3.4.4 Replicability issues 24
3.5 Hydrogen 25
3.5.1 Technology description 25
3.5.2 Benefits (energy, environment, economy etc) 27
3.5.3 Obstacle and Barriers 27
3.5.4 Replicability issues 28
3.6 Biogas Injection into Natural Gas Grid 28
3.6.1 Technology description 28

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This project has received funding from the European Union Horizon Research and Innovation programme under grant agreement No 101178059

3.6.2 Benefits (energy, environment, economy etc) 29
3.6.3 Obstacle and Barriers 30
3.6.4 Replicability issues 30
3.7 Storage technologies 31
3.7.1 Technology description 31
3.7.2 Different types of storage technology 31
3.7.3 Benefits (energy, environment, economy etc) 33
3.7.4 Obstacle and Barriers 34
3.7.5 Replicability issues 35
3.8 Hybrid Systems 35
3.8.1 Technologies' combination 35
3.8.2 Benefits (energy, environment, economy etc) 36
3.8.3 Obstacle and Barriers 36
3.8.4 Replicability issues 36
4 The case of Ptolemaida District Heating System 38
4.1 Description of DH of Ptolemaida and projection of energy needs at a 10-year level 38
4.1.1 Driving forces and/or opportunities that favour DH expansion 42
4.1.2 Barriers to the expansion of DH 43
4.2 Energy potential analysis 44
4.2.1 Solar Thermal Systems 44
4.2.2 Wind Power 44
4.2.3 Biomass Boilers 45
4.2.4 Biogas injection into Natural Gas Grid 45
4.2.5 Conclusion 45
4.3 Development of scenarios for greening the DH 46
4.3.1 Scenario 1: Biomass Boilers 46
4.3.2 Scenario 2: Electrification 47
4.3.3 Scenario 3: Hybrid solution 49
5 Conclusions 55
References 57
Annexes 61

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List of Figures

Figure 1: Flat plate collector (source: *Prospective scenarios for the full solar energy development in Malaysia. Renewable and Sustainable Energy Reviews*) 14

Figure 2: Direct-flow evacuated-tube collectors and heat pipe evacuated-tube collectors (source: *Prospective scenarios for the full solar energy development in Malaysia*) 15

Figure 3: Aquifer thermal energy storage and borehole thermal energy storage (source: *Research progress of seasonal thermal energy storage technology based on supercooled phase change materials)* 15

Figure 4. Wind turbine driven heat pump system for heating (source: *Design and evaluation of a wind turbine-driven heat pump system for domestic heating in Scotland*) 23

Figure 5. A typical hydrogen technology application system (source: *Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials*). 26

Figure 6. Schematic network for WWTP biogas DH (Source: *District heating based on biogas from wastewater treatment plant*) 29

Figure 7. A real photo of Dronninglund pit storage (source: *Dronninglund water pit thermal energy storage dataset*) 33

Figure 8. Production and transportation of hot water for district heating in Ptolemaida 39

Figure 9. Distribution network of DHCP 41

Figure 10. Energy balance for scenario 2 48

Figure 11. Monthly energy surplus or shortage for scenario 2 49

Figure 12. Thermal energy demand for the operation of district heating system 50

Figure 13. Energy balance of primary network for scenario 3 51

Figure 14. Monthly energy surplus or shortage of thermal energy for scenario 3 52

Figure 15. Energy balance of secondary network for scenario 3 53

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Figure 16. Monthly energy surplus or shortage of electrical energy for scenario 3..... 54

List of Tables

Table 1. Characteristics of DHCP's network 41

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Abbreviations

Abbreviations	Full name
RES	Renewable Energy Source
DH	District Heating
GHG	Greenhouse Gases
CHP	Combined Heat and Power
TES	Thermal Energy Storage
FPC	Flat Plate Collectors
ETC	Evacuated Table Collectors
BTES	Borehole Thermal Energy Storage
ATES	Aquifer Thermal Energy Storage
ORC	Organic Rankine Cycle
BECCS	Bioenergy Carbon Capture and Storage
GHPs	Geothermal Heat Pumps
DHC	District Heating and Cooling
HVAC	Heating, Ventilation and Air Conditioning
P2H	Power-to-Heat
COP	Coefficient of Performance
PTES	Pit Thermal Energy Storage
SMR	Steam Methane Reforming
POX	Partial Oxidation
CCUS	Carbon, Capture, Utilization and Storage
GoOs	Guarantees of Origin
EESS	Electrical Energy Storage System

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BESS	Batteries Energy Storage System
PPC	Public Power Corporation
DHCP	District Heating Company of Municipality of Ptolemaida
NSRF	National Strategic Reference of Framework
PPPs	Public-Private Partnerships
SPF	Seasonal Performance Factor
LHV	Low Heat Value

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1 Abstract

Deliverable 6.1, titled "RES Technologies", was developed within the framework of WP 6 "Energy Symbiotic Flows" and focuses on the integration of innovative Renewable Energy Sources (RES) into District Heating (DH) systems. Specifically, it explores a range of RES technologies suitable for DH applications—including solar thermal systems, biomass boilers, geothermal heat pumps, and wind power—alongside the potential use of alternative fuels such as hydrogen and the injection of biogas into the natural gas network.

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The final section of the report centres on the Pilot Site of Ptolemaida, evaluating its potential for integrating renewable energy solutions into the existing district heating infrastructure, with the aim of supporting its transition toward a greener energy model.

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2 Introduction

The operational principles of district heating can be traced back to the Roman era where thermal energy was distributed via rudimentary channels to heat public baths and horticultural enclosures. However, the modern conceptualization of district heating systems—characterized by centralized thermal energy production, distribution networks and end-user delivery—began to crystallize in the mid-19th century. During this period, industrial Britain pioneered the reuse of excess thermal energy from factory operations to supply communal bathhouses.

Since then, district heating and cooling systems have undergone extensive technological evolution, driven by advancements in thermodynamic efficiency, materials, network and control systems. These developments have been instrumental in shaping more resilient and energy-efficient urban infrastructures. Today, district energy systems are recognized as key components in strategies aimed at the decarbonisation of urban heat supply and the broader energy transition.

As of 2024, Europe hosts an estimated number of 17,000 operational district heating systems, collectively serving the thermal energy needs of over 70 million citizens. These systems contribute to a total final energy consumption exceeding 450 TWh annually, underscoring their critical role in regional energy security and system-level load balancing. Focusing on district heating technologies is imperative when considering that approximately 50% of the European Union's final energy consumption is associated with the heating and cooling sectors. Moreover, projections indicate a substantial rise in cooling demand by 2050, with residential cooling expected to increase by up to 750% and commercial sector demand projected to grow by 275%. Simultaneously, the building sector alone accounts for 40% of total final energy consumption and contributes to 36% of greenhouse gas (GHG) emissions, of which roughly 70% are attributable to space heating and cooling requirements. These figures highlight the urgency of transforming thermal energy systems through low-carbon, high-efficiency alternatives.

The fundamental technical and environmental challenge lies in the primary energy used for the DH systems operation. Historically, these systems have predominantly relied on waste heat from industrial processes or combined heat and power (CHP) plants—many of which are fossil fuel-based. Despite efficiency gains associated with cogeneration, fossil fuels such as coal, lignite, and natural gas continue to dominate as primary energy sources, posing a barrier to long-term sustainability. Therefore, beyond infrastructure expansion and technology optimization, the future viability of DH systems hinges on their integration with renewable energy sources, as well as thermal energy storage (TES) technologies to enhance flexibility and seasonal load management.

This deliverable directly addresses the systemic challenge of decarbonizing district heating systems. The first section offers a comprehensive analysis of emerging green technologies suitable for integration into modern DH systems, including their operational characteristics, compatibility and potential for scalability. The second section provides a focused case study of the district heating network in the city of Ptolemaida. It assesses the current operational status of the system, evaluates opportunities for renewable energy integration, and presents three distinct transition scenarios. These scenarios are developed to reflect varying degrees of technological, financial, and policy ambition and are intended to serve as pragmatic roadmaps toward a sustainable, low-emission heat supply system for the region.

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3 RES technologies to DH

The integration of RES into DH systems offers a range of significant benefits—most notably in terms of environmental performance, GHG emissions reduction and long-term sustainability. However, this transition is not without challenges. The primary technical and operational constraints stem from the intermittent and non-dispatchable nature of many renewable energy sources. Specifically, renewable energy generation often does not align temporally with heat demand profiles, resulting in mismatches between supply and demand in both timing and quantity. Moreover, geographic and site-specific limitations further constrain the applicability of certain RES technologies. The following sections provide a comprehensive assessment of the advantages, limitations, and applicability of various RES technologies in the context of district heating. This includes a detailed evaluation of their technical feasibility, integration complexity, scalability, and compatibility with existing thermal infrastructure.

3.1 Solar Thermal Systems

Solar thermal energy systems harness solar radiation to produce heat, which can then be integrated into district heating networks. These systems provide an efficient and sustainable alternative to conventional fossil fuel-based heating, contributing to the decarbonization of urban energy infrastructures.

3.1.1 Technology description

Solar thermal energy systems use solar collectors to capture sunlight and convert it into thermal energy, which is then transferred to a heating network for space heating and hot water. The fundamental principle of solar thermal technology in district heating networks lies in the ability to absorb solar radiation using specially designed collectors, transfer the heat through a fluid (usually water or an antifreeze solution), and then deliver the heat to the network to supply the buildings connected to it.

There are several types of solar collectors, with **flat plate collectors** (FPC) being the most common for district heating networks. FPCs consist of an insulated, flat, and usually black absorber plate that absorbs sunlight and heats a fluid passing through pipes attached to the plate. The heated fluid is pumped through a system of pipes that transport the thermal energy to a central distribution point in the district heating network.

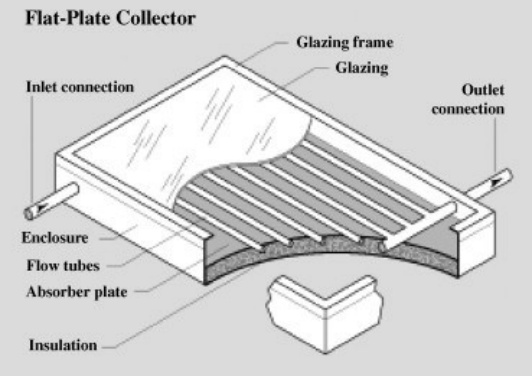


Figure 1: Flat plate collector (source: *Prospective scenarios for the full solar energy development in Malaysia. Renewable and Sustainable Energy Reviews*)

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In contrast, **evacuated tube collectors** (ETC) use vacuum-sealed glass tubes to reduce heat loss and increase efficiency, making them suitable for colder climates or areas with lower sunlight intensity. These tubes capture heat more effectively, especially in regions where winter conditions could otherwise limit performance.

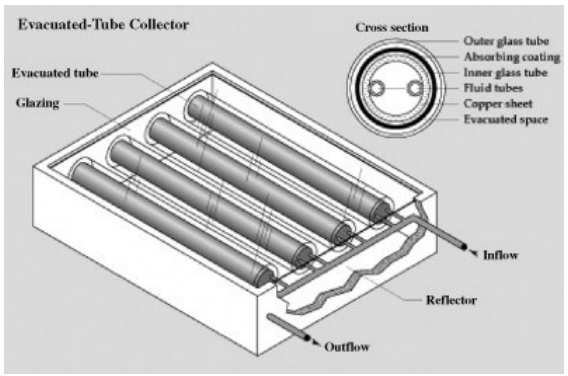


Figure 2: Direct-flow evacuated-tube collectors and heat pipe evacuated-tube collectors (source: *Prospective scenarios for the full solar energy development in Malaysia*)

The integration of solar thermal energy into district heating systems requires an effective heat transfer mechanism to ensure stable heat supply. Once heat is absorbed by the collectors, it is transported through insulated pipes to either a heat exchanger or a thermal storage system. In many cases, **thermal energy storage (TES)** is essential to manage fluctuations in solar energy availability. Short-term storage typically consists of large insulated water tanks, which allow excess heat generated during the day to be stored for use during nighttime or periods of low solar radiation. For seasonal storage, more advanced systems such as borehole thermal energy storage (BTES) or aquifer thermal energy storage (ATES) can be used, where heat is stored underground for long-term use, ensuring a stable supply throughout the winter months.

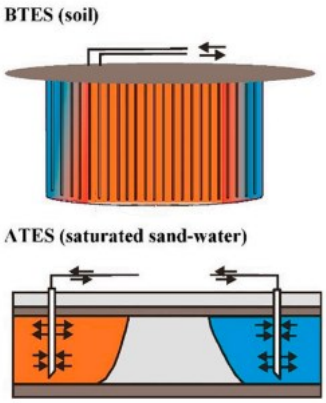


Figure 3: Aquifer thermal energy storage and borehole thermal energy storage (source: *Research progress of seasonal thermal energy storage technology based on supercooled phase change materials)*

In essence, solar thermal systems in heating networks work by collecting solar energy through collectors, transferring this energy via heat exchangers, and distributing it to the heating network. These systems can

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either work in a hybrid manner with other heat sources, or in standalone systems when combined with storage solutions that ensure continuous heat supply.

3.1.2 Benefits

Solar thermal systems offer numerous advantages when incorporated into district heating networks. Environmentally, they provide a renewable and clean energy source, reducing dependence on fossil fuels and significantly cutting greenhouse gas emissions. This makes them a crucial component in the transition towards low-carbon energy solutions.

From an economic perspective, although the initial investment in solar collectors and infrastructure can be substantial, operational costs remain low. Since solar energy is free, fuel expenses are significantly reduced over the system's lifetime. Additionally, solar thermal energy enhances energy security by reducing reliance on imported fossil fuels, protecting economies from energy price volatility and supply disruptions.

Beyond cost savings, integrating solar thermal systems into district heating networks contributes to grid stability and helps meet renewable energy targets set by governments and international climate agreements. These systems align with sustainability policies, encouraging further investments in clean energy infrastructure.

Overall, the benefits of solar thermal systems in district heating networks are clear. They provide a sustainable, cost-effective, and reliable solution for heating that contributes to reducing carbon emissions.

3.1.3 Obstacle and Barriers

Despite the numerous advantages of solar thermal systems in district heating networks, several obstacles hinder their widespread adoption. These challenges can be grouped into technical, economic, and land-related barriers.

A major technical challenge in implementing solar thermal systems at a large scale is the intermittency and variability of solar energy. Solar radiation varies depending on weather conditions, seasons, and geographic location, which can lead to inconsistent heat production. To ensure a stable heat supply, reliable energy storage solutions are required. While short-term storage options, such as thermal water tanks, can manage daily fluctuations, long-term storage solutions like Borehole Thermal Energy Storage (BTES) or ATES are expensive and technically complex to implement. The need for such advanced storage systems adds to the overall system complexity and investment.

Although operational costs are relatively low once the infrastructure is in place, the high upfront costs associated with solar collectors, storage systems, and their integration into existing district heating networks can be a significant barrier.

Large-scale solar thermal installations require a substantial amount of land to accommodate the solar collectors. In urban areas, where space is both limited and costly, finding suitable locations for such systems can be a challenge. The availability of land for solar thermal plants may be restricted in densely populated or industrialized areas, making it difficult to replicate successful projects in similar urban environments.

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3.1.4 Replicability issues

A notable example of large-scale solar district heating is the Silkeborg solar thermal plant in Denmark, one of Europe's largest installations of its kind. Designed to supply a substantial portion of the city's heating demand using solar energy, this facility showcases the potential of solar thermal technology in urban energy systems.

Covering an area of 156,700 m² with 12,436 solar panels, the Silkeborg plant generates approximately 80,000 MWh of thermal energy per year, covering around 20% of the city's annual heating consumption. The produced heat is distributed through the district heating network, reducing reliance on fossil fuels such as natural gas and significantly cutting carbon emissions. By avoiding approximately 15,000 tonnes of CO_2 emissions annually, the project exemplifies the environmental benefits of solar thermal integration.

