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Online training materials for professionals/policy-makers

Deliverable 3.1.4

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Content

Executive summary

This deliverable presents the Online Training Materials for Professionals and Policy-Makers, developed under Activity A.3.1 of the REHEATEAST project to support Specific Objective 3.

The materials aim to strengthen professional and institutional capacities to enable the transition toward efficient, low-carbon, and renewable-based DHC systems, in line with EU climate and energy objectives.

The training addresses the need to reduce fossil fuel dependency in heating and cooling by improving energy efficiency, integrating renewable and waste heat sources, and supporting coordinated planning and governance. It contributes to the implementation of the Energy Efficiency Directive (EED), the Energy Performance of Buildings Directive (EPBD), and the criteria for Efficient DHC, supporting climate-resilient DHC transformation in the Danube Region.

The online materials provide structured, modular, and practice-oriented content covering the full DHC value chain, including system fundamentals, heat generation and cooling technologies, thermal storage, network design and operation, optimisation, green procurement, standardisation, and emerging smart energy trends. Technical, regulatory, strategic, and economic aspects are integrated to ensure real-world applicability.

Developed through a structured methodology based on sector needs and learning objectives, the training targets a wide range of stakeholders, including utilities, engineers, public authorities, planners, decision-makers, and investors. Accessible through an online platform and adaptable to national contexts, the materials support informed decision-making, capacity building, and the accelerated deployment of sustainable and future-proof DHC solutions.

1. Introduction

1.1. Overview on the Reheateast Project and Activity A.3.1

The REHEATEAST project focuses on reducing fossil energy demand in district heating and cooling (DHC) systems by cutting energy losses in buildings and networks while integrating renewable sources, particularly geothermal, and waste heat. It fosters multi-stakeholder, cross-sector, and public–private cooperation, and designs, tests, and disseminates practical, technical, and nature-based solutions that support large-scale rehabilitation programs and climate adaptation efforts.

Through knowledge exchange, awareness-raising, and stakeholder collaboration, REHEATEAST advances adaptable, catalytic solutions to curb dependence on fossil fuels. The project promotes an integrated approach over siloed strategies, enabling transformative investments in energy efficiency, waste heat recovery, thermal storage, geothermal energy, and improved billing practices. Its communication initiative, *"Over 10 under 100,"* aims to reduce annual heat consumption in apartment buildings with at least ten dwellings—located in cities with over 10,000 DHC users—to below 100 kWh/m^2. This aligns with the Energy Efficiency Directive (EED), which enshrines "energy efficiency first" in policy and investment decisions. Meeting the targets of the EU Energy Performance of Buildings Directive (EPBD) is not feasible without efficient DHC systems.

On the supply side, REHEATEAST is designed to meet the EED criteria for "Efficient DHC," which require at least 50% renewable energy, 50% waste heat, 75% cogenerated heat, or an appropriate combination of these sources. This strategy is grounded in robust energy planning and management to ensure that capacities match demand without waste.

The overarching aim of Specific Objective 3 is to strengthen the policy and sectoral framework for DHC systems in REHEATEAST countries. This will be achieved by formulating and facilitating policy recommendations at multiple levels of governance, enabling the adoption and integration of cooperation and optimization models developed under SO2. The objective is further supported by communication and capacity-building activities that enhance the attitudes, awareness, and knowledge of key target groups capable of influencing DHC energy efficiency.

Activity A.3.1, which underpins the development of this deliverable, centers on policy dialogue at local, regional, and national levels to elaborate and communicate policy recommendations to decision-makers and institutions. These recommendations are grounded in knowledge jointly developed within the project. The process seeks to align local policies with previously developed and tested cooperation and optimization models, thereby facilitating the energy-, cost-, and climate-efficient transformation of DHC systems.

1.2. Overview of Online Training Materials

The online training materials provides structured learning content designed to equip energy professionals, planners, and decision-makers with the knowledge needed to support the sustainable transformation of District Heating and Cooling (DHC) systems

The training materials cover a broad range of technical and strategic topics, including energy efficiency improvements; the integration of renewable and low-temperature energy sources (e.g. geothermal, solar thermal, and waste heat); thermal storage; and digital tools for system planning and optimisation. Green procurement, standardisation and certification, as well as regulatory frameworks, are also addressed to help users identify viable pathways for sustainable DHC development.

The materials also include references to relevant literature and resources, enabling professionals and policymakers to further explore methodologies, standards, and emerging practices. Adopting a holistic approach, the training materials supports the design and implementation of innovative, practical, and scalable solutions across the DHC value chain. It aligns with Europe's climate neutrality goals and supports the transition toward smart, efficient, and renewable-based heating and cooling networks.

1.3. Target audience

The learning materials have been developed for professionals and policymakers involved in the planning, development, regulation, and operation of DHC systems. Whether engaged in technical implementation or strategic decision-making, users of these training materials will find practical, targeted content that supports real-world application in the energy transition of heating and cooling systems.

This includes professionals in:

- Utilities and DHC operators
- Public authorities and regulators (municipal energy departments, urban planners, energy agencies)
- Engineers/technical staff and consultants (incl. ESCOs)
- Facility and building managers
- Technology vendors and integrators
- Academia/research, NGOs/professional associations, standardisation/certification bodies, and financing/PPP actors

2. The methodology

2.1. Goal of the Online Training Materials

The goal of the online training materials is to enhance the capacity of professionals and policy-makers to plan, decarbonise, operate, and regulate efficient, low-temperature district heating and cooling (DHC) systems in line with EU objectives. The training materials are designed to provide baseline knowledge and practical insights that can be immediately applied in users' daily work.

2.2. Learning Objectives

By using the structured learning materials, professionals and policy-makers will be able to:

- Gain a solid understanding of the role of DHC in the energy transition.
- Apply practical knowledge of low-carbon technologies, energy efficiency measures, thermal storage, and digital tools to modernize DHC networks.
- Gain insights into policy, and regulatory frameworks that support sustainable DHC development.
- Strengthen skills to promote stakeholder collaboration, apply green procurement, and design scalable, integrated DHC solutions.

2.3. Selection of the Content

The content for the Online Training Materials for Professionals and Policy-Makers was selected and developed through a structured, multi-criteria methodology. This ensures the materials are up to date and tailored to the needs of professionals and policy-makers in the energy sector, with a focus on DHC systems within the REHEATEAST framework. The process involved the following four main steps:

- **Identification of sector needs and gaps**

A comprehensive review of current DHC practices, policy frameworks, and technological developments was conducted to identify priority areas where knowledge gaps and capacity-building needs are most significant.

- **Definition of learning objectives**

Clear and measurable learning objectives were formulated to guide the training structure and ensure a coherent learning pathway from fundamentals to the key concepts, approaches, and solutions developed and promoted through the REHEATEAST project.

- **Evaluation of relevance and practicality**

Possible topics were evaluated for relevance and practical applicability in REHEATEAST countries, ensuring that the training supports realistic operating conditions and reflects regional contexts as well as (policy) targets.

2.4. Description of Training Materials

2.4.1. Format and accessibility

The training materials are made available in digital format through an online learning platform, ensuring easy access. Professionals and policy-makers can download the materials for offline study, enabling flexible and continuous learning.

2.4.2. Translation and adaptation across REHEATEAST countries

The materials are being developed initially in English, with translations into REHEATEAST country languages where needed to broaden accessibility and uptake.

The content can be localized by including country-specific case studies and adapting references to relevant regulatory and policy frameworks so that the training reflects local circumstances and specificities. This localisation ensures the training remains practical and directly applicable to the realities and policy targets of each participating country.

2.4.3. Learning Outcomes

Upon completion of the training materials, users will be able to:

- Describe the role and strategic value of DHC in the clean energy transition and in achieving EU and/or national climate and energy targets.
- Identify appropriate low-carbon heat and cooling sources ((e.g., geothermal, solar thermal, waste heat, heat pumps, etc.) and understand basic requirements as well as pros and cons for their integration.
- Evaluate and apply energy efficiency measures and temperature-reduction principles across the value chain to optimize existing or planned DHC systems.

- Utilize digital tools and smart technologies to support planning, monitoring, optimisation, and performance management or control.
- Understand the enabling conditions for implementation of efficient DHC, including financing options and the regulatory or policy context ;
- Engage stakeholders effectively, communicate benefits clearly, and support behavioural change within organisations and communities;
- Develop practical and scalable action plans for advancing and decarbonising DHC solutions in urban and/or industrial settings.

There are more other learning outcomes, specific to some target groups, such as :

- Technical professionals (utilities/operators, engineers, planners, etc.):
    - Conduct a basic system assessment and performance baseline
    - Select and justify technology and operational options, including thermal storage,
    - Use digital solutions more directly for network design, optimisation, monitoring, and control improvement.
- Policy-makers and regulators (ministries, agencies, municipalities):
    - Use training materials insights for making / adapting policy and regulatory measures that enable low-temperature, renewable-based DHC,
    - Support local heat planning and coordination, aligning municipal actions with national strategies and EU requirements.
- Decision-makers and investors:
    - Compare alternatives, define an implementation roadmap and prioritise phased investments,

These learning outcomes support the EU's climate and energy goals and are designed to enable professionals and policy-makers to contribute effectively to real-world transitions toward sustainable district heating and cooling solutions.

2.5. Prerequisites

The online training materials are designed to be accessible to a wide range of professionals or stakeholders. There are no formal prerequisites as the training materials starts with core concepts and builds step by step toward more advanced topics. To get the most from the training materials, it can be helpful (but not required) to have:

- A basic understanding of energy systems and how heating is supplied and used
- Some familiarity with the concepts related to urban development, sustainability, or energy policy.
- Experience in fields such as utilities, local government, consulting, engineering, or policy development.

3. Content Overview

4. Interface Systems for End Users in District Heating Networks

4.1 Substations and heat modules

4.2. Heat meters

5. District heating and cooling optimisation

5.1 Demand-Side Measures

5.2 Supply-Side Measures

6. Green procurement in DHC

6.1 Definition and Objectives

6.2 Application Areas in DHC

6.3 Procurement Criteria and Standards

6.4 Benefits of Green Procurement in DHC

6.5 Implementation Challenges

7. Standardisation and certification

7.1 Role of Standardisation in DH

7.2 Standards for District Heating

7.3 Certification Schemes

7.4 Benefits of Standardisation and Certification

8. Contemporary energy trends

8.1 Energy and Its Associated Global Effects

8.2 Towards smart energy systems

4. Concluding remarks

The Online Training Materials for Professionals and Policy-Makers is a strategic capacity-building initiative designed to support the deployment of sustainable, efficient, and low-carbon thermal energy systems.

By providing accessible, tailored learning materials, it enables tangible progress toward the decarbonisation of heating and cooling in both urban and industrial contexts. Adopting a holistic and multidisciplinary approach, the online training materials develops not only technical expertise but also the strategic competencies needed to drive systemic change.

Aligned with European climate and energy objectives, it contributes to building a skilled workforce capable of implementing practical, scalable solutions for the energy transition.

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https://interreg-danube.eu/projects/reheateast/library

D.3.1.4

ONLINE TRAINING MATERIALS FOR PROFESSIONALS/POLICY MAKERS

Contents

1. Introduction and fundamentals

1.1 Historical Development of District Heating

District heating systems have the characteristic that heat is produced at central locations and distributed through pipelines to a large number of end users. By using district heating, low-value or even waste heat - such as excess heat from industry - can be effectively utilized [1]. Over the past five decades, district heating has become a key component of heat supply in many countries, particularly in Northern and Eastern Europe. This development has led to a more efficient use of fossil fuels and a significant reduction in CO_2 emissions [2].

Today, national and regional energy systems are increasingly approached from a holistic perspective, integrating heat, electricity, and transport. Within this context, district heating is being progressively recognized as a fundamental component of the broader energy infrastructure. In some countries, it is even considered essential for enabling a higher reliance on variable renewable electricity sources [2].

District heating is designed for small communities or cities with high energy density areas, where heating costs are more advantageous compared to decentralized solutions. The energy sources used in district heating vary depending on the availability of the source and the required thermal power. The energy source for centralized heating systems can be fossil fuels or other energy sources, and hybrid systems that combine two or more energy sources – such as natural gas, wood waste, municipal solid waste, and industrial waste heat – are feasible. Fossil fuels have been used as the primary energy sources for heat supply, but hybrid systems that combine renewable or alternative energy technologies – such as solar collectors, heat pumps, cogeneration or even trigeneration, and biomass systems – have started to be used as energy sources. To maximize efficiency and bridge the gap between energy demand and the availability of energy sources, heat storage can be utilized [3,4].

Regarding heat transport and distribution, pre-insulated pipes buried directly in the ground are used. Each building is equipped with a control valve and an energy meter, and a heat exchanger is also installed to separate the district heating system from the building's internal heating system [5].

In the planning and operation of central heating systems, a clear long-term trend is the progressive reduction of the thermal agent's temperature. Currently, fourth-generation district heating systems (4GDH) are being deployed globally. These systems are defined by supply temperatures ranging from 50 to 60 °C and return temperatures around 25 °C [6]. Figure 1-1 illustrates the typical temperature levels and energy efficiency associated with each generation of district heating.

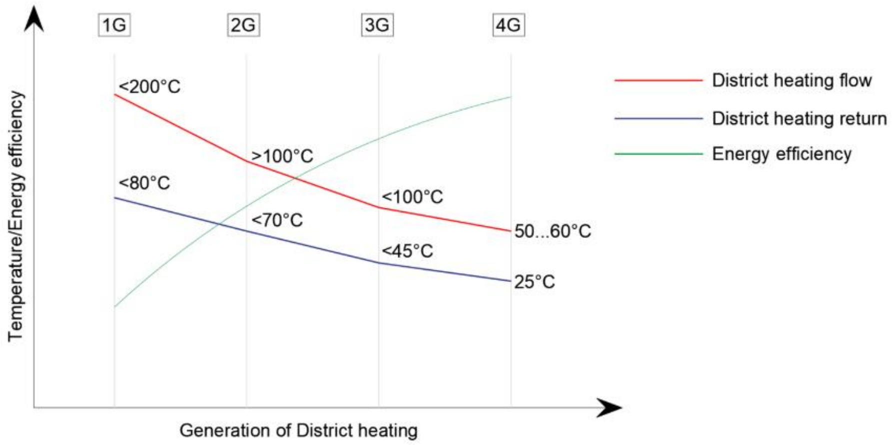


Figure 1-1 The characteristic temperatures and energy efficiency for each generation of district heating [7].

The first generation of district heating systems, introduced in the late 19th century, used steam as the thermal agent and distributed it through concrete pipelines. Remarkably, this type of system is still in operation today in certain parts of cities like New York and Paris. From the 1930s to the 1980s, the second generation of district heating systems emerged, using hot water with temperatures exceeding 100 °C. The thermal agent was transported via insulated steel pipes, and heat was delivered to consumers through tubular heat exchangers. By the late 1970s, third-generation district heating systems became widespread. These systems also use hot water, but at lower temperatures – typically up to 90 °C – and rely on pre-insulated, prefabricated pipes buried underground for distribution [8–10]. Figure 1-2 presents the evolution of generations of district heating systems.

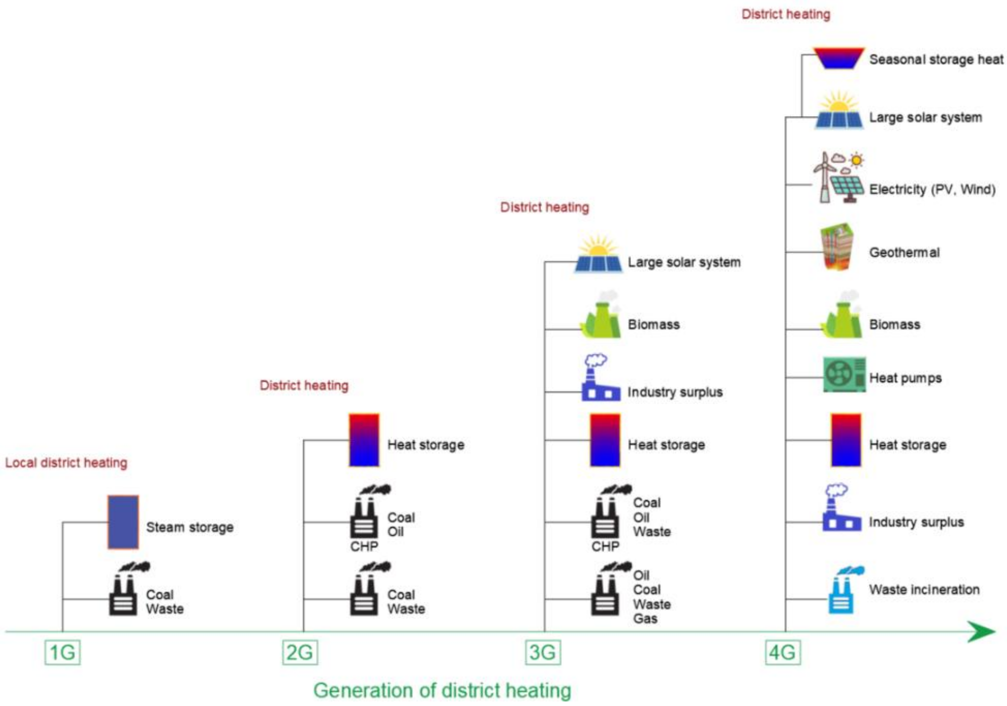


Figure 1-2 Evolution of generations of district heating systems [7].

In the initial three generations of district heating systems, heat was predominantly generated using fossil fuels and supplied to buildings with high energy demand. Due to the decline in fossil fuel availability and the increasing urgency to cut carbon emissions, a new generation of district heating has emerged. This fourth-generation system is based on renewable energy sources and is designed to serve energy-efficient buildings with low heat requirements. The rollout of 4GDH is scheduled for the period between 2020 and 2050 [9,11,12] .

In the context of 4GDH, solar heating systems can serve as a viable alternative to conventional heat supply in urban heating networks. However, due to the seasonal mismatch between solar radiation availability and the heating demand of buildings, the integration of seasonal thermal energy storage systems becomes essential to increase the contribution of solar energy. Long-term heat storage is also beneficial for integrating other heat sources into the network. In addition to renewable sources, 4GDH systems can utilize residual heat recovered from industrial processes and waste incineration, often through combined heat and power (CHP) systems, leading to significant energy savings and environmental benefits [9,13].

At present, fifth-generation district heating systems (5GDH) are the subject of international research and are in the early stages of implementation. These systems operate with thermal agents at temperatures close to ambient, which means they cannot be used directly for heating. As a result, water-to-water heat pumps must be installed between the thermal network and individual buildings to raise the temperature of the thermal agent to the levels required for space heating and domestic hot water (DHW) production. The key advantages of 5GDH include lower thermal losses in the distribution network and improved efficiency in using low-temperature energy sources, thanks to the ability to adapt supply temperatures to each consumer's demand. However, these systems also come with certain limitations, such as more complex and expensive substations compared to traditional systems. In addition, the small temperature difference between the supply and return lines requires higher flow rates, which in turn demands larger pipe diameters [9,14,15].

Table 1-1 presents a comparative analysis of district heating systems from the first to the fifth generation, highlighting the main technical and functional characteristics of each development stage.

Table 1-1 Comparative Analysis of District Heating Systems (Generations 1–5) [8]

Generation	Supply Water Temperature	Heat Losses	Heat Source Availability	Supplementary Heating	Simultaneous Heating & Cooling
1	Over 120 °C	Extremely high	Single source	Not required	No
2	Over 100 °C	High	Single source	Not required	No
3	Around 90 °C	Medium	Single source	Not required	No
4	50 – 70 °C	Low	Few sources	Required	No
5	25 – 50 °C	Very low	Multiple sources	Required	Yes

The development of 4GDH and 5GDH district heating systems creates a favorable context for the integration of renewable energy sources. This transition inherently contributes to improved energy efficiency, reduced greenhouse gas emissions, and enhanced energy security [13,14].

Globally, the demand for cooling exceeds that for heating. In this context, it is expected that current practices of using individual cooling solutions for each building or room will be gradually replaced by centralized cooling systems. Centralized cooling operates on the same principles as district heating, offering higher energy efficiency, saving valuable urban space, and simplifying operation and maintenance for users. Currently, centralized cooling is primarily applied in commercial buildings [6]. While the market is smaller than that of district heating, it is rapidly expanding and expected to grow significantly—especially in warmer countries, where population growth, construction activity, and income levels are also projected to rise. As a result, the demand for cooling is anticipated to increase substantially [11].

1.2 Benefits of district heating

In order to evaluate the advantages of district heating, it is essential to compare it with decentralized (individual) heating solutions. Individual systems usually depend on a single fuel type – such as coal, oil, or natural gas – making end users fully vulnerable to price increases of that specific energy source. With district heating, it becomes possible to take advantage of market dynamics that influence price fluctuations across various fuel types. District heating also offers the advantage of independence from fuel imports. A key benefit is the significantly greater ease of switching fuels compared to the complexity of replacing heating systems in thousands of individual homes [4].

In district heating systems, multiple types of fuel can be used, making energy production highly flexible. This flexibility enhances both supply security and production efficiency. At any given time, the district energy provider can choose the most cost-effective fuel option [1,4].

When heat is produced by advanced combined heat and power (CHP) plants—especially combined-cycle systems—using low-temperature heat can improve electricity generation, resulting in higher revenues from energy sales. Cogeneration is economically advantageous and helps reduce greenhouse gas emissions and fuel consumption in communities. The European Parliament recognizes cogeneration as a key strategy for increasing energy efficiency and reducing CO_2 emissions. Well-designed cogeneration systems can achieve energy efficiencies exceeding 80%. Fuel efficiency can be enhanced by leveraging a large temperature difference in a district heating, since this enables a greater amount of energy to be transferred per unit volume of circulating fluid [1,4].

In systems where domestic hot water (DHW) is supplied at low temperatures (around 50°C), the use of compact piping and direct-use systems without DHW storage minimizes the risk of Legionella without the need for high temperatures [9,13].

The district heating network, particularly the piping system, plays a crucial role in determining the system's energy efficiency, CO_2 emissions, and operational and maintenance costs. The lifespan of today's pre-insulated piping systems exceeds 30 years, ensuring that modern piping infrastructure safeguards the significant investments involved in the transport and distribution of district heating [3,4,16].

A long service life for a piping system means that choosing a high-quality solution far outweighs the initial higher cost. Calculations, tests, and experience show that the majority of the total Cost of Ownership (TCO) comes from heat losses. Therefore, the main objective is to minimize heat losses throughout the system's operational life to significantly improve efficiency and, consequently, reduce the network's operating costs. Heat loss can be significantly reduced by using TwinPipe systems instead of single-pipe systems, even those with thicker insulation layers. Additionally, pipelines equipped with a diffusion barrier between the outer polyethylene (PE) casing and the polyurethane (PUR) foam help maintain low initial heat losses over the entire service life of the system, ensuring long-term thermal efficiency [3,4,16]. The twin-pipe system for district heating is presented in Figure 1-3.

Figure 1-3 Twin pipes system for district heating [16,17].

The service life of the entire piping system (pipes, T-joints, valves) is also extended by the quality of the connections, meaning that the lifespan depends not only on the products themselves but also on proper installation. The long service life of the project also relies on continuous monitoring of the pipeline system. This monitoring system must be capable of detecting, at any time, whether a defect has occurred or if moisture has infiltrated the insulation foam. If such an issue arises, an alarm is triggered immediately, allowing for timely repair and preventing further damage [4].

Measured data forms the foundation for improving efficiency. This has been demonstrated in the district heating system of Assens, Denmark. By using meters that collected consumption data from users, it was possible to analyze and optimize system performance, leading to a reduction in network temperatures by 6–8 degrees Celsius. This improvement translates into significant benefits for the utility company, which managed to reduce its annual heat production by 2.5% and cut heat losses from the network by 12%. Before the optimization, the supply temperature was set based on the needs of the end-users located farthest from the heat source, resulting in a higher temperature than necessary. Currently, it is optimized according to the actual conditions across the entire network [4].

District heating can reduce greenhouse gas (GHG) emissions in two key ways [1]:

- By using non-carbon energy sources for heating and cooling, such as geothermal energy, solar thermal energy, or industrial waste heat;
- By replacing less efficient individual heating and cooling systems in buildings with a more efficient centralized energy system.

District heating contributes to mitigating climate change, air pollution, stratospheric ozone depletion, and acid rain. Air quality concerns remain when biomass and waste are burned in district energy plants [1].

1.3 Types of District Heating and Cooling Systems

District energy systems can be classified based on their application and the market served, particularly by considering usage density [1]:

- Densely populated urban areas: In high-density areas, a district energy system can serve a large number of customers and meet multiple energy needs. These networks tend to be complex and require significant financial investment.
- **High-density building clusters**: This category includes high-rise residential buildings, institutional facilities, shopping malls, or mixed-use suburban developments with high customer concentration. Energy systems here must respond to diverse demands and ensure high reliability and efficiency.
- **Industrial complexes**: These are similar in scale to high-density clusters, but the thermal energy requirements (hot water, steam, or both) are determined by

specific industrial processes. The type of network and its economic viability depend on these requirements.

- **Low-density residential areas**: Typically consisting of single-family homes or duplexes, the district energy systems in these areas are simpler and smaller in scale, usually featuring a central source with a capacity of less than 10 MW.

In general module function if distributed to heat there are 3 system types:

- Centralized
- Decentralized
- Hybrid

District heating systems can be either centralized or decentralized, depending on how thermal energy is produced and delivered to consumers [1].

A **centralized system** generates heat at a large central plant and distributes it through an extensive network of insulated pipes to multiple buildings. This model is energy-efficient, especially when combined with cogeneration (simultaneous production of electricity and heat), and allows for better control of emissions. However, it involves high infrastructure costs, potential heat losses over long distances, and offers limited flexibility at the local level. Centralized systems are best suited for large cities or densely populated urban areas [1,14].

A **decentralized system** relies on smaller, local heat sources such as building-level boilers, heat pumps, or solar thermal systems. These serve individual buildings or small groups and typically have lower distribution losses and greater flexibility in integrating renewable energy. Still, they may be less efficient per unit and require more complex management due to the number of systems involved. Decentralized systems are more appropriate for rural areas, suburban neighborhoods, or small communities. Buildings can also supply thermal energy to the network—for example, by recovering waste heat from air conditioning systems or industrial processes. This creates a highly flexible model, oriented toward "prosumers"—users who are both producers and consumers of energy. Heat pumps are the main source of thermal energy in decentralized systems, providing high efficiency and compatibility with low temperatures. They enable the integration of renewable energy sources and help reduce emissions [18].

The heat pumps used in 5GDH systems can operate bidirectionally, providing both heating and cooling. The system, based on two three-way valves, allows efficient integration between the reversible heat pump and the two-pipe district heating and cooling network. In heating mode, the thermal fluid is circulated from the high-temperature line of the network to the heat pump evaporator and then returned to the low-temperature line, while heat is delivered to the secondary fluid circuit via the condenser [18].

In cooling mode, the process is reversed: the fluid is drawn from the low-temperature pipe, passes through the condenser, and is then discharged into the high-temperature pipe [18].

Switching between heating and cooling modes is achieved by reversing the position of the three-way valves and reconfiguring the internal four-way valve of the heat pump, which alternates the function of the evaporator and condenser relative to the compressor [18]. An example of a prosumer substation, featuring a decentralized pumping system and a heat pump, is shown in Figure 1-4.

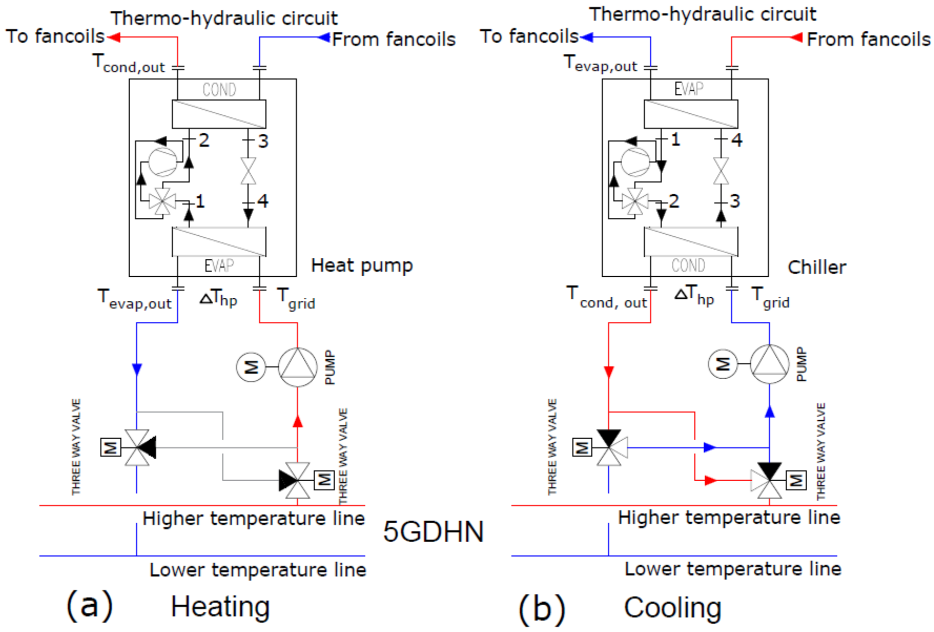


Figure 1-4 Prosumer substation (decentralised pumping system and heat pump) [18]

(a) Heating configuration. (b) Cooling configuration.

In the case of 5GDH, the use of local thermal energy sources and decentralized substations offers the potential to move away from the traditional monopolistic structure of district heating systems and to develop innovative business models for multi-utility providers. The next step in district heating research and development could lead to futuristic thermal networks where decentralized substations interact and exchange energy quantities at a negotiated price [18].

In practice, many communities adopt **hybrid approaches** that combine elements of both systems to maximize energy efficiency, reliability, and sustainability. It can integrate small-scale thermal storage, advanced control systems, and thermal smart grid technologies. A hybrid system for heating, cooling, and power generation based on solar energy, utilizing parabolic solar collectors, has been demonstrated to be viable. This type of collector is proven to be more efficient than conventional solar thermal technologies [1]. Figure 1-5 shows a district heating system with both centralized and decentralized production.

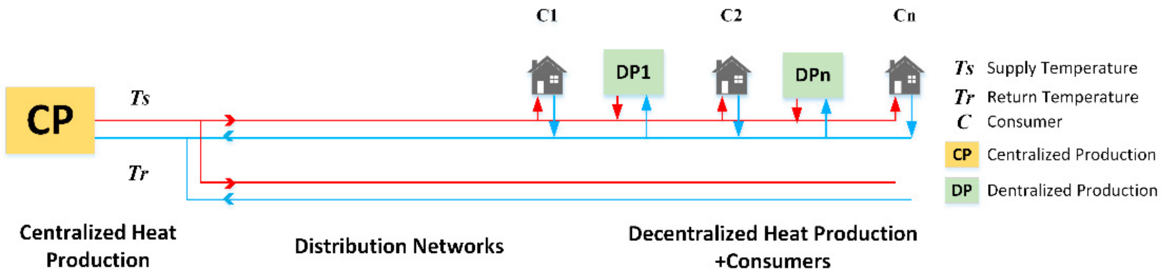


Figure 1-5 District heating system with combined centralized and decentralized production [19].

1.4 Global and Regional Trends in District Heating and Cooling (DHC) Development

New-generation district heating systems prioritize the efficient use of all available sustainable energy resources. This involves harnessing surplus heat from various sources, transitioning from fossil fuels to renewable energies such as solar and biomass, and ensuring seamless integration between heat and electricity systems. Moreover, these systems enable large-scale seasonal heat storage, allowing surplus thermal energy collected in summer to be used during the winter months [20].

Geothermal sources currently account for 49% of the installed heating capacity in Europe, 29% in Asia, and 17% in the Americas. In geothermal-based heating systems, ground source heat pumps are typically used, which generally have a coefficient of performance (COP) of around 4. These systems operate by transferring heat into the ground during the summer and extracting it during the winter. Geothermal energy is regarded as a promising alternative to fossil fuels, offering simplicity, safety, and environmental benefits [1].

Another promising technology for the future is biomass gasification, which enables the production of a wide range of feedstocks and downstream fuels, such as methanol, synthetic natural gas (SNG), and Fischer–Tropsch diesel. Common biomass sources for district heating include wood chips, wood waste, peat moss, and other natural biomass, widely used in district heating plants in Sweden [1].

Regional governments and industries actively collaborate on projects promoting centralized energy systems. In Sweden, integrated cooperation between regional authorities and the pulp and paper industry has supported the development of district heating systems, as seen in the cities of Borlänge and Falun. In Delft, the Netherlands, a district heating system was designed to utilize waste heat from pharmaceutical production, demonstrating its economic, environmental, and institutional viability [1]. In the EU, policies such as the European Green Deal and REPowerEU, and in China, the Five-Year Plans, prioritize low-carbon heating and cooling[21–23]. Carbon pricing targets and emission reduction goals are driving investments in DHC systems.

Table 1-2 provides a comparative analysis of global and regional trends in the development of DHC systems.

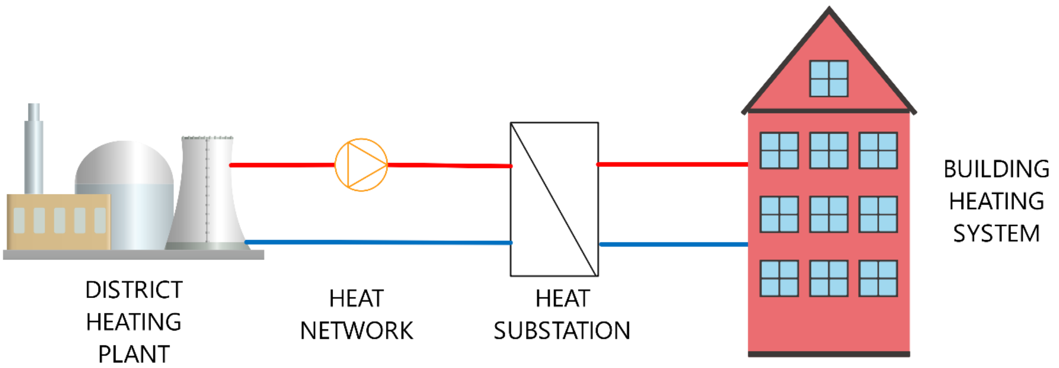
Table 1-2 Comparative analysis of global and regional trends in the development of DHC systems

Region / Country	**Trends**	**Dominant Energy Sources**	**Development Stage**
EU	- European Green Deal, REPowerEU - integration of renewables - use of excess heat from data centers and industry	Geothermal, biomass, excess heat, heat pumps, solar thermal	Mature, expanding towards 4GDH and 5GDHC
China	- Five-Year Plans - transition to low-emission DHC - electrification and energy efficiency	Coal (declining), natural gas, heat pumps, renewables	Rapid development and modernization
United States	- DHC in university campuses, government buildings, hospitals - focus on efficiency and cogeneration	Natural gas, cogeneration, some renewables	Fragmented, emerging in major cities
Nordic Countries (Sweden, Denmark, Finland)	- innovation in 4GDH/5GDHC - strong decarbonization policies	Biomass, waste, heat pumps, geothermal, cogeneration	Highly advanced and sustainable
Central and Eastern Europe	- modernization of old networks - EU support for energy transition	Coal (transitioning to biomass, natural gas, RES)	In transition to cleaner solutions
Japan / South Korea	- integration with smart technologies, CHP - high urban density favorable for DHC	Cogeneration, natural gas, excess heat	Advanced development with focus on efficiency

North America	- modernization of existing systems - expansion in urban centers	Natural gas, biomass, waste heat, renewables	Moderate development
Middle East	- centralized cooling - high demand - solar integration	Electricity, thermal cooling, PV + storage	Fast developing
Africa and Latin America	- pilot projects - urban cooling - climate resilience	Hybrid sources, renewables, PV, geothermal	Early stage

1.5 Core components and system architecture

A centralized district heating system is a functional technological ensemble designed for the production, transportation, and distribution of thermal energy to consumers. It is organized into several interconnected energy loops or *subsystems*, each with a distinct role in ensuring the reliable and efficient delivery of heat.



Production Subsystem

Heat/Cold source & Thermal energy storage (TES)

This subsystem comprises heat/cold generation facilities such as thermal power plants, combined heat and power (CHP) units, large-scale boilers, and central cooling technologies.

A variety of fuels can be utilized, including natural gas, coal, biomass, waste heat from industrial processes, and renewable sources such as geothermal or solar thermal energy.

Thermal energy is produced at centralized facilities, offering higher overall efficiency and lower emissions compared to decentralized heating systems. To maintain a balance between heat supply and demand, Thermal Energy Storage (TES) systems are employed. These can range from short-term hot water tanks to large-scale seasonal storage solutions such as borehole or aquifer systems.

Heat Transport and Distribution Subsystem

Once produced, hot water is transported to consumers through insulated supply pipelines. Within each building, heat is transferred from the network to the local heating and domestic hot water systems via heat exchangers. After releasing its heat, the cooled water returns to the central plant through return pipelines, where it is reheated and recirculated.

Substations serve as the interface between the distribution network and end users. Each substation typically includes:

- Heat exchangers (for energy transfer between network and building circuits),
- Control valves (to regulate flow and temperature), and
- Monitoring and metering equipment.

Automated control systems within substations adjust flow rates and temperatures based on real-time demand, ensuring high energy efficiency and consistent indoor comfort.

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2. Production technologies

2.1 Heat Generation Technologies

2.1.1 Combined heat and power

Context

The 2023 Energy Efficiency Directive (EED) establishes progressive targets for district heating and cooling (DHC) networks in the European Union.

To qualify as “efficient district heating”, systems must gradually increase their share of renewable energy (RES), waste heat, and high-efficiency cogenerated heat, reaching 100% renewable or recovered energy by 2050.

Key Time Milestones and Minimum Requirements

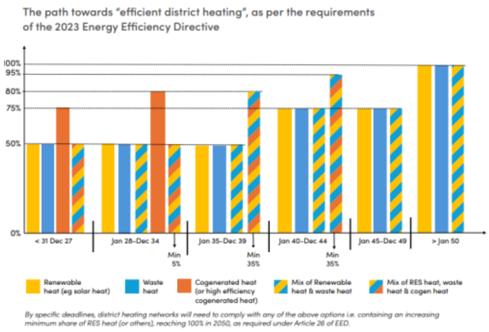


Figure 2-1 The roadmap for “efficient district heating” as defined by the 2023 Energy Efficiency Directive (EED) [1]

The left-hand side (<2027) shows that most current networks already meet efficiency criteria via CHP and partial renewable integration.

From 2028 onwards, renewables and waste heat must play an increasing role, with CHP gradually phased down as the grid and heating sector decarbonize.

By 2040, efficient district heating systems will rely predominantly on renewable and recovered heat, supplemented by thermal storage and sector coupling (e.g., power-to-heat).

By 2050, all district heating systems must operate entirely on renewable or recovered heat, eliminating fossil fuels.

Definition

Cogeneration refers to the simultaneous production of thermal and electrical energy from a single primary energy source within one integrated system. Also known as Combined Heat and Power (CHP), this technology enables highly efficient energy utilization by capturing and reusing heat that would otherwise be wasted during conventional electricity generation.

In recent years, cogeneration has become an increasingly attractive solution across a wide range of industrial, commercial, and residential applications, owing to its potential to enhance energy efficiency and reduce greenhouse gas emissions.

The primary energy sources used in cogeneration systems may include fossil fuels (such as natural gas or coal) as well as renewable resources (such as woody biomass, biogas, or various forms of waste). The mechanical energy generated is typically employed to drive electric generators, though it can also power auxiliary equipment such as compressors or pumps.

Meanwhile, the thermal energy that would normally be lost to the environment—through steam condensers, cooling towers, engine cooling systems, or flue gases—is recovered and repurposed. This recovered heat can be utilized for space heating, domestic hot water production, or industrial processes, significantly improving overall system efficiency while contributing to reduced fuel consumption and lower pollutant emissions.

In Figure 2-2, the functional structure of a Combined Heat and Power (CHP) system is presented, illustrating the components and energy flows.

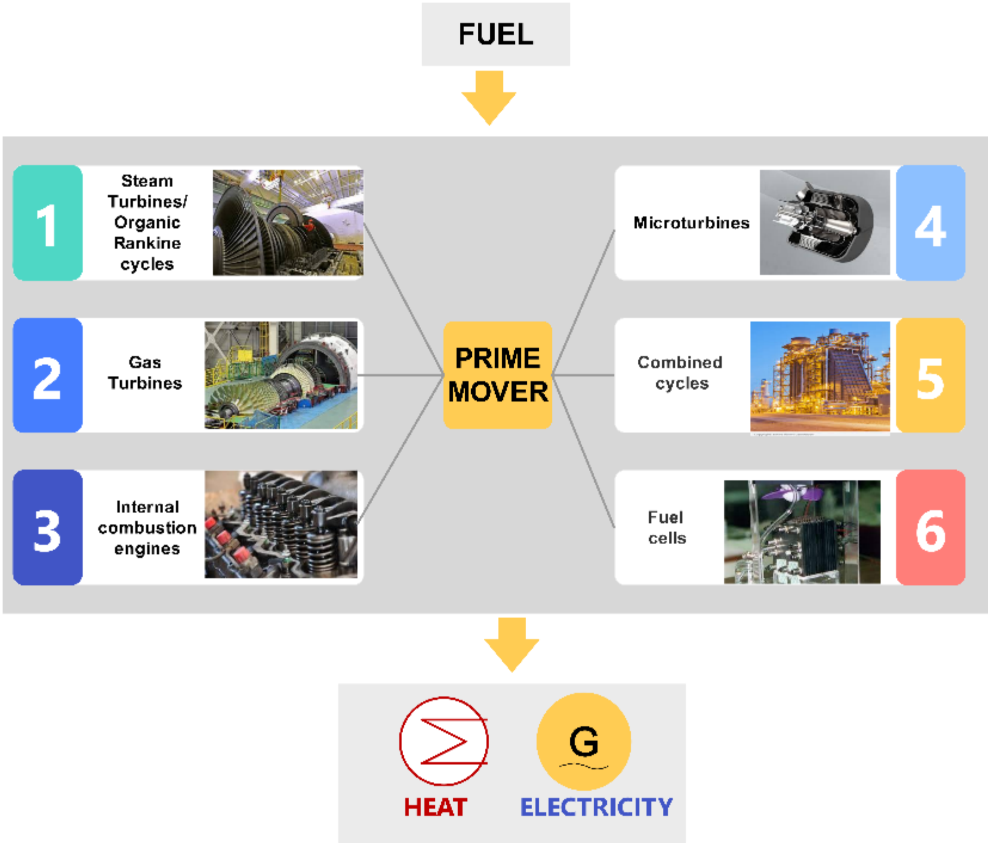


Figure 2-2 Functional structure of a Combined Heat and Power System

Cogeneration technologies

Depending on the application and energy requirements, several types of prime movers can be employed:

1. *Steam turbines / Organic Rankine cycles* – suitable for large-scale plants using high-temperature steam or organic fluids.
2. *Gas turbines* – commonly used in medium- to large-scale CHP systems, often in combination with heat recovery boilers.
3. *Internal combustion engines* – flexible and efficient for small to medium decentralized plants.
4. *Microturbines* – compact units suitable for distributed generation and commercial buildings.

5. *Combined cycles* – integrate gas and steam turbines to achieve high overall efficiency.
6. *Fuel cells* – emerging technology offering low emissions and high electrical efficiency.

The mechanical output of the prime mover is converted into electricity, while the waste heat from the process is recovered and used for heating or industrial processes, significantly improving overall energy efficiency.

A comparative analysis of cogeneration technologies is provided in Table 2-1.

Table 2-1 Comparative Overview of Cogeneration (CHP) Technologies [2],[3],[4]

Technology	Steam turbine	Organic Rankine cycle	Gas turbines	Microturbines	Reciprocating engines	Fuel cells	Combined cycles
Performances							
Size [MW]	0.5 – 250	0.05 – 2	1 – 500+	0.03 – 0.25	0.05 – 20	0.05 – 5 (up to 50 large-scale)	5 – 500+
Electric efficiency [%]	15 – 35	10 – 20	25 – 40	20 – 30	30 – 45	35 – 60	45 – 60
Thermal efficiency [%]	30 – 60	50 – 70	30 – 50	40 – 50	40 – 50	25 – 35	20 – 30
Total efficiency [%]	60 – 85	70 – 85	65 – 85	65 – 80	75 – 90	70 – 85	70 – 90
Power to heat ratio [-]	0.2 – 0.5	0.1 – 0.3	0.5 – 1.0	0.4 – 0.7	0.6 – 1.0	1.0 – 1.8	0.8 – 1.2
Fuel and Operation							
Fuel type	Coal, biomass, natural gas, oil	Low-temperature heat, biomass, geothermal, solar thermal	Natural gas, biofuels, H2 blends, oil	Natural gas, LPG, biogas	Natural gas, biogas, LPG, diesel, syngas	Hydrogen, natural gas (reformed), biogas	Natural gas, H2 blends, oil
Fuel pressure	Low–medium (depends on boiler/fuel)	Low	Medium–high	Low–medium (often needs booster)	Low–medium	Low–medium	Medium–high
Emissions	High unless clean fuels & controls	Very low (if waste heat/solar); biomass dependent	Moderate (low NOx with DLN/SCR)	Low	Moderate; low with catalytic converters; particulates	Very low (near-zero NOx/PM)	Moderate–low with controls

					with liquid fuels		
Thermal use	Steam/hot water; drives absorption chillers	Low-grade heat for heating; can support single-effect absorption	High-temp exhaust for HRSG steam/HW; absorption chillers	Hot water/low-pressure steam; absorption chillers	Hot water (70–120°C), low-pressure steam; absorption chillers	Hot water/steam; clean CHP	High-quality steam/HW; absorption chillers
Available Temperature level	Medium–high (steam 150–540°C; DH 70–120°C)	Low–medium (50–120°C)	High (exhaust 400–600°C)	Medium (exhaust 250–320°C)	Exhaust 400–500°C; cooling water 70–90°C	Low (PEM 60–90°C) to High (SOFC/MCFC 200–1,000°C)	High (steam up to 565°C)
Noise level	Medium–high	Very low	High	Medium	High (requires acoustic insulation)	Very low	High
Start up	Hours	Minutes – tens of minutes	10 – 30 minutes	2 – 10 minutes	Seconds – minutes	PEM: minutes; SOFC: hours	30 – 90 minutes
Costs							
Capital costs (Euro/kWe)	1,500 – 3,000	2,000 – 5,000	700 – 1,500	1,000 – 2,500	800 – 1,500	3,000 – 7,000	900 – 1,500
Maintenance costs (Euro/kWh)	0.005 – 0.020	0.003 – 0.010	0.005 – 0.015	0.010 – 0.020	0.010 – 0.020	0.010 – 0.030	0.004 – 0.012
Maintenance							
Availability	90 – 95	95 – 98	90 – 98	95 – 98	90 – 95	85 – 95	90 – 95

Advantages and Benefits of Cogeneration

Cogeneration offers multiple advantages that contribute to both economic efficiency and environmental sustainability.

By simultaneously producing electricity and thermal energy, it enables a *significant reduction in energy costs for consumers.* The technology enhances *economic competitiveness* through lower operating expenses and improved utilization of fuel resources.

Another major benefit is the *continuity of electricity supply*, as cogeneration systems can operate independently from the national grid, thereby *increasing the reliability and resilience of energy systems*. Cogeneration leads to a *higher overall energy efficiency* by reducing the consumption of primary energy sources compared to separate generation.

From an environmental perspective, cogeneration contributes to a *reduction in pollutant emissions,* allowing industrial and commercial operators to maintain production capacity while complying with environmental regulations and avoiding potential penalties.

Performance indicators of Cogeneration Systems

- *Overall efficiency*

$$\eta_t = \frac{P + \dot{Q}}{\dot{Q}_{fuel}} [-]$$

Overall efficiency	The ratio of total useful energy output (electricity and heat) to the total fuel input.
P	Electrical power output
$\dot{Q}$	Useful thermal power output
$\dot{Q}_{fuel}$	Fuel input power

- *Primary Energy Savings (PES)*

According to EU Directive 2012/27/EU, a system qualifies as high-efficiency cogeneration if the primary energy savings are ≥ 10% compared to separate generation.

$$PES = \left(1 - \frac{1}{\frac{\eta_{th,\,CHP}}{\eta_{th,Ref}} + \frac{\eta_{e,\,CHP}}{(\eta_{e,\,Ref})}}\right) \cdot 100$$

Primary Energy Savings (%)	Represents the percentage reduction in primary energy consumption achieved by a cogeneration system compared to separate (conventional) generation of electricity and heat. A PES ≥ 10% indicates a high-efficiency cogeneration system, as defined by EU Directive 2012/27/EU
$\eta_{e,CHP}$	Electrical efficiency of the CHP system
$\eta_{th,CHP}$	Thermal efficiency of the CHP system
$\eta_{e,Ref}$	Reference efficiency for separate electricity generation
$\eta_{th,Ref}$	Reference efficiency for separate heat generation

- *The Power-to-Heat Ratio (PHR)* $PHR = \frac{E}{Q}\left[\frac{kWh}{kWh}\right]$; $PHR = \frac{P}{\dot{Q}}\left[\frac{kW}{kW}\right]$

Power to Heat Ratio	is a defining performance indicator of a cogeneration system. It expresses the proportion between electrical power (or energy) produced and the useful

	thermal power (or energy) delivered during simultaneous generation in full cogeneration mode
E	Electrical energy output
Q	Useful thermal output
P	Electrical power output
$\dot{Q}$	Useful thermal power output

2.1.2 Boilers

Types of Boilers Used in District Heating Systems

District heating networks employ various types of boilers, selected according to the required temperature level, system design, and application area.

Hot Water Boilers (70–120 °C)

Commonly used in low- to medium-temperature district heating networks, these boilers supply heat for space heating and domestic hot water applications. They are widely implemented in modern urban systems due to their simplicity, safety, and compatibility with renewable heat sources.

High-Temperature Water Boilers (up to 200–250 °C)

Typically found in older or high-demand district heating systems, these boilers operate at elevated temperatures to meet larger heat loads or to serve industrial consumers with higher thermal requirements.

Steam Boilers (150–540 °C, saturated or superheated)

Used primarily in industrial district heating networks or combined heat and power (CHP) applications, steam boilers provide both process steam and thermal energy for space heating. They are suitable where industrial heat demand and cogeneration opportunities coexist.

Condensing Boilers for District Heating

Condensing boilers represent a high-efficiency technology increasingly adopted in modern district heating systems, particularly those operating at lower supply temperatures. Unlike conventional boilers, condensing boilers are designed to recover latent heat from the water vapor in flue gases, which would otherwise be lost during standard combustion. This process occurs when the exhaust gases are cooled below the dew point, causing vapor condensation and enabling the recovery of additional thermal energy. As a result, overall efficiency can exceed 90–95% (LHV basis) under optimal conditions.

Fuel Flexibility in District Heating Boilers

Modern district heating boilers are designed to accommodate a wide range of fuel sources, enhancing energy security and decarbonization potential:

- Conventional fuels: natural gas, coal, and oil.
- Renewable and low-carbon fuels: biomass, biogas, municipal solid waste, and hydrogen or hydrogen-blend fuels.
- Hybrid integration: boilers can be operated in parallel with solar thermal systems, geothermal heat sources, or industrial waste heat recovery units to optimize efficiency and sustainability.

2.1.3 Solar thermal systems

European district heating networks rely on a diverse mix of energy sources, combining both fossil fuels and renewable or recovered energy. In 2024, bioenergy and natural gas were the dominant fuels, while renewable and waste heat sources continued to expand under the EU's decarbonization goals.

Although the contribution of solar thermal energy to European district heating networks remains relatively small (around 0.2%), it is steadily expanding, particularly in Scandinavia and Central Europe.

This growth is driven by the deployment of large-scale solar district heating fields, which integrate flat-plate or evacuated-tube solar collectors with seasonal thermal energy storage (TES).

These systems can supply a significant share of annual heat demand — in some cases up to 50% or more — especially when combined with other renewable or waste heat sources.

Energy sources in European district heating systems are presented in Figure 2-3.

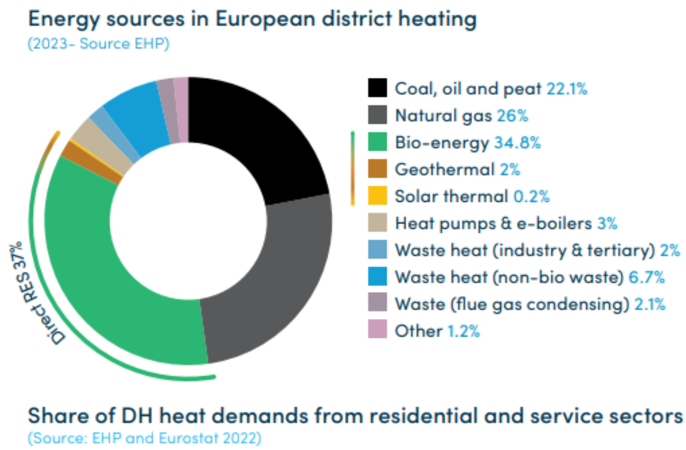


Figure 2-3 Energy Mix of European District Heating: Current Shares and Renewable Contribution [1]

They can operate as base-load renewable sources in summer (when heat demand is lower) and as supplementary sources during winter in hybrid systems with boilers, cogeneration, or heat pumps. Large-scale solar DH plants, often combined with thermal storage, already operate successfully in countries like Denmark, Germany, and Austria [5].

The largest sub-sector of large-scale solar heating systems is solar district heating. By the end of 2024, there were 346 large-scale solar district heating systems reported as operational, each with a capacity greater than 350 kW_{th} (500 m^2). Their total installed capacity was 1,982 MW_{th}, corresponding to a collector area of 2.8 million square meters [6]. Figure 2-4 shows the current situation of solar district heating.

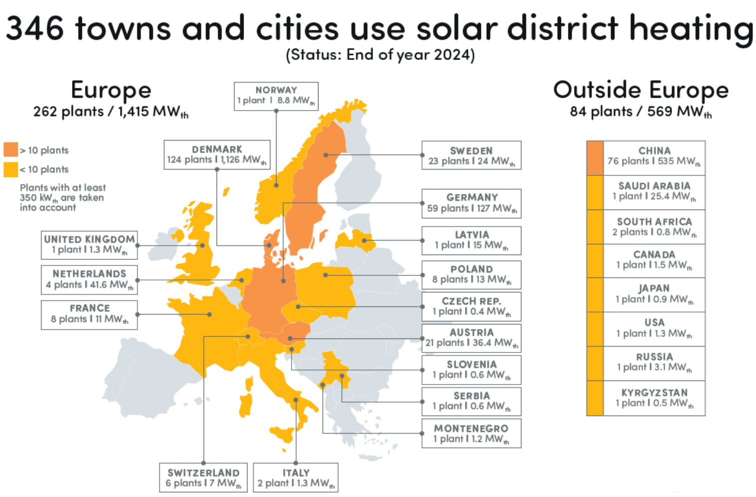


Figure 2-4 Current situation of solar district heating [7].