An essential feature of the Silkeborg system is its thermal energy storage capability. During sunny periods, excess heat is stored in large insulated reservoirs, allowing continuous supply even during winter. This storage mechanism enhances the system's reliability and efficiency, ensuring that solar energy remains a viable heating source throughout the year. During summer months, the plant can nearly fully meet the city's heating demand, further decreasing dependence on conventional energy sources.

The Silkeborg project serves as a model for other cities aiming to incorporate solar thermal technology into their district heating systems. Its success demonstrates that large-scale solar heating can be both economically viable and environmentally responsible, paving the way for future renewable energy initiatives in urban areas.

3.2 Biomass Boilers

3.2.1 Technology description

Biomass boilers are thermal energy conversion systems that utilize organic materials, such as wood chips, agricultural residues, or pellets, as fuel. These systems are commonly integrated into district heating networks due to their ability to provide a sustainable and locally sourced energy supply. The core principle of biomass boilers is combustion, where biomass fuel is burned in a chamber, generating heat that is transferred to water through heat exchangers. This heated water is then distributed via district heating pipelines to supply residential, commercial, or industrial buildings.

Modern biomass boilers are often equipped with advanced combustion control mechanisms, enabling high energy conversion efficiencies while minimizing emissions. Some of these systems incorporate thermal energy storage, which enhances operational flexibility by allowing surplus heat to be stored and utilized during peak demand periods. Moreover, biomass-fuelled combined heat and power (CHP) systems have been developed to optimize energy efficiency by simultaneously generating electricity and heat, making them ideal for district heating applications.

A variety of CHP technologies can be employed in biomass-based district heating systems, including:

Steam Turbines: Convert steam from biomass combustion into mechanical energy to drive a generator.

Organic Rankine Cycle (ORC): Uses an organic fluid with a low boiling point to generate electricity efficiently at lower temperatures.

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Gasification CHP: Converts biomass into a synthetic gas (syngas) that can be burned in gas engines or turbines.

Biomass boilers can achieve high temperatures of up to approximately 500°C, making them capable of meeting large amounts of energy demand.. Additionally, the integration of Bioenergy Carbon Capture and Storage both heat and power demands (BECCS) offers the potential for negative CO_2 emissions, enhancing the environmental benefits of biomass energy.

3.2.2 Benefits

Biomass boilers offer multiple advantages across energy, environmental, and economic dimensions:

Energy Security: Biomass is a renewable, storable energy source that reduces dependence on fossil fuels. The ability of biomass boilers to provide baseload heat and power generation makes them highly reliable for district heating applications.

Environmental Advantages: Biomass combustion is nearly carbon-neutral over its entire lifecycle, as the CO2 released during combustion is offset by plant absorption during growth. Additionally, the use of agricultural residues in district heating systems contributes to waste reduction and supports circular economy principles.

Economic Benefits: Biomass fuel is often more cost-effective than fossil fuels, particularly when sourced locally. The development of biomass district heating systems creates employment opportunities and promotes local economic growth.

Technological Efficiency: Biomass CHP systems can achieve high efficiency, particularly when used in cogeneration configurations. They also offer flexibility by participating in balancing energy markets and covering residual heat and electricity loads.

3.2.3 Obstacle and Barriers

Despite their advantages, biomass boilers face several challenges:

Indirect Greenhouse Gas Emissions and Pollutants: While biomass is considered a cleaner alternative to fossil fuels, combustion still generates particulate matter and nitrogen oxides (NOx), necessitating the implementation of advanced emission control technologies.

Limited Biomass Availability: The potential of biomass for large-scale deployment is constrained by land requirements, competition with other biomass applications (such as food production or material manufacturing), and supply chain limitations.

High Initial Investment and Infrastructure Costs: The capital expenditure required for biomass boiler installation, district heating networks, and necessary transport infrastructure is often significant, which can be a major barrier to adoption.

Fuel Supply Chain and Logistics: Ensuring a stable and sustainable biomass fuel supply is critical for uninterrupted operation. Variability in fuel availability, transportation logistics, and price fluctuations can impact the economic viability of biomass heating systems.

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Competition for Biomass Resources: The demand for biomass is increasing in various sectors, leading to potential competition for supply, which may affect pricing and availability.

Storage and Transportation Challenges: Biomass fuel requires adequate storage space and a well-established transport network to ensure a reliable supply chain, particularly in regions with limited infrastructure.

3.2.4 Replicability issues

In Turku, Finland, biomass has been successfully integrated into the city's district heating system through a CHP plant. According to the Case study on Biomass use in CHP in Turku, Finland, the plant is a key component of the city's strategy to achieve carbon neutrality. The system uses locally sourced biomass, primarily wood chips and forest residues, which helps to reduce dependence on imported fossil fuels and supports the local economy.

The biomass CHP plant in Turku has an installed capacity of around 40 MW electrical and 90 MW thermal, allowing it to supply both electricity to the grid and heat to the district heating network. The plant operates with a high overall efficiency, reaching above 85% thanks to the cogeneration process. The heat is distributed through an extensive underground network that supplies residential, commercial, and public buildings throughout the city.

One important technical feature of the Turku plant is its flexibility: it can adjust the power-to-heat ratio depending on seasonal demand, optimizing both electricity production and heat supply. During the colder months, priority is given to heat production to meet the high thermal load, while in summer, the plant shifts towards greater electricity generation. Additionally, advanced flue gas cleaning systems are installed to minimize particulate emissions, ensuring that environmental standards are met.

The integration of biomass into Turku's district heating system demonstrates that local renewable resources can be efficiently used to decarbonize urban energy supplies. However, replicating such a system elsewhere would require stable biomass supply chains, strong political support, and investments in high-efficiency CHP technologies.

3.3 Geothermal Heat Pumps

3.3.1 Technology description

Geothermal Heat Pumps (GHPs), also known as ground source heat pumps, are a mature and highly efficient technology used for space heating, cooling, and domestic hot water production. Their operation is based on the principle of heat exchange with the ground, whose temperature remains relatively stable throughout the year compared to air temperatures.

In a typical system, a closed-loop network of pipes, often referred to as ground heat exchangers, is buried vertically (in boreholes) or horizontally (in trenches). These pipes circulate a heat transfer fluid (usually water or a water-antifreeze solution), which either absorbs heat from the ground (for heating) or rejects heat to

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the ground (for cooling). A heat pump then amplifies this thermal energy and transfers it to the building's distribution system.

Recent developments, as outlined in *Shallow Geothermal Energy Systems for District Heating and Cooling Networks: Review and Technological Progression Through Case Studies*, emphasize the use of **shallow geothermal systems** (depths typically less than 500 meters) integrated into **district heating and cooling (DHC) networks**. Instead of serving a single building, the geothermal system feeds a network supplying multiple users, increasing the overall system efficiency and allowing better load balancing.

Several configurations are employed:

- **Decentralized systems**: each building is connected to a shared ground loop but has its own heat pump.
- **Centralized systems**: a large-capacity heat pump injects thermal energy directly into the district network.
- **Hybrid systems**: combine shallow geothermal with other heat sources or seasonal storage to optimize performance.

Importantly, the integration of shallow geothermal energy into DHC systems often requires adaptation of the **temperature levels** in the network. Lower temperature networks (4th and 5th generation DHC) are ideal because they match the moderate output temperatures of GHPs and minimize thermal losses.

Case studies reviewed show innovative uses of **aquifers** and **geostructures** (like energy piles) to enhance thermal exchange performance, while maintaining the sustainability of underground thermal resources.

3.3.2 Benefits

Geothermal Heat Pumps present numerous advantages at energy, environmental, and economic levels.

From an **energy perspective**, the systems are highly efficient. According to *Geothermal Heat Pumps: Environmental Benefits and Efficiency* (EPA, cited in Energyhomes.org), GHPs can achieve efficiencies of **300% to 600%** on the coldest winter nights, compared to 175%-250% for air-source heat pumps. Approximately **70% of the energy** consumed by GHPs comes directly from renewable ground energy, significantly reducing the need for primary energy inputs.

In terms of **environmental benefits**, GHPs are classified among the most environmentally friendly heating and cooling options. Their greenhouse gas emissions are substantially lower than those of conventional HVAC systems. Life-cycle analyses indicate a **40-70% reduction in CO_2 emissions** compared to gas or electric heating systems.

When deployed at the district scale, as detailed in the case studies of *Shallow Geothermal Energy Systems for District Heating and Cooling Networks*, the impact is even more significant. The aggregation of multiple consumers allows for **load smoothing**, **waste heat recovery**, and better **seasonal balancing** between heating and cooling needs. Networks can incorporate smart controls to dynamically optimize the energy flows, further improving carbon savings.

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On the **economic side**, while the initial capital costs (especially for drilling) are high, the operational costs are low due to the system's superior efficiency and minimal maintenance requirements. Over a 20-30 year life span, GHPs typically offer lower total cost of ownership than conventional systems. Additionally, integration into district networks allows **cost sharing** between users and improves project bankability through economies of scale.

Moreover, in regions with high renewable electricity shares, coupling GHPs with clean grids can offer a **fully decarbonized** solution for heating and cooling — a major advantage in meeting climate goals.

3.3.3 Obstacle and Barriers

Despite their advantages, the development and deployment of geothermal heat pumps in district heating networks face several barriers.

The **high upfront cost** remains a major obstacle. Drilling, even for shallow geothermal systems, requires specialized equipment and permits, representing a significant financial burden. In urban areas, where district networks are most viable, space for drilling and installation can be limited or heavily regulated.

Moreover, *Obstacles to the Introduction of Heat Pumps in District Heating* highlights **economic barriers** related to **electricity costs**. Since heat pumps rely on electrical energy to operate, high electricity prices — especially when they are taxed heavily compared to fossil fuels — can make the operation less economically attractive. This situation is aggravated in regions where fossil fuels are subsidized.

Technical challenges also exist. Retrofitting existing high-temperature district heating networks (designed for temperatures above 80°C) to lower temperature levels compatible with GHPs (typically around 30-60°C) requires substantial investments. Thermal storage integration, network optimization, and consumer-side adaptation (e.g., low-temperature radiators) are often necessary.

3.3.4 Replicability issues

In Hungary, the city of Kecskemét has successfully integrated geothermal energy into its district heating system, providing a relevant example of how geothermal can be used for sustainable urban heating. The district heating system in Kecskemét relies on deep geothermal wells drilled to around 1,500 meters to extract heat from the Earth. These wells provide a continuous thermal supply to the network through heat exchangers, which transfer heat from the geothermal fluid to the district heating network. The system is designed to supply heating and hot water to residential, commercial, and industrial buildings across the city, addressing a thermal demand of approximately 50 MW during peak winter months.

The geothermal heat is transferred to the distribution network, which consists of insulated underground pipes that carry hot water at a temperature of 50–80°C. This is lower than the temperatures typically required by traditional fossil-fuel-based heating systems, which is why the system integrates low-temperature heat pumps to enhance the temperature when needed. The integration of thermal storage also helps to smooth demand fluctuations, ensuring consistent heating throughout the year, especially during the summer months when demand for heating is lower.

While the integration of geothermal energy into the district heating network significantly reduces the city's reliance on fossil fuels, there are notable challenges that limit its replicability in other European cities. One

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key issue is the geological variability of geothermal resources. In Kecskemét, the geothermal conditions are favorable, but other cities may lack the same resource potential, making deep geothermal projects less viable without significant technological advancements.

Additionally, the system's capital costs are high, particularly due to the drilling costs and the need to retrofit existing infrastructure. For example, the initial drilling of the deep geothermal wells can exceed several million euros, which may deter other municipalities from adopting similar solutions. The integration of geothermal heat into existing high-temperature district heating networks, which often rely on natural gas, requires careful technical adaptation of the network, including the modification of heat exchangers and the installation of low-temperature radiators in buildings.

Government policies and financial support are also critical factors for the successful implementation of geothermal energy. In Hungary, supportive policies and financial incentives have played a key role in making this system possible. However, in other European countries where regulatory frameworks are less conducive to geothermal energy development, replication becomes more challenging.

Overall, while the geothermal district heating system in Kecskemét offers valuable insights, its replicability in other European cities is constrained by geological, economic, and regulatory factors. Successful replication would require tailored solutions based on local geothermal resources, alongside supportive policies, financial backing, and technical innovations to overcome these barriers.

3.4 Wind Power

Wind energy can be effectively integrated into district heating systems through Power-to-Heat (P2H) technologies. By converting surplus wind-generated electricity into thermal energy, wind power offers a sustainable and low-carbon alternative to fossil fuel-based heating. This approach enhances the flexibility of both electrical and thermal energy systems and supports the decarbonization of urban heat supply.

3.4.1 Technology description

Wind power does not generate heat directly, but its electricity can be converted into thermal energy using electric boilers or large-scale heat pumps. This process is known as **Power-to-Heat (P2H)**. When excess electricity is available from wind turbines—often during periods of low demand or high wind speeds—this surplus power can be diverted to produce hot water or steam, which is then fed into the district heating network.

The most common P2H technologies in district heating are **electric boilers** and **heat pumps**. Electric boilers use resistive heating to generate hot water, offering a simple and cost-effective method with efficiency levels close to 100%. In contrast, heat pumps extract heat from the environment (air, ground, or water) and require less electricity for the same thermal output, achieving coefficient of performance (COP) values of 3 or more, depending on the source temperature.

Thermal Energy Storage (TES) is essential for the effective integration of wind power into district heating. By storing excess heat produced during peak wind periods, TES systems help balance supply and demand. Short-term storage typically involves large insulated water tanks, while long-term or seasonal storage solutions,

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such as **borehole thermal energy storage (BTES)** or **pit thermal energy storage (PTES)**, enable the use of wind-generated heat even during periods of low wind availability. Further reference to storage systems is made in chapter 3.7 of this document.

Overall, wind-powered district heating systems function by converting wind-generated electricity into heat, storing that heat as needed, and distributing it through an existing or dedicated thermal network. These systems can operate as **hybrid solutions** alongside biomass, geothermal, or waste heat sources, or they can function autonomously when coupled with sufficient storage capacity.

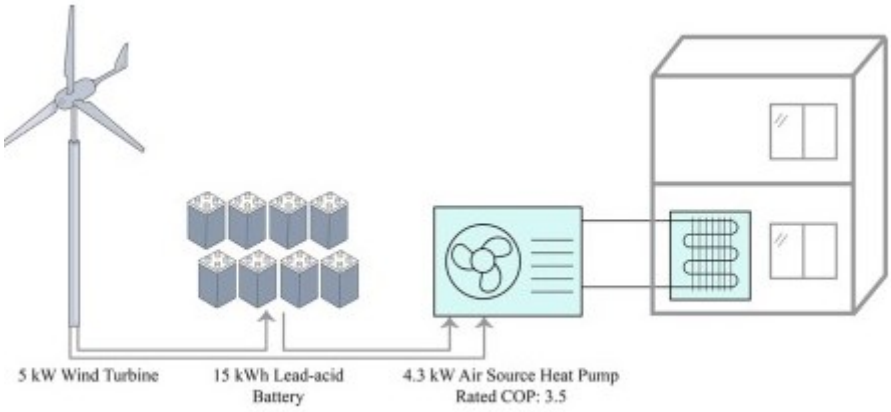


Figure 4. Wind turbine driven heat pump system for heating (source: *Design and evaluation of a wind turbine-driven heat pump system for domestic heating in Scotland*)

3.4.2 Benefits

Integrating wind power into district heating networks offers multiple environmental, economic, and system-level advantages. From an environmental standpoint, using wind-generated electricity to produce heat results in zero direct emissions, supporting local and national efforts to reduce greenhouse gas emissions and transition to carbon-neutral energy systems.