The most representative solar heating systems in the world in terms of size are presented in Table 2-2.

Table 2-2 The 20 largest solar heating systems [6]

Project name	Country	Year of installation	Solar collector surface	Installed thermal power
[-]	[-]	[-]	[m^2]	[MW]
Silkeborg	DNK	2016	156694	110
Inner Mongolia	CHN	2016	93000	65
Vojens stage 2	DNK	2015	52492	37
Groningen	NLD	2024	48800	34
Longzi, Tibet	CHN	2023	45036	32
Dronninglund	DNK	2014	37573	26
Lazi, Tibet	CHN	2023	36700	26
Rhiad	SAU	2011	36305	25
Qusum Country, Tibet	CHN	2024	36000	25
Gram stage 2	DNK	2015	34851	24
Zhongba, Tibet	CHN	2019	34650	24
Dingri, Tibet	CHN	2023	34250	24
Ringe	DNK	2019	31224	22
Seni, Tibet	CHN	2023	28356	20
Brønderslev	DNK	2016	26929	19
Aabybro	DNK	2018	26195	18
Sæby, stage 2	DNK	2019	25313	18
Hadsten	DNK	2019	24517	17
Aalestrup	DNK	2016	24129	17
Langkasi, Tibet	CHN	2018	22275	16

The primary goal in sizing solar-integrated district heating systems is to maximize the *solar fraction*, which is the amount of the total thermal load supplied by solar heat. Systems that use large-scale seasonal storage can achieve solar fractions of up to 50% of the annual thermal load. This is made possible by capturing and storing excess solar heat generated in the summer and using it later during the high-demand winter heating period [8].

Solar collectors for district heating networks can be installed on either the ground or on building rooftops.

The choice of location depends on factors such as *land availability* and *cost*. If the collector area is large and land prices are low, collectors are installed on the ground close to the heating plant. This makes the installation easy and cost-effective.

Ground-mounted collectors are arranged in rows of 10 to 25 modules connected in series, which are then connected in parallel. To maximize panel efficiency, they must be positioned so that the outlet temperature of each row is identical.

The general principles for placing *rooftop collectors* are similar to those for ground-mounted systems. However, practical issues can arise depending on the installation method. Collectors can either be installed with the same tilt and azimuth as the roof itself (integrated into or mounted on top of the roofing material) or by using a support structure. The second option is typically used for flat roofs or when the desired tilt and azimuth angles for the collectors do not match the roof's orientation [9].

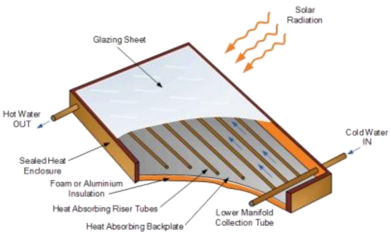
Collector Types for District Heating

Table 2-3 provides an overview of solar collector types applicable to district heating, highlighting their temperature range, typical applications, and main advantages and limitations.

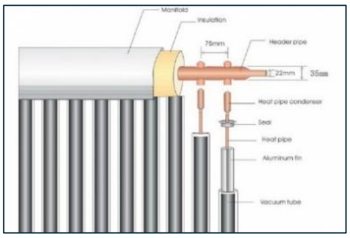
Table 2-3 Suitable Collector Types for District Heating [10–13]

Collector Type	Temperature Range	Typical Use in DH	Advantages	Limitations
Flat-plate collectors (FPC)	30–80 °C	Low-temperature networks (4th gen DH); Domestic hot water; Seasonal storage charging	Low cost; Robust, easy to maintain; Suited for large collector fields in open areas	Efficiency drops significantly at supply temperatures >80 °C
Evacuated tube collectors (ETC)	50–150 °C	Medium-temperature networks; Efficient in colder climates;	Good performance with diffuse radiation	More expensive; Fragile glass tubes
Compound parabolic concentrators (CPC)	80–250 °C	Absorption chillers for cooling; Medium-to-high temperature DH;	Operate at higher supply temperatures; Can use diffuse radiation	Higher cost and complexity than flat plate collectors and compound

		Industrial DH applications		parabolic concentrators
Parabolic trough collectors (PTC) and Linear Fresnel collectors (LFC)	150–400 °C	High-temperature DH	High thermal output per unit area; Suitable for integration with power and cooling cycles	Require direct solar radiation and tracking; Higher CAPEX



a) Flat plate collector[14]



b) Evacuated tube collector

c)Compound parabolic concentrator[15]

d) Parabolic trough collector[16]

e) Linear Fresnel collector[17]

Figure 2-5 Solar collector for district heating

Integration into District Heating Systems

Depending on the temperature level of the district heating network, solar collectors can be utilized in the following ways [11]:

- Low-temperature DH (4th generation, 40–70 °C): Best suited for flat-plate collectors installed in large solar fields, combined with seasonal thermal storage (pit or tank storage).
- Medium-temperature DH (70–120 °C): Evacuated tube and compond parabolic concentrator collectors provide reliable output, even in colder climates.

- High-temperature DH (>120 °C): Parabolic trough collectors and linear Fresnel collectors are preferred, particularly where trigeneration is applied
- Hybridization: Solar collectors are typically coupled with boilers, CHP or large heat pumps to ensure heat stable supply

Examples: Solar District Heating in Practice

Regarding the country-specific trends in the deployment of solar district heating (SDH) systems, Table 2-4 provides a concise overview. It highlights representative projects, the types of solar collectors applied, and characteristics of each country's approach to integrating solar energy into district heating networks.

Table 2-4 Country-specific trends in the use of solar collectors within district heating systems [5,6,9]

Country	Project Name/City	Type of Solar Collectors	Capacity / Details
Denmark	Various projects (e.g., Silkeborg)	Flat-plate solar collector fields	Over 1.5 GWth of installed capacity. Denmark is a world leader, with numerous projects that use underground seasonal pit thermal energy storage to store heat.
Germany	Sondershausen, Munich	Flat-plate and evacuated tube collectors	Germany stands out with a variety of technologies, from high-temperature flat-plate collectors to systems integrated into building rooftops.
Austria	Graz, Mürzzuschlag	Flat-plate solar collectors	A pioneer in the field, Austria has many projects integrated into existing district heating networks, with an emphasis on efficiency and the use of available space.
Sweden	Härnösand, Lyckebo	Concentrating (parabolic) and flat-plate collectors	Sweden has developed innovative pilot projects, including one featuring 100,000 m^3 of seasonal storage in a water-filled rock cavern.
France	Perpignan, Saillans	Medium-sized flat-plate solar collectors	Solar district heating projects in France are often smaller in scale, integrated into existing heating networks to increase the share of renewable energy.

Italy	Varese, Bolzano	Flat-plate and evacuated tube collectors	Italy uses SDH to reduce its dependence on fossil fuels in urban areas, with projects that often also integrate other renewable energy sources.
China	Various industrial projects	Parabolic troughs	China uses SDH technology, especially concentrating collectors, to integrate solar heat directly into industrial production processes.

Below are three relevant examples illustrating the integration of solar energy systems into district heating networks.

The Langkazi plant in Tibet consists of 22,275 m² of solar collectors and a hot water tank for heat storage with a capacity of 15,000 m³ [5]. The district heating system supplies 100,000 m² of residential area through a thermal network with supply and return temperatures of 65°C and 35°C, respectively. During periods of low solar radiation, two electric boilers with a total installed power of 3 MW provide the necessary heat. The system's solar fraction exceeds 90%, with solar heat used exclusively for space heating in the winter [18]. Figure 2-6 illustrates the configuration of the solar district heating system in Langkazi.

Figure 2-6 Solar district heating system in Langkazi, Tibet [19].

The solar district heating system in Salaspils, Latvia, comprises a 21,672 m² solar field and a 3 MW biomass boiler. Thermal energy is stored in an 8,000 m³ hot water tank. This system provides 90% of the district heating network's thermal energy needs [20]. Figure 2-7 shows the solar district heating system in Salaspils, Latvia.

Figure 2-7 Solar district heating system in Salaspils, Latvia [20].

One of the largest solar fields for district heating was recently put into operation in Groningen, Netherlands (Figure 2-8). Producing 25 GWh of solar heat annually, this 37 MW solar district heating plant utilizes 48,000 m² of TVP Solar High Vacuum Flat Panels. This system provides a 25% solar share of the city's energy consumption and reduces emissions by 6,000 tons of CO_2 per year. The solar thermal plant is designed to operate effectively in challenging conditions, injecting heat directly into the network at temperatures between 69°C and 93°C even in sub-zero winter weather with low sunlight. Its high yearly average efficiency of 52% is a key feature, as it allows the plant to produce a significant amount of energy while occupying a relatively small footprint of just 12 hectares [21].

Figure 2-8 Solar district heating in Groningen, Netherlands [21].

Solar thermal energy has a strong potential to increase its market share within the district heating sectors. Its advantages, such as widespread and availability, combined with continuously improving economics, make it a viable option for utilities and heat suppliers. However, this growth is limited by high initial investment costs, low energy density, and the large land areas required for collector installation. In the future, solar thermal will always be a complementary solution that must be integrated with other heat sources [8].

2.1.4 Heat pumps

Status of the heat pump implementation in Europe

The REPowerEU plan, published by the European Commission in May 2022, outlines measures to eliminate fossil gas use in heating and industry. It identifies large-scale heat pumps, integrated with district heating and cooling networks, as a key pathway for decarbonizing Europe's heating sector, particularly in densely populated regions [22].

Currently, large heat pumps account for approximately 2.5 GW_{th} of installed capacity in European district heating and cooling networks, representing only about 1% of total system capacity. Most existing installations are concentrated in highly electrified countries such as Sweden and Denmark. However, with the rapid expansion of renewable electricity across the EU, the growth potential is substantial [22].

Figure 2-9 summarizes the current deployment status of large heat pumps in district heating, based on data reported by EHP members to the EHP Market Intelligence Unit (2021) [23].

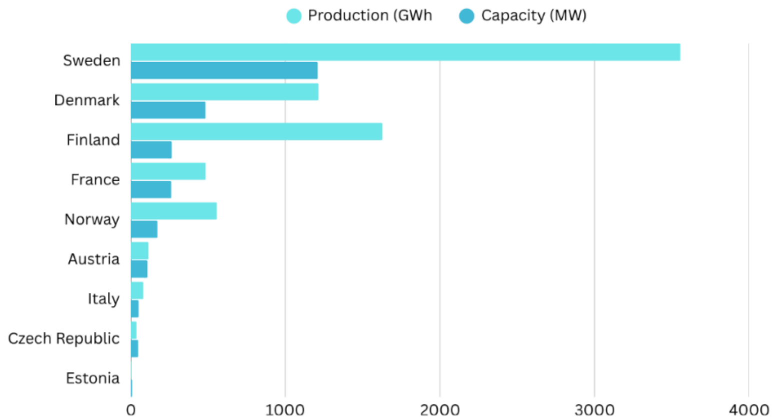


Figure 2-9 Large scale heat pumps in District Heating in Europe [23]

Figure 2-10 summarizes the distribution of large-scale heat pumps in district heating by source type (ambient and waste heat) and by installed capacity and annual heat production across several European countries.

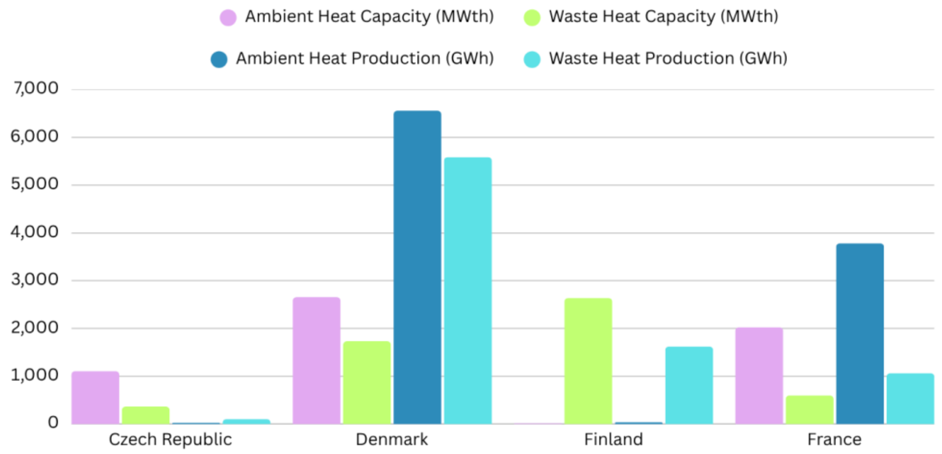


Figure 2-10 Distribution of large-scale heat pumps in district heating by source type (ambient and waste heat) [23]

The basic schematic of a heat pump system integrated into an urban district heating network is presented in Figure 2-11.

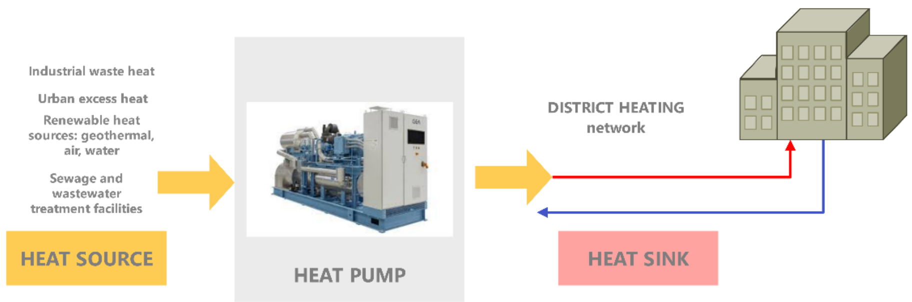


Figure 2-11 The basic schematic of a heat pump system integrated into an urban district heating network

Operation Principle of Heat Pumps

Heat pumps are thermal machines that *take heat from an environment with a lower temperature and give it to an environment with a higher temperature*, as can be seen on the energy diagram in the adjacent figure. This can be considered the simplest model of refrigeration installation, as it does not contain any element of a constructive nature. From this point of view, it can be assimilated to a *"black box"*, whose functioning will be analyzed, and which is to be *"opened"* to study its composition and reveal its secrets of design, operation and control.

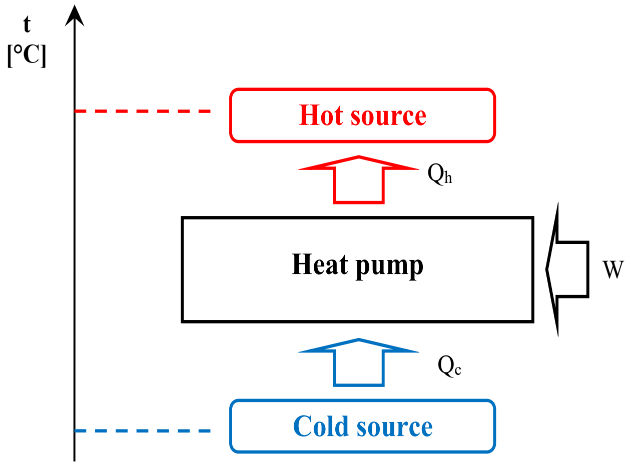


Figure 2-12 Energy scheme of heat pumps

The environment with a lower temperature, from which heat is taken is called *the cold source,* and the environment with a higher temperature, to which heat is released, is called *the hot source.* The heat absorbed from the cold source was denoted with Q_c [kW], and the heat given to the hot source was denoted with Q_h [kW]. *According to the second principle of thermodynamics,* for the transport of heat, from a lower temperature to a higher temperature, energy consumption or mechanical work denoted W is required.

The work agent, which operates in these installations, is called refrigerant. To be able to extract heat from the cold source, the refrigerant must have a lower temperature than this. The most effective way to extract heat by the refrigerant is to maintain the temperature constant, through evaporation in a heat exchanger called evaporator. Similarly, the most effective way to evacuate heat by the refrigerant is to maintain the temperature constant, through condensation in a heat exchanger called condenser. The useful effect of heat pumps is achieved in the condenser.

The evaporating temperature (t_e [°C]) of the refrigerant is lower than the cold source temperature (t_c [°C]) and the condensing temperature (t_k [°C]) of the refrigerant is higher than the hot source temperature (t_h [°C]).

The vaporization temperature corresponds to a unique saturation pressure (p_e [bar]) called *evaporation pressure.* Analogous to the condensing temperature, it corresponds to a single saturation pressure (p_k [bar]) called *condensing pressure.* It is obvious that the condensing pressure is higher than the evaporation pressure.

The increase in the pressure of refrigerant vapor from the evaporation pressure to the condensation pressure can be achieved in a machine called *a compressor,* of course by mechanical energy consumption.

The reduction of liquid pressure from condensation pressure to evaporation pressure is achieved by adiabatic lamination, either in a *capillary tube,* in low-power systems, or in a *expansion valve*, in medium or high-power systems.

In the figure below on the left, in a low-power installation the lamination is carried out by capillary tube, and on the right, in a medium-power installation the lamination is carried out in a thermostatic expansion valve.

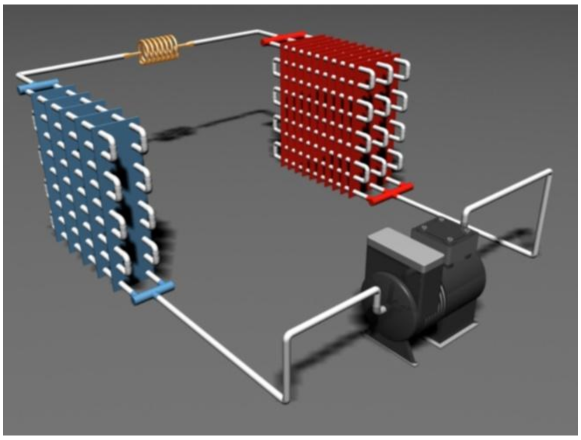


Figure 2-13Equipment with capillary tube

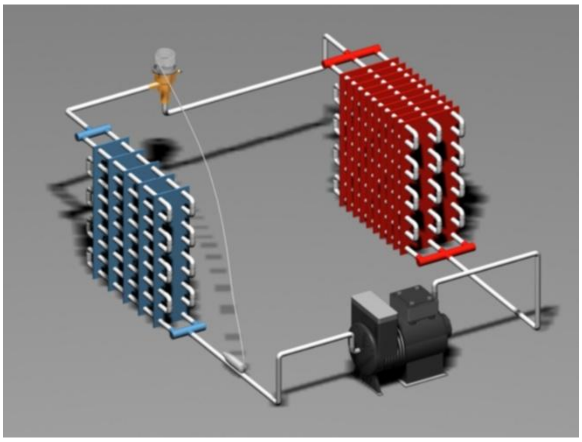


Figure 2-14Equipment with expansion valve

The bulb that can be observed on the suction pipe has the role of controlling the expansion process, to eliminate the danger of any drops of non-evaporated liquid reaching the compressor. Lamination is controlled by the value of the vapor temperature at the outlet of the vaporizer, hence the name of this device: thermostatic expansion valve.

From thermodynamic point of view, the working cycle of the refrigerating equipment and of the heat pump is identical. *What differs is only the temperature level of the heat sources,* compared to the ambient temperature (T_a [°C]).

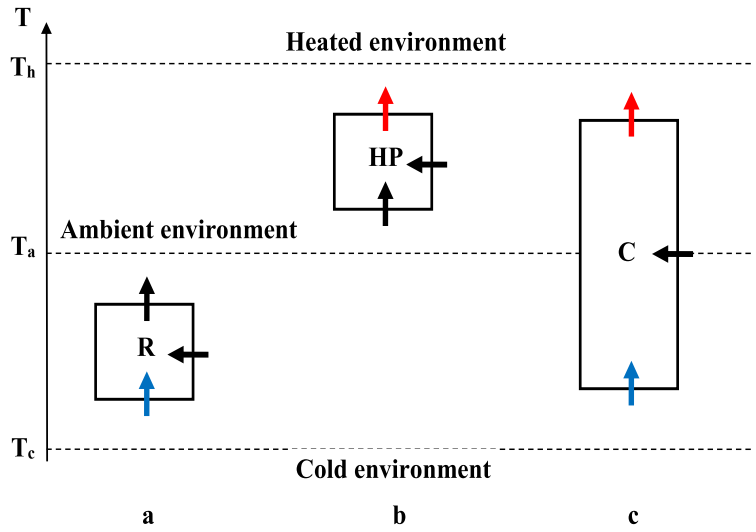


Figure 2-15Equipment operating after reversed thermodynamic cycles

a) Refrigeration equipment (R); b) Heat pump (HP); c) Combined equipment (C)

From the energy point of view, the performance parameter of these installations is the ***C****oefficient* ***O****f* ***P****erformance* (COP), defined by the ratio of useful heat (or thermal power) and the consumed mechanical work (or mechanical power).

COP can be calculated for each equipment:

- For refrigerating equipment: $COP = Q_c / W$
- For heat pumps: $COP = Q_h / W$
- For combined equipment: $COP = (Q_c + Q_h) / W$

Heat Sources for Heat Pumps [24]

District heating heat pumps can utilize a wide range of renewable and recovered heat sources, including:

- Renewable energy sources: geothermal heat, air, ground, or surface water
- Industrial waste heat: Heat recovered from industrial processes: refineries, chemical plants, or data centers can be upgraded by heat pumps to district heating supply temperatures
- Urban excess heat: Surplus heat from commercial and residential buildings, supermarkets, underground transport systems, or server and data centers can serve as low-grade heat sources for local or centralized heat pump integration.
- Sewage and wastewater treatment facilities:
  Wastewater provides a heat source for large-scale water-source heat pumps, which can efficiently transfer this energy into the district heating network
- District heating return lines or multi-source systems that combine several heat inputs.

Operating temperature and compatibility with different generations of district heating systems

The classification of compression heat pumps according to their operating temperature ranges and their compatibility with different generations of district heating systems [25]:

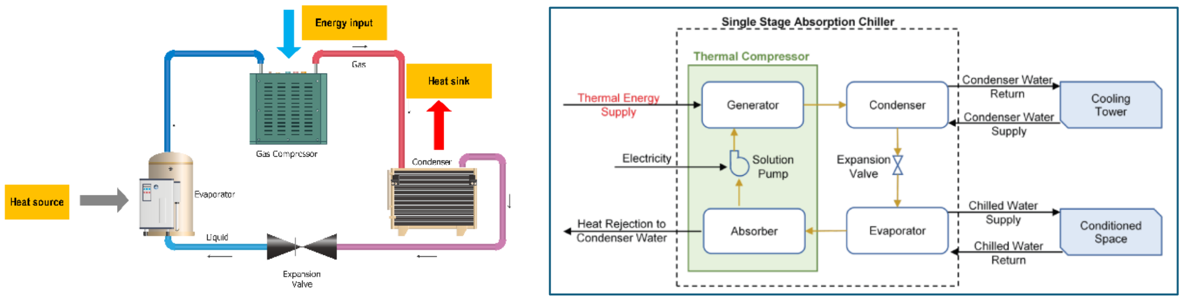
- Conventional heat pumps (HP) operate with heat source temperatures between 0 °C and 40 °C and deliver heat sink temperatures below 80 °C, making them suitable for fourth-generation (4G) and fifth-generation (5G) district heating networks.
- High-temperature heat pumps (HTHP) function within a source temperature range of 40 °C – 60 °C and provide sink temperatures between 80 °C – 100 °C, typically compatible with third-generation (3G) networks.
- Very high-temperature heat pumps (VHTHP) operate with source temperatures between 60 °C – 120 °C and sink temperatures up to 160 °C, aligning with second-generation (2G) district heating systems that require higher supply temperatures.

Heat Pump Technology and Driving Energy

Heat pumps can operate based on different driving principles:

- Mechanical systems – such as *vapor compression cycles*, which are driven by electricity to power the compressor.
- Thermal systems – such as *absorption* or *adsorption heat pumps*, which are driven by thermal energy (from combined heat and power (CHP) plants, industrial waste heat, or other high-temperature heat sources).

Some advanced or integrated configurations may also employ hybrid or alternative energy sources (e.g., solar thermal, gas-driven compressors) for compression and regeneration processes.



a) b)[26]

Figure 2-16 Vapor compression (a) and absorption heat pumps (b)

Heat Pump Stages and Operation Modes

Depending on the required temperature lift and system configuration, heat pumps can operate as:

- Single-stage units – suitable for moderate temperature differences, or
- Multi-stage units – used when higher supply temperatures are needed (e.g., 80–90 °C for older DH networks).

Placement and Connection within DH Systems [25]

- Central placement: integrated within large DH plants, serving the main grid.
- Local placement: near secondary substations or local heat sources.
- Individual placement: at building or neighborhood level, often as distributed systems.

Heat pumps may be connected in single, parallel, or series configurations, depending on network topology and desired flexibility.

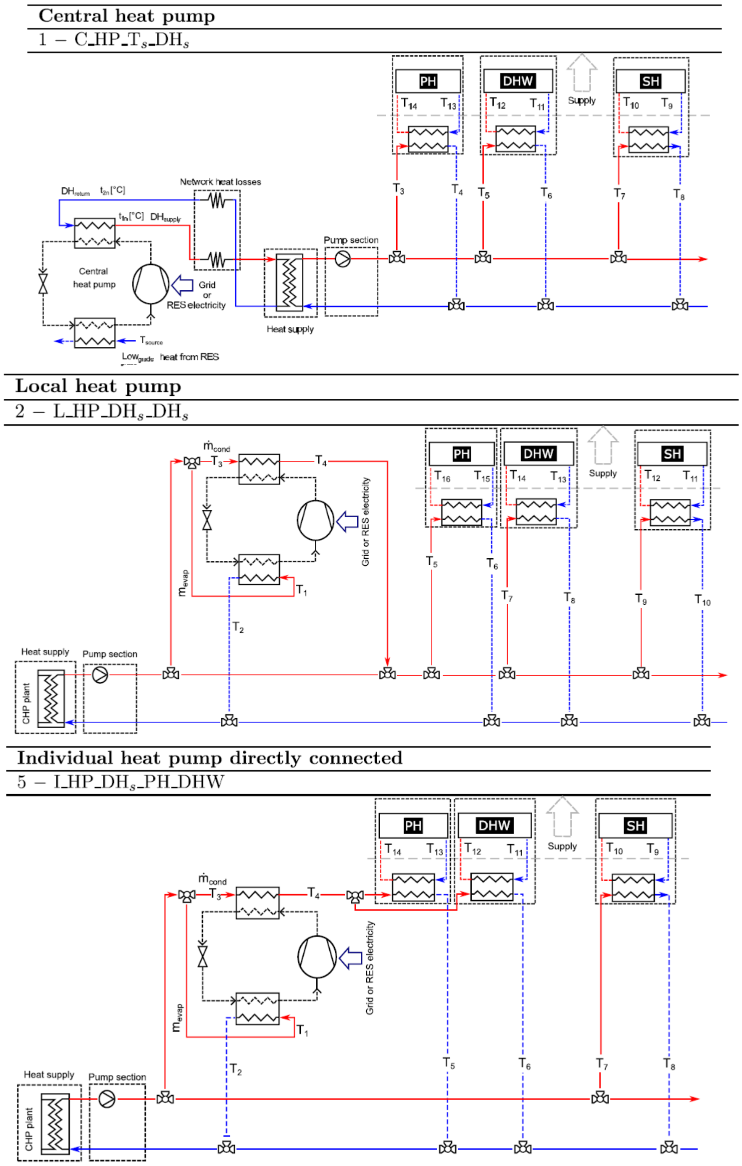


Figure 2-17Configurations for the integration of heat pumps into DH networks [25]

Examples of large heat pumps implementation in district heating

District heating system in Aalborg (Denmark) [27]

Characteristics	

Heat output: 177 MW (4 units)
Refrigerant: CO_2, oil free compressors
Heat source: seawater at 1 – 15 °C (Limfjord intake)
Heat sink: up to 98 °C for district heating
Replaced heat source: coalfired power plant
COP=3-3.5
Heat production for 120,000 residents
Estimated reduced emissions: 210,000 tones/year

[28]

District heating system in Grosskraftwerk Mannheim (Germany)[29]

Characteristics
Heat output: 162 MW (2 units)
Refrigerant: isobutane
Heat source: Rhine water 5-25 °C
Heat sink: up to 130°C for district heating
Replaced heat source: coalfired power plant
COP=3-3.5
Heat production for 120,000 residents
Estimated reduced emissions: 210,000 tones/year

2.1.5 Geothermal systems

Geothermal energy represents one of the most stable and reliable renewable sources for district heating. Unlike solar or wind energy, geothermal heat is available continuously, independent of weather conditions, making it a valuable base-load resource for urban and industrial heating networks.

The worldwide installed capacities of geothermal heating and cooling, broken down by region, are shown in Figure 2-18.

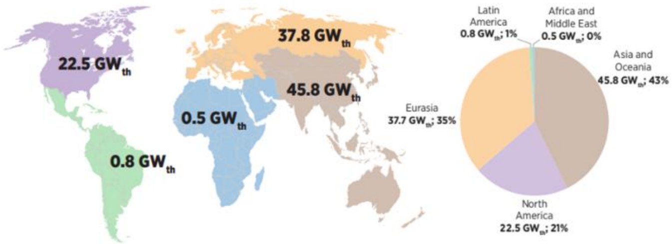


Figure 2-18Geothermal heating and cooling installed capacities by region, 2020 [30]

Geothermal energy has strong potential to support sustainable district heating in Europe, which is already a world leader in this area.

In 2022, there were 395 geothermal district heating and cooling systems operating across 29 countries, with a total installed capacity of 5,608.31 MW_{th} [31].

This growth shows Europe's clear commitment to renewable energy and proves that geothermal systems can work well in many different locations. With more projects underway, the sector is expected to expand quickly and reach new markets. Geothermal district heating and cooling will continue to play an important role in helping Europe reduce carbon emissions and strengthen its clean energy future.

Figure 2-19 presents the largest and emerging European geothermal district heating and cooling systems in 2022, illustrating the number of operational systems and those currently in development [31].

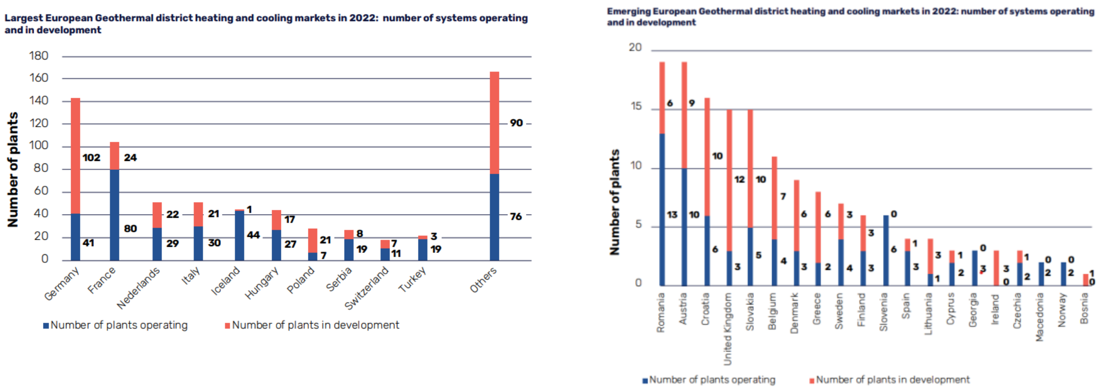


Figure 2-19the largest and emerging European geothermal district heating and cooling systems in 2022 [31]

Although Europe has thousands of megawatts (MW_t) of geothermal heating capacity installed, only about 30 MW of that total is used for district cooling purposes. [32].

Geothermal systems classified by [33] according to the temperature of geothermal fluids and their suitability for different generations of district heating and cooling (DHC) systems are presented in Table 2-5.

Table 2-5 Classification of geothermal systems [33]

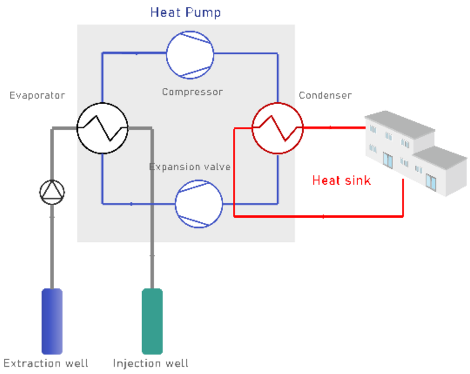
Geothermal system	Wellhead fluid temperature	Generation of DHC	Equipment to supply building's system		
			SH	DHW	Cooling
Shallow	< 25 °C	5GDHC (ambient temperature)	HP	HP	EC/direct
Medium-deep	25–90 °C	4GDH (low temperature)	HP/HEX/direct	HP/HEX/direct	AC
Deep	> 90 °C	3GDH and 2GDH (high temperature)	HEX/direct	HEX/direct	AC
SH – space heating; DHW – domestic hot water; HP – heat pump; HEX – heat exchanger; EC – electric chiller; AC – absorption chiller.					

The categorization reflects how geothermal resources at different depths can be integrated into DHC networks through appropriate technologies for space heating (SH), domestic hot water (DHW), and cooling.

Shallow geothermal systems

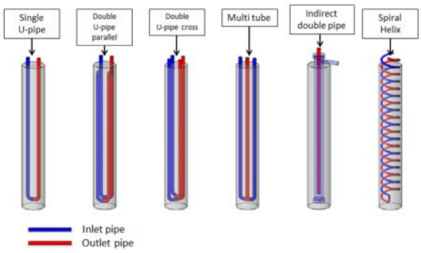
Shallow geothermal systems (fluid temperature below 25 °C) are compatible with 5th-generation DHC (5GDHC) networks, which operate at ambient temperature levels. These systems rely primarily on heat pumps (HPs) to upgrade the temperature for both space heating and hot water supply. Cooling can be provided either directly from the ground or using electric chillers (EC).

These systems are classified into open-loop and closed-loop configurations. In open-loop systems, groundwater is extracted and re-injected after its thermal energy has been utilized. Closed-loop systems exchange heat with the ground through ground heat exchangers (GHEs), which can be either installed horizontally (1.5–2 m deep) or vertically (typically 50–150 m deep). In vertical systems, the most common configurations are U-tube and coaxial boreholes.



[34]

[35]



[36]

Figure 2-20 Open loops (a) and closed loop shallow geothermal

The thermal performance of borehole heat exchangers (BHEs) and the specific extraction rates of horizontal ground heat exchanger systems are presented in the following tables 2-6 and 2-7.

Table 2-6 Specific Thermal Power Provided by Horizontal Collectors Depending on Soil Type [37]

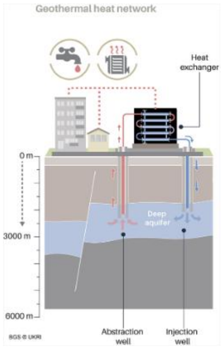
Type of Soil	**Specific Thermal Power [W/m²]**
Dry sandy soil	10–15
Moist sandy soil	15–20
Dry clay soil	20–25
Moist clay soil	25–30
Soil with groundwater	30–35

Table 2-7 Specific Thermal Power Provided by Vertical Collectors Depending on Soil Type [37]

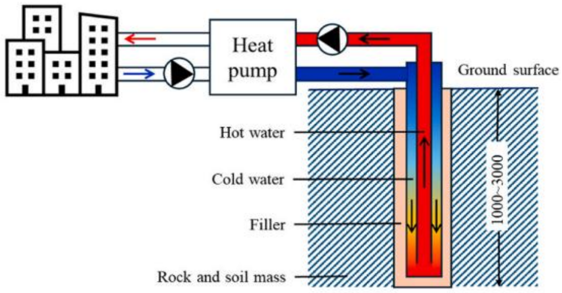
Type of Soil	**Specific Thermal Power [W/m]**
Dry sandy soil	20
Moist sandy soil	40
Clay soil	60
Soil with groundwater	80–100

Medium-deep geothermal systems, with fluid temperatures typically ranging from 25–90 °C, are well suited for fourth-generation district heating and cooling (4GDH) networks that operate with low-temperature supply.

Depending on the available fluid temperature, these systems can utilize either heat pumps or direct heat exchangers (HEX) for space heating (SH) and domestic hot water (DHW) production, while absorption chillers (AC) may be employed for cooling applications.



(a) [38]



b) [39]

Figure 2-21 Configurations for medium-deep geothermal source exploitation: (a) system with heat exchanger, and (b) system with heat pump.

Deep geothermal systems (temperatures above 90 °C) are applicable to 3rd- and 2nd-generation DHC networks (3GDH, 2GDH), characterized by high supply temperatures. The thermal energy from these sources can be utilized directly through heat exchangers for heating and hot water production, and absorption chillers for cooling in trigeneration configurations.

Deep geothermal energy can be utilized for several applications, including:

- Electricity generation, using direct steam, flash, or binary cycle technologies;
- Direct use of geothermal heat for various heating applications; and
- Combined heat and power (CHP) production, where both electricity and thermal energy are generated simultaneously.

Example of integration

Most of the information presented in this document were taken from [40]In the Municipality of Beiuş, city located in Bihor County, Romania at the coordinates: 46.667 N and 22.353 V, the heating and the domestic hot water (DHW) are provided by a district heating (DH) system, powered 100 % by geothermal water. The map of the city of Beiuş, with about 10000 inhabitants, is presented in the figure below.

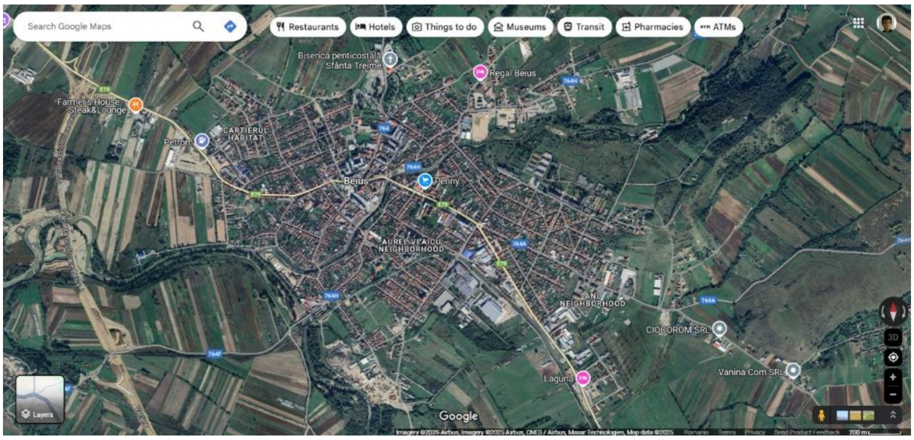


Figure 2-22 City of Beiuș on Google maps

The DH is composed of 5 substations and many individual clients, including schools, the hospital, etc.The figure below presents the scheme of the DH with the 3 geothermal wells and the 5 substations.

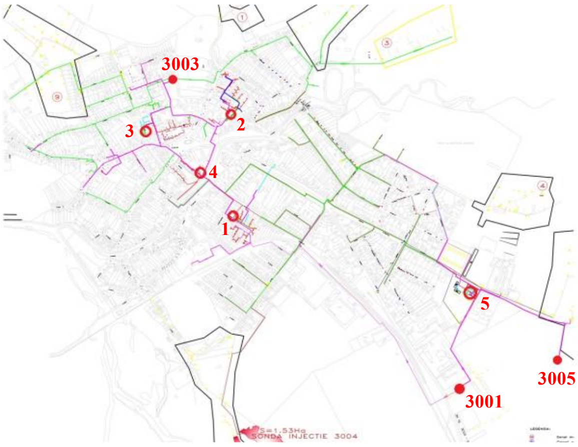


Figure 2-23 The scheme of the DH system
3001; 3003; 3005: Geothermal wells; 1; 2; 3; 4; 5: Heating and DHW substations

The figure below shows a simplified scheme of the DH system.

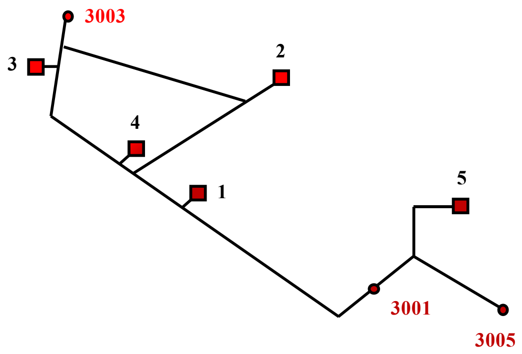


Figure 2-24 The simplified scheme of the DH system
3001; 3003; 3005: Geothermal wells; 1; 2; 3; 4; 5: Heating and DHW substations

The general characteristics of the geothermal wells are presented in the table below.

Table 2-8General characteristics of the geothermal wells

Well 3001		Well 3003		Well 3005	
Temperature [°C]	**Flow rate [l/s]**	**Temperature [°C]**	**Flow rate [l/s]**	**Temperature [°C]**	**Flow rate [l/s]**
81	55	73	65	81	80

In principle, all the substations can be fed with geothermal hot water from any geothermal well, but usually:

- The substations 1; 4 and 5 are fed from the geothermal well 3001
- The substations 2 and 3 are fed from the geothermal well 3003

The geothermal wells in Beiuş are interconnected to supply with thermal energy the actual DH system. The geothermal water is provided by the well 3003 provide in the North – West and by the wells 3001 and 3005 in the South – East.

The most important consumer is the hospital, with a global annual share of 55.3 %, followed by the schools counting together 39.7 %, and by the substations counting together 5.0 % of the total heat provided.

To balance the pressure and flow in the DH system more interconnections would be benefic and are under consideration for further developments.

One of the major problems of the DH system is that it has reached its limits and it is difficult if not impossible to connect with new consumers. This situation is in contradiction with the development plans of the municipality.In the study [40] the possibility of extending the thermal power of the existing DH was investigated. The technical solution that was found is the use of heat pumps (HP) proposed to be connected at the outlet of the geothermal water from the substations and / or thermal models, in the case of large consumers.The figure below shows the thermal regime of both the existing DHW system and proposed DHW system with HP connected at the outlet of the geothermal water.

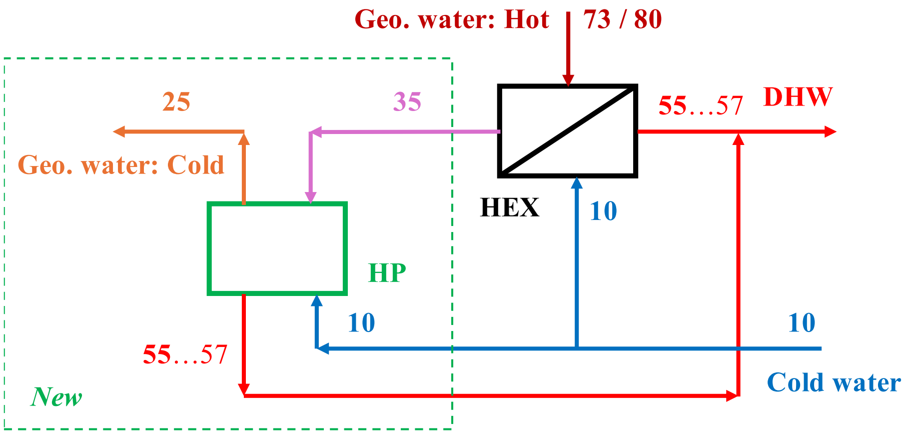


Figure 2-25 Thermal regime of the DHW system (with HP)

The HP can provide hot water at (55...57) °C as it is the case in Beiuş.The figure below shows the thermal regime of both the existing heating system and proposed heating system with HP connected at the outlet of the geothermal water.

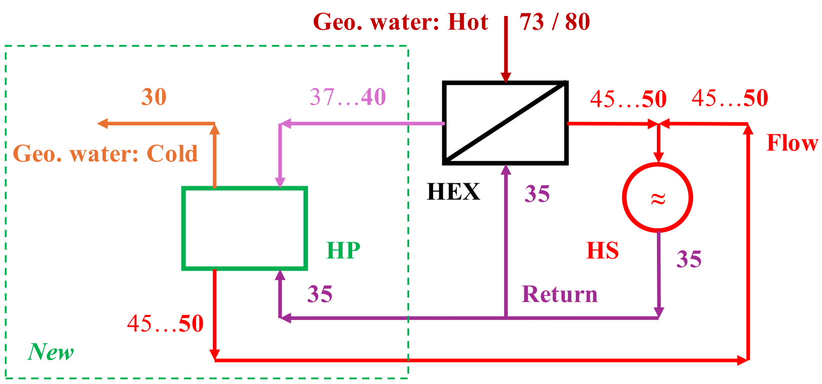


Figure 2-26 Thermal regime of the heating system (with HP)

The HP can provide hot water at (45...50) °C as it is the case in BeiuşThe figure below presents the principle scheme of HP connection into the DH system.

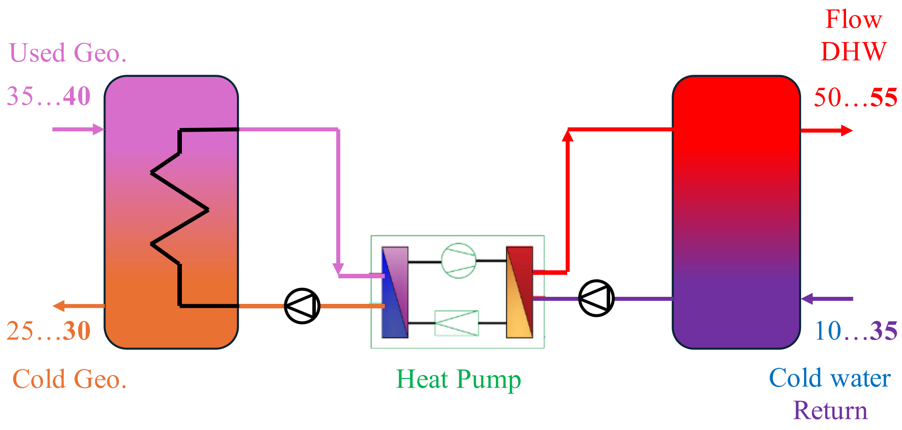


Figure 2-27Principle scheme of HP connection into the DH system

It is recommended to connect the HP into the DH system by two storage tanks, one for geothermal water used in the existing DH system, and one for the thermal agent, or the DHW prepared by the HP. The storage tanks are needed both for eliminating the risk of short working cycles and for handling the flow variation on the geothermal water circuit and on the heating or DHW circuits.

The main conclusion is that it is possible to extend the thermal power and the heating capacity of the DH of Beiuş and still maintain the high efficiency of the DH.The technical solution to extend the thermal power of the DH: Water to water HP to extract more heat from the outlet geothermal water of the DH system. The proposed HP uses CO_2 (R744) as an environmentally friendly refrigerant ODP = 0, GWP = 1.A synthesis of the proposed configuration and characteristics of the heat sources in the DH is presented in the table below.

Table 2-9Configuration and characteristics of the heat sources in the DH

Objective	**Share in DH* [%]**	**No. of HP DHW**	**No. of HP Heating**	**Share of Geo [%]**	**Share of HP [%]**	**COP [-]**
Subst. 1	0.9	1 x 14 kW	1 x 120 kW	77.8	22.8	4.18
Subst. 2	1.2	1 x 40 kW	1 x 120 kW	79.2	20.8	4.21
Subst. 3	1.8	1 x 75 kW	2 x 120 kW	77.8	22.8	4.17
Subst. 4	0.8	1 x 14 kW	2 x 120 kW	77.3	22.7	4.15
Subst. 5	0.4	1 x 14 kW	1 x 40 kW	79.2	20.8	4.26
Primary school	4.5	-	4 x 120 kW	80.1	19.9	3.97
Techn college	7.5	-	6 x 120 kW	81.4	18.6	3.97
HS. Vulcan	12.9	-	11 x 120 kW	80.6	19.4	3.94

HS. Bolcas	14.9	-	13 x 120 kW	80.4	19.6	3.97
Hospital	55.3	9 x 120 kW	34 x 120 kW	81.9	18.1	4.33
Total						

* Only the objectives mentioned of DH were considered

A technical measure that can be considered to reduce the heating demand of the DH system is the deep renovation of the buildings in Beiuş.

The deep renovation can consider different actions, such as:

- Improvement of the envelope of the buildings (walls and windows)
- Replacement of the heating system components
- Implementation of renewable energy systems on the buildings
- Mechanical ventilation with heat recovery
- Etc.

Different types of buildings can be considered for deep renovation: residential, offices, commercial, educational, medical, etc.

A technical measure that can be considered to increase the heating capacity of the DH system is to drill new geothermal wells capable of supplying more geothermal water.A technical measure that can be considered to increase the operation capability of the district heating system is to analyze the opportunity to replace old sections of the thermal networks, if necessary.

2.1.6 Waste heat recovery

Waste heat represents an important and viable energy source for district heating systems, with several operational projects already demonstrating the potential of utilizing different waste heat sources (Figure 2-22). By capturing and reusing heat that would otherwise be lost to the environment, modern DH systems can significantly reduce overall energy consumption and greenhouse gas emissions within urban energy infrastructures.

Figure 2-28 Waste heat sources for district heating [41]:

Waste heat can be categorized based on its temperature level [41] as follows:

- low-grade (< 100 °C);
- medium-grade (100–400 °C);
- or high-grade (> 400 °C).

Waste heat integration into district heating systems can be achieved through heat exchangers or heat pumps, which enable the transfer and upgrading of low-temperature heat to suitable supply levels. Additionally, excess waste heat can be stored in thermal energy storage systems to balance temporal mismatches between heat generation and demand [41].

The integration of waste heat into district heating systems offers multiple advantages, including [41]:

- improved overall efficiency;
- reduced carbon emissions;
- and lower operational costs.

However, several challenges must be addressed to ensure reliable and economically viable operation [41]:

- variability in heat availability,

- technical complexities of system integration
- and institutional or economic barriers such as limited incentives and regulatory constraints.

Data centers

Due to their continuous operation and significant cooling requirements, data centers represent one of the most commonly utilized sources of waste heat in existing district heating networks. The waste heat released from data center cooling systems typically has a temperature level between 25 °C and 60 °C, depending on the cooling technology employed.

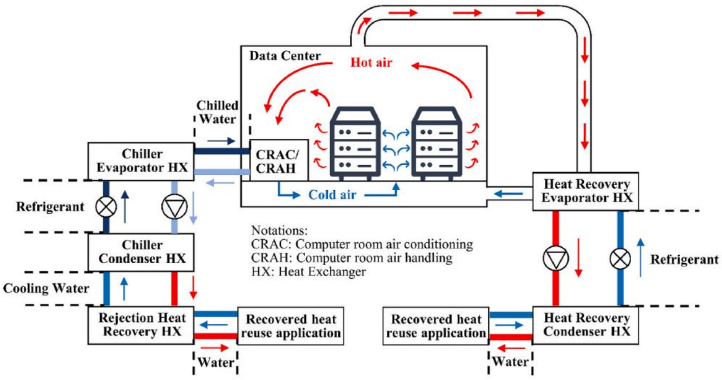
Waste heat sources and potentials

According to [42] , the waste heat sources and their recovery potentials in data center systems are summarized in Tables 2–10 These data illustrate how different cooling technologies, such as air-side, air-to-liquid, and liquid cooling offer different temperature levels and recovery potentials, influencing their suitability for integration into low- or medium-temperature district heating networks.

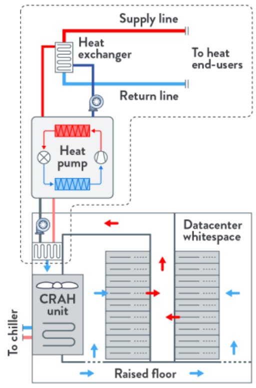
Table 2-10 Waste heat temperature levels for different cooling systems in data centers [42]

DC Cooling Form		Description	Potential Heat Source	Temperature (°C)
Air-side cooling	CRACs	Room-level cooling	Return warm water	15–20
	CRAHs /		Return hot air	25–47
			Condenser coolant	40–50
Air to liquid	Heat exchanger	In-row & rear door cooling	Return warm water	20–30
			Condenser coolant	40–50
Liquid cooling		—	Return hot water	50–60

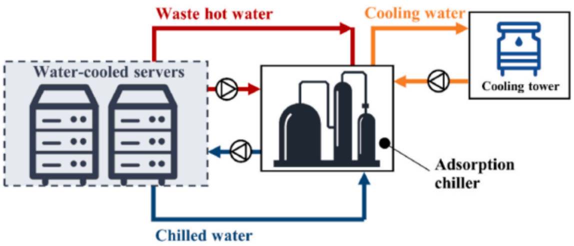
Although this temperature range is generally too low for direct use in conventional district heating networks, it can be effectively upgraded using heat pumps, making it suitable for integration into low- and medium-temperature district heating systems [41].



a) [42]



b) [43]



c) [42]

Figure 2-29Data center heat reuse for district heating (a) (b) and cooling (c)

Data centre supplies local heating in Mäntsälä, Finland [44]

Characteristics	 [45]
Installed heat capacity: 4.0 MW	
Heat source: Cooling of data centre (40 ◦C)	
Heat pump COP: 4.0	
Heat sink: 85°C	
Emission reduction: 11,000 ton CO2 annually	

Industrial waste heat (IWH)

The industrial sector is a significant global energy consumer. During its processes, it generates substantial amounts of recoverable waste heat, often accounting for 20% to 50% of its total input energy [41]. The largest amounts of waste heat in industries are usually found in food and tobacco and pulp and paper, basic metals, chemical industry, and non-metallic minerals.

The highest amounts of industrial waste heat are typically produced in sectors with energy-intensive processes, such as the food and tobacco, pulp and paper, basic metals, chemical, and non-metallic mineral industries [46].These sectors operate continuously and rely heavily on thermal energy for production, resulting in significant quantities of recoverable waste heat at various temperature levels. Due to the scale and stability of their operations, they represent some of the most promising sources for integration into district heating networks (DHNs), where recovered heat can be utilized to reduce fossil fuel consumption and support the decarbonization of urban energy systems

Challenges to Industrial Waste Heat Utilization:

- Different temperature levels available
- Variable heat supply
- Distances between sources and consumers
- Regulatory and economic barriers

Benefits of IWH:

- Efficient industrial cooling
- Creation of additional revenue streams
- Reduction of overall emissions

Example of integration:
Grundfos Factory Excess Heat Recovery for District Heating[47]

Characteristics
Installed heat capacity: 3.7 MW
Heat source: Excess heat (40 °C)
Heat pump COP: 4.6
Supplied consumers: 2800
15 % of the district heating is based on excess heat from Grundfos factory

[48]

Supermarkets

Supermarkets preserve fresh food using supermarket refrigeration systems, which generate significant amounts of waste heat. In recent years, carbon dioxide (CO_2) has increasingly been adopted as a refrigerant; it can reject heat at relatively high temperatures, typically between 30°C and 75°C, compared to conventional refrigerants. The heat recovered from is commonly reused for space heating within supermarkets and has also been explored as a potential heat source for district heating networks.