Economically, the cost of wind energy has decreased significantly, making it one of the most affordable renewable electricity sources. Utilizing this low-cost electricity for heating purposes can reduce operational costs, particularly when excess electricity is available at low or even negative prices. In addition, P2H systems enhance the flexibility of energy systems by acting as demand-side management tools, helping stabilize electricity grids by absorbing surplus power and converting it into useful heat.

By reducing reliance on imported fuels and fossil-based heating methods, wind-powered district heating improves **energy security** and protects against price volatility in global energy markets. Moreover, this approach aligns with governmental policies and climate commitments aimed at expanding the share of renewables in both electricity and heating sectors.

Wind-to-heat systems also facilitate the **sector coupling** of electricity and heating, promoting a more integrated and efficient energy system. This integration supports higher penetration of variable renewables by providing a flexible, controllable load that enhances grid reliability.

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3.4.3 Obstacle and Barriers

Despite its advantages, the integration of wind power into district heating networks faces several challenges. The primary technical barrier is the **intermittent nature** of wind energy, which can lead to fluctuations in heat availability. While short-term storage systems can mitigate daily variations, **seasonal imbalances** may require more advanced and capital-intensive storage solutions, increasing system complexity and cost.

From an economic perspective, although the operational costs are low, the **initial capital investment** required for electric boilers, heat pumps, thermal storage, and integration with the district heating infrastructure can be significant. The cost-effectiveness of wind-powered heating systems often depends on the availability of **low-cost wind electricity** and appropriate **tariff structures** that incentivize flexible energy use.

Another barrier is **grid capacity and flexibility**. In some regions, existing electrical grids may not be able to handle the increased demand from P2H installations, especially during peak wind periods. Grid upgrades or demand management measures may be necessary to fully utilize wind energy for heating purposes.

Finally, public acceptance and regulatory frameworks can also influence the feasibility of such systems. In some cases, legal or policy barriers may limit the integration of electricity-based heating systems into traditional district heating networks.

3.4.4 Replicability issues

An exemplary case of wind-powered district heating can be found in **Denmark**, which has been a pioneer in the development of **Power-to-Heat** systems for urban heating. Cities like **Aarhus** and **Frederikshavn** have implemented large-scale electric boiler systems connected to their district heating networks, utilizing surplus wind energy to generate heat.

For instance, in **Frederikshavn**, a 35 MW electric boiler has been installed to convert wind electricity into thermal energy, reducing the city's dependence on fossil fuels and cutting emissions. The system is supported by a large thermal storage tank, which helps manage fluctuations in both wind generation and heat demand. During periods of excess wind power, the electric boiler produces hot water that is stored and later distributed to meet heating needs.

The success of such systems in Denmark is largely attributed to favorable **policy frameworks**, **high wind penetration**, and **mature district heating infrastructure**. However, replicating these models in other regions requires careful assessment of local conditions, including wind resource availability, electricity pricing structures, heating demand profiles, and the existence of suitable storage and distribution systems.

Nonetheless, the Danish experience demonstrates that with the right technical and regulatory support, wind energy can play a significant role in the decarbonization of urban heating systems. As more countries seek to increase renewable energy integration and reduce fossil fuel dependence, wind-powered district heating offers a scalable and effective solution.

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3.5 Hydrogen

Hydrogen (H_2) is a colorless, odorless, non-toxic, and highly combustible gaseous chemical element. Its combustibility is one of the key properties that make it valuable and viable for energy production. Hydrogen is widely regarded as a cornerstone of the energy transition and is particularly promising for district energy solutions, with the overarching aim of enhancing energy self-sufficiency.

3.5.1 Technology description

Although hydrogen as a chemical element and its physicochemical properties are well known, its application in energy production and the development of associated technologies have only accelerated in recent years.

One emerging area of interest is the integration of hydrogen into district heating systems through a range of technological pathways.

The first solution involves the use of hydrogen boilers. This type of boilers are considered environmentally sustainable heating solutions suitable for medium- to large-scale applications, including district heating networks, industrial facilities and as localized heat sources in commercial and residential complexes. The operational principle of a hydrogen boiler is similar to that of a conventional natural gas boiler. However, due to hydrogen's distinctive properties—such as its high diffusivity and flammability—as well as the relative novelty of hydrogen boiler technology on a large scale, a transitional approach is currently being explored. This involves the utilization of hydrogen–natural gas blends, typically comprising 30–70%, which allows for gradual adaptation of infrastructure and operational parameters while mitigating technical and safety concerns.

A second technological approach entails the injection of hydrogen into existing natural gas distribution networks. In this configuration, hydrogen is blended with natural gas and transported via the current gas infrastructure. Prior to widespread implementation, several critical factors must be rigorously assessed, including the permissible hydrogen concentration in the blend, the thermodynamic conditions (e.g., pressure, temperature) within the pipelines, material compatibility, and the performance and safety of end-use combustion appliances operating with the modified fuel mixture.

A third promising application of hydrogen in the context of district heating is its use in combined heat and power (CHP) systems. These systems, particularly in countries such as Greece, were historically powered by high-emission fossil fuels such as lignite and coal. The recognition of the substantial environmental impact associated with these fuels has led to transition towards cleaner alternatives, with natural gas serving as a transitional fuel. The next evolutionary step involves the gradual substitution of natural gas with hydrogen in CHP systems, beginning with partial admixtures and progressing towards full or predominant hydrogen utilization as technological and regulatory frameworks evolve.

An additional scenario for hydrogen integration into district heating involves the broader electrification of heating systems. Among the most promising decarbonization strategies is the use of green electricity—generated from renewable energy sources—to meet thermal energy demands. This can be achieved via electric boilers or heat pumps. Within this paradigm, hydrogen serves as a flexible energy carrier: it is produced through water electrolysis using surplus renewable electricity, stored, and subsequently

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reconverted into electrical energy through fuel cells during periods of low renewable energy availability, thereby enhancing grid flexibility and reliability.

It is important to emphasize that the sustainability of hydrogen as an energy technology is contingent upon the method of its production. From both environmental and economic perspectives, the classification of hydrogen as “green” or sustainable depends on the use of low-carbon or renewable energy sources in the production process. As such, the evaluation of hydrogen’s role in future energy systems must be grounded in a comprehensive life-cycle assessment of its environmental impacts and cost-effectiveness.

The main technologies for hydrogen production are steam methane reforming (SMR), partial oxidation (POX) of hydrocarbons, coal gasification and water electrolysis. The first three methods, all of which are thermochemical processes of fossil fuels, result in significant by-products, including carbon dioxide (CO_2) emissions and, in the case of methane pyrolysis, solid carbon. These emissions necessitate the integration of carbon capture, utilization, and storage (CCUS) technologies to mitigate their environmental impact and align with decarbonization objectives.

Conversely, water electrolysis represents a cleaner alternative, as its sole by-product is high-purity oxygen, which can be safely released into the atmosphere or utilized in industrial applications. The sustainability of the electrolysis process, however, is inherently dependent on the carbon intensity of the electricity supply. When powered by electricity derived from renewable energy sources (RES), electrolysis enables the production of so-called "green hydrogen"—a key enabler in the transition to a low-carbon energy system.

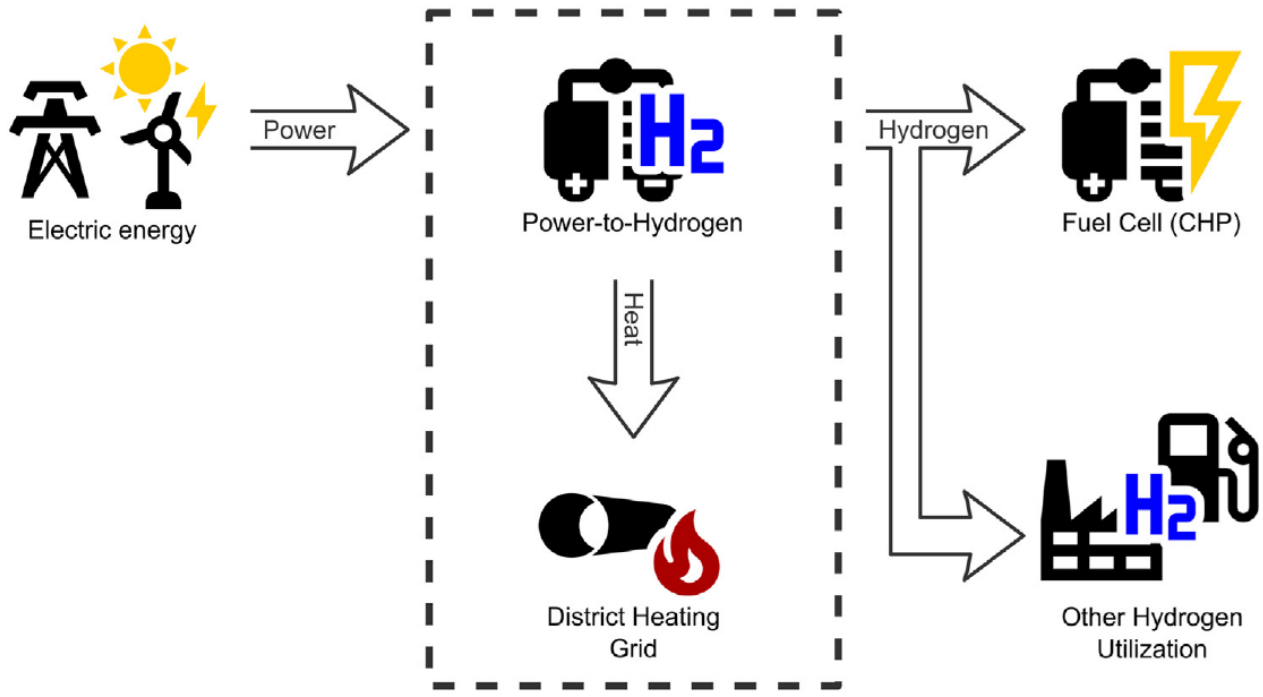


Figure 5. A typical hydrogen technology application system (source: *Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials*).

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3.5.2 Benefits (energy, environment, economy etc)

The integration of hydrogen into district heating systems offers two primary advantages, related to environmental sustainability and energy security.

From an environmental perspective, hydrogen combustion produces only oxygen, with no emissions of pollutants such as CO_2 or other greenhouse gases (GHGs). This makes hydrogen a clean and environmentally friendly energy carrier. Its use in district heating contributes significantly to the decarbonization of the sector, promoting a transition toward low-emission, sustainable urban energy systems.

On the energy side, hydrogen presents key benefits that distinguish it from other clean energy sources, particularly RES. While RES such as wind and solar are inherently variable and dependent on weather conditions, hydrogen can be stored in large quantities and deployed on demand. This ensures both reliability and immediacy of energy supply, as hydrogen combustion can deliver the required thermal energy at any time, independent of real-time production constraints.

Moreover, the production of hydrogen through water electrolysis powered by renewable energy offers a dual benefit. On the one hand, it enables the utilization of surplus renewable electricity that would otherwise be curtailed during periods of overproduction. On the other hand, it facilitates the generation of "green hydrogen" which can then be used to support the electrification and decarbonization of district heating systems. In this way, hydrogen serves not only as a clean fuel but also as a flexible energy storage medium that supports the broader integration of renewable energy into the heating sector.

3.5.3 Obstacle and Barriers

Hydrogen technology—both for use in district heating systems and more broadly—is still in a very early stage of development. The methods for producing and utilizing hydrogen have not yet been tested on a large scale, representing one of the key challenges that must be addressed to enable its effective deployment.

A significant barrier to the integration of hydrogen into district heating systems is the volume required. Hydrogen has a lower calorific value compared to conventional fuels, meaning that a greater volume is needed to generate the same amount of energy. This directly translates into the need for additional storage capacity.

Hydrogen storage is arguably the most technically challenging aspect, as it requires strict control and determination of various conditions. The storage method must be defined before other processes can proceed, as it is foundational to the system's design. There are two main options for storing hydrogen: in liquid or gaseous form. In the case of liquefaction, hydrogen must be cooled to extremely low temperatures (around -253°C) to convert it into a liquid. This requires specially insulated containers to prevent evaporation, and while the process offers a high storage density, it is also highly energy-intensive. Alternatively, gaseous hydrogen is stored in robust, high-pressure containers—typically at 350 to 700 bar—which must be equipped with safety systems to prevent leaks and accidents.

In both storage approaches, container materials must be compatible with hydrogen and able to withstand dangerous conditions. Safety remains paramount due to hydrogen's flammable nature.

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Another technical challenge in applying hydrogen to district heating systems is the development of suitable hydrogen boilers. Although several hybrid models (e.g., natural gas/hydrogen or biogas/hydrogen) have been created and tested, boilers that run exclusively on hydrogen have not yet undergone large-scale trials, and their efficiency and performance remain under investigation.

The final critical factor that must be resolved to make hydrogen a viable and sustainable solution for district heating is the economic dimension. Both the production and storage of hydrogen involve high material and operational costs. Moreover, the lack of existing infrastructure further exacerbates these economic barriers. As a result, the use of hydrogen in district heating systems is currently considered unfeasible, especially concerning the financial framework—though it holds considerable potential for improvement in the future.

3.5.4 Replicability issues

As repeatedly highlighted in this chapter, hydrogen technology remains at a nascent stage and has yet to undergo comprehensive research or validation at scale. Consequently, district heating systems utilizing hydrogen—whether as a direct fuel source or as an energy carrier—have not been developed or deployed in practice. Furthermore, even small-scale components of hybrid systems incorporating hydrogen have not been implemented, primarily due to the prohibitive costs associated with large-scale application of the technology at its current level of maturity.

To date, the primary insight into the potential role of hydrogen in district heating comes from simulation studies. These computational models suggest that, under specific conditions, hydrogen could emerge as a technically feasible and economically viable solution—particularly when used as an energy carrier. In this context, hydrogen functions as a form of "natural battery", enabling the storage and subsequent utilization of surplus electrical energy, contingent on further technological advancements and cost reductions.

3.6 Biogas Injection into Natural Gas Grid

3.6.1 Technology description

Biogas injection into the natural gas grid involves upgrading raw biogas to biomethane and feeding it into existing gas infrastructure. Raw biogas, typically produced from anaerobic digestion of organic materials (such as agricultural waste, sewage sludge, or food waste), consists of methane (CH_4), carbon dioxide (CO_2), and trace impurities. To be compatible with natural gas infrastructure and end-use applications, biogas must undergo a purification process to remove CO_2, hydrogen sulfide (H_2S), moisture, and other contaminants resulting in high-purity biomethane with a methane content typically exceeding 96%.

Once upgraded, the biomethane is injected into the gas distribution or transmission network via a dedicated injection point, equipped with quality monitoring and odorization systems. This integration enables the use of renewable gas for heating and power generation, effectively decarbonizing sectors traditionally reliant on fossil natural gas.

Recent advancements, as discussed in the IEA Bioenergy Task 37 Report on Biomethane Injection into Gas Grids, include membrane separation, pressure swing adsorption, and water scrubbing technologies that

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improve the efficiency and cost-effectiveness of biogas upgrading. Furthermore, the development of smart gas grids allows for better tracking of injected biomethane, enhancing grid flexibility and facilitating certification schemes such as Guarantees of Origin (GoOs) for renewable gas.

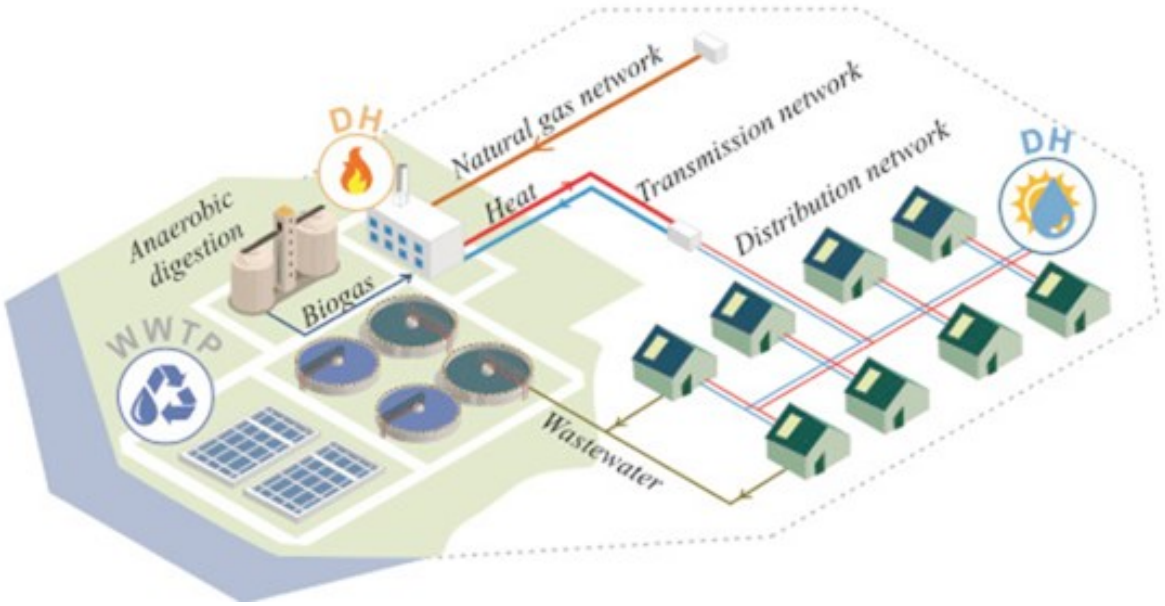


Figure 6. Schematic network for WWTP biogas DH (Source: *District heating based on biogas from wastewater treatment plant*)

3.6.2 Benefits (energy, environment, economy etc)

The injection of biomethane into the gas grid offers multifaceted benefits across environmental, energy, and economic domains.

From an environmental perspective, biomethane is carbon-neutral or even carbon-negative when derived from waste biomass that would otherwise release methane into the atmosphere. According to the European Biogas Association, replacing natural gas with biomethane can reduce life-cycle greenhouse gas emissions by up to 90%, depending on feedstock and upgrading technology.

Energetically, biomethane serves as a drop-in replacement for fossil natural gas. This compatibility allows full use of existing gas infrastructure — including pipelines, storage facilities, and end-user equipment — without significant modifications. It also supports energy system integration by providing a storable and dispatchable renewable energy vector, which complements intermittent renewable electricity sources such as wind and solar.

Economically, biogas systems contribute to rural development and circular economy models by valorizing local organic waste streams. Grid injection further enables producers to access broader energy markets and benefit from feed-in tariffs or renewable gas certificates where available. In countries with supportive policy frameworks (e.g., Germany, France, and the Netherlands), biomethane injection has proven cost-competitive and scalable, particularly when co-located with agricultural or municipal waste treatment facilities.

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In addition, biogas injection aligns with European Union climate goals, supporting the decarbonization of hard-to-electrify sectors and enhancing energy security by reducing dependence on imported fossil fuels.

3.6.3 Obstacle and Barriers

Despite the promising potential of biomethane grid injection, several obstacles limit its broader deployment.

The primary barrier remains the high capital and operational costs of biogas upgrading and injection infrastructure. Upgrading units, compression systems, and grid interconnection points require substantial investment, often making projects financially unviable without policy support. Small-scale producers, in particular, face challenges in achieving the economies of scale needed to justify grid injection.

Regulatory and administrative hurdles also impede progress. In many jurisdictions, the permitting process for grid connection is complex and time-consuming. Gas grid operators may impose strict technical standards for gas quality, flow control, and odorization, which can further delay project implementation and increase compliance costs.

Additionally, the availability of injection capacity within the gas network may be limited, especially in rural or decentralized locations. In some cases, the nearest injection point may be several kilometers away, necessitating the construction of new pipelines further escalating costs.

Market-based barriers exist as well. Where natural gas prices are low or fossil gas is subsidized, biomethane may struggle to compete without targeted incentives. Moreover, the lack of harmonized certification systems across countries complicates cross-border trade and undermines investor confidence.

3.6.4 Replicability issues

The success of biomethane injection projects varies significantly across Europe, largely influenced by local conditions and regulatory environments.

A leading example is the Netherlands, where national policy has supported biogas grid integration through feed-in premiums, streamlined permitting, and investment subsidies. The country now operates dozens of injection sites and has established a green gas certificate system to ensure traceability and market value for renewable gas.

However, this success is not easily replicable everywhere. In countries with fragmented waste management practices or limited agricultural waste availability, feedstock procurement remains a barrier. Additionally, in regions with poorly developed gas infrastructure or monopolistic grid access conditions, project development is significantly constrained.

For instance, in Central and Eastern Europe, although there is growing interest in biogas, insufficient grid coverage in rural areas and limited policy support have slowed the adoption of injection projects. Similarly, without clear incentives or obligations for gas suppliers to include renewable gas in their portfolios, demand remains uncertain.

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Replication also depends on harmonized standards for gas quality, robust metering and monitoring systems, and transparent biomethane tracking mechanisms. The absence of such frameworks can deter investment and hinder market growth.

3.7 Storage technologies

Thermal Energy Storage (TES) and Electrical Energy Storage Systems (EESS) are critical components in modern energy infrastructures. Their integration into district heating networks and renewable-based electricity grids enhances flexibility, reliability, and efficiency. Both storage types enable the decoupling of energy generation from consumption, allowing surplus energy thermal or electrical to be stored when available and released when needed. These systems are especially important for integrating variable renewable energy sources (e.g., solar, wind), improving grid stability, and achieving decarbonization goals.

3.7.1 Technology description

Thermal Energy Storage (TES) systems are designed to **accumulate heat when it is abundantly available**, typically during periods of high renewable energy production or low demand and to **release it when needed**, such as during peak demand periods or when energy generation is limited. In district heating, TES is typically used to **balance supply and demand**, increase system efficiency, and reduce operational costs.

TES is integrated into the district heating network through heat exchangers and managed by smart control systems that optimize charging and discharging based on energy prices, heat demand forecasts, and renewable generation profiles.

Electrical Energy Storage Systems (EESS) are increasingly being integrated into district heating networks, particularly as electrification and renewable energy sources become more prevalent. These systems store surplus electricity often generated from variable renewable sources such as wind and solar, and make it available when needed. In the context of district heating, EESS contribute in two main ways:

Direct Grid Support:
Stored electricity powers electrically driven heating technologies (e.g., heat pumps, electric boilers) during periods of low-cost or excess renewable generation.

Indirect:
Electrical energy is converted into heat and stored in TES systems for later use in the district heating network.

3.7.2 Different types of storage technology

There are three main categories of TES technologies used in district heating:

Short-Term Storage

Short-term storage is primarily used to balance daily fluctuations in heat demand. The most common solution is **hot water tanks**, also known as **stratified thermal storage tanks**, which store hot water in insulated

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reservoirs. These tanks can range from small-scale units serving individual buildings to large central tanks supplying entire neighborhoods.

Medium-Term Storage

This form of TES serves to manage storage over several days to weeks, particularly useful during transitional seasons when heating needs vary. Medium-term storage solutions include **tank-in-tank systems**, **sand or gravel beds**, and **PCM (Phase Change Material)** storage, offering higher energy density and improved thermal retention.

Long-Term or Seasonal Storage

Seasonal TES stores thermal energy over several months, enabling the use of **summer-generated renewable heat in winter**. The most common technologies include:

- **Pit Thermal Energy Storage (PTES):** Large, insulated earth pits filled with water and covered with thermal insulation layers. These are cost-effective for large volumes of storage.
- **Borehole Thermal Energy Storage (BTES):** Uses a grid of deep boreholes drilled into the ground to store heat in the surrounding soil and rock.
- **Aquifer Thermal Energy Storage (ATES):** Involves storing and extracting heat from underground water-bearing layers (aquifers), enabling seasonal cycling of thermal energy.

TES systems are typically integrated into the district heating network through **heat exchangers**, and their operation is managed by smart controls that optimize charging and discharging based on energy prices, heat demand forecasts, and renewable generation profiles.

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Figure 7. A real photo of Dronninglund pit storage (source: *Dronninglund water pit thermal energy storage dataset*)

Electrical Energy Storage (EESS)

Battery Energy Storage Systems (BESS):
Primarily lithium-ion batteries for their flexibility and commercial maturity. They allow dynamic operation of electric boilers and heat pumps.

Power-to-Heat (P2H):
Electric boilers and large-scale heat pumps convert surplus electricity into heat, which can be stored in TES systems for later use.

3.7.3 Benefits (energy, environment, economy etc)

The incorporation of thermal and electric storage systems into district heating networks brings a wide range of operational, environmental, and economic benefits.

One of the most important advantages is system flexibility. Thermal energy storage (TES) allows for the decoupling of heat generation and consumption, enabling heat production during periods of low energy prices or high renewable availability, and storage for later use during peak demand. Electric energy storage

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(EES) offers similar flexibility by allowing electricity-dependent components—such as large-scale heat pumps or Power-to-Heat systems—to operate independently of real-time electricity prices or supply fluctuations.

Storage systems also support the integration of renewable energy. TES and EES enable the capture and utilization of surplus electricity from variable renewable sources like wind and solar. Instead of curtailing excess production, this energy can be stored as heat and dispatched when needed, contributing to the decarbonization of both heating and power sectors.

From an energy system perspective, both TES and EES play a crucial role in peak shaving and grid stabilization. By shifting energy demand away from high-load periods, storage reduces the reliance on fossil-fueled peak-load boilers and mitigates the need for costly grid reinforcements. This capability is especially valuable in densely populated urban areas with aging grid infrastructure.

Economic optimization is another key benefit. In electricity markets with dynamic pricing or time-of-use tariffs, storage enables district heating operators to capitalize on low or negative electricity prices. By producing and storing heat when energy is cheapest, operators can significantly lower operational costs and improve the financial viability of renewable-based district heating systems.

Finally, storage enhances system resilience and reliability. Both short-term and seasonal storage options provide a buffer that allows for continued heat supply during outages, renewable shortfalls, or planned maintenance activities. This ensures uninterrupted service for consumers and reinforces the stability of the overall district heating infrastructure.

3.7.4 Obstacle and Barriers

Despite their advantages, the development and deployment of thermal and electric storage systems in district heating networks face several barriers.

The high capital cost remains a significant obstacle. Large-scale or seasonal thermal energy storage systems—such as pit or borehole storage—require substantial investments in excavation, insulation, and integration infrastructure. Similarly, battery-based EES systems involve high upfront costs and often lack sufficient financial incentives or revenue certainty to justify investment.

Spatial requirements also pose a challenge. Technologies like Pit Thermal Energy Storage (PTES) and Borehole Thermal Energy Storage (BTES) demand considerable land or subsurface space, which is often limited in dense urban environments where district heating is most relevant. This limitation can make implementation difficult or drive up land acquisition costs.

Efficiency losses are another concern. While thermal energy storage systems are generally efficient in the short term, seasonal systems are prone to heat losses over extended periods. Electric storage systems, such as lithium-ion batteries, also experience round-trip energy losses and performance degradation over time, affecting long-term reliability and economic viability.

Integration complexity further complicates deployment. Coordinating the operation of storage systems with heat generation units, district heating distribution, and electricity grids requires advanced control systems and digital infrastructure. This challenge is heightened in integrated or "smart" energy systems where multiple energy vectors—electricity, heat, and sometimes gas—must be managed simultaneously.

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Finally, regulatory and market frameworks are often not well-suited to support storage deployment in district heating. In many regions, existing energy policies lack clear incentives for storage investments or impose restrictive rules on ownership and operation. Additionally, tariff structures may not favor the flexible operation of Power-to-Heat systems or storage assets, limiting their economic potential.

3.7.5 Replicability issues

Several successful implementations of TES systems in district heating illustrate the feasibility and scalability of this technology.

A leading example is the **Vojens Pit Thermal Energy Storage** system in Denmark , currently one of the largest of its kind globally. With a storage volume of **203,000 m³**, the system stores excess heat produced during summer (mostly from solar thermal collectors) and releases it in winter to meet heating demands. The TES is connected to a 50,000 m² solar thermal plant and supports over 2,000 households.

Another example is the **Drake Landing Solar Community** in Alberta, Canada, which uses **Borehole Thermal Energy Storage (BTES)** to store summer solar heat underground for winter heating. The system achieves over 90% of the community's heating needs from solar energy, demonstrating the long-term effectiveness of seasonal storage in cold climates.

Replicability depends heavily on **local conditions** including available land, subsurface geology, and existing heating infrastructure as well as on **regulatory support and financing mechanisms**. Urban areas may need to rely more on medium-term or hybrid storage solutions, while suburban and rural locations can more easily adopt large-scale PTES or BTES systems.

These examples illustrate that with appropriate planning and investment, TES can serve as a **cornerstone of flexible, renewable-based district heating systems**, paving the way for energy-efficient, low-carbon urban infrastructure.

3.8 Hybrid Systems

3.8.1 Technologies' combination

Several successful implementations of hybrid systems in district heating illustrate the versatility and resilience of combining multiple renewable energy sources with thermal energy storage. By integrating technologies such as solar thermal, biomass, heat pumps, and waste heat recovery, hybrid district heating systems optimize resource utilization while reducing carbon emissions and ensuring reliable heat supply across varying seasonal and daily demands.

One prominent example is the city of Silkeborg in Denmark, which operates one of the world's largest solar-assisted district heating plants. The system combines a 110,000 m² solar thermal field with gas-fired boilers and large-scale thermal energy storage, enabling flexible operation and a significant reduction in fossil fuel consumption. The integration allows solar energy to cover up to 20% of the city's annual heat demand while the storage unit balances short-term fluctuations in solar availability.

Another case is the district heating system in Ludwigsburg-Kornwestheim, Germany, where a hybrid approach merges solar thermal collectors, biomass CHP, and industrial waste heat recovery, all supported by

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a 45,000 m³ thermal storage tank. This combination enables the system to adapt to changing weather patterns and market conditions while maintaining a high share of renewable heat supply.

These examples demonstrate that hybrid configurations offer a practical pathway toward decarbonizing heating sectors, particularly in regions with variable renewable resource availability.

3.8.2 Benefits (energy, environment, economy etc)

Hybrid district heating systems based on renewable energy sources offer significant advantages in the transition towards sustainable energy systems. By integrating multiple renewable technologies—such as solar thermal, geothermal, biomass, large-scale heat pumps, and waste heat recovery—these systems achieve high flexibility and reliability in heat supply. The diversified energy mix allows for continuous operation even under variable weather conditions or resource availability, while advanced control algorithms optimize energy dispatch to maximize efficiency and minimize costs. The incorporation of thermal energy storage enables better management of temporal mismatches between heat supply and demand, particularly across seasons. Overall, hybrid RES district heating systems contribute substantially to the decarbonization of the heating sector, reduce dependence on fossil fuels, improve local energy security, and offer long-term economic benefits.

3.8.3 Obstacle and Barriers

Despite their advantages, hybrid renewable district heating systems face several technical, economic, and operational challenges. The integration of diverse heat sources increases system complexity, requiring sophisticated design, planning, and real-time management to ensure optimal performance. High upfront capital investments are needed for infrastructure development, including renewable generation units, extensive thermal storage capacities, and intelligent control systems. Additionally, seasonal imbalances between renewable heat production (e.g., solar thermal surpluses in summer) and peak heating demand (typically in winter) necessitate the deployment of large-scale seasonal storage, which can be both space- and cost-intensive. Advanced digitalization, accurate forecasting, and sector coupling with the electricity grid are essential to manage variability and optimize system operation, but they demand specialized expertise and robust data management frameworks. Moreover, regulatory, market, and policy frameworks must evolve to support the deployment and economic viability of such complex, integrated systems.