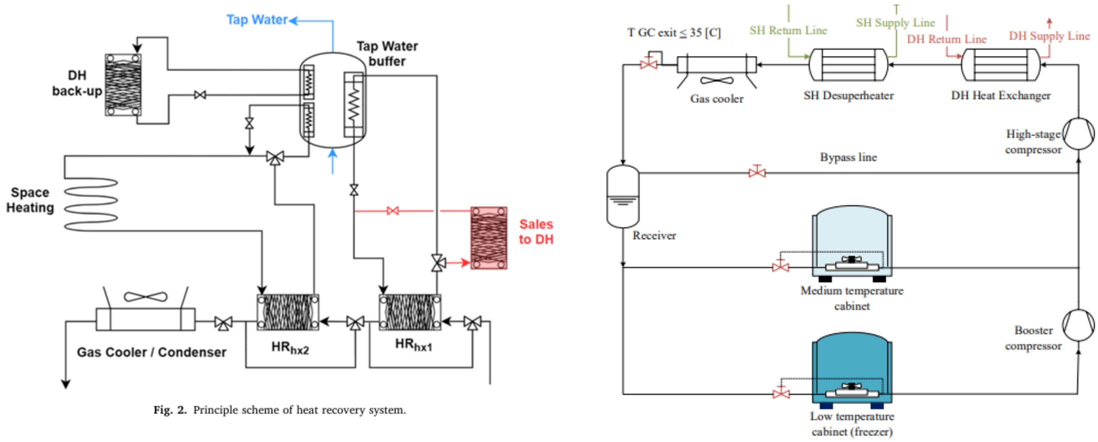


Figure 2-30 Supermarkets heat recovery integration solutions [49] [50]

Examples of integration:*Høruphav, Denmark [44]*

<table>
<tr><th>Characteristics</th><td rowspan="4">[51]</td></tr>
<tr><td>Heat source: heat from cooling the supermarket</td></tr>
<tr><td>CO2 refrigerant system (cooling capacity: 160 kW)</td></tr>
<tr><td>Supplied consumers: 16 households</td></tr>
</table>

Power and waste incinerator plants

Power plants and urban waste facilities are also important sources of waste heat utilized in district heating systems. In thermal and nuclear power plants, large quantities of excess heat are generated during electricity production; instead of being released into the environment, this residual heat can be recovered and supplied to district heating networks, significantly improving the overall energy efficiency of the plant. Such integration reduces thermal pollution, enhances fuel utilization, and supports the decarbonization of urban heating systems through the effective reuse of otherwise wasted energy.

Similar, municipal solid waste incineration plants and wastewater treatment facilities also sources of low- to medium-temperature waste heat. Heat recovered from municipal solid wasre incineration is available at temperatures between 80°C and 200°C, suitable for direct use in medium-temperature district heating networks. Wastewater have stable temperatures throughout the year (typically 10–25°C), making it a heat source for heat pump–assisted systems. These urban waste heat sources are particularly attractive due to their proximity to demand centers, reducing transmission losses and infrastructure costs.

2.2 District cooling

District cooling (DC) is a centralized system that produces and distributes chilled water (usually 4–6 °C) through a network of insulated pipes to multiple consumers residential, commercial, institutional, and/or industrial consumers for use in space cooling and dehumidification [52].

Across Europe, there are over 200 cooling networks, representing over 1,375 kilometres of pipes, with two-thirds of supplies in Sweden and France and Finland [53,54].

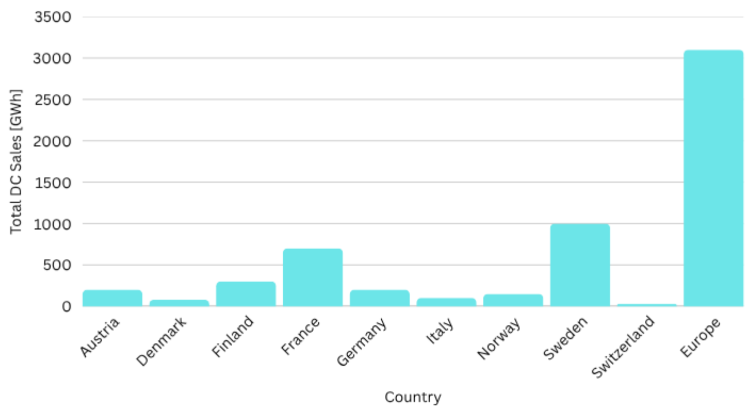


Figure 2-31 District cooling sales (GWh) in Europe in 2021 (adapted from [53])

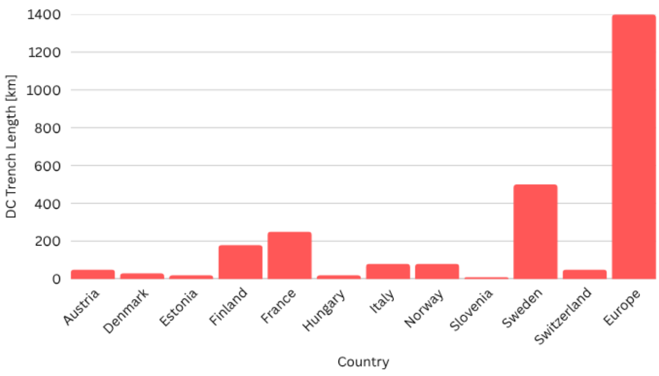


Figure 2-32 District cooling trench length in Europe in 2021, adapted from [53]

The main components of a district cooling systems are as follow [52]:

- Chill Water Production plant

The central plant generates chilled water using electric, absorption chillers or free natural cooling

- Distribution Network:

Chilled water is circulated through supply pipes to consumer buildings and returns via return pipes after absorbing indoor heat

- Heat Rejection:

Absorbed heat is discharged through cooling towers, dry coolers, or natural bodies of water such as rivers, seas, or aquifers.

- End-User Systems

Include building-level heat exchangers and air-handling units (AHUs) that transfer the cooling effect to indoor air.

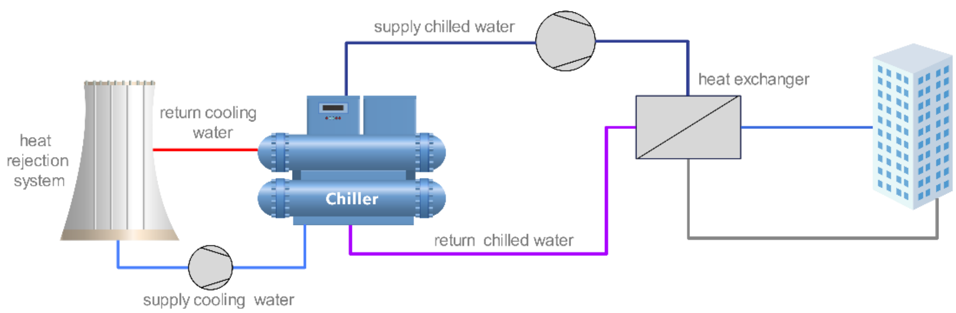


Figure 2-33 Basic structure of a district heating system (adapted from [52])

Cooling technique in District Cooling Systems:

1. Electric Compression Chillers

Operate on vapor-compression cycles powered by electricity and is the most common technology used for cooling in industrial, commercial, and residential applications. It operates on a closed thermodynamic cycle with a refrigerant as a working fluid.

Heat absorption occurs through the evaporation of the refrigerant, while heat rejection takes place through its condensation. These two processes occur in separate heat exchangers, known as the evaporator (V) and the condenser (K), respectively. The other main components of the system, the compressor and the expansion device, ensure the proper operating conditions required for the efficient functioning of the condenser and the evaporator. In the evaporator, the refrigerant absorbs heat from the space or fluid to be cooled and evaporates at low pressure. The vapor is then compressed by a mechanical compressor, increasing its pressure and temperature before releasing heat to the environment in the condenser, where it condenses back into a liquid. The liquid refrigerant passes through an expansion valve, reducing its pressure and temperature before re-entering the evaporator to repeat the cycle [55].

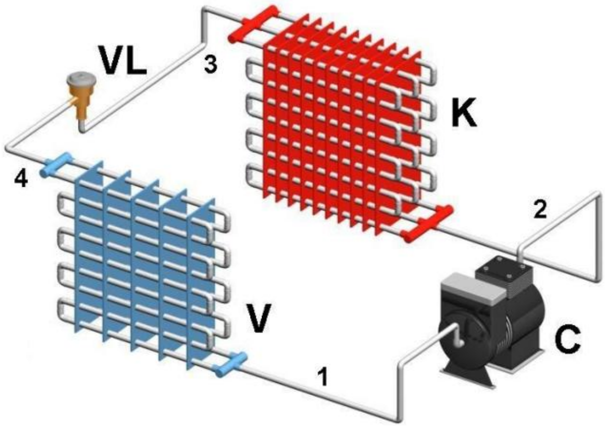


Figure 2-34 Basic schematic of a refrigeration system [55]

The coefficient of performance (COP) is defined as the ratio between the cooling capacity (useful refrigeration effect) and the work input required by the compressor:

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{cooling}}}{W}$$

where $\dot{Q}_{\text{cooling}}$ represents the rate of heat removed from the cooled space, and W is the mechanical or electrical power input to the compressor.

In practice, vapor-compression systems typically have COP values between 2.5 and 6, depending on the design, operating conditions, and temperature difference between the heat source and heat sink.

2. Absorption Chillers

Absorption refrigeration systems, or thermochemical compression systems, use heat available at a temperature higher than the ambient environment as the energy source for cooling production. The lower the temperature at which cooling is desired, the higher the minimum temperature required for the heat source [56].

Unlike conventional vapor-compression systems that rely on mechanical energy, absorption systems can operate using residual or low-cost thermal energy, such as waste heat from industrial processes, solar thermal energy, or exhaust gases from combined heat and power (CHP) plants.

Absorption chillers produce cooling through a thermochemical process that relies on the evaporation and condensation of a liquid solution. The working solution used in absorption chillers consists of two components a refrigerant and an absorbent which together enable the transfer of heat within the system [57].

The most common absorbent–refrigerant pairs are lithium bromide–water ($LiBr–H_2O$) and water–ammonia ($H_2O–NH_3$). $LiBr–H_2O$ systems are typically used for air-conditioning and chilled-water production within a temperature range of 6–12 °C. In this pair, water acts as the refrigerant, while lithium bromide serves as the absorbent. $H_2O–NH_3$ systems can operate across a similar range but are also capable of achieving sub-zero temperatures, down to approximately –60 °C, making them suitable for industrial and low-temperature refrigeration [57].

Typical values for the thermal coefficient of performance (COP) of absorption chiller are presented in below.

Table 2-11 Typical values for the thermal coefficient of performance (COP) of absorption chiller [58]

No.	Characteristic	Single-stage	Two-stage
1	Form of energy consumed	Hot water at 65–80°C	Steam or flue gases above 170°C
2	Refrigerants (working fluids)	H_2O + BrLi, NH_3 + H_2O	H_2O + BrLi, NH_3 + H_2O
3	COP (Coefficient of Performance)	0.6...0.75	1.2

3. Free Cooling

Free cooling systems utilize naturally cold sources (deep lake water, seawater, or groundwater aquifers) to provide cooling with minimal energy input. By taking advantage of these low-temperature natural reservoirs, the district cooling systems can reduce or even eliminate the need for conventional chillers.

Examples of district cooling systems in Europe

The District Cooling system in Stockholm City, Sweden [59]

The District Cooling system in Stockholm City, Sweden, is one of the largest and most efficient in Europe. It has a cooling capacity of about 170 MW and provides around 240 GWh of energy each year. The network supplies cooling to nearly 300 customers, such as office buildings and public institutions. Its main pipes stretch over 8.6 km, with another 12 km of smaller city pipes, most of which are placed in tunnels or buried underground to avoid disrupting city traffic. The system uses water at +6 °C for supply and returns it at +16 °C, ensuring efficient operation. In 1998, an aquifer thermal energy storage system was added, allowing about 25 MW of extra cooling during peak demand by storing and reusing cold energy.

2.3 Thermal Storage

Role of the storage in DHC systems

The duration of thermal energy storage can range from a few hours (short-term or daily storage) to several months (seasonal storage). In certain climates, homes require heating during the winter and cooling during the summer. Seasonal thermal energy storage systems make it possible to capture and store heat generated during the summer months, so it can be used to meet heating demands during the colder winter period. STES systems enable the decoupling of thermal energy generation and demand, especially in district heating networks with seasonal variability [60].

Seasonal heat storage facilitates sector coupling, offering a cost-effective solution – in some cases, storing heat can be up to 100 times cheaper per kilowatt-hour than storing electricity, depending on the storage method, site availability, and land costs [61].

Renewable energy sources come with the challenge of intermittency and seasonality. For instance, solar thermal energy is abundant during the summer months, when the demand for heat is at its lowest. By storing thermal energy, part of the high heating demand during winter can be covered using a seasonal storage system.

Thermal energy storage (TES) technologies enable energy systems to function more efficiently by reducing losses and improving overall system performance. The following case studies highlight the successful implementation of such systems, along with their techno-economic implications.

A seasonal thermal energy storage tank with a volume of 5700 m³ of water, constructed from prefabricated concrete elements, is operating within the district heating system in Munich, Germany.

Figure 2-35 Seasonal thermal energy storage tank with a volume of 5700 m³, built in Munich, Germany [62].

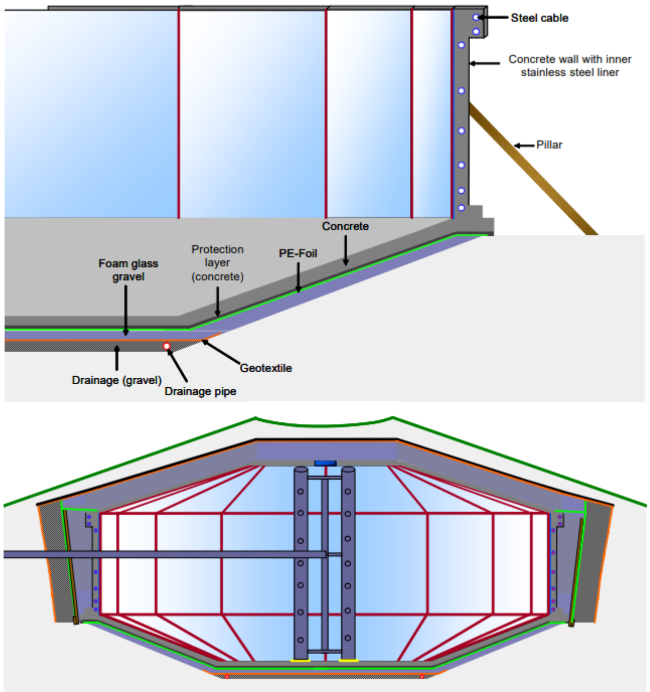


Figure 2-36 Vertical section and construction of the storage tank in Munich, Germany [63].

The storage tank is integrated into a district heating system that supplies heat to 300 apartments. The heat stored in the tank comes from a 2,900 m² solar field, with the system covering approximately 47% of the annual heat demand.

The lower section (base) of the tank was constructed on-site, while the sidewalls and the roof were made from prefabricated concrete elements, which feature a stainless steel lining on their inner surfaces. These linings served as formwork during the production of the concrete elements. The concrete components were prestressed, and the stainless steel plates were welded together to ensure water and vapor tightness. The tank was insulated externally on the sidewalls and on the top with expanded glass granules, with the insulation reaching a maximum thickness of 70 cm at the top. The bottom of the tank was insulated with a 20 cm layer of foam glass granules, selected for their high structural stability. Moisture protection for the insulation was achieved using vertical drainage. Thermal stratification and the usability of the stored heat were improved by means of a stratification device [64].

The largest solar district heating system in the world is located in Silkeborg, Denmark. This system supplies heat to 22,000 households, with solar energy covering 20% of the total energy demand—referred to as the solar fraction. The installation includes 12,436 solar collectors, spanning a total area of 156,694 m². These collectors generate both thermal energy and electricity and are made from recyclable materials such as aluminum, copper, glass, mineral wool, and rubber. When heating the thermal agent, the collectors operate at an efficiency that is 3–4 times higher than when generating electricity. The seasonal thermal energy storage system comprises four unpressurized steel tanks, each with a capacity of 16,000 m³ [65].

Figure 2-37 Solar district heating system from Silkeborg, Denmark [66].

One of the largest solar systems in the world has been operational since 2016 in Vojens, Denmark. The system includes a solar field covering 70,000 m² and a covered basin used for heat storage, with a total volume of 200,000 m³. The seasonal heat storage system allows the solar collectors to supply more than half of the annual heat demand. Even though Vojens is situated in a region with low solar potential, the solar thermal system combined with the seasonal heat storage system contributes to 50% of the annual heat demand. The reduction in CO_2 emissions amounts to approximately 6,000 tons per year [67,68] .

Figure 2-38Solar district heating system from Vojens, Denmark [69].

The Drake Landing Solar Community in Alberta, Canada, utilizes a solar district heating system with seasonal thermal energy storage. The project incorporates 144 boreholes for long-term heat storage, supplying up to 90% of the community's annual heating needs. This case study highlights the exceptionally high efficiency of seasonal storage and its significant role in reducing CO_2 emissions, demonstrating the feasibility of this technology in Canada's cold climate [70].

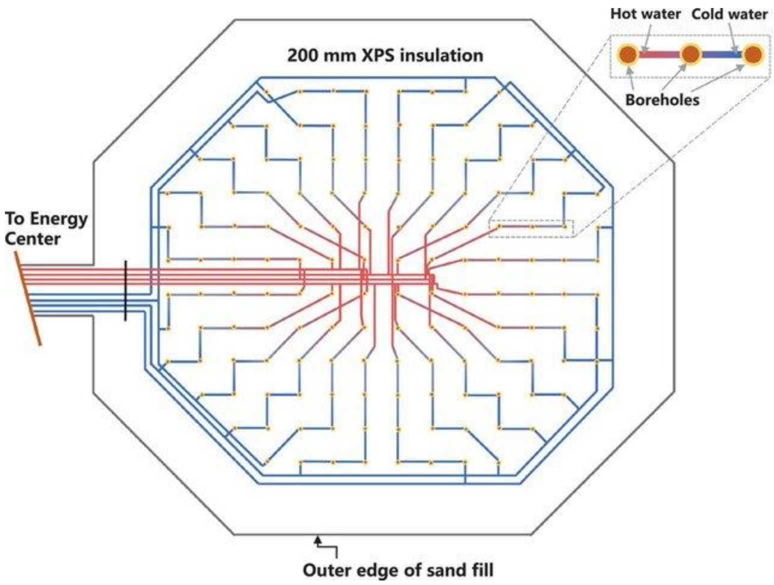


Figure 2-39 Borehole Thermal Energy Storage system at the Drake Landing Solar Community in Okotoks, Alberta [71]

To better understand the impact of seasonal storage on the system's energy efficiency, it is necessary to grasp the specific characteristics of each storage method.

Type of storage

The main methods used for seasonal thermal energy storage rely on sensible heat [72]. In this approach, thermal energy is stored by changing the temperature of the storage material. The amount of heat stored is directly proportional to the material's density, specific heat capacity, volume, and the temperature difference it undergoes [73]. A full storage cycle consists of three main stages: charging, storage, and discharging [74].

Reducing energy losses for large storage volumes and long storage durations is achieved through underground solutions, where soil temperature fluctuations are significantly lower than those of the outside air.

Currently, four main types of seasonal storage systems are in use: tanks, covered pits, boreholes, and aquifers [9]. The key characteristics of these seasonal thermal energy storage concepts are summarized in Table 2-12.

Table 2-12 Characteristics of the main Seasonal Thermal Energy Storage concepts [72,75–80]

Parameter	U.M.	Tanks	Pits	Boreholes	Aquifers
Storage medium	[-]	water	gravel – water	soil	sand - water
Energy density	[kWh/m^3]	60 - 80	30 - 50	15 - 30	30 - 40
Equivalent water volume	[m^3 water]	1	1.3 - 2	3 - 5	2 - 3
Specific costs	[€/m^3]	30 - 500	30 - 500	50 - 150	40 - 100
Depth/Height	[m]	5 - 15 m	5 - 15 m	20 - 50 m	30 - 200 m
Geological conditions	[-]	stable soil	stable soil	drilling ground	aquifer layer

Tanks are structures typically made of prestressed reinforced concrete or stainless steel, with water commonly used as the storage medium. Due to their large heat transfer surfaces, hot water tanks are often insulated with thick layers of thermal insulation. For instance, the storage tanks in Friedrichshafen and Hamburg, Germany, were insulated with 0.3 meters of mineral wool, while in Cosenza, Italy, the tank was insulated with a 0.2-meter layer of expanded glass foam gravel. To minimize thermal losses, insulation layers up to one meter thick are used, made from materials such as glass wool, polyurethane, extruded polystyrene (XPS), or expanded polystyrene (EPS). These tanks are usually installed underground, but can also be placed above ground, adjacent to a building. For example, in Hamburg, Cosenza, and Hannover, the tanks were buried underground; in

Friedrichshafen and Munich, they were partially buried; and in Ilmenau and Rise, they were installed above ground. The tanks operate based on the principle of thermal stratification - because of density differences, the water at the top of the tank remains hotter than the water at the bottom [75,76,79,81].

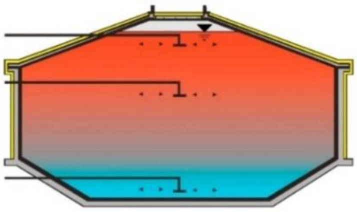
Covered pits are excavations in the ground that are sealed using welded polymer liners on the sides and bottom to ensure watertightness. The storage medium is either water or a mixture of gravel and water. These systems do not require a supporting structure like reinforced concrete, as the gravel itself distributes the load to the basin's walls and base, significantly reducing construction costs. This technology is considered one of the most cost-effective options when very large thermal capacities are needed. To date, covered pits have been built with volumes of up to 200,000 m^3. For example, such systems have been implemented in Dronninglund (62,000 m^3), Marstal (75,000 m^3), Gram (122,000 m^3), and Vojens (200,000 m^3). To minimize heat losses, the basin's sides, bottom, and top surface are thermally insulated. When using a gravel–water mixture instead of water alone, the specific heat capacity of the storage medium is lower. As a result, the storage volume must be approximately 50% larger than that of a pure water tank to compensate for the lower energy density. Nevertheless, gravel–water storage systems offer a significant reduction in construction costs and are a viable low-cost alternative for large-scale seasonal thermal energy storage [9,75–78,81].

Borehole systems utilize the thermal capacity of the ground – such as clay, sand, or rock – to store and exchange thermal energy. These systems consist of arrays of deep vertical boreholes drilled into the earth or bedrock, typically ranging from 30 to 200 meters in depth. The optimal borehole depth depends on several factors, including soil thermal conductivity, ground temperature, the level of the groundwater table, the thermal load profile, and the proximity to other similar storage systems. To minimize thermal losses to the surrounding environment, the top section of the borehole field is usually insulated and sealed with a watertight membrane. Several borehole thermal energy storage (BTES) systems have been implemented, such as in Braedstrup (19,000 m^3), Neckarsulm (528 boreholes, 63,000 m^3), and Crailsheim (37,500 m^3) [9,76–78,82].

Aquifers are natural geological formations that contain groundwater. In aquifer thermal energy storage (ATES) systems, the aquifer serves as the storage medium, with groundwater acting as the heat transfer fluid. These systems operate by extracting cold groundwater through a designated cold well, heating it externally, and then injecting it back into the aquifer through a separate warm well. The implementation of ATES systems requires regulatory approval from the relevant groundwater management authorities, as they involve the extraction and reinjection of subsurface water [9,78,79].

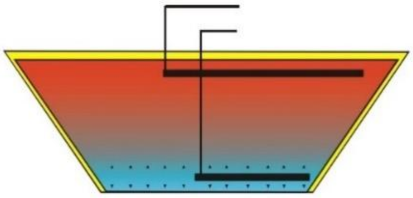
The main advantages and disadvantages of seasonal thermal energy storage systems are illustrated in Figure 2-33.

Tanks



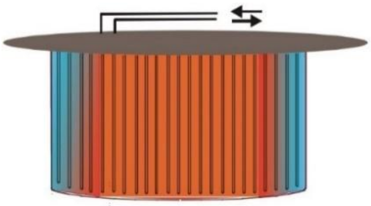
+ High thermal capacity
+ High charging/discharging power
+ Flexible geometry options
+ Supports thermal stratification
+ Accessible for maintenance and repairs
- Limited in size (<100000 m^3)
- Requires auxiliary heat sources
- High construction costs

Pits



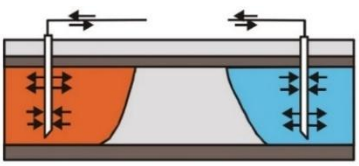
+ Reasonable construction costs
+ Medium (gravel–water) to high (water) thermal capacity
+ Virtually unlimited size
+ Medium charging/discharging power
- Covering system for water pits is complex and costly
- Limited design flexibility due to slope angle constraints
- Maintenance and repairs are difficult or impossible

Borehole



+ Low construction costs
+ Easy to expand
- Low thermal capacity
- Low charging/discharging power
- Limited site availability
- No thermal insulation possible on sides or bottom
- Maintenance and repairs are difficult or impossible

Aquifers



+ Low construction costs
+ Medium thermal capacity
- Low to medium charging/discharging power
- Very limited site availability (requires suitable aquifer)

- No thermal insulation possible, leading to relatively high heat losses

Figure 2-40Advantages and disadvantages of Seasonal Thermal Energy Storage systems [76]

The most suitable storage method, regardless of location, consists of storage tanks. This is why we will further detail aspects related to the sizing of storage tanks.

Design considerations for storage tanks

The specific design characteristics of hot water storage tanks include the following:

- Volume (V)
- Surface area to volume ratio (A/V)
- Geometric shape
- Height-to-diameter ratio (h/d) – for cylindrical tanks
- Installation type (e.g., above-ground, underground, partially buried)
- Structural design (e.g., material, reinforcement)
- Thermal insulation (type and thickness)

The **volume** of a seasonal thermal energy storage tank is considered a key optimization parameter of the system. It directly affects both the system's efficiency and economic viability. The storage volume can be calculated using the following relation [83]:

$$V = \frac{3.6 \cdot 10^6 \cdot Q_{ETS}}{\rho \cdot c_p \cdot (T_{max} - T_{min}) \cdot \eta_a}$$

where:

- V [m^3] – volume of the thermal energy storage tank
- Q_{ETS} [MWh] – amount of thermal energy to be stored
- ρ [kg/m^3] – density of water (typically ~1,000 kg/m³)
- c_p [kJ/kg·K] – specific heat capacity of water (typically ~4.18 kJ/kg·K)
- T_{max} [K] – maximum temperature of the water in the tank
- T_{min} [K] – minimum temperature of the water in the tank
- η_a [−] – efficiency of the storage tank (commonly between 0.85 and 0.95)
- $3.6 \cdot 10^6$ – conversion factor from MWh to kJ (1 MWh = 3600000 kJ)

The large volume required for seasonal thermal energy storage systems makes them more suitable for underground installation. In cities with harsh winters, the storage volume tends to be even larger to meet increased heating demands [75,84].

Generally, large-volume sensible heat storage systems are more efficient than smaller ones, assuming the same energy density. Seasonal storage becomes energetically efficient for systems with a storage volume of at least 1,000 m³ [81,85].

The **A/V ratio** refers to the ratio between the total surface area of the storage tank and its volume. Designing a system with a low surface-to-volume ratio (which indicates lower heat loss relative to capacity) is an effective way to minimize heat losses and reduce the need for costly insulation. The A/V ratio directly influences the height and diameter of the tank. Larger storage volumes generally improve storage efficiency. From a theoretical standpoint, a spherical tank is the most optimal shape, as it has the lowest A/V ratio, minimizing surface-related heat losses [77,81,85,86].

The **geometric shape** of hot water storage tanks should be selected to minimize heat losses and maximize storage efficiency. For underground tanks, the vertically oriented cylindrical shape has been found to be the most optimal configuration. Soil conditions play an important role in determining the appropriate geometry, especially in relation to the maximum available surface area and the maximum excavation depth permitted at the installation site [73,76].

The **h/d ratio** represents the ratio between the height and diameter of a cylindrical storage tank. It is a characteristic parameter used specifically for cylindrical tank designs. Once the storage volume (V) is known, the other dimensions can be calculated based on this ratio [84].

$$d = \left(\frac{4 \cdot V}{\pi \cdot \frac{h}{d}}\right)^{\frac{1}{3}}$$

$$h = \frac{h}{d} \cdot d$$

$$A = \left(\frac{h}{d} + 0.5\right) \cdot \pi \cdot d^2$$

where:

- d [m] – diameter of the tank
- V [m^3] – volume of the tank
- h [m] – height of the tank
- A [m^2] – total surface area of the tank

The h/d ratio (height-to-diameter) for cylindrical thermal storage tanks typically ranges between 0.22 and 3.8.

Next table presents the geometrical characteristics of various seasonal thermal energy storage tanks across Europe.

Table 2-13 Geometric characteristics of seasonal storage tanks in Europe

City	Country	V [m^3]	A [m^2]	d [m]	h [m]	A/V [1/m]	h/d [-]	References
Hamburg	DEU	4500	1650	25.7	10.7	0.37	0.42	[76]
Friedrichshafen	DEU	12000	2796	32.4	19.4	0.23	0.60	[76]
Ilmenau	DEU	300	262	7.2	8	0.87	1.11	[76]
Hanover	DEU	2750	1135	19	11.1	0.41	0.58	[76]
Attenkirchen	DEU	500	350	8.9	8	0.70	0.90	[76]
Crailsheim	DEU	480	362	6.3	14.5	0.75	2.30	[76]
Munich	DEU	6000	1800	24.6	16.1	0.30	0.65	[76]
Studsvik	SWE	1200	450	-	-	0.38	-	[87]
Lombohov	SWE	10000	1750	-	-	0.18	-	[87]
Rottweil	DEU	597	470	13	5	0.79	0.38	[81]
Cosenza	ITA	500	-	10	7.3	-	0.73	[81]
Neuchatel	CHE	1000	1075	14.6	16.15	0.45	1.1	[81]
Rise	DNK	4000	1445	20	13	0.36	0.65	[81]
Mühldorf	DEU	16.4	42.7	1.8	7	2.6	3.8	[81]
Vaulruz	CHE	3517	6331	30.5	6.2	1.8	0.22	[81]

Seasonal thermal storage tanks are most commonly installed underground to help reduce heat losses. In solar district heating systems, burying the tank also contributes to increasing the solar fraction of the system. However, underground installation typically involves higher construction costs due to the need for excavation. Alternatively, tanks can be installed partially buried, on rooftops, or above ground. While partially buried tanks reduce excavation costs, they often require additional thermal insulation on the upper surface, which can raise the overall cost. Above-ground tanks, on the other hand, are not subject to hydrogeological constraints, as they do not come into contact with groundwater [72,76,79,85]. The different installation configurations for storage tanks are illustrated in Figure 2-34.

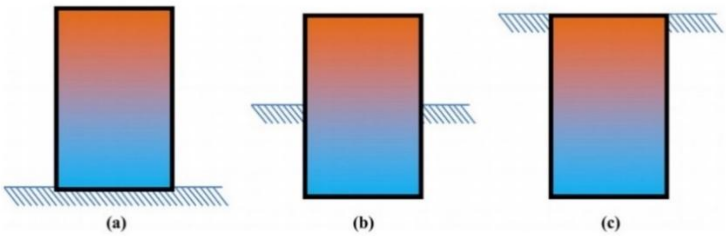


Figure 2-41Different installation types of storage tanks [76]
a) Above ground; b) Partially buried; c) Fully buried

Next table presents the installation method and geometric shape of selected seasonal thermal energy storage tanks in various locations across Europe.

Table 2-14 Installation method and geometric shape of selected Seasonal Thermal Energy Storage Tanks in Europe [81]

Location	Country	Installation	Geometric shape
Rottweil	DEU	Partially buried	Cylinder
Cosenza	ITA	Buried	Dome/Cylinder
Friedrichshafen	DEU	Partially buried	Cylinder
Neuchatel	CHE	-	Cylinder
Ilmenau	DEU	Above ground	Cylinder
Hannover	DEU	Buried	Cylinder
Rise	DNK	Above ground	Cylinder
Munich	DEU	Partially buried	Cylinder
Hamburg	DEU	Buried	Cylinder
Mühldorf	DEU	Above ground	Cylinder
Vaulruz	CHE	Buried	Truncated cone

The structure of the storage tank must be designed to withstand the mechanical stresses it is subjected to. The most commonly used structural materials include concrete, high-density concrete, steel, steel–concrete composites, stainless steel, and fiberglass-reinforced plastic. The performance of thermal storage systems depends not only on the construction materials but also on the surrounding hydrogeological conditions. For underground tanks, the properties of the surrounding materials significantly influence performance. These materials are defined by their density, thermal conductivity, thermal diffusivity, and heat capacity. Among common surrounding materials, coarse gravel is preferred over granite and limestone due to its favorable thermal characteristics [81]. The structural materials and wall thicknesses used in selected seasonal thermal energy storage tanks in Europe are summarized in table below.

Table 2-13 Structural materials and wall thicknesses of selected Seasonal Thermal Energy Storage Tanks in Europe [77,81]

Location	Country	Structural material	Wall thickness [m]
Rottweil	DEU	Concrete	0.25
Cosenza	ITA	Concrete	0.2-0.5
Friedrichshafen	DEU	Concrete	0.3
Neuchatel	CHE	Concrete	-
Ilmenau	DEU	Fiberglass-reinforced plastic	0.02 (0.17)
Hannover	DEU	Concrete	0.3
Rise	DNK	Steel	-
Munich	DEU	Concrete	0.16
Hamburg	DEU	Concrete	0.3
Mühldorf	DEU	Stainless steel	0.2
Vaulruz	CHE	-	-
Hoerby	DNK	Concrete	-
Herlev	DNK	Concrete and steel sheeting	-
Ingelstad	SWE	Concrete	-

The insulation surrounding the storage tank is designed to minimize heat losses. The insulation layer, which can be up to one meter thick, is typically made from various materials such as glass wool, polyurethane, extruded polystyrene (XPS), expanded polystyrene (EPS), glass foam, and others. Increasing the insulation thickness raises installation costs, but it also significantly reduces thermal energy losses. The most economical insulation thickness is achieved when the combined cost of insulation and energy losses is minimized. Insulation can be distributed around the tank shell in different ways [75,88]. Generally, the bottom of the tank is not insulated, unless it is installed at a depth where the groundwater table is present. In some cases, a non-uniform insulation layout is recommended—where the top section of the tank has a thicker layer of insulation, gradually decreasing toward the bottom. This approach improves insulation around the hotter region of the tank, while the colder lower section is surrounded by a thinner layer. This method can help reduce costs, enhance thermal stratification, and improve system efficiency [76]. The non-uniform insulation distribution model is illustrated in Figure 2-35.

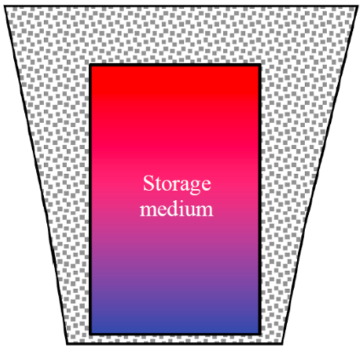


Figure 2-42 Optimal non-uniform distribution of tank insulation [76].

Table 2-14 presents the insulating material and insulation thickness used in various seasonal thermal energy storage tanks across Europe.

Table 2-14 Insulating material and insulation thickness for seasonal thermal storage tanks in Europe [77,81]

Location	Country	Base insulation material	Wall insulation material	Top insulation material	Insulation thickness [m]
Rottweil	DEU	not insulated	mineral fibers	mineral fibers	-
Cosenza	ITA	expanded glass foam gravel	expanded glass foam gravel	expanded glass foam gravel	0.2
Friedrichshafen	DEU	not insulated	mineral fibers	mineral fibers	0.3
Neuchatel	CHE	not insulated	mineral fibers + XPS	mineral fibers + XPS	-
Ilmenau	DEU	not insulated	polyurethane foam	polyurethane foam	-
Hannover	DEU	not insulated	expanded glass granules	expanded glass granules	-
Rise	DNK	not insulated	mineral fibers	mineral fibers	-
Munich	DEU	expanded glass foam gravel	expanded glass granules	expanded glass granules	-
Hamburg	DEU	not insulated	mineral fibers	mineral fibers	0.3
Mühldorf	DEU	perlite	perlite	perlite	-
Vaulruz	CHE	not insulated	EPS	EPS	-

The **efficiency analysis of seasonal thermal energy storage systems** is performed using the following **parameters**:

- **Overall thermal storage efficiency**: **c**[-]
- **Discharge efficiency**: η_{dch} [-]
- **Charging efficiency**: η_{ch}[-]
- **Exergy efficiency**: ψ_{sto} [-]
- **Stratification number**: **Str** [-]
- **Mixing number**: **MIX** [-]

The overall thermal storage efficiency (η_{st}) is a parameter that describes the performance of a thermal energy storage system. It can be expressed as the ratio between the amount of thermal energy recovered from the storage tank during the discharging process, and the amount of thermal energy charged into the tank during the charging process [73,89]. Mathematically, it is given by the formula:

$$\eta_{st} = \frac{Q_{ss}}{Q_{st}} = \eta_{ch} \cdot \eta_{dch}$$

where:

- η_{st} [-] = overall thermal storage efficiency
- Q_{ss} [J] = thermal energy recovered from the storage tank during the discharging process
- Q_{st} [J] = thermal energy accumulated in the tank during the charging process
- η_{ch} [-] = charging efficiency
- η_{dch} [-] = discharging efficiency

The **overall thermal storage efficiency** (η_{st}) of seasonal thermal energy storage (STES) systems typically ranges between 60% and 90%, depending on several factors such as [78,84,86,89–94]:

- the quality of insulation,
- the duration of storage (longer storage periods usually lead to higher losses),
- and the charging/discharging strategies.

Higher efficiencies (close to 90%) are usually achieved in well-insulated, compact systems with shorter storage durations, while larger-scale or underground systems storing heat over multiple months tend to show efficiencies closer to 60%–70%.

The discharge efficiency (η_{dch}) is a parameter that characterizes the effectiveness of the thermal discharge process in a storage system. It reflects how much of the stored energy can actually be recovered during the discharge phase [73,89]. It is expressed as:

$$\eta_{dch} = \frac{Q_{ss}}{Q_{ss} + Q_{l}}$$

where:

- η_{dch} [–] is the discharge efficiency,
- Q_{ss} [J] is the useful thermal energy recovered from the storage during discharge,
- Q_l [J] is the thermal energy lost from the storage system during the storage period.

The **charging efficiency** (η_{ch}) is a parameter that characterizes the effectiveness of the **charging process** of the thermal energy storage system. It indicates how efficiently the input energy is transferred and retained in the storage [73,89]. It is defined as:

$$\eta_{ch} = \frac{Q_{ss} + Q_l}{Q_{st}}$$

where:

- η_{ch} [–] is the charging efficiency,
- Q_{ss} [J] is the useful thermal energy recovered from the storage during discharge,
- Q_l [J] is the thermal energy lost from the storage during the storage period,
- Q_{st} [J] is the thermal energy charged into the storage system.

This efficiency reflects how much of the input energy (Q_{st}) remains in the system either as usable heat (Q_{ss}) or lost heat (Q_l), indicating how effectively the system accepts and stores thermal energy.

The **exergetic efficiency** (ψ_{st}) is a parameter that describes the **exergy performance** of the thermal energy storage system. It evaluates how effectively the system preserves the **quality of energy** during the storage period [73,78,89]. It is defined as the ratio between the **exergy recovered** from the storage during discharge and the **exergy charged** into the system during charging:

$$\psi_{st} = \frac{\psi_d}{\psi_c}$$

where:

- ψ_{st} [–] is the exergetic efficiency during the storage period,
- ψ_d [J] is the exergy recovered from the storage during discharge,
- ψ_c [J] is the exergy input to the storage during charging.

Exergy takes into account both the quantity and the thermodynamic quality of energy. Thus, ψ_{st} provides a more accurate measure of how well the system conserves usable energy potential, especially in relation to ambient conditions [90–92].

The “stratification number” (Str) is an efficiency parameter used to illustrate thermal stratification in a thermal energy storage system. It provides insight into the thermal layering inside the storage tank, which can influence energy recovery performance. Although stratification is often desirable (to preserve thermal layers), this parameter has been used in some studies to evaluate the negative impact of stratification under certain conditions [76,95]. The stratification number is defined as:

$$\mathrm{Str(t)} = \frac{\overline{(\partial T/\partial z)_t}}{\left(\overline{\partial T/\partial z}\right)_{max}}$$

The average temperature gradients are expressed by the following equation:

$$\overline{(\partial T/\partial z)_t} = \frac{1}{n-1}\left[\sum_{i=1}^{n-1}\frac{T_{i+1}-T_i}{\Delta z}\right]$$

The maximum temperature gradient is expressed as follows:

$$\left(\overline{\partial T/\partial z}\right)_{max} = \frac{T_{max}-T_{in}}{(n-1)\cdot\Delta z}$$

Where:

- n = number of vertical temperature measurement points,
- T_i = temperature at the i-th level,
- Δz = vertical distance between adjacent temperature sensors.

A Str value close to 1 indicates high stratification (good separation of hot and cold layers), while a lower value suggests more mixing, which may lead to reduced exergy and energy efficiency.

The MIX number is dimensionless and expresses the degree of mixing that occurs during a storage tank charging process. The MIX number is calculated based on the “moment of energy”. The moment of energy for a storage tank represents the integration along its vertical axis of the sensible energy it contains [76,96]. In practice, it is calculated by summing over a number of n storage segments along the vertical axis. The moment of energy is expressed as follows:

$$M_E = \sum_{i=1}^{n} z_i \cdot Q_i = \sum_{i=1}^{n} z_i \cdot (\rho \cdot V) \cdot c_p \cdot T_i$$

where:

- M_E [J·m] is the moment of energy,
- z_i [m] is the height of the storage tank segment,
- Q_i [J] is the amount of heat stored,
- c_p [J/kg·K] is the specific heat of the storage material,
- T_i [K] is the temperature of the storage material,
- V [m³] is the total volume of material in the tank,
- ρ [kg/m³] is the density of the storage material.

The **MIX number** is calculated using the following equation:

$$\mathrm{MIX} = \frac{M_{E,str} - M_{E,exp}}{M_{E,str} - M_{E,mix}}$$

where:

- **MIX** [-] is the MIX number,
- $M_{E,str}$ [J·m] is the moment of energy for the perfectly stratified tank,
- $M_{E,exp}$ [J·m] is the moment of energy representing the actual temperature profile of the tank,
- $M_{E,mix}$ [J·m] is the moment of energy for the fully mixed tank.

This indicator is important because it allows the assessment of the degree of thermal stratification in the storage tank. A value of **0** indicates a perfectly stratified (non-mixed) tank, while a value of **1** indicates a fully mixed tank [76,95–97].

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3. Design and operation of Heat Transport and Distribution Network

3.1 Heat density

Heat density is the ratio of the amount of heat annually required for heating and the area occupied by the heated targets.

Heat density is an essential criterion for designing district heating systems and several elements must be considered:

- Estimation of the district heating systems potential;
- Estimation of the economic viability (District heating systems are ***easier to implement when consumers are closer***, as the pipes are shorter and require less investment, so heat can become cheaper than individual heating solutions. ***Shorter pipes cause less heat loss***, with a significant impact on operating costs).

High heat density and low operating costs are important prerequisites for the ability to ensure low heating costs.

For the sizing of district heating systems in EU countries, the sizing principle used in Denmark has been adopted, according to which ***heat densities above 150 TJ/km² and above (40-50) kWh/m², respectively, are suitable for district heating networks***. (In areas where the heat supplied by district heating systems is low – for example due to cheap heat sources, these values can be even lower.)

It is recommended that the construction of district heating systems be phased according to the heat density values. (The highest heat densities will be found in densely populated urban areas, particularly where there are high rates of residential development.)

Creating a map of heating load is one of the first steps to be taken in the conception of a district heating system.

After establishing the routes for the pipes of the thermal network, ***the linear heat density*** (the heat requirement per linear meter of pipe, or the amount of heat to be transported per linear meter of pipe) can be calculated, which is an even more accurate indicator for evaluating the viability of the district heating system.

Heat losses are an important parameter of thermal networks:

In district heating systems, ***heat losses from the heating network*** have the most important weight in economic analyses.

The approximate share of heat losses in thermal networks is:

- (15-35) % in old networks with low heat density;
- (5-8) % in modern, extended networks in areas with high heat density;
- (10-15) % in typical Western and Northern European networks;
- (15-25) % in typical Eastern European networks;
- 7% in Copenhagen;
- 10% in new, modern systems that comply with best practices.

Annual heat losses depend on:

- linear heat density
- heat distribution temperature,
- pipe diameter
- thickness of insulation
- thermal conductivity of the insulation.

An atlas of heat density maps ***for the European Union (***Pan-European Thermal Atlas*) is available* on the internet at: https://heatroadmap.eu/peta4/ (12.11.2025). The atlas was carried out within the framework of the European project: "*Heat Roadmap Europe 4 (HRE4)*", which proposes ***heating and cooling strategies with low CO_2 emissions***.

Below are some examples of ***heat density maps*** and ***cold density maps*** for two cities in Romania. In the adjacent table, the meanings of the legends for these maps are presented.

< 50 TJ/km²
50 - 120 TJ/km²
120 - 300 TJ/km²
> 300 TJ/km²

Heat densities

< 1 TJ/km²
1 - 3 TJ/km²
3 - 10 TJ/km²
> 10 TJ/km²

Cold densities

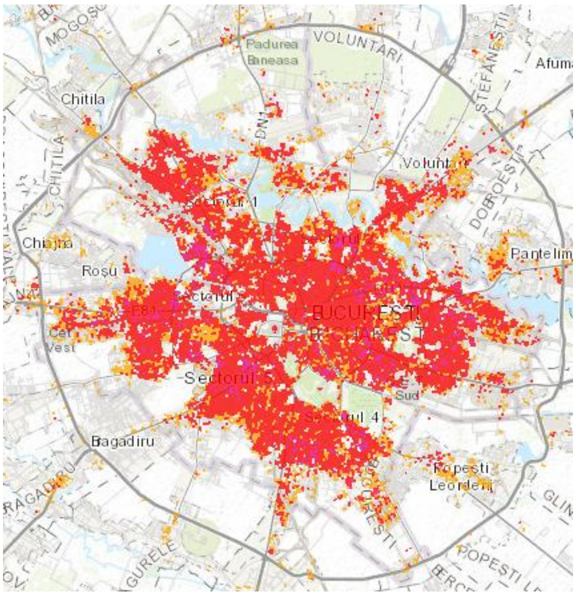


Figure 3-1 Heat density map for Bucharest

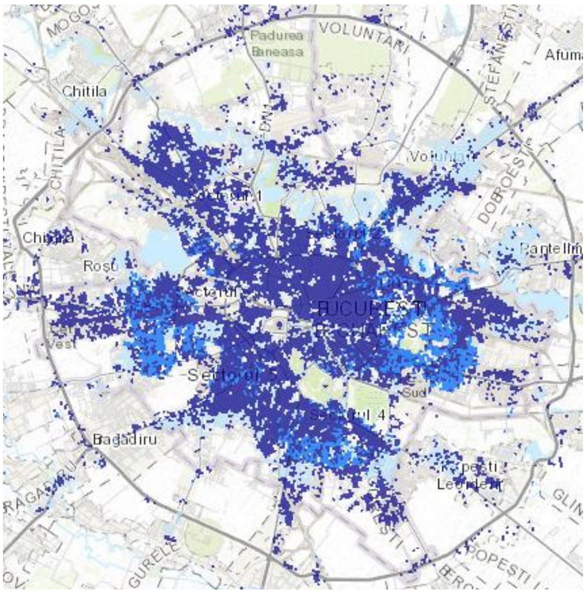


Figure 3-2 Cold density map for Bucharest

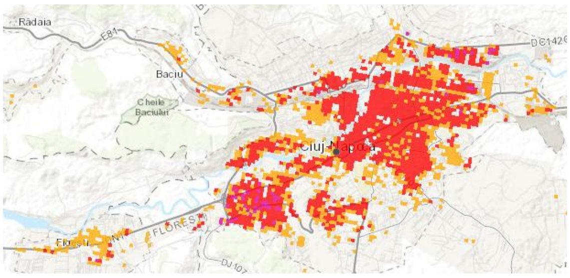


Figure 3-3 Heat density map for Cluj-Napoca

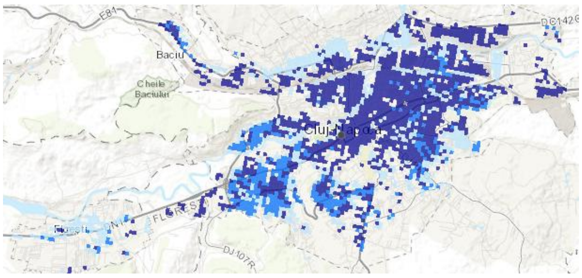


Figure 3-4 Cold density map Cluj-Napoca

In order to estimate the feasibility, it is mandatory to estimate the following parameters:

- ***Maximum thermal output*** (kW) "peak load"
- ***Annual heat consumption*** (MWh/year).

These parameters determine:

- ***Heat Powers of*** Heat Sources
- ***Characteristics of the thermal network***
- ***The potential for return on investment (***from the sale of the heat produced).

Given the importance of these parameters, their determination must be carried out with the greatest possible precision.

3.2 Planning and implementing district heating systems

The realization of a district heating system implies the achievement of important objectives, with the assumption of various responsibilities, as suggested in the figure below.

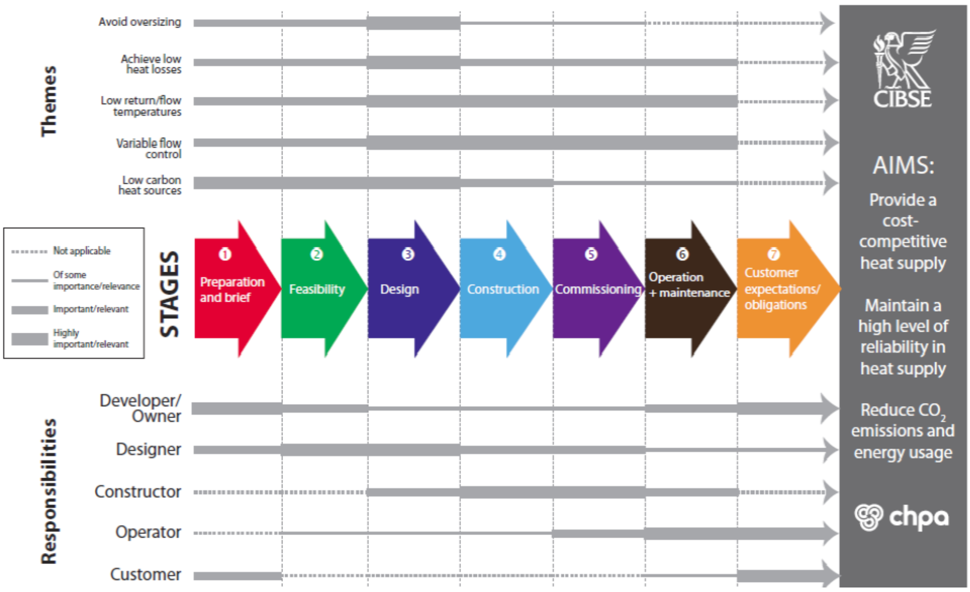


Figure 3-5 Work plan for the realization of a district heating system [1]

The objectives to be achieved are presented as follows.

Correct sizing. Designers tend to look at new technologies with circumspection, which can lead to "conservative" sizing (i.e. oversizing), which can be both expensive and energy-inefficient.

Ensuring reduced heat losses in the network. Heat losses from the network cause:

- High operating costs
- High risks of oversizing
- High CO_2 emissions

Ensuring a low return temperature and generally low temperature regimes.

- For a certain flow temperature, ***the reduced temperature on the return reduces flow rates***, which allows the reduction of pipe sizes and therefore the reduction of infrastructure costs.
- Under partial load conditions, ***reducing the return temperature, reduces heat loss and reduce the energy required for pumping***.
- ***The design of systems with low return temperatures allows to increase energy efficiency (***e.g. by using heat pumps or by extracting steam at lower pressure and temperature from turbines).
- ***Achieving low return temperatures starts with the correct choice of radiators*** and the correct balancing of radiators, correlated with the other heat distribution systems in buildings (heating systems).

Correct regulation of flow rates. Flow regulation allows operation with low flow rates and ensures low return temperatures at partial loads. To regulate the flow rates, variable speed pumps will be used, which will be controlled so as to maintain a minimum pressure level at the ends of the network.

Use of low-CO_2 energy sources. *The main energy sources of the grid must be characterised by low CO_2 emissions*. Their sizing must be carried out in such a way as to ensure the annual operation in the longest possible periods of time. Control systems and energy storage systems must maximise the contribution of low-emission sources and operate them at the lowest possible cost.

The design and implementation of district heating systems must provide high-quality technical systems, in which the risks are correctly managed and the impact on the environment is minimal.

3.3 Heating load calculation

One of the most used indicators for the sizing of district heating systems is the **annual number of degree-days**, which is a characteristic of the climate-microclimate correlation for buildings, depending on their specificity and the climatic and geographical area in which they are located. The number of degree-days is determined for any locality, by summing the daily temperature differences between a certain indoor temperature considered as a reference and the average daily outdoor temperature, if the latter is lower than a certain reference value. The sum is made during a year. In Romania, the reference indoor temperature is 20 °C, and the reference outdoor temperature is 12 °C.

Note: The method of calculating the heat requirement for buildings, based on the number of degree-days, is used in many European countries, but it is not harmonized, as each country has its own calculation methods. One of **the disadvantages of determining the heat requirement based on the number of degree-days is that this method does not consider the reasonable level of insulation of buildings**, which in turn depends on climatic conditions. (**For example, the degree-day method considers that the level of insulation of a building in southern Italy is the same as that of a building in northern Sweden**) [2].In the figure below, a map of the variation in the number of degree-days in Europe, determined for 80 localities in the EU, is presented.