3.8.4 Replicability issues

The successful deployment of hybrid district heating systems depends on several factors, including access to diversified renewable resources, appropriate storage capacity, grid integration capabilities, and supportive policy frameworks. While large-scale hybrid systems may require significant upfront investments and careful planning, their long-term benefits include enhanced energy security, cost stability, and substantial reductions in greenhouse gas emissions.

Replicability depends heavily on local conditions, including available land for large solar thermal fields or biomass storage, subsurface geology for potential seasonal thermal storage, and proximity to industrial waste heat sources. Moreover, urban areas may face space limitations and higher infrastructure complexity, favoring medium-term storage solutions or compact hybrid systems, while suburban and rural locations can more easily adopt large-scale PTES or BTES systems.

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With continued technological advancements and supportive regulations, hybrid district heating systems can become a cornerstone of sustainable, resilient urban energy infrastructures.

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4 The case of Ptolemaida District Heating System

The district heating system used in the city of Ptolemaida is primarily powered by the Public Power Corporation (PPC) thermal power generation units located in the surrounding region. A small-scale application was launched in 1960, providing heat to the PPC residential settlement in the Eordeia suburb via thermal energy derived from the Ptolemaida Thermal Power Plant. The large-scale implementation of district heating for the urban area commenced in 1994. Today, the system delivers reliable, safe, and cost-effective thermal energy to more than 15,000 residential and commercial properties. Additionally, it presents opportunities for supporting development initiatives in the primary sector, including agriculture and agro-industrial activities.

4.1 Description of DH of Ptolemaida and projection of energy needs at a 10-year level

The District Heating Company of the Municipality of Ptolemaida (D.H.C.P.), located in Western Macedonia, operates a district heating system that supplies the city of Ptolemaida with heat for both sanitary hot water and space heating, the latter being provided during the heating season from October to May. The system comprises several key components, including thermal energy production facilities, an insulated transmission network with associated thermal energy pumping stations, an insulated distribution network with additional pumping stations, thermal substations and pumping stations within various city areas, a thermal energy storage facility, and consumer-level thermal substations and networks.

District heating of Ptolemaida was supplied (for the last 30 years) by the Public Power Corporation S.A (PPC) lignite-fired steam power plants using steam extraction (resulting in reduced electric power). Figure 8 provides a schematic overview of the thermal energy transfer process from the Public Power Corporation (PPC) generation facilities to the district heating distribution network at the entry point of the city of Ptolemaida. The figure illustrates the interface infrastructure responsible for delivering centralized thermal energy to the urban heat distribution system.

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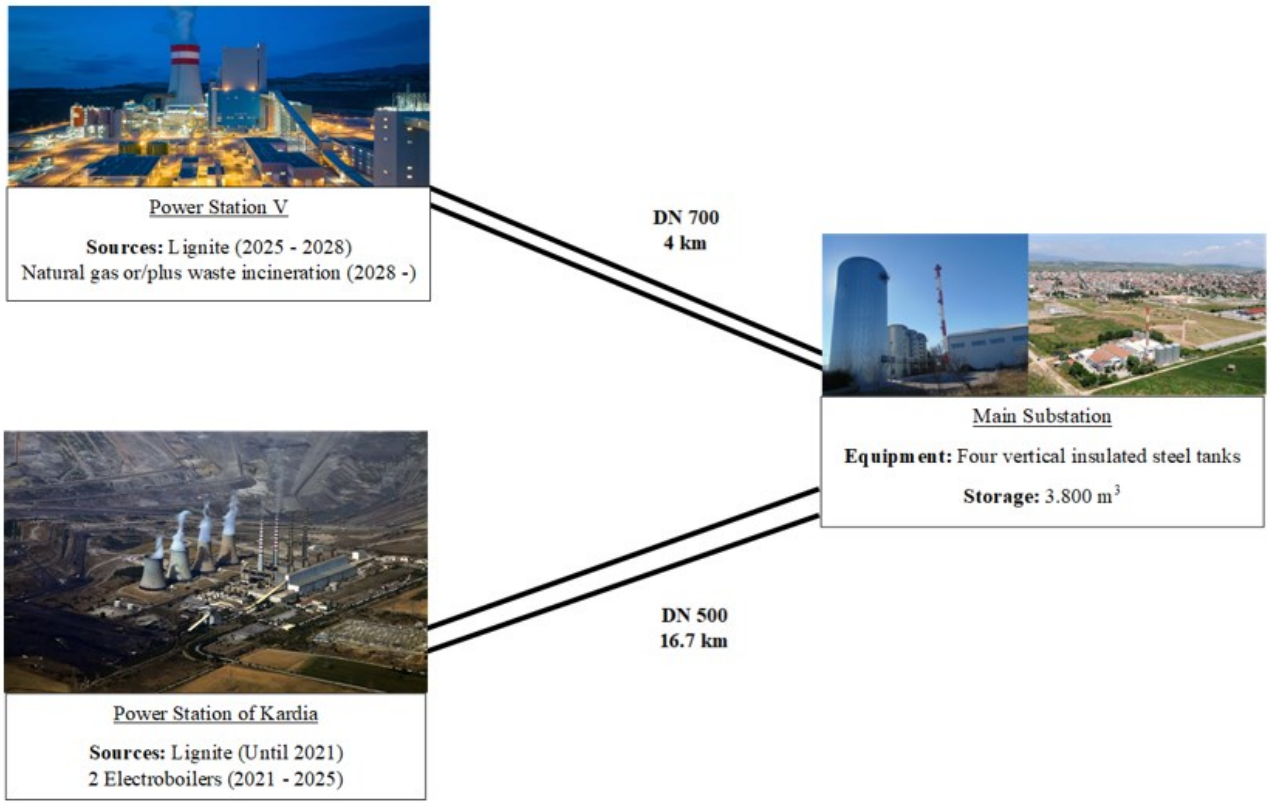


Figure 8. Production and transportation of hot water for district heating in Ptolemaida

The share of heat is provided exclusively for space heating and hot water preparation in the residential sector, accounting for approximately 98.8% of the total heat demand, which amounts to **231 GWh annually**. A small portion of the heat demand (around 1.2%) is allocated to the commercial sector for service-related purposes. The final beneficiaries include consumers, primarily households, commercial establishments, service shops, and public service buildings (such as healthcare, educational, and leisure centers) in the residential area of Eordea. The district heating system covers a total heated floor area of 1,772,011 m². As mentioned above the annual thermal energy production amounts to approximately 231 GWhth. The system's efficiency is around 74%, while the losses occurred from the operation of the district system rise on around 25.5%. More specifically, 10–12% of the losses can be attributed to inefficiencies in the transmission and distribution network, 5% to water losses, and the remaining percentage to the aging infrastructure and outdated equipment. The total emissions from the district heating system amount to 56.000 ton CO2 annually. After the final withdrawal of PPC's lignite units, and for a transitional period, the production of the base thermal energy will be carried out by the electric boilers, which are installed in the PPC KARDIA power plant and for its peak needs thermal load and reserve (using oil combustion in the boiler).

In the case of D.H.C.P. (Municipality of Ptolemaida/Eordaia) the system consists of **two electric hot water boilers** (2 x 40 MW_{th}). Hot water boilers using immersed electrodes which are electrically supplied with **6kV**. The electrical supply to each electric boiler is provided through respective cables and switches by two **150/6kV** transformers (M/S). The electrodes heat the desalinated water content of the electric boiler to a temperature of **130°C**. The hot desalinated water, feeds a water/water heat exchanger (secondary network

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flow capacity 711m3/h, nominal pressure 16bar, temperature 70/120°C), to which the existing hot water transport pipes are connected.

Heated water is transported at a nominal temperature of approximately 120 °C via a 16.7 km long transmission pipeline with a diameter of DN 500, extending from the former Kardia plant to the central pumping station of the District Heating Municipal Company of Ptolemaida (DHCP). A parallel return pipeline of equal length and diameter conveys the cooled water—at approximately 65 °C—back to the boilers for reheating. The hot water storage units are located at the Central Pumping Station of the DHCP, situated at the southern entrance of the city. The system includes four vertical steel storage tanks with a total volume of 3,800 m³ and a nominal operating pressure of 6.5 bar. These tanks are constructed from steel plates, mounted on reinforced concrete foundations, and insulated with rock wool to reduce thermal losses.

Additionally, the site houses a peak-load and backup boiler facility, which operates on fuel oil and includes a boiler with a thermal output capacity of 25 MWth, ensuring energy supply security during periods of high demand or maintenance.

The transportation of hot water from the Central Pumping Station to the city of Ptolemaida is facilitated by the district heating distribution network. This network spans a total length of 47.5 kilometres and is divided into two subsystems: the primary and the secondary distribution networks. The primary network is responsible for delivering hot water both to the eleven main District Thermal Substations—strategically located across the city—and directly to individual buildings equipped with Consumer Thermal Substations. The pipelines of the primary network have a diameter of DN 200, and the system operates with supply and return water temperatures of 115 °C and 65 °C, respectively. At the consumer level, the water temperature is typically around 80 °C. This temperature is achieved either through plate heat exchangers (water-to-water) installed within individual buildings or via connections to the area's thermal substations, which are also equipped with water-to-water heat exchangers. These consumer connections are served by the secondary distribution network, which comprises pipelines ranging in diameter from DN 25 to DN 100. This secondary system operates with supply and return water temperatures of 80 °C and 65 °C, respectively. The commissioning of the Ptolemaida V power unit, by PPC, has significantly altered the energy landscape of the region. Designed for the co-generation of heat and electricity, the new unit utilizes lignite as its primary fuel and delivers a total thermal output of 140 MWth. The construction of this state-of-the-art facility was accompanied by the development of a thermal transmission network connecting it to the Central Pumping Station of the District Heating Municipal Company of Ptolemaida (DHCP). This pipeline infrastructure features an increased diameter of DN 700.

Looking ahead, Ptolemaida V is designed with fuel flexibility in mind and is expected to transition to natural gas or potentially even waste-derived fuels in the future, aligning with broader decarbonization and sustainability goals. While the exact length of the newly constructed transmission network has not been officially disclosed, the geographical distance between the DHCP Central Pumping Station and the Ptolemaida V facility is estimated to be approximately 4 kilometers. The following figure briefly illustrates the district heating distribution network in the city of Ptolemais.

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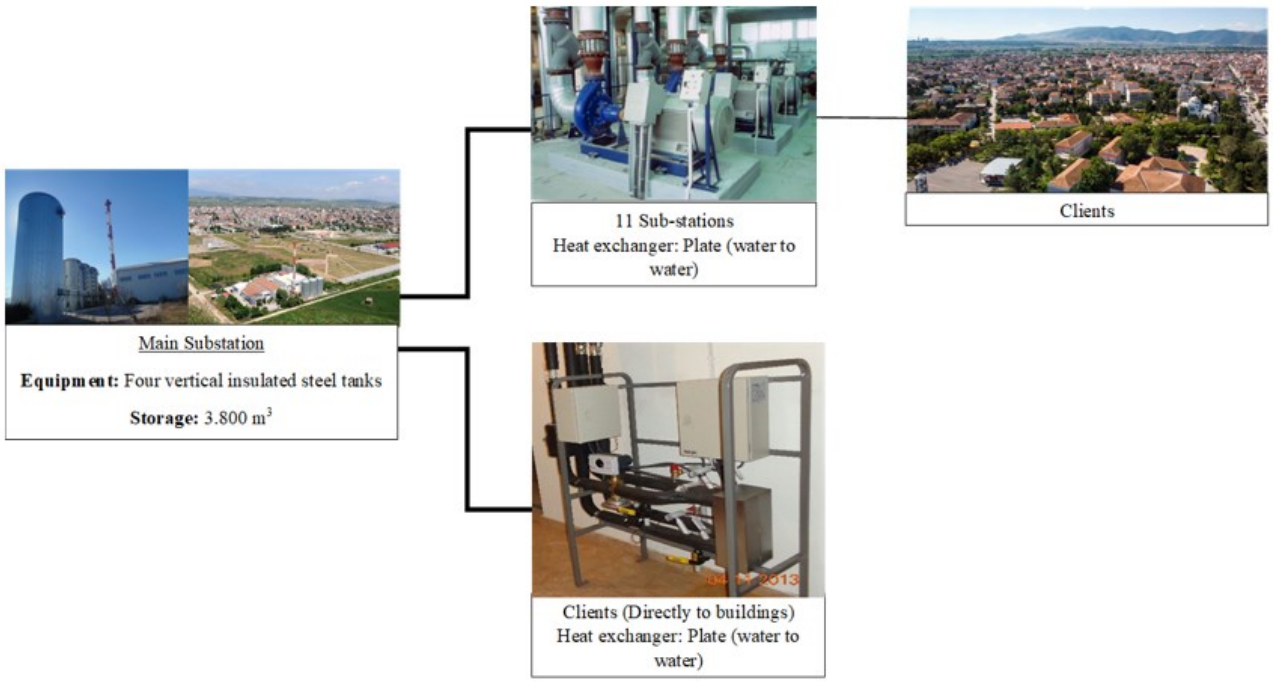


Figure 9. Distribution network of DHCP

In addition, Table 1 represents the main technicalcharacteristics of DHCP's network.

Table 1. Characteristics of DHCP's network

Name	Location	Network length (km)	Number of households served	Decarbonisation plan	Number of customers served by District Heating	Number of citizens served by District Heating
D.H.C.P.	Municipality of Eordaia (Ptolemaida)	Transmission network 75.2 km Distribution network 276.2 km	10.667	Nothing official yet	16.502	32.000

It must be emphasised that Ptolemaida is one of three cities in Western Macedonia that utilizes district heating. The overall proposal for the future of district heating in Western Macedonia, following the closure of the lignite-fired power plants, is guided by several fundamental principles. These include the maximum possible utilization of existing infrastructure, alignment of the implementation schedule with the planned withdrawal of lignite units, and optimization of the fuel mix and thermal energy production methods to

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ensure low consumer tariffs. Additionally, the proposal emphasizes the development of synergies among stakeholders active in the region and the district heating sector, as well as the formulation of future plans and business models by leveraging all available financial instruments.

4.1.1 Driving forces and/or opportunities that favour DH expansion

The transition toward a decarbonized energy system, coupled with the progressive abandonment of lignite-based power generation, presents substantial challenges for regional energy infrastructure. Nevertheless, the DH network in Ptolemaida represents a critical asset in facilitating this transformation. As a mature and extensive infrastructure system, the DH network enables the centralized and efficient distribution of thermal energy to a large number of residential, commercial, and institutional consumers. This centralized model significantly reduces reliance on individual heating units, contributing to lower greenhouse gas emissions and enhancing the overall environmental profile of urban heating. The existing network is particularly advantageous in the context of integrating RES, such as biomass, in a technically and economically efficient manner. This allows for a smoother, phased transition toward **sustainable heating solutions** while **ensuring uninterrupted service, high availability and cost competitiveness for end users**.

One of the primary advantages lies in its dominant market position, which results in a lack of direct competition and supports operational stability. The organization benefits from highly experienced personnel with extensive domain-specific expertise in district energy systems, enabling a high standard of service delivery and system reliability. The technical infrastructure, having undergone a significant modernization effort between 2006 and 2008, is equipped with advanced components that ensure network reliability and operational resilience. In addition, the system exhibits high adaptability, offering **opportunities to expand into adjacent sectors such as natural gas, electricity generation and other forms of renewable energy**.