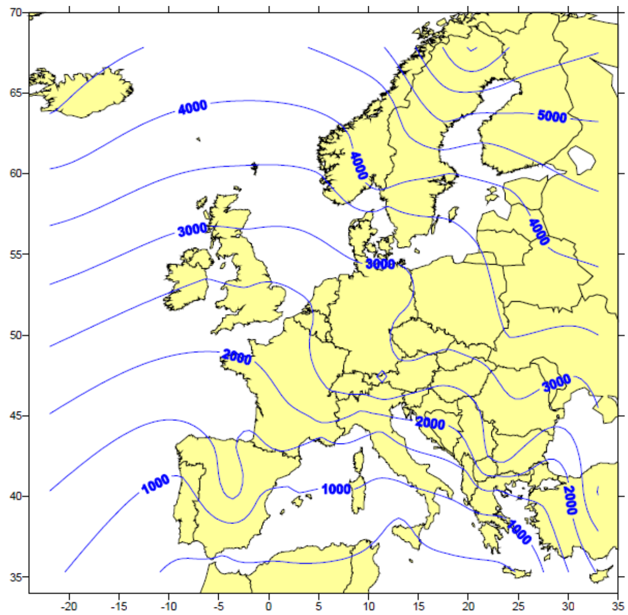


Figure 3-6 Number of degree-days in Europe, determined for 80 localities [2]

Note: As can be seen from the figure, the number of degree-days in southern Italy is about 500, while in northern Sweden it is over 5000, being more than 10 times higher. In terms of heat needs, it is not 10 times higher in northern Sweden, compared to southern Italy.

Due to the problems identified in the method of sizing the heat requirement based on the number of degree-days, a new global indicator was proposed, more appropriate for these calculations, namely the ***European Heating Index*** *(EHI),* which also considers the reasonable level of insulation of a building, depending on the climatic zone. The methodology for calculating the EHI is presented in [2].

Note: The European Warming Index (EHI) shows that climate differences cause variations in heat needs of only ±20% [2]. Only about 50% of the differences in heat requirements in different localities can be explained by differences in climatic conditions, the other half being represented by other factors such as: heat price, indoor temperatures, hot water consumption and the degree of affordability of heat [2,3].

A map of the variation of EHI in Europe, for 80 municipalities in the EU, is shown in the figure below.

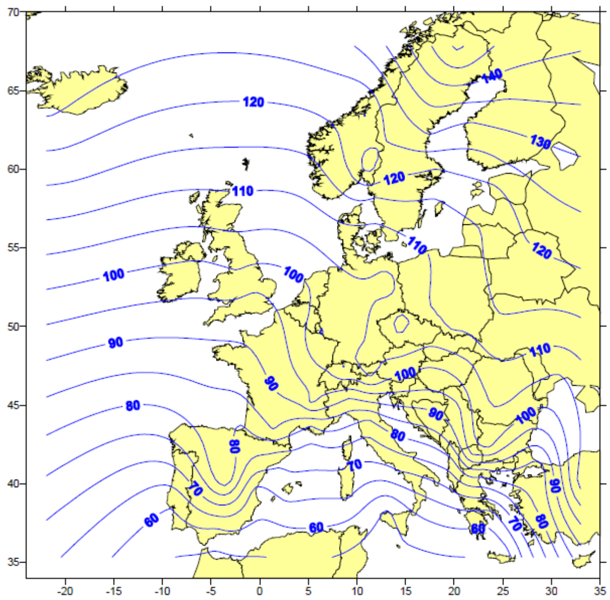


Figure 3-7 European *Heating Index (EHI),* for 80 localities [2]

The European Warming Index is proportional to the square root of the number of degree-days.

3.4 Diversity of demand

The diversity of demand (*diversity factor*), at a certain point of the thermal network (usually in a thermal network point, or a thermal power plant), is determined by the relation:

$$\frac{\text{Maximum thermal power}}{\text{Sum of the maximum thermal power for downward consumers}} \frac{[\text{kW}]}{[\text{kW}]}$$

The maximum required thermal power of a consumer is also the maximum thermal power that the consumer can absorb from the thermal network and is established at commissioning, by regulating the maximum flow rate of thermal agent. Sometimes the maximum thermal power of a consumer (determined in the design phase) can be higher than the maximum effective thermal power, due to the safety margins adopted at the design time.

The accompanying figure shows an example of calculating the degree of simultaneity for a thermal point (Energy Centre).

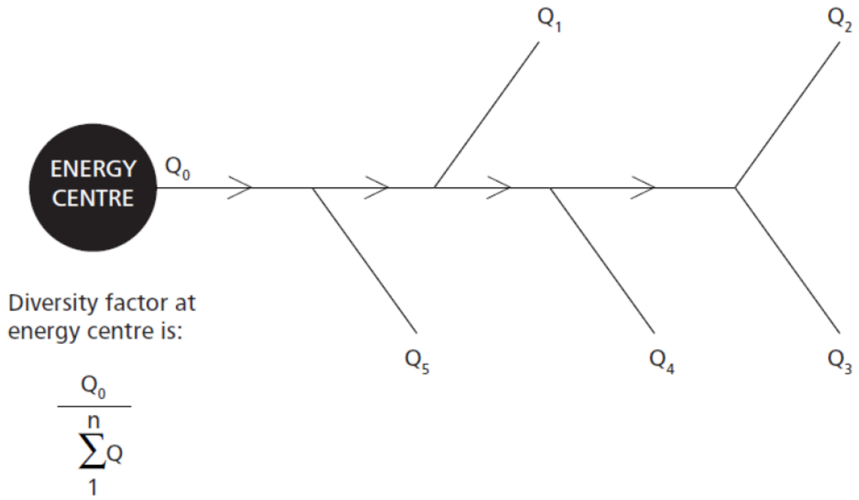


Figure 3-8 Example of calculating the degree of simultaneity for a thermal point (Energy Centre) [1]

In large systems with a wide variety of customer types, the diversity of demand for consumption (heat and hot water) may be relatively low (e.g. approx. 70 %) which allows a smaller dimensioning of the pipes and heat sources from the respective thermal point, below the nominal values of the flow rates and the heat output.

In small systems, with the same type of consumers, it is safer to consider that the diversity of demand is 100%.A particular case is represented by the consumption of domestic hot water, which for an apartment, can present peaks of the required thermal power, around (35-50) kW.The probability that all customers consume water simultaneously is very low, so the diversity of demand of hot water consumption is also very low and is presented in the adjacent figure, for different references.

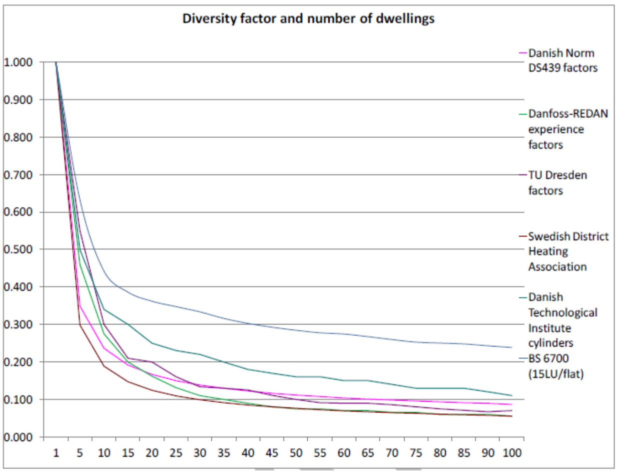


Figure 3-9 The diversity of demand of hot water consumption depending on the number of apartments [1]

The curves for determining the diversity of demand of the hot water consumption are based on the calculation relationship of the maximum thermal power required for the preparation of the a.c.m. ($\dot{Q}_{\max}$ [kW]) according to DS 439 [4]:

$$\dot{Q}_{\max} = 1.19 \cdot N + 18.8 \cdot N^{0.5} + 17.6$$

According to this relation:

for N=1 =>$\dot{Q}_{\max}$=37.59 kW (/ apartment)

for N=1000 =>$\dot{Q}_{\max}$=1802.1 kW ≈ 1.8 kW/apartment

***Note**: For more than 200 apartments, due to the diversity factor of the low hot water consumption, the thermal power required at the thermal point is 3 kW/apartment for heating, respectively 2 kW/apartment for DHW preparation.*

3.5 Variable flow and temperature

One of the principles that allows the economic exploitation of thermal networks is that ***the flow rate and temperature of the thermal agent must be controlled so that they correspond to the requirements of the customers***.

This principle has proven to be ***effective for the entire lifetime operation of the networks***, due to:

- reducing heat loss
- increasing the efficiency of pumping the heat agent (with variable speed pumps)
- minimizing pipe sizes

When operating with variable flow rate and temperature, the ***system is designed to provide the maximum heat requirement with the maximum flow rate and temperature***. During operation, ***as the heat requirement decreases, the flow rate and temperature of the heating agent are reduced***, *in order to ensure energy savings*.

Consumption peaks represent short periods in the daily and seasonal heat consumption profile, when maximum thermal powers are required.

The variable temperature of the heat agent is best controlled at the level of the heat sources. In the case of the existence of several heat sources connected to a single network, characterized by different prices at which they can supply heat, ***the best overall price at which heat can be supplied*** *can be ensured by* **controlling the starting sequence of the heat sources**.

Cheaper heat sources will be turned on more often, and the most expensive ones will be used as much as possible, only to ensure peak loads, as in the example below.

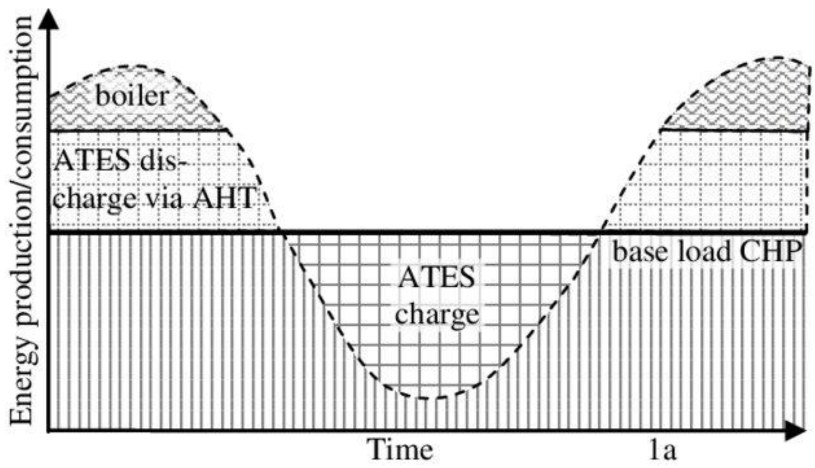


Figure 3-10 Example of a seasonal profile of heat consumption and use of heat sources or seasonal heat storage [5]
„base load CHP" – Cogeneration with "base" load operation
*ATES – Aquifer Thermal Energy Sto*rage
Boiler – Peak boiler

The operating regimes of the energy sources are as follows:

- The cogeneration system works to ensure the "basic" heat requirement of the seasonal consumption profile.
- When the production capacity exceeds consumption, cogeneration is operated to obtain the economic advantages from the sale of electricity, and the heat produced during these periods is transferred to the heat storage aquifer system.
- When the heat requirement falls below the cogeneration capacity to provide heat, the difference is extracted from the storage system.
- The consumption peaks are covered by the peak boiler.

The temperature of the heat agent is usually modulated according to a predetermined variation curve*, most often depending on the outside temperature*.

The heat flow rate is regulated to ensure the minimum return temperature*, thus ensuring minimum pumping costs*.

In the accompanying figures are presented two examples of curves for regulating the thermal regime (flow/return) and the mass flow rate of the heating agent, depending on the ambient temperature.

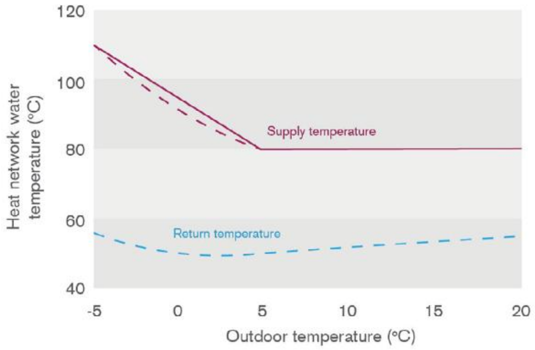


Figure 3-11 Example of thermal regime variation depending on ambient temperature [6]

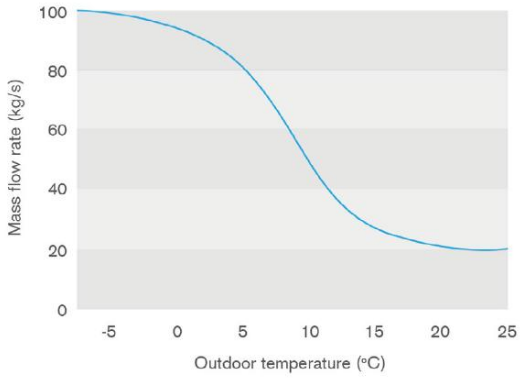


Figure 3-12 Example of flow variation depending on ambient temperature [6]

The return temperature is only an estimate and depends on the type of heat distribution system (in the customers' buildings) and the characteristics and adjustments of the customers' thermal points.

The heat flow rate is adjusted according to the heat requirement, through the control system of the distribution pumps to maintain the minimum pressure required at the ends of the network. If the outside temperature drops, the consumer's heat requirement increases and the control valve on the primary circuit of the thermal point opens (partially or totally). The more open position of the control valve corresponds to a lower pressure drop in the heating network. The pressure variation is also sensed by the control system, which commands the increase in the flow rate of the pump(s) in response to the increase in heat requirements. This type of flow regulation is continuous and responds to daily or seasonal variations in the heat requirement, by changing the flow rate accordingly.

At least the minimum flow rate that ensures the supply of heat to the entire network is always maintained. Basically, at least the flow rate that maintains a minimum pressure value in the points of the network, the furthest from the place of the pumping system, is ensured.

The flow temperature must allow the preparation of DHW in conditions that ensure the possibility of controlling the process and minimizing the risk of growth of Legionella bacteria.

For new buildings, the working temperatures of the heat dissipation systems can be selected, according to the table below.

Table 3-1 Recommended temperatures for the thermal agent in heat dissipation systems, for new buildings

Circuit	**Flow temperature [°C]**	**Return temperature [°C]**
Radiators	Max. 70	Max. 40
Fan Coils	Max. 60	Max. 40
Air Handling Units	Max. 60	Max. 40
Underfloor heating	Note	Note
Instant household DHW systems	Min. 65	Max. 25
Coil DHW tank	Min. 70	Max. 45
DHW tank with external Hex with plates	Min. 70	Max. 25

Note*: Underfloor heating systems will operate as usual, with the floor temperature below 35 °C and the typical temperature of the heating agent per shift of 45 °C, which is advantageous for the heating network, as it will result in a low return temperature.*

Note*: There are also low-temperature fan coils, which operate in practically the same temperature regime as underfloor heating systems.*

In the feasibility studies, the ***modification of the thermal regime of the radiators in the existing buildings*** will be considered, from the return temperatures of 82 / 71 °C (typical regime in the UK), to those of 80 / 60 °C (typical regime in RO and desired in the UK).

For plate heat exchangers, ***the temperature difference between the return to the primary circuit and the return to the secondary circuit should be less than 5 °C***, but it is recommended to be reduced at 3 °C.

The thermal regime of the central cooling systems is even stricter than that of the thermal networks, because the temperatures per turn are close to 0 °C, and the temperatures on the return are close to 20 °C. In the case of a single building, the typical temperature regime is 6(7) / 12 °C. To reduce the size of the district cooling pipes, the temperature difference between the flow and return will increase to 10 °C, so that temperatures could reach 5 / 15 °C. Even so, for the same thermal powers, the diameters of cooling pipes will be much larger than those of district heating pipes. One consequence is that for cooling, the possibility of directly connecting buildings to the cooling network must be considered, so as not to further affect the thermal regime.

3.6 Network design

The role of the *district heating network* is to connects heat generation sources to end consumers [7]. Distribution systems has two distinct loops:

- Primary loop – trasport water from the source or storage systems to substations;
- Secondary loop (connected to the primary loop trough substations) delivers heat to end users.

This structure, supported by strategically positioned interconnections, enhances operational flexibility and enables accurate, localized management of heat distribution throughout the network.

The thermal network consists of all pipelines and branches that transport and distribute heat from the central generation source to the inlet valves of the heat substations [8].

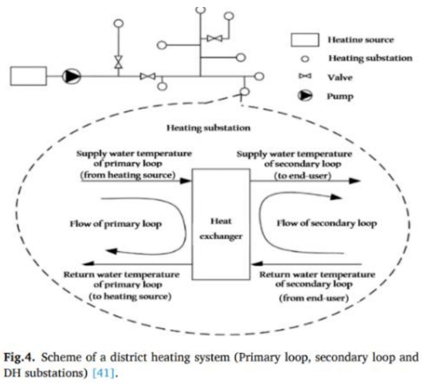


Figure 3-1Schematic of the district heating system [9]

The main pipe (or transport pipeline) runs from the heat station to the supply areas. Branch or distribution pipes extend laterally from the main pipe to serve specific sub-regions. House connection pipes are running from either a main or branch pipe directly to individual consumers [7].

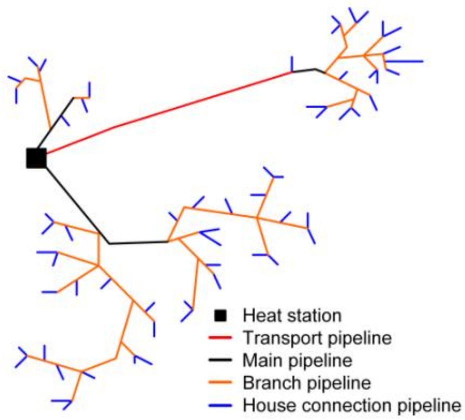
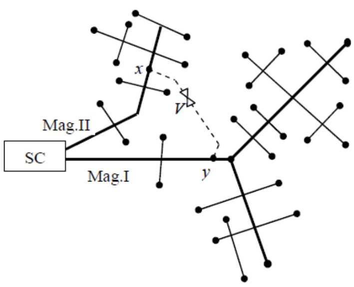


Figure 3-2 Network design and pipe types [7]

Network Topologies

Radial District Heating Networks

In this configuration, the diameter of the main pipeline decreases with increasing distance from the heat source. Such networks are inexpensive and easy to operate; however, a major drawback is that any failure on the main or distribution pipeline interrupts supply to all consumers downstream of the fault. This limitation can be addressed by installing a bypass connection between two main branches. These bypass lines (x–y) are typically sized to accommodate 50% of the thermal load carried by the main pipeline with the highest demand [10]



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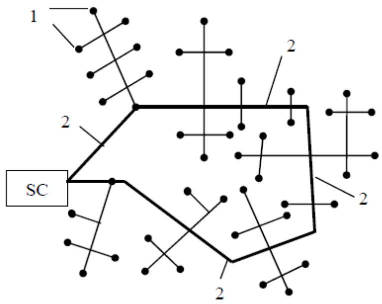

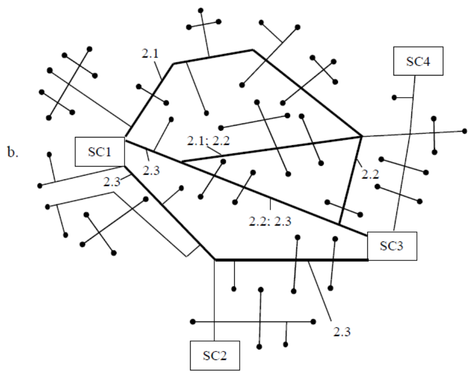

Figure 3-3 Network topologies [10]

a) Radial b) Ring c) mixed networks

(x–y)- bypass connection;
V – normally closed valve;
Mag. I, II – main pipelines I and II;
SC – heat source (boiler plant or CHP);
• thermal substations or heat interface units
1 – thermal substations;
2.1 – first ring network section (1);
2.2 – second ring network section (2);
2.3 – third ring network section (3);

- *Looped networks* are designed for system resilience, providing an alternative path that allows for the uninterrupted supply of heat during a fault, with service loss limited only to the segment isolated by valves. They are used both in district heating systems with a single heat source and in systems with multiple heat sources.This type of network requires higher investment costs (the ring main, which has a constant diameter, must be sized for the maximum thermal load) and is more difficult to operate under normal operating conditions. In practice, purely looped networks rarely exist; instead, mixed configurations are used, consisting of a ring main combined with several radial distribution mains [10].

- *Mixed (radial-ring) networks*

Type of pipelines used in district heating networks

Pipelines in district heating networks may be installed either above ground or underground, depending on site-specific conditions, technical constraints, and economic considerations.

Since the 1970s, the dominant solution has been the use of pre-insulated pipe systems, which allow the pipelines to be buried directly in the ground without the need for additional ducts or channels. These factory-made systems provide high thermal performance, long service life, and reduced installation time compared with earlier technologies [10] [11][12][13]

A typical pre-insulated district heating pipe consists of three structural layers:

- *Carrier pipe (steel or plastic)* – This inner pipe transports the heating water.

Steel carrier pipes offer high mechanical strength, excellent pressure resistance, and long service life, making them suitable for high-temperature and high-pressure district heating systems.

Plastic carrier pipes (e.g., PEX) are lighter, easier to handle, and provide greater flexibility, making them well suited for lower-temperature distribution networks and for installations where rapid or curved routing is required.

- *Insulation layer* – Surrounding the carrier pipe is a layer of polyurethane (PUR) foam, which provides very low thermal conductivity. This insulation minimizes heat losses along the pipeline, increases system efficiency, and contributes significantly to reducing operating costs.
- *Outer casing* – The entire assembly is enclosed in a high-density polyethylene (HDPE) jacket, which protects the pipe from moisture, soil pressure, mechanical impacts, and environmental degradation. This casing ensures durability and enables direct burial with minimal maintenance.

Figure 3-4 Insulated underground pipes for district heating[14]

3.7 Pressure and thermal losses

District heating (DH) water is distributed from the heat source to consumers through supply pipes and is returned to the plant once the heat has been extracted within the buildings.

This circulation is maintained by pumps that establish the required pressure differential between the supply and return pipelines.

Pump selection must ensure that the generated pressure head is sufficient to overcome all hydraulic resistances in the network, including friction losses in both the supply and return pipes as well as the pressure differential required by the customer installation located at the hydraulically most remote point[7].

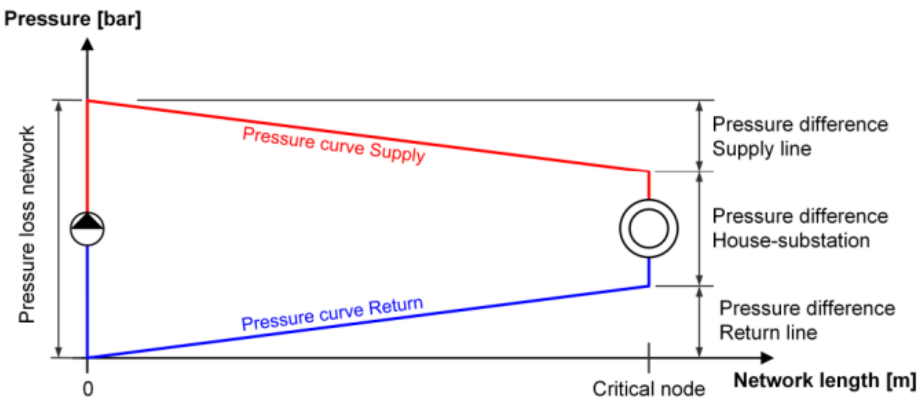

Figure 3-5 DH network pressure diagram[7]

Pressure losses depend mainly on flow velocity and pipe length, but also on pipe roughness and flow regime. They are proportional to the square of the flow velocity.

Local pressure losses in each section (elbows, valves, etc.) are typically considered to represent about 20–30% of the linear pressure losses. To account for these, the effective length of each section is increased by the corresponding percentage.

Recommended values for specific pressure losses ($\Delta\psi_i$ [Pa/m]), per unit length of pipe (L_i [m]), are as follows:

- $\Delta\psi_i$ = 30–60 Pa/m for main pipelines;
- $\Delta\psi_i$ = 60–80 Pa/m for distribution network sections;
- $\Delta\psi_i$ = 150–300 Pa/m for service connections.

Heat and pressure losses in thermal networks play a major role both in sizing calculations and in techno-economic analyses or feasibility studies. Both heat losses and hydraulic losses (i.e., pressure drops) can be evaluated technically and economically and can even be expressed in monetary units.

The diameters of the pipes in district heating networks must be selected so that they can fully supply the maximum required thermal power for each section of the network.

The lower the temperature of the return thermal agent, the smaller the required flow rate in that section of the pipe. Consequently, smaller-diameter pipes can be used, leading to a reduction in the initial investment cost.

However, smaller-diameter pipes have lower specific heat losses (per meter of pipe length), since their outer surface — through which heat transfer to the surroundings occurs — is smaller. At the same time, their specific pressure losses increase because the flow velocity is higher, and pressure losses are proportional to the square of the velocity.

Therefore, there is an inverse relationship between heat losses and pressure losses:

Small-diameter pipes → lower heat losses but higher pressure losses;

Large-diameter pipes → higher heat losses but lower pressure losses.

To calculate the heat lost through a pipe of a given length over a certain time interval, the following parameters must be considered:

- Pipe length (L [m]);
- External temperature (t_e [°C]), taken as the average value over the analyzed period (typically one month, i.e., 30 days);
- Internal temperature (t_i [°C]), considered constant or as the average value corresponding to the mean temperature of the thermal agent, correlated with the external temperature;
- Duration of the analyzed period (τ [s]), expressed in seconds.

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4. Interface Systems for End Users in District Heating Networks

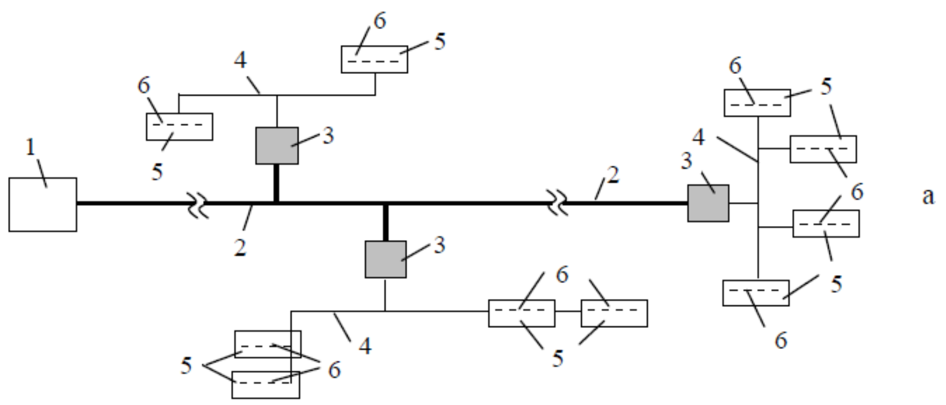
4.1 Substations and heat modules

Heat substations and thermal modules represent the primary interface between the district heating (DH) network and the internal installations of consumers.

Through this function, they provide hydraulic, thermal, and operational decoupling between the distribution network and end-user systems, while enabling the integrated supply of space heating and domestic hot water (DHW).

These units regulate flow, pressure, and temperature according to building requirements and ensure safe, efficient, and stable energy transfer under variable load conditions.

Figure 4-1 illustrates typical configurations of heat transport and distribution in district heating systems with centralized substations and decentralized thermal modules) [1];



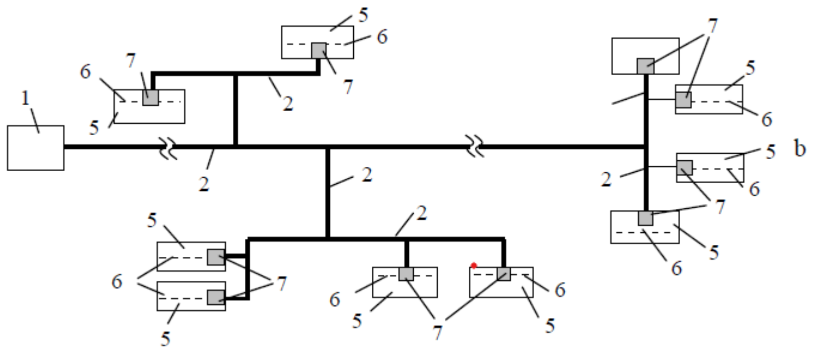


Figure 4-1 Heat transport and distribution solutions in district heating systems with substation(a) and thermal modules (b) [1];

1 – heat source; 2 – high-temperature hot water transmission network; 3 – centralized heat substations ; 4 – secondary hot water network for space heating (supply/return) and domestic hot water (supply and recirculation); 5 – condominium-type buildings; 6 – internal heat distribution within buildings; 7 – thermal modules (MT).

In centralized heat substation configurations, the installations are typically housed in dedicated buildings or specially arranged technical spaces and only exceptionally within the consumer's building—primarily in tertiary or industrial facilities where purpose-designed rooms are available.

By contrast, decentralized heat substations (thermal modules) are designed such that all substation components are installed directly within the technical basement of the consumer's building [1]

A heat substation or thermal module typically incorporates components such as heat exchangers, circulation pumps, storage vessels, and water-softening or water-treatment systems. Heating and domestic hot water (DHW) systems are typically integrated within the same substation.

Buildings may be connected to a district heating or cooling (DH/C) network in two fundamental ways:

Direct Connection

The DH/C network water circulates directly through the building's internal heating or chilled-water system. In this case, the district network and internal installation form a single hydraulic circuit.

Indirect Connection

A heat exchanger separates the DH/C network from the internal system, creating two hydraulically independent circuits. Thermal energy is transferred across the heat exchanger without mixing fluids, providing enhanced protection against pressure fluctuations and ensuring better control of operating conditions.

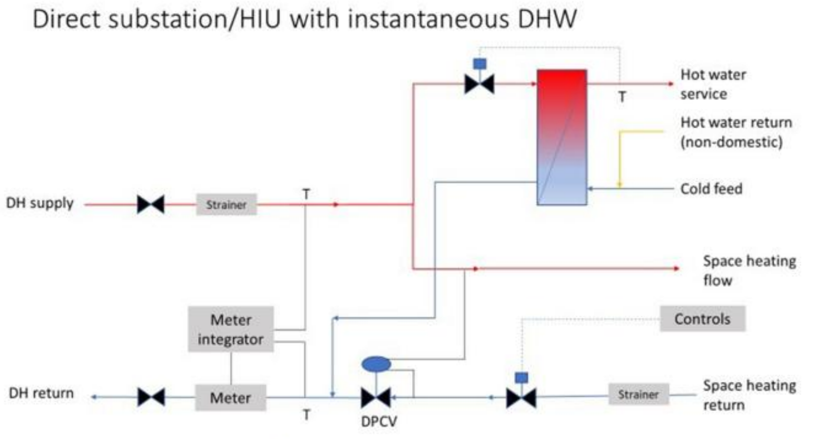


Figure 4.3. Direct substation schematic (simplified).

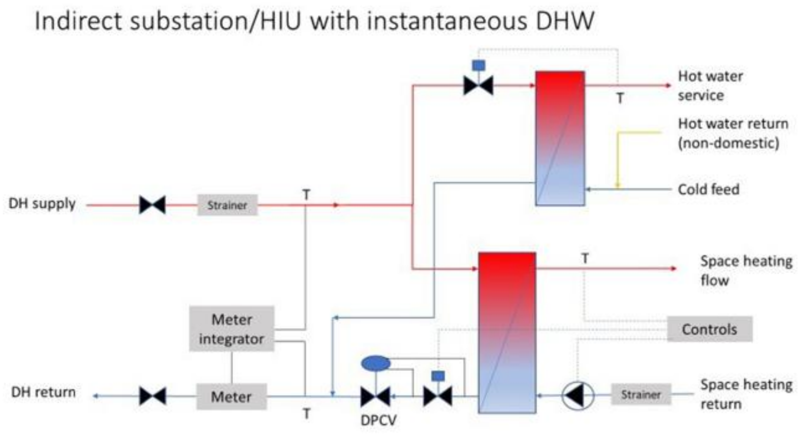


Figure 4.2. Indirect substation schematic (simplified).

Figure 4-2 Direct and indirect connection [2]

4.2 Heat Meters

Heat metering plays a fundamental role in district heating systems by enabling the accurate measurement of thermal energy wherever it is traded, billed, or monitored .

This essential function is now highly regulated in the EU due to the European Energy Efficiency Directive (EED), which aims to meet efficiency targets, reduce emissions, and empower consumers. The EED requires the use of competitively priced meters that accurately reflect end-users' heat consumption. Specifically, it mandates individual meters (or heat cost allocators) in multi-apartment or multi-purpose buildings, provided they are technically feasible and cost-effective to install. To increase consumer awareness and streamline data collection, the Directive further stipulates that by January 1, 2027, these meters and heat cost allocators must also be remotely readable under the same feasibility conditions [3].

A morphological box illustrating key parameters used to assess national regulation of district heating (DH) metering is presented in figure.

Parameter	Elements			
Main form of (national) regulation*	No regulation on metering DH	Regulation for heat meters following EU legislation	Regulation going further than EU legislation for smart heat meters and remote control	
Installation	No mandatory installations of meters	Mandatory installation of meters	Mandatory installation of smart heat meters and remote control	
Type of meter	No standards or regulations for the type of meter	Regulation of type of meters, i.e. standards	Regulation of type of smart meters	
Frequency of providing meter data (and billing)	No frequency defined	Yearly	Monthly	Daily
Individualised metering	No regulation on individualised metering	Regulation on individualised metering in a multi-apartment / multi-use building		
Allocation rules	No heat cost allocation rules	Heat cost allocation rules for metering in a multi-apartment / multi-use building		

* Data available and used in section 4. Colour of field reflects intensity of policy, i.e. darker colour corresponds to stricter regulation.

Fig. 3. Morphological box for regulation of metering of DH (building on Bacquet et al., 2022b).

Figure 4-3 Morphological box for regulation of metering of district heating systems [3]

Because heat is subject to losses during transport, the selection of the metering point is essential [4]. The metering location determines which party—either the heat supplier or the consumer—is financially responsible for losses occurring between the production source, distribution network, and end-user installations.

For this reason, heat meters are typically installed at the consumer connection, i.e., where the building or dwelling is hydraulically linked to the district heating network. Metering at this boundary ensures transparency, fairness, and improved control of energy consumption.

Heat supplied to end users may be billed either on the basis of individual meters installed in each dwelling or via a communal meter serving an entire building or housing block[4].

A standard heat meter consists of three main components:

1. Flow meter – measures the volumetric flow rate of district heating water circulating through the consumer’s system. Flow sensors may use ultrasonic, mechanical, or electromagnetic measurement principles.
2. Temperature sensor pair – one sensor is placed on the supply pipe and the other on the return pipe. These sensors provide continuous measurements of the inlet and outlet water temperatures.
3. Heat calculator – uses the measured temperature difference (ΔT), flow rate, specific heat, and density of water to compute the energy transferred to the consumer. Modern calculators automatically adjust for temperature-dependent changes in water properties to ensure accurate energy calculation.

The thermal energy transferred in a district heating system over a time interval Δt:

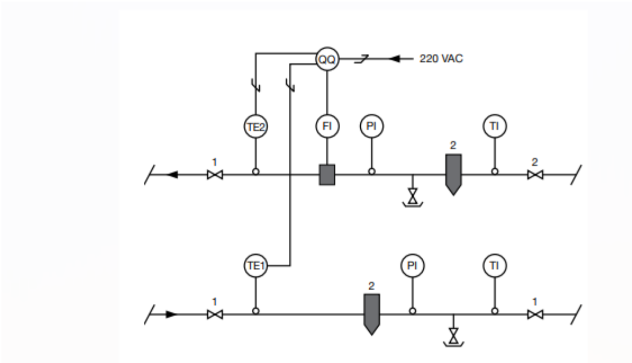
$$E_{\text{th}} = \dot{V}(c_{p,\text{sup}}\rho_{\text{sup}}T_{\text{sup}} - c_{p,\text{ret}}\rho_{\text{ret}}T_{\text{ret}})\Delta t$$

This formula represents the general expression used by heat calculators in accordance with EN 1434 and other international metering standards.

Symbol	Meaning
E_{th}	Thermal energy transferred (J or kWh)
$\dot{V}$	Volumetric flow rate of the heating fluid (m^3/s)
$c_{p,\text{sup}}$, $c_{p,\text{ret}}$	Specific heat capacities at supply and return temperatures (J/(kg·K))
ρ_{sup}, ρ_{ret}	Water densities at supply and return temperatures (kg/m^3)
T_{sup}, T_{ret}	Supply and return temperatures (°C or K)
Δt	Measurement interval (s)

Heat meters are commonly owned, installed, maintained, and verified by the heat supplier, ensuring standardized accuracy and compliance with metrological regulations. The heat purchaser (consumer) may record readings manually or rely on automated data collection systems, depending on the technological infrastructure and the billing model.

A typical arrangement of heat metering is presented, according to [4] in Figure 4-1 :



TE1 – Temperature sensor (return line)
TE2 – Temperature sensor (supply line)
P1 – Pressure gauge
FI – Flow meter
QQ – Calculator for heat energy (heat meter computer)
1 – Isolation valve
2 – Dirt trap (strainer)

Figure 4-4Arrangement of heat metering [4]

Automatic Meter Reading (AMR) technology enables modern heat meters to remotely collect and transmit consumption data via wireless M-Bus, radio, cellular networks optical fiber, or hybrid communication systems. By eliminating manual readings, AMR reduces operational costs and errors while providing high-resolution data useful for demand forecasting, system optimization, leak detection, and hydraulic performance monitoring. Smart meters extend these capabilities by offering real-time consumption reporting, automated fault and outage detection, heat quality monitoring, integration with advanced metering infrastructure, remote firmware updates, and bidirectional communication. Although still evolving in terms of standardization, smart meters are expected to play an increasingly important role in future district heating systems, particularly in low-temperature and demand-responsive networks.

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5. District heating and cooling optimisation

In the context of the energy transition and the rising sustainability targets, optimizing the performance of District Heating and Cooling systems requires a simultaneous consideration of demand-side measures and supply-side interventions.

These two complementary approaches are essential for maximizing energy efficiency, reducing operating expenditures (OPEX), and enabling the effective integration of variable renewable energy sources.

5.1 Demand side measures

District heating and cooling systems represent complex centralized infrastructures in which energy efficiency depends not only on the performance of generation equipment and the distribution network, but also on the manner in which thermal energy is utilized within the connected end-use applications. Traditionally, optimization strategies have focused on upgrading generation units, reducing pipeline losses, and adjusting energy flows within the network [1]. However, as sustainability requirements and the integration of renewable energy sources continue to increase, it is becoming increasingly evident that focusing exclusively on production optimization and distribution fails to meet current requirements. [2]

Modern approaches acknowledge the critical role of demand-side optimization through the implementation of consumption-side measures. These measures aim to adjust the energy consumption profile such that the supplied thermal energy is utilized more efficiently and flexibly, without requiring interventions in heat supply sources or generation processes [3] Through this approach, DHC systems are able to manage demand fluctuations more effectively, thereby mitigating peak loads that impose stress on generation assets and the distribution infrastructure, and enhancing the alignment of energy consumption with the availability of energy resources, including intermittent renewable sources. [4]

Demand-side optimization contributes to enhancing the overall technical performance of the system. By increasing consumption flexibility and adjusting the demand profile, the utilization of the installed generation capacity is maximized, operational losses are reduced, and the stability of network operation is improved. Moreover, this approach facilitates the transition toward more sustainable energy systems by lowering the reliance on backup equipment and fossil-fuel-based generation during peak-load periods. [5]

From a broader perspective, integrating demand-side optimization into the operational strategy of DHC systems enables a more comprehensive assessment of system performance, not only in terms of production and distribution efficiency, but also in relation to the system's capacity to adapt to consumption dynamics. Thus, demand-side optimization becomes a complementary pillar of energy-efficiency and sustainability strategies, providing a technical framework for the development of smarter, more flexible DHC systems capable of meeting the requirements of modern energy infrastructures. [6]

Therefore, the implementation of effective consumption-side measures positions demand-side optimization as a fundamental operational component of DHC system performance, enhancing and reinforcing conventional production- and distribution-oriented optimization strategies. The main demand-side measures in district heating and cooling systems encompass optimizing building energy efficiency, implementing advanced automation and demand-side control, applying active demand-side management, integrating passive technologies and internal energy-recovery solutions, and promoting user engagement and behavioral awareness.

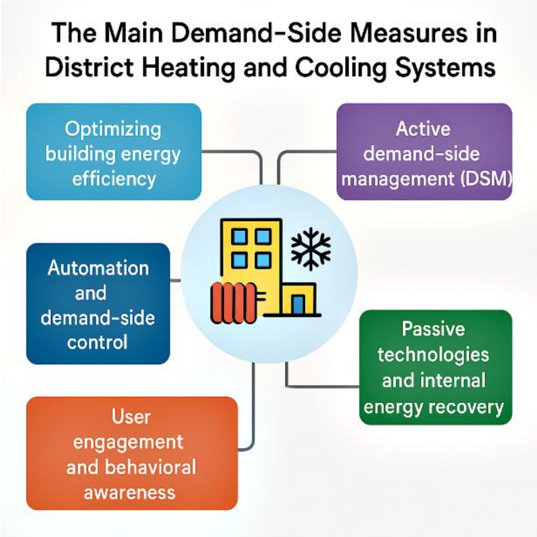

Figure 5-1Demand side measures

Optimizing building energy efficiency

Implementing advanced thermal insulation solutions across the building envelope (including walls, roofs, and high-performance windows and doors with increased thermal resistance) in order to significantly reduce conductive and convective heat losses and thereby lower the overall Energy Use Intensity (EUI, kWh/m²/year).

To meet the minimum energy performance requirements, it is recommended that all building envelope components comply with the condition R' ≥ R'min, where R' / R'min [m²·K /W] represents the corrected thermal resistance and the minimum (reference) corrected thermal resistance, respectively, for each thermal envelope element, with values specified in Table 5.1. [7]

Table 5-1Recommended Minimum Corrected Thermal Resistances

Envelope element	nZEB residential buildings	Renovated residential buildings	nZEB non-residential buildings	Renovated non-residential buildings
	R’ minim (m²·K/W)	R’ minim (m²·K/W)	R’ minim (m²·K/W)	R’ minim (m²·K/W)
External walls (excluding glazed surfaces, including walls adjacent to open joints)	4,00	3,00	3,00	3,00
Exterior joinery (windows and roof windows)	0,90	0,83	0,83	0,83
Exterior joinery (manually operated doors)	0,77	0.77	0,77	0,77

Exterior glazing systems (curtain-wall façades and vertical skylights)	0,83	0.83	0,77	0,77
Floor slabs above the top level, beneath terraces or attics	6,67	5,00	6,00	5,00
Floor slabs above unheated basements and cellars	3,40	2,50	3,40	2,50
Walls adjacent to closed joints	1,50	1,10	1,50	1,10
Floor slabs delimiting the building at the lower side toward the exterior (in bay windows, passageways, etc.)	5,00	4,50	5,00	4,50
Ground slabs (above the finished ground level)	5,00	4,50	5,00	4,50
Slabs at the lower side of heated semi-basements or basements	5,30	4,80	5,30	4,80
Exterior walls below the finished ground level in heated semi-basements or basements	3,40	2,90	3,40	2,90

Energy Use Intensity (EUI) represents a building's energy performance indicator, expressed as the ratio between the annual energy consumption and the building's usable floor area. EUI is typically measured in kWh/m²/year and enables the comparison of energy efficiency across buildings of different sizes, typologies, and functions. In residential buildings, EUI primarily reflects the energy consumption associated with heating, cooling, domestic hot water, and household appliances, whereas in non-residential buildings it also includes consumption related to lighting, ventilation, IT equipment, or specific industrial processes. The EUI values corresponding to different building typologies are presented in Table 5.2. [8] [9] [10]

Table 5-2Energy Use Intensity

Building type	Romania	Austria	Germany	France	Italy	Sweden	EU average
New residential nZEB buildings	90–120	50–70	50–80	60–80	70–90	50–70	~70
Existing residential buildings	150–200	100–150	100–150	120–160	130–180	100–140	~130
Office buildings	100–180	70–100	80–120	90–130	100–150	80–110	~110
Schools / Educational buildings	100–160	80–110	90–130	100–140	110–150	90–120	~110
Hospitals / Medical buildings	200–350	150–250	180–300	200–300	220–350	180–250	~230
Commercial / Retail spaces	150–300	100–150	120–180	130–180	140–200	120–170	~150
Industrial buildings / warehouses	100–250	80–120	90–140	100–150	110–160	90–130	~120

- Thermal insulation and optimization of domestic hot water (DHW) distribution networks, with controlled recirculation, to reduce pipeline losses and minimize specific consumption (kWh/person/year). Table 5.3 provides an overview of the technical solutions.

Table 5-3Technical Solutions for Thermal Insulation and Optimization of Domestic Hot Water Networks

Category	Technical measure	Details/Parameters	Impact on performance
Insulation of DHW pipes	High-performance insulation materials	Rigid polyurethane foam (λ ≈ 0.022–0.028 W/m·K), Armaflex (λ ≈ 0.034 W/m·K), mineral wool with reflective foil (λ ≈ 0.035 W/m·K)	Reduction of thermal losses, condensation prevention, fire protection
	Insulation thickness	20–50 mm, depending on pipe diameter and temperature [11,12]	Minimum 30–50% reduction in pipe heat losses
	Insulation of valves and fittings	Pre-formed insulation for elbows, tees, valves	Eliminates localized losses and thermal bridges
	Sealing of insulation	Continuous installation, no gaps, using heat-resistant tape	Maximize energy efficiency
Controlled recirculation	Pump with variable-speed drive	Adjusts flow depending on demand	Reduces pump energy consumption
	Automatic control	Temperature sensors, on/off based on demand, hourly scheduling	Limits unnecessary operation, maintains constant DHW temperature
	Demand-side regulating valve	Adjust flow in areas with low consumption	Avoids excessive circulation and unnecessary losses
	Network sizing	Short routes, correctly sized diameters	Reduces water stagnation and losses
Optimization of specific consumption	DHW temperature	50–55 °C at point of use (max. 60 °C)	Prevents Legionella development, reduces energy consumption
	Stratified and insulated tanks	Thermal-reflective jacket or mineral wool	Reduces tank losses, increases pump efficiency
	Monitoring and leak detection	Online measurement of temperature and consumption	Proactive adjustment of flow and temperature, reduces losses

	Air removal and periodic maintenance	Cleaning filters, checking insulation and valves	Maintains system performance and durability
	Hybrid renewable sources	Solar thermal energy, heat pumps, hydrogen-based boilers	Reduction of primary energy consumption

- Upgrading internal thermal energy distribution equipment (radiators, convectors, fan-coil units) to increase the coefficient of performance (COP) of thermal systems.

Automation and demand-side control

- Implementing programmable thermostats, zoned control architectures, and predictive control algorithms to regulate indoor temperature in accordance with occupancy profiles, spatial typology, and prevailing weather conditions.
- Integrating smart-building and IoT-based systems to enable real-time optimization of the demand profile, thereby reducing excessive energy consumption while maintaining thermal comfort in accordance with EN 15251 [13]or ASHRAE 55 [14] standards.

Active demand-side management

- Applying load shifting and load shedding strategies by adjusting demand according to dynamic tariffs, the availability of renewable energy, and real-time price signals.[15,16]

Table 5-4 Active Demand-Side Management

Technical aspect	Load Shifting	Load Shedding
Definition	Shifting thermal energy consumption over time without affecting comfort	Temporary reduction of thermal energy consumption during critical periods
Main purpose	Optimizing demand distribution and reducing peak loads	Preventing overload of the plant and the network
Implementation method	• Pre-heating or pre-cooling during off-peak periods • Storing energy in thermal tanks • Time-of-use tariffs	• Lowering supply temperatures • Limiting DHW or cooling • Prioritizing critical consumers

Dedicated technologies and equipment	• Thermal storage tanks (hot water, chilled water) • Variable-speed pumps and fans • EMS / automatic control systems • Smart circulation systems	• Zonal control valves • SCADA / EMS for automatic load shedding • Smart meters and IoT sensors
Impact on the consumer	Comfort maintained with no noticeable interruptions	Possible temporary reduction of comfort in non-critical buildings
Advantages	• Reduced losses and costs • Efficient integration of renewable energy • Lower peak demand	• Protection of the plant and the distribution network • Reduced costs during critical periods • Avoidance of failures or unplanned shutdowns
Disadvantages / Limitations	Requires storage systems or automated control; dependent on building flexibility	Comfort may be affected; requires user agreement and clear prioritization
Examples in DHC	• Pre-heating residential buildings at night • Charging DHW storage tanks during off-peak periods • Passive cooling or cold-storage strategies	• Lowering temperatures in non-critical buildings • Limiting DHW or cooling during peak periods • Prioritizing critical buildings (hospitals, data centres)

- Shifting consumption from peak-load intervals to periods of lower demand, thereby optimizing the thermal load on the DHC network and reducing the required peak thermal energy capacity.

Passive technologies and internal energy recovery

- Capturing passive solar energy through optimized building orientation, high-performance solar-control glazing, and architectural design strategies that minimize heating and cooling demand.
- Recovering residual heat from internal processes, ventilation systems, and hydraulic installations to reduce the net thermal load on the DHC network and improve overall energy efficiency (kWh/m²/year).
- Increasing building thermal inertia through the use of high-mass construction materials and phase-change materials (PCMs), thereby enhancing passive temperature stabilization and mitigating short-term peak thermal loads.
- Employing natural ventilation techniques, stack-effect airflow, and night-time free cooling to decrease mechanical ventilation and cooling requirements, effectively reducing dependence on the DHC system.[17] [18]

Enhancing user engagement and energy-awareness practices

- The development of structured energy-feedback schemes and comprehensive consumer education programs enables users to understand their thermal and cooling energy consumption patterns, fostering proactive behavioral adjustments that contribute to reducing overall demand and enhancing system-level efficiency.
- The implementation of advanced individual monitoring platforms—integrated with personalized performance reports and analytics—supports users in identifying inefficient consumption behaviors, promoting adherence to energy-performance benchmarks such as reductions in specific energy use ($kWh/m^2/year$) and associated CO_2 emissions.
- The introduction of incentive-driven behavioral frameworks, including dynamic pricing mechanisms, reward-based participation models, and evidence-based behavioral nudges, enhances user involvement in demand-side optimization processes and strengthens responsiveness to system signals and renewable energy availability.
- The provision of specialized training programs and targeted informational campaigns for facility managers and building operators improve operational decision-making, ensuring that building-level control strategies and user interactions align with best practices for efficient integration with DHC systems.
- The integration of user-centric digital interfaces within smart-building platforms enables real-time visualization of consumption profiles, automated recommendations tailored to occupancy and usage patterns, and continuous engagement in energy-saving actions, thereby reinforcing building-user collaboration in achieving enhanced thermal and energy performance.
  [19] [20]

Table 5.5 provides a structured comparative overview of the main demand-side measures applicable to district heating and cooling (DHC) systems, detailing their operational mechanisms, relevant performance indicators, and the estimated impacts on energy consumption and associated emissions.

Table 5-5 Comparative Overview of Key Demand-Side Measures in DHC Systems

Thermal insulation of walls, roofs, and windows; modernization of heating and cooling equipment; optimization of domestic hot water (DHW) networks	EUI (kWh/m²/year); equipment COP; heat loss (%)	20–40% reduction in thermal energy consumption; corresponding decrease in CO_2 emissions	Thermal insulation of walls, roofs, and windows; modernization of heating and cooling equipment; optimization of domestic hot water (DHW) networks
Programmable thermostats, zone-based control, smart-building systems, and predictive algorithms	System energy efficiency (%); thermal comfort in accordance with EN 15251 / ASHRAE 55	10–25% reduction in peak demand; continuous optimization of overall consumption	Programmable thermostats, zone-based control, smart-building systems, and predictive algorithms
Load shifting, load shedding, demand adjustment based on dynamic tariffs and renewable availability	Peak demand (kW); DHC network load factor	15–30% reduction in peak demand; improved system flexibility	Load shifting, load shedding, demand adjustment based on dynamic tariffs and renewable availability
Capturing passive solar energy; recovering residual heat from ventilation and internal processes	Recovered energy (kWh/year); reduced DHC demand (kWh/m²)	10–20% reduction in net demand; proportional decrease in emissions and primary energy use	Capturing passive solar energy; recovering residual heat from ventilation and internal processes
Energy-feedback systems, educational programs, and individual consumption monitoring	Reduction in individual specific consumption (kWh/m²/year); user engagement level (%)	5–15% reduction in total consumption through behavioral efficiency; indirect contribution to lowering emissions	Energy-feedback systems, educational programs, and individual consumption monitoring
Thermal insulation of walls, roofs, and windows; modernization of heating and cooling equipment; optimization of domestic hot water (DHW) networks	EUI (kWh/m²/year); equipment COP; heat loss (%)	20–40% reduction in thermal energy consumption; corresponding decrease in CO_2 emissions	Thermal insulation of walls, roofs, and windows; modernization of heating and cooling equipment; optimization of domestic hot water (DHW) networks

Integrated PESTEL–SWOT Analysis for Demand-Side Measures in DHC Systems

The integrated PESTEL–SWOT analysis provides an overview of the external and internal factors that influence the implementation of *Demand Side Measures* in the context of optimizing the performance of district heating and cooling systems. This approach enables the correlation of macro-contextual dimensions (political, economic, social, technological, environmental, and legal) with internal elements of potential and vulnerability, contributing to the identification of action directions for increasing energy efficiency and reducing environmental impact. Essentially, the analysis serves as a diagnostic and planning tool aimed at optimizing the performance of DHC systems through demand-side interventions — namely, by reducing consumption, improving the energy efficiency of buildings, and encouraging the active participation of end users.

Table 5-6 SWOT - PESTEL analysis

PESTEL Factor	Strengths	Weaknesses	Opportunities	Threats
Political	Energy efficiency and renovation programs	Dependent on government priorities; limited funding	Favorable European policies (EPBD) support implementation	Changes in government may halt subsidy programs
Economic	Small–medium investments, rapid payback through bill reduction	Some vulnerable households cannot afford initial investments	Green subsidies and loans are accessible to the population	Economic crises may reduce purchasing power and interest in renovation
Social	Increased thermal comfort and lower bills; user engagement	Requires behavioral change and active user involvement	Education for energy efficiency and climate awareness	Social inequalities – limited access for low-income households
Technological	Accessible technologies: individual meters, thermostatic valves, smart home solutions	Fragmented integration