Additional strategic advantages include the anticipated deployment of a natural gas distribution network in Western Macedonia and the incorporation of digital technologies throughout the DH value chain. Innovations such as system automation, infrastructure digitization, and remote monitoring enhance both operational efficiency and consumer engagement. Finally, the DH network benefits from a well-established customer base, with high satisfaction levels that underscore the system's reliability and service quality.

Organizationally, the DH entity maintains a level of flexibility uncommon in the broader public sector. Its decision-making processes are streamlined, allowing for rapid response to operational issues and consumer service requests, with minimal bureaucratic delay. This efficient governance model supports the successful execution of large-scale upgrade and expansion projects. Furthermore, the company adheres to ISO 9001 quality certification standards, ensuring continuous quality assurance in all processes.

Social responsibility and ecological orientation are integral to the utility's strategy, as evidenced by its promotion of environmentally responsible practices and its preparedness to incorporate RES and cogeneration technologies. This readiness is reinforced by the company's ability to secure funding from national and EU programs, including the National Strategic Reference Framework (NSRF), as well as its capacity to enter into Public-Private Partnerships (PPPs) to broaden its technological and financial base. The liberalization of the national energy market and recent changes to the regulatory framework concerning electricity production further enhance the potential for diversification and innovation.

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In conclusion, despite the challenges inherent to the energy transition, the District Heating network in Ptolemaida is uniquely positioned to serve as a cornerstone of regional decarbonisation efforts. Through the exploitation of its established infrastructure, technical know-how, regulatory adaptability, and integration of emerging technologies, the system can facilitate a low-carbon, resilient, and consumer-oriented energy future.

4.1.2 Barriers to the expansion of DH

DCHP historically operated under a cost-effective model by sourcing thermal energy from the PPC, which utilized lignite-based thermal units in the region. However, the ongoing national and EU-mandated decarbonization process, which includes the progressive decommissioning of lignite-fired power plants, has critically impacted the operational model of DCHP. This transition has necessitated the company's reliance on alternative and significantly more expensive, energy sources—primarily electricity. This paradigm shift has introduced a complex set of technical, financial and regulatory challenges that threaten the economic sustainability and competitive viability of the district heating service. A primary concern is the integration of RES under market-competitive conditions to ensure the delivery of thermal energy at affordable and socially acceptable tariffs.

From technical point of view, DCHP is currently facing high operational and maintenance costs, which are compounded by aging infrastructure and persistent leaks in the distribution network. These inefficiencies increase the technical losses and reduce the overall energy efficiency of the system. The heating demand itself is also declining due to the tangible effects of climate change, including shorter heating seasons and rising average winter temperatures. This not only affects revenue forecasts but also questions the long-term load factors necessary for the economic operation of large-scale heating systems.

From an administrative perspective, the implementation of legislative reforms, and in particular the Kallikrates reform (a reform that involves the merger of existing small municipalities and communities into larger ones), has imposed financial and operational constraints on local governments and affiliated entities such as DCHP. These institutional constraints limit the company's ability to undertake strategic investment initiatives. In addition, continuous legislative amendments, often without transitional periods or supporting mechanisms, further destabilize the investment environment, delaying critical projects and eroding investor confidence. Complicating matters further is an unstable and frequently changing legislative framework, particularly in the domain of RES and biomass utilization. The lack of clear, consistent, and long-term regulatory guidelines introduces significant planning and investment risk.

On the other hand, socioeconomic dynamics add another layer of complexity. The population's purchasing power is shrinking, resulting in growing difficulties among consumers in settling thermal energy bills. At the same time, there is a widespread perception among end users that district heating should be provided at the lowest possible price, regardless of underlying production and infrastructure costs. This expectation creates a structural pricing gap between cost-recovery and consumer acceptance.

Continuing the examination of the case from a financial perspective other critical issues arose. The organization is unable to internally finance the capital-intensive projects required for modernization and transition toward RES. Budgetary limitations have also resulted in salary reductions and diminished incentives, adversely affecting human resource retention and motivation. The cost of thermal energy procured from PPC has risen due to both the liberalization of the energy market and the partial privatization

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of PPC, which has led to pricing uncertainties and the potential for further escalations in supply costs. The full decommissioning of PPC's lignite units necessitates the urgent evaluation and deployment of alternative thermal energy sources. Concurrently, the heating market has become increasingly competitive. Households are increasingly shifting toward decentralized, lower-cost heating options such as individual gas boilers, high-efficiency wood-burning stoves, biomass heaters, and new technologies like heat pumps and solar thermal systems. These alternatives often offer consumers lower initial capital costs, higher autonomy, and more attractive payback periods, intensifying the market pressure on DCHP. Finally, the continued increase in global fuel prices—spanning oil, natural gas, and biomass—further exacerbates the challenge of offering competitively priced thermal energy. In parallel, rising electricity tariffs directly impact DCHP's operational costs, particularly in the absence of lignite-based supply.

4.2 Energy potential analysis

As described in the previous chapter, the district heating system of Ptolemaida requires approximately 231 GWh of thermal energy annually and presents significant potential for renewable energy integration. This section evaluates the most suitable renewable energy sources—solar thermal, wind (indirectly via electricity), biomass, biogas, and geothermal energy—based on local resource availability, expected output, and technical feasibility.

4.2.1 Solar Thermal Systems

Solar thermal energy can play a valuable role in decarbonizing the heat supply. A system comprising approximately 15,000 to 20,000 square meters of selective solar collectors could generate between 10 and 12 GWh of heat annually, depending on local solar irradiation levels. The expected efficiency for selective collectors is approximately 700 kWh per square meter per year. To ensure optimal utilization of the collected solar heat—especially during the summer months when demand is lower—it is essential to integrate the system with both heat pumps and adequate thermal storage capacity. The existing 3,800 m³ thermal storage tank, while beneficial, is insufficient on its own for large-scale seasonal balancing. Therefore, it is recommended to supplement it with an additional 45,000 m³ thermal storage unit. This recommendation aligns with typical design guidelines, which suggest a required storage volume of 3 to 5 m³ per square meter of collector surface, depending on the storage technology employed. For this application, an average value of 3 m³/m² is adopted. Given the planned collector area, such an expansion would enable more effective seasonal heat shifting and better alignment of solar thermal production with the district's heating needs.

Assuming a solar thermal system with an annual output of 10–12 GWh, the integration of a high-temperature heat pump can significantly enhance energy utilization. According to manufacturer data, such heat pumps can achieve a Seasonal Performance Factor (SPF) between 3.6 and 4.0. Taking a conservative average SPF of 3.8, the heat pump could deliver approximately 38–45 GWh of usable thermal energy annually from the 10–12 GWh of input energy.

4.2.2 Wind Power

Wind energy, although not a direct source of heat, can indirectly support the system by powering heat pumps or electric boilers. With appropriate siting and average wind speeds of 5 meters per second at heights above

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50 meters in the Eordaia municipality, the installation of 2 to 3 medium-scale wind turbines (2–3 MW each) could generate approximately 15–20 GWh of electricity per year. This electricity can then be converted into useful thermal energy through high-efficiency technologies.

4.2.3 Biomass Boilers

Biomass is another viable and well-established option. A biomass boiler system with a thermal output of 35–40 MW could supply 80–90 GWh of heat annually. This would require an estimated 30,000 tonnes of dry biomass per year, which could be sourced from forest residues, agricultural by-products, or dedicated energy crops. To ensure sustainability, the biomass supply chain must be locally sourced and carefully managed. Additionally, modern emissions control technologies would be necessary to minimize environmental impacts.

Due to their ability to produce heat directly through combustion, biomass boilers represent an ideal solution for a backup system. A backup boiler with a thermal output of approximately 25 MW could effectively cover emergency situations and peak-load demands within the Ptolemaida district heating network.

4.2.4 Biogas injection into Natural Gas Grid

As part of the energy transition and efforts to reduce greenhouse gas emissions, we propose the injection of upgraded biogas (biomethane) into the natural gas network to supply a thermal boiler connected to the District Heating (DH) system of Ptolemaida.

The biomethane will be produced via anaerobic digestion and upgrading of sewage sludge from the municipal wastewater treatment plant (WWTP) of Ptolemaida, along with livestock waste. With a methane content of 95–96%, the upgraded gas is fully compatible with existing natural gas infrastructure.

Its calorific value, close to 10 kWh/Nm³, is comparable to conventional natural gas. Approximately 5 metric tons ≈6,944 Nm³ of biomethane will be available annually, representing 69,440 kWh of renewable energy, to be blended into the network at a 12% ratio.

This can support a 100 kW thermal boiler, operating for 8 months per year, producing up to 579,000 kWh of heat annually.

Since the biomethane meets natural gas specifications in terms of energy content, pressure, and purity, its injection is technically feasible, and no equipment modifications are required for boiler operation using the blended fuel. Furthermore, because it is utilized in an internal combustion boiler, this application is ideal for facilities with immediate or on-demand heat requirements, offering high responsiveness and operational flexibility.

4.2.5 Conclusion

In summary, a well-designed hybrid system that combines different renewable energy sources could feasibly meet Ptolemaida's district heating demand. The integration of thermal storage infrastructure and heat pumps is essential for maximizing the use of intermittent and low-temperature energy sources. With the appropriate investment and planning, such a system could serve as a model for sustainable district heating in regions transitioning away from coal dependency.

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4.3 Development of scenarios for greening the DH

This chapter examines three alternative scenarios for the modernization and green transition of the district heating system in Ptolemaida. All three scenarios are based on the integration of renewable energy technologies, aiming to reduce the environmental footprint, improve energy efficiency, and ensure the long-term sustainability of the system.

4.3.1 Scenario 1: Biomass Boilers

This technical proposal concerns the installation and operation of a biomass boiler plant with a total thermal capacity of 80 MW, aiming to utilize renewable feedstock for the production of thermal energy. The plant is designed to operate for 8 months per year and is expected to achieve an annual energy output of approximately 230 GWh. The use of biomass as fuel offers significant advantages, as it **relies on locally available agricultural and forestry residues**, making the system energy-independent, environmentally sustainable, and economically viable.

Unlike other renewable energy technologies that are intermittent (such as solar or wind), biomass enables continuous and predictable heat generation. In fact, it is one of the very few renewable energy systems capable of fully and autonomously covering total thermal demand, whether for large-scale industrial facilities, district heating networks, or entire residential areas, without requiring backup from fossil fuel systems. The 80 MW thermal capacity is sufficient to support a wide range of applications, including thermal energy for industrial processes, district heating, or even combined heat and power (CHP) generation, should suitable equipment be added.

The key advantages of this system include a substantial reduction in CO_2 emissions, increased energy self-sufficiency, and the stimulation of the local economy through the utilization of agricultural and forestry by-products. Moreover, the implementation of this project contributes to the decentralization of energy production while creating new jobs across the supply, operation, and maintenance chains.

To further enhance system flexibility and efficiency, the existing hot water storage tanks with a total capacity of 3,800 m^3 will be utilized for thermal energy storage. These tanks enable the decoupling of production and consumption, smoothing out demand fluctuations and improving the operational stability and responsiveness of the heating network. This storage capacity also allows the plant to operate more efficiently during peak load periods and provides a buffer to reduce unnecessary boiler cycling.

Nonetheless, certain challenges must be taken into account. Successful operation requires a stable and sufficient biomass supply chain, which may be affected by seasonal fluctuations and variability in agricultural outputs. Additionally, the relatively low energy density of biomass increases storage and transportation requirements, while its combustion—although environmentally acceptable—requires modern emission control systems to ensure compliance with environmental standards.

The seasonal operation of the plant (8 months per year) introduces considerations related to scheduling and maintenance planning in order to achieve optimal annual performance. While the initial capital expenditure is considerable, it is offset by long-term fuel cost savings and the economic stability offered by energy independence.

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To meet an annual thermal demand of approximately 230 GWh using an 80 MW biomass boiler, a substantial quantity of solid biomass fuel is required. Assuming the use of woody biomass with a moisture content of around 20%, the lower heating value (LHV) of the fuel is estimated at approximately 4,000 kWh per ton. Considering a boiler thermal efficiency of 85%, the useful energy yield per ton of biomass is approximately 3.4 MWh. Based on these assumptions, the total annual biomass requirement to produce 230 GWh of thermal energy is estimated at roughly 68,000 tons. This calculation reflects the scale of supply and storage infrastructure needed to ensure the sustainable and uninterrupted operation of the district heating system.

In conclusion, the installation of 80 MW biomass boilers represents a technically mature and environmentally favorable solution capable of meeting increasing energy demands in a sustainable manner. With proper technical planning, effective energy system integration, and a secured fuel supply, the project can serve as a model for large-scale green energy deployment and a key pillar of the energy transition.

4.3.2 Scenario 2: Electrification

As part of the modernization and decarbonization of the Ptolemaida district heating system, a fully electrified scenario is proposed. This includes the continued operation of the two already-installed electric boilers, each with a capacity of 80 MW, which will serve the primary distribution network. The primary circuit consumes 124.2 GWh of thermal energy annually. Since this energy is produced via electric boilers with a coefficient of performance (COP) of 0.99, the corresponding electricity consumption amounts to approximately 125.45 GWh per year.

In addition, it is proposed to install high-temperature heat pumps with a total installed capacity of 56.2 MW across the 11 area substations that supply the secondary distribution network. The secondary network has an annual thermal demand of 105.8 GWh. Thanks to the use of high-efficiency heat pumps with a COP of 3, only 35 GWh of electricity will be required annually to meet this demand. To further support the system during peak demand or periods of low ambient temperatures, an auxiliary high-temperature heat pump with a thermal output of 8.1 MW will also be installed. This unit will deliver 10 GWh of thermal energy annually, requiring only 5.1 GWh of electricity due to a lower COP of 2 under colder conditions.

The existing thermal energy storage infrastructure, with a total volume of 3,800 cubic meters, will be retained and utilized to enhance the system's flexibility and reliability. In parallel, the integration of two large-scale lithium-ion Battery Energy Storage Systems (BESS) is proposed, providing a combined capacity of 40 MW/120 MWh (4-hour duration). While the thermal storage will help manage fluctuations in heat demand, the BESS units will play a critical role in balancing electricity supply and demand by storing excess renewable electricity during periods of high generation and low consumption, and discharging it during peak demand or low generation periods. Together, these storage solutions will enhance grid reliability, improve overall system resilience, and enable the efficient and flexible operation of the fully electrified district heating system.

To meet the total annual electricity demand required to operate the district heating system, amounting to 166 GWh, new renewable energy sources will be developed and integrated into the system. Specifically, a 72 MW solar park is planned, expected to generate approximately 133 GWh annually. This will be complemented by a wind farm consisting of five wind turbines, each with a capacity of 4 MW, with a combined annual output of 43.8 GWh. Both the solar and wind facilities will inject electricity into the grid throughout the year, enabling an energy offset through net metering. This configuration ensures that the total electricity consumed by the system—approximately 165.55 GWh annually—is fully balanced by clean,

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renewable sources, achieving a zero-emissions district heating solution with high efficiency and long-term sustainability.

The following diagram illustrates the monthly energy balance projected under Scenario 2, following its full implementation. As previously analyzed, PV electricity generation is significantly higher during the summer months due to increased solar irradiance. However, during this period, thermal energy demand is minimal, resulting in surplus electricity production with limited immediate on-site utilization. In parallel, the contribution of wind energy—characterized by greater consistency and lower seasonal variability—is also accounted for in the energy balance. Wind turbine output, according to the weather data of the region, remains relatively stable throughout the year, enhancing the overall reliability of renewable electricity supply. The diagram also depicts the monthly electricity demand associated with the full electrification of the district heating system.

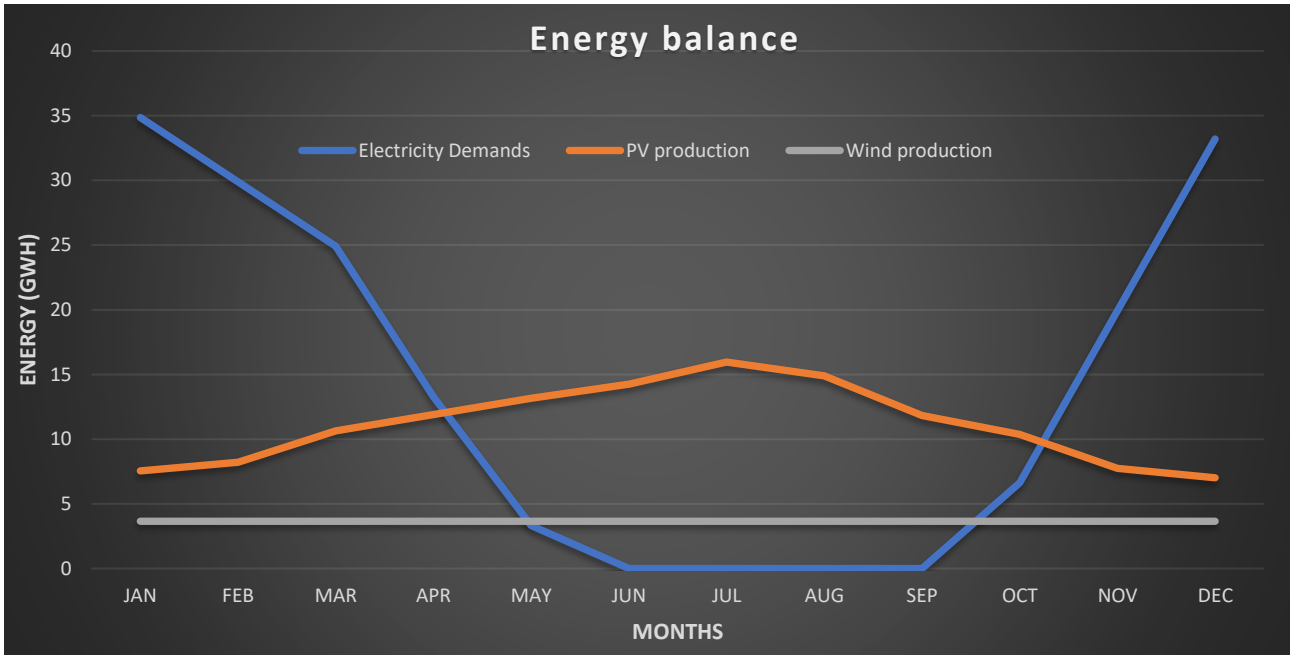


Figure 10. Energy balance for scenario 2

To provide a clearer understanding of the annual energy balance and to highlight the necessity of establishing a net metering agreement, the following diagram illustrates the seasonal mismatches between renewable energy production and the electricity demand of the fully electrified district heating system. Specifically, the diagram depicts the surplus renewable electricity, mainly during the summer months, when thermal energy demand is minimal as well as the energy deficit observed during the winter months, when electricity demand for district heating peaks due to increased thermal loads and renewable generation alone is insufficient for immediate coverage. As previously discussed, the total annual renewable energy production—when aggregated—is adequate to fully meet the electricity requirements for operating the district heating system. However, due to the temporal mismatch between generation and consumption, the implementation of a net metering or energy exchange framework is essential. This mechanism enables surplus electricity generated during low-demand periods to be credited and offset against consumption during peak demand periods, thus ensuring annual energy self-sufficiency and system-wide operational continuity.

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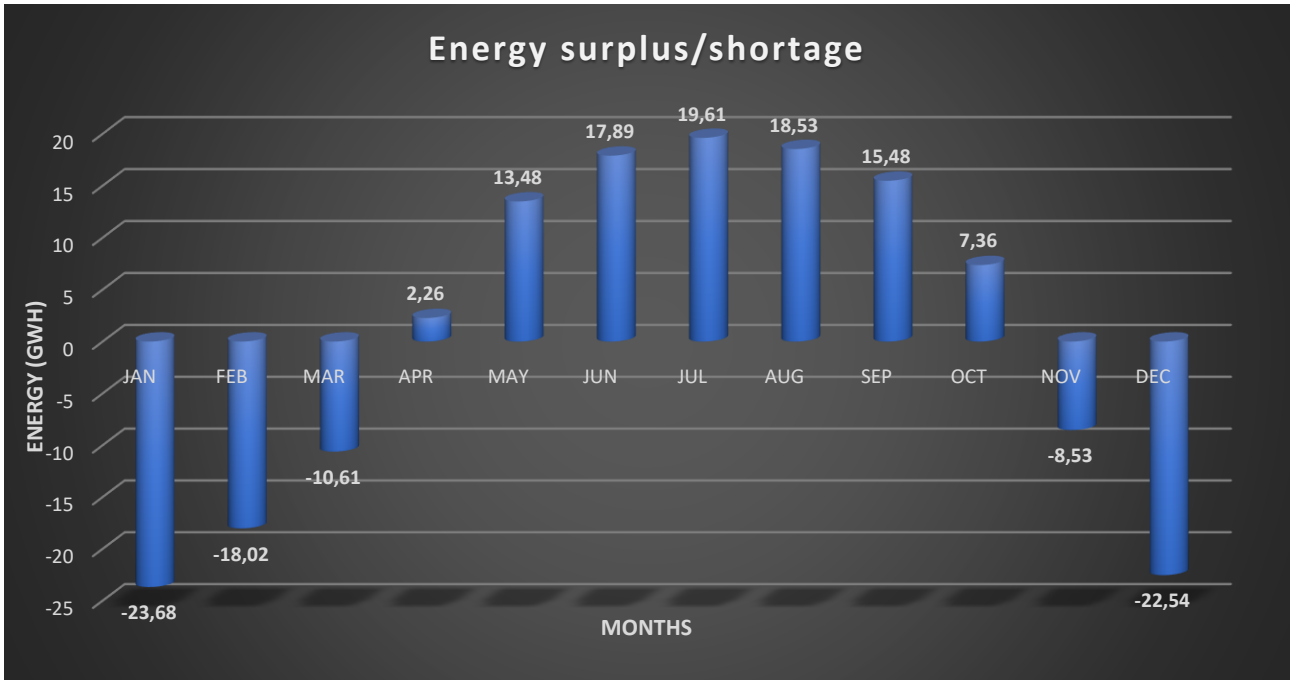


Figure 11. Monthly energy surplus or shortage for scenario 2

4.3.3 Scenario 3: Hybrid solution

The third proposed scenario for the modernization and decarbonization of the Ptolemaida district heating system is based on a hybrid approach that combines biomass-based cogeneration with renewable electricity and thermal storage technologies. The total annual thermal energy demand of the system amounts to 230 GWh, of which 125 GWh is distributed through the primary network and 105 GWh through the secondary network. The following diagram illustrates the thermal energy demand profile of the district heating system, detailing the monthly distribution of heating requirements throughout the year.

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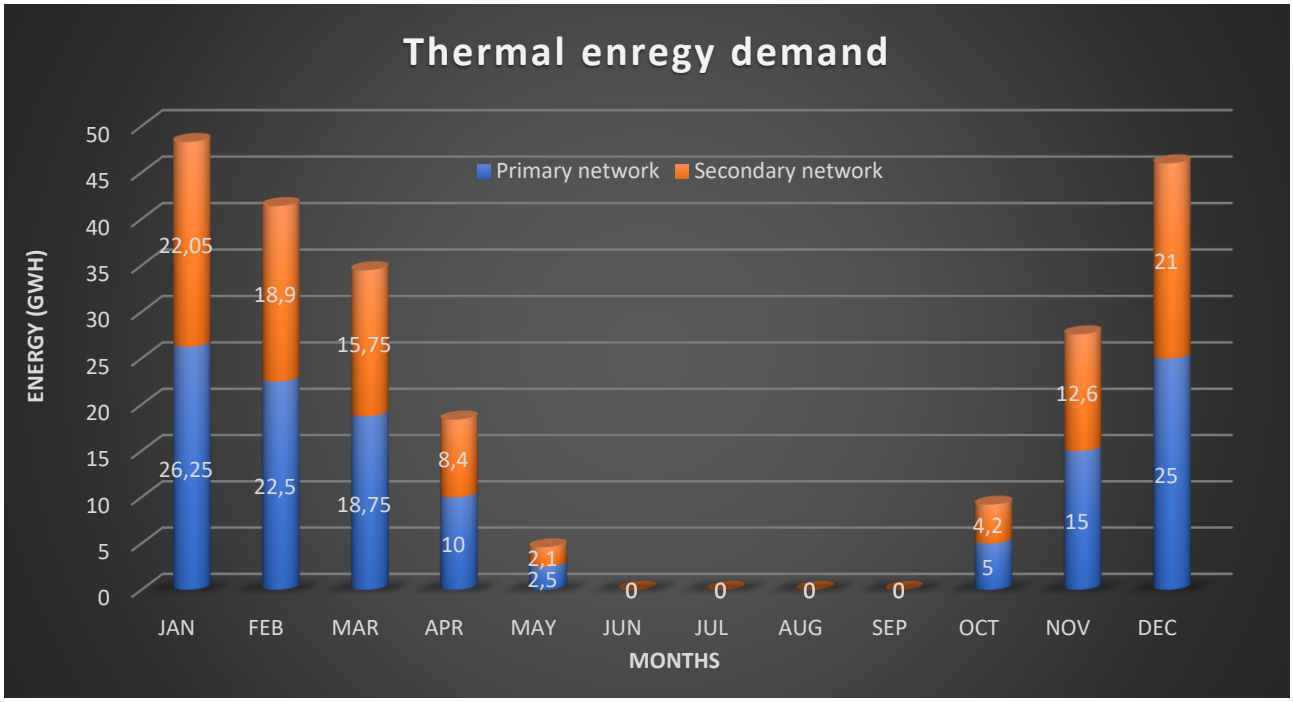


Figure 12. Thermal energy demand for the operation of district heating system

To supply the primary circuit, the scenario proposes the installation of a biomass-fired combined heat and power (CHP) plant with a thermal capacity of 32 MW and an electrical output of 15,2 MW. This CHP unit will provide continuous thermal energy while simultaneously generating electricity, increasing overall system efficiency. The annual thermal production of the CHP unit is estimated at 69.1 GWh . A 40 MW / 120 MWh battery energy storage system will be charged primarily by the CHP unit and will be used to supply electricity to the electric boiler during peak demand hours, for up to four hours per day. The existing 40 MW electric boiler, already in operation, will be retained as a supplementary heat source and will operate strategically during these peak periods.

The system will also include a large-scale solar thermal plant consisting of 45,000 square meters of selective collectors, with an annual output of 32 GWh and an installation area requirement of approximately 90.000 m^2. This installation will be paired with 7,800 cubic meters of thermal water buffer tanks, of which 3,800 m^3 are already installed and currently used by the existing system. Together, they will contribute significantly to the energy supply of the primary network, particularly during periods of high solar irradiation. Figure 13 presents the thermal energy balance of the primary district heating system. The solar thermal energy output reflects the expected seasonal variability, driven primarily by fluctuations in solar irradiance and ambient weather conditions. In contrast, the combined heat and power (CHP) unit provides operational flexibility, enabling dispatchable thermal energy generation as needed to compensate for intermittent renewable supply or to meet peak demand.

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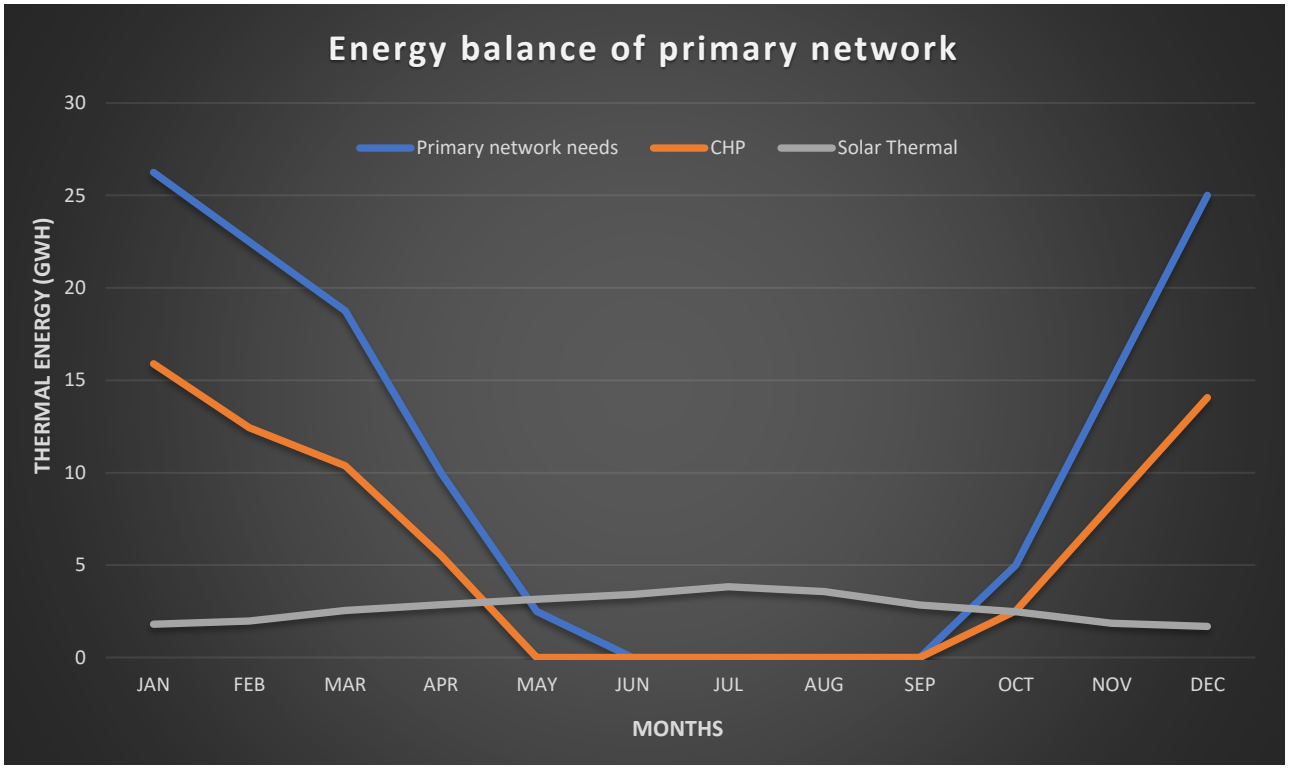


Figure 13. Energy balance of primary network for scenario 3

However, as illustrated in Figure 14, the combined thermal output from the two technologies does not fully satisfy the system's thermal energy demand across all operating conditions. This is the reason of the integration of thermal energy storage buffers and the supplementary use of electric boilers, which provide additional capacity and operational flexibility to ensure continuous and reliable heat supply.

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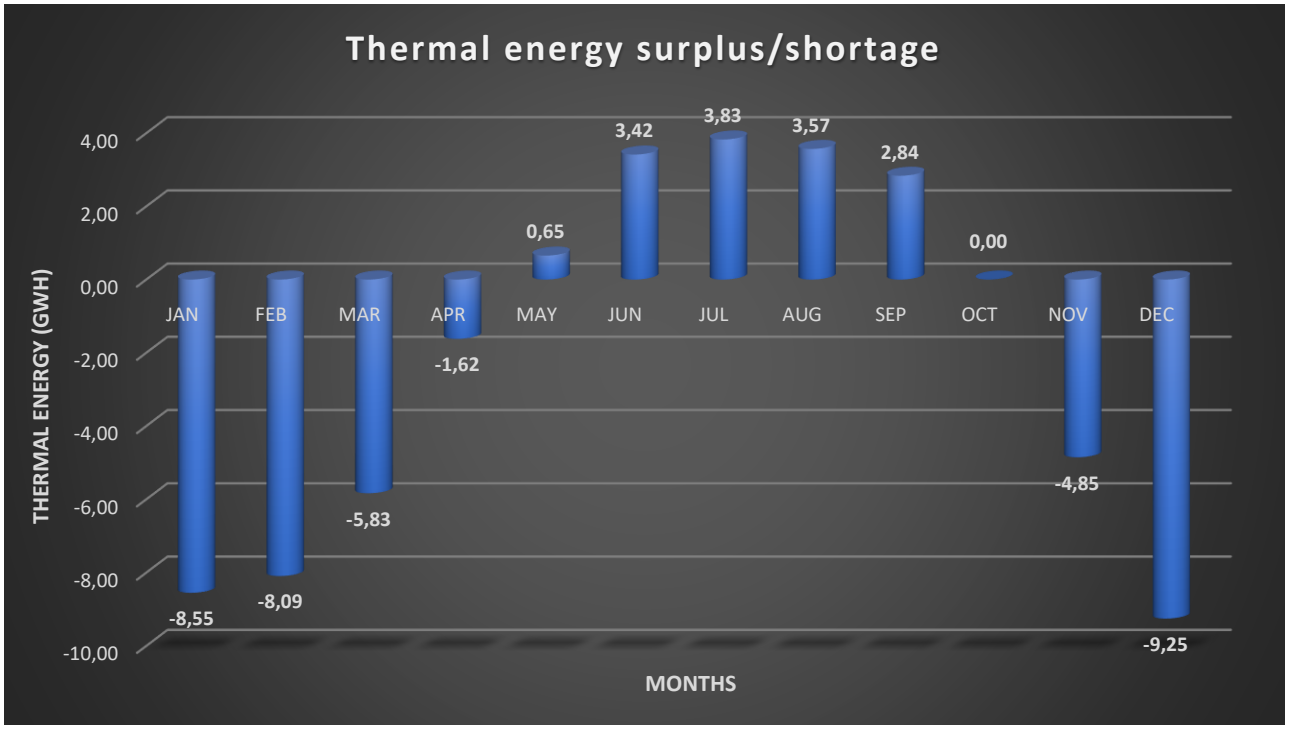


Figure 14. Monthly energy surplus or shortage of thermal energy for scenario 3

For the secondary network, the scenario follows the electrification model through the deployment of high-temperature heat pumps. A total installed capacity of 56.2 MW will be distributed across the substations of the secondary circuit, supported by an auxiliary heat pump with a capacity of 8.1 MW. These high temperature heat pumps will provide the required 105 GWh of thermal energy to the secondary network. As described in the electrification scenario above, a wind farm consisting of five wind turbines each with a capacity of 4 MW will be developed to meet the electrical demands of the heat pumps and other system components. This renewable energy source will be supported by a second 40 MW / 120 MWh battery storage system to balance fluctuations in power generation and demand. Figure 15 illustrates the electricity demand profile of the secondary grid, alongside the projected electrical output from the installed wind turbines. The comparison highlights the potential contribution of wind energy to the grid's load coverage and supports the assessment of energy balance and system adequacy under varying operating conditions.

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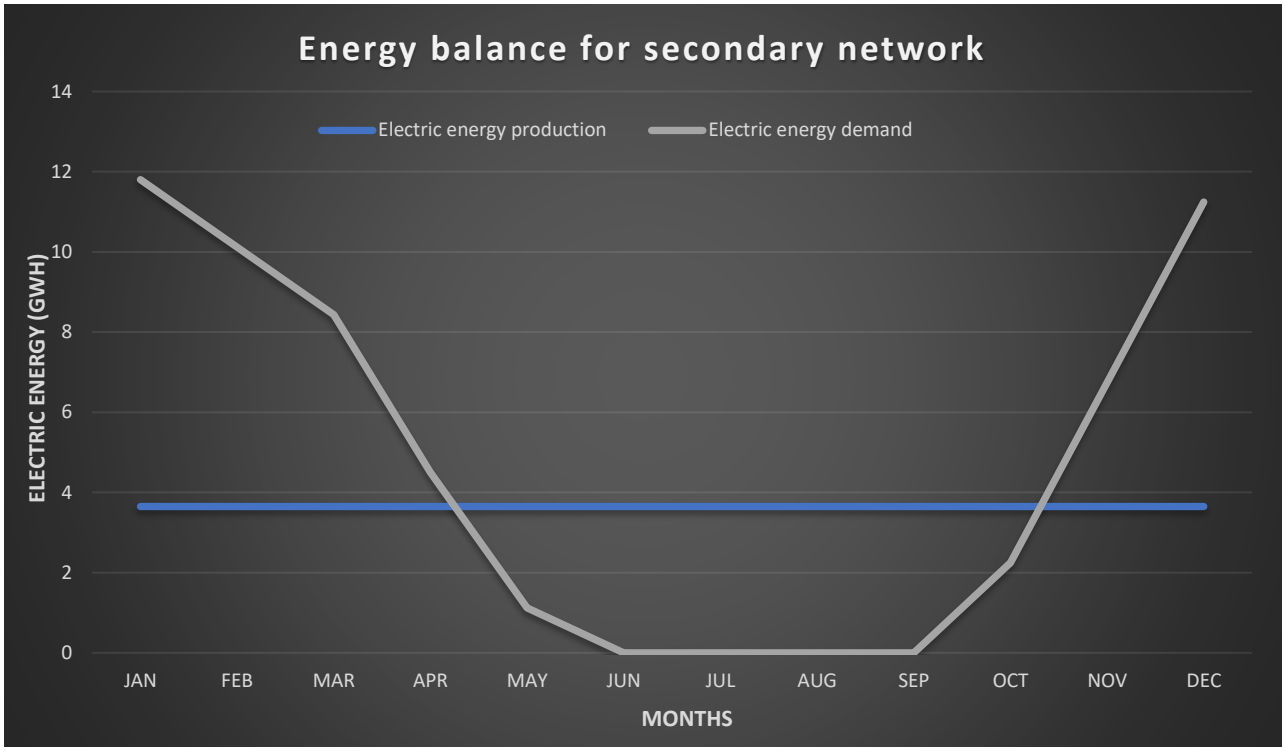


Figure 15. Energy balance of secondary network for scenario 3

In this scenario, as depicted in Figure 16, there is a significant and persistent mismatch between electricity demand and on-site renewable generation throughout the year. This discrepancy, evident across all months, underscores the necessity for the integration of a battery energy storage system (BESS) to enhance load balancing, improve self-consumption rates, and increase system flexibility.

Despite the incorporation of storage, the electricity demand of the secondary grid is not fully met by the proposed renewable generation assets. To achieve the overarching objective of complete decarbonization of the network's operation, a strategic agreement with the national electricity provider (PPC) is foreseen. This agreement is twofold:

1. Net energy offsetting, allowing surplus electricity generated on-site to be credited against future consumption;
2. Procurement of residual electricity demand, estimated at approximately 10 GWh annually, which will be sourced exclusively from certified renewable energy sources (RES) to ensure full alignment with the system's carbon neutrality targets.

This hybrid approach—combining on-site generation, energy storage, and certified green electricity procurement—ensures the continuous and fully renewable operation of the network, even under variable generation and high-demand conditions.

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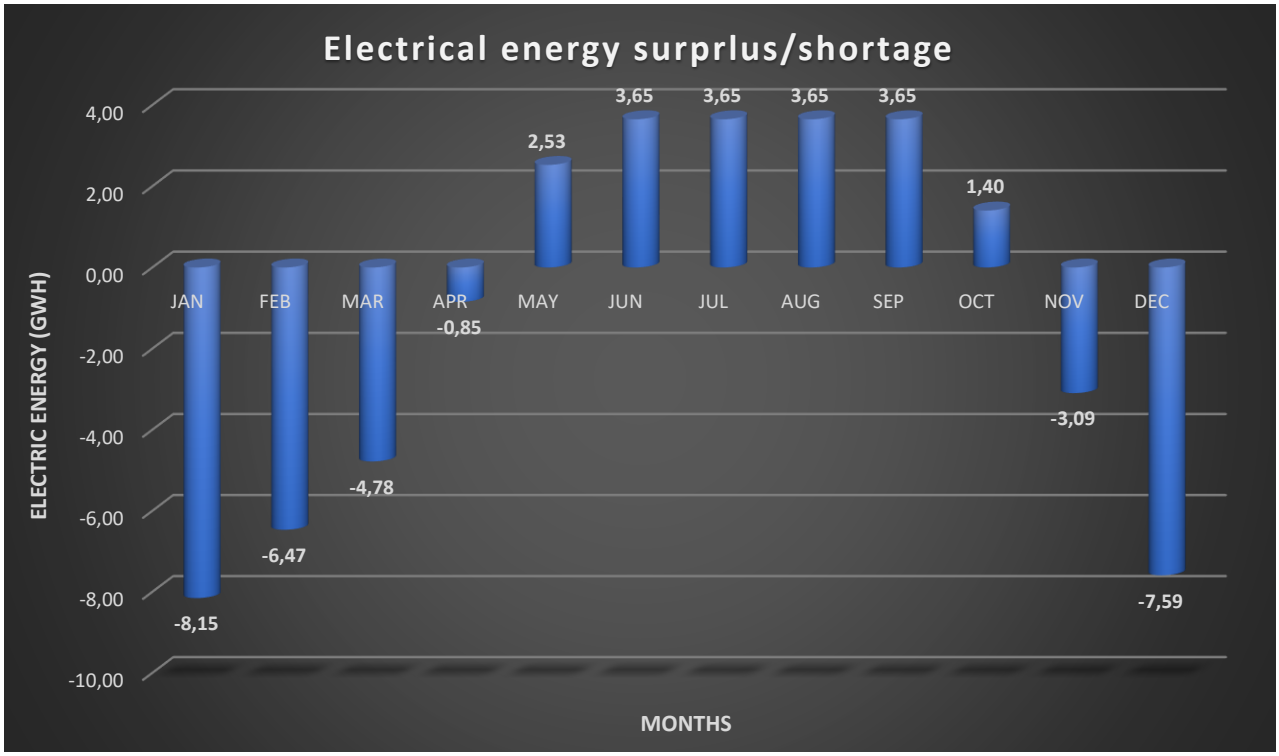


Figure 16. Monthly energy surplus or shortage of electrical energy for scenario 3

This integrated scenario proposes the deployment of a multi-source district heating system for the city of Ptolemaida, combining biomass-based combined heat and power (CHP), solar thermal energy, heat pump-driven electrification, and thermal energy storage. The objective is to establish a secure, resilient, and low-carbon thermal energy infrastructure capable of delivering reliable year-round service. By harnessing the complementary characteristics of these technologies—dispatchability of biomass CHP, seasonality of solar thermal, high efficiency of heat pumps, and load balancing via storage—the system minimizes dependence on fossil fuels and enhances operational flexibility. Furthermore, this approach aligns with national and EU climate neutrality targets, supports the decarbonization of the heating sector, and contributes to long-term energy system resilience and sustainability.

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5 Conclusions

District heating is a mature and time-tested technology, with over a century of successful implementation worldwide. Originally designed to meet space heating demands, it has evolved to also support cooling requirements in many modern applications. Today, district heating systems serve millions of users, offering a centralized, efficient and scalable approach to thermal energy distribution. Their core strength lies in their environmentally friendly operation and their technical, energetic and economic sustainability—attributes that position them as a key enabler of energy transition in urban infrastructure.

The main challenge facing the further development and optimization of district heating systems is the decarbonization of the energy sources used to operate them, as the majority of existing networks rely heavily on thermal energy derived from fossil fuel combustion. This reliance presents a significant obstacle in the broader context of European Union decarbonization goals—particularly for Greece, where the transition to a low-carbon economy is both urgent and complex. Integrating RES into district heating represents a promising and pragmatic pathway toward achieving climate neutrality. The shift toward RES not only enhances the sustainability of heating networks but also aligns with broader energy policy objectives at both the national and EU levels.

The analysis conducted in this Deliverable identifies a wide array of technologies capable of supplying the thermal and electrical energy required for district heating operations. These technologies can be categorized as follows:

- **Established and Proven Technologies**: Solar thermal collectors, wind turbines, and geothermal energy systems are mature and widely deployed. These technologies offer high reliability and significant potential for integration into district heating systems.
- **Technologies with Limited Potential**: Biomass, although widely used, presents constraints in terms of availability, logistics, emissions, and sustainability, thereby limiting its scalability in certain regions.
- **New and Innovative Technologies**: Hydrogen and biogas injection into the natural gas grid represent forward-looking solutions. However, they remain in the early stages of development and have not yet been deployed at scale for district heating purposes.

From this technology review, three critical conclusions emerge:

1. **No Single Technology Is Sufficient**

A district heating system cannot rely on a single renewable source. The only technically, economically, and environmentally viable approach is the deployment of **hybrid systems** that combine multiple RES technologies to ensure reliability and flexibility.

2. **Energy Storage Is a Non-Negotiable Requirement**

Efficient operation of modern district heating networks demands integrated **energy storage solutions**. These may include thermal storage (e.g., buffer tanks, geothermal boreholes) or electrical storage (e.g., batteries, hydrogen as an energy carrier). Storage ensures supply continuity and enhances system resilience.

3. **System Design Must Be Location-Specific**

The choice of technologies must be tailored to the **local energy potential** of the deployment area. For instance, regions with high wind energy capacity should prioritize wind turbine integration, whereas areas with limited solar irradiance may find solar thermal unfeasible.

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Focusing on the Greek context, particularly the city of Ptolemaida, the decarbonization—or "greening"—of the existing district heating network represents a significant but strategically important challenge for the local community and regional authorities.

The main advantage of the region lies in its favourable renewable energy profile. The area benefits from high solar irradiance throughout the year, offering substantial potential for the deployment of solar thermal systems. In addition, sufficient wind resources in nearby locations make the installation of wind turbines a technically and economically viable option. The region also possesses noteworthy biomass potential, further diversifying the renewable energy mix. Moreover, the presence of active research and innovation stakeholders—including CERTH, University of Western Macedonia and regional professional chambers—creates a robust ecosystem for the research, demonstration, and deployment of emerging technologies, such as green hydrogen and biogas. Importantly, the local community exhibits a high degree of social acceptance and openness to innovation, a critical factor for the successful implementation of transformative energy projects. A secondary yet equally significant advantage is the existence of a fully operational district heating network and associated infrastructure. This installed base provides a ready-made platform for system upgrades and expansions, substantially reducing initial capital investment and project lead time.

However, the most prominent challenge lies in the fact that the existing system was originally engineered to operate under specific thermal conditions, utilizing waste heat from PPC's lignite-fired power plants. As such, the complete "greening" of the district heating network will require comprehensive technical modifications, including adaptations to accommodate lower-temperature renewable sources, integration of diversified energy inputs and enhancement of control and storage systems.

The three alternative decarbonization scenarios, which have been developed for the Ptolemaida district heating system represent three different technologically and energetically viable configurations, fulfilling the three core prerequisites for sustainable district heating outlined previously designed to:

- Consist of **hybrid systems**
- Leverage **locally available renewable energy sources**
- Incorporate **energy storage solutions** (thermal and/or electrical)

In conclusion, the modernization and expansion of district heating systems—coupled with the full integration of renewable energy sources—constitute the most technically sound, environmentally responsible and economically feasible solution for meeting increasing demands for heating and cooling in urban areas. In the case of Ptolemaida, the "greening" of the district heating network is not merely an engineering task; it is a regional development challenge of strategic significance. Successfully overcoming it will serve as a model for other post-lignite regions across Europe and will demonstrate the viability of RES-powered district heating in supporting a just and sustainable energy transition.

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Annexes

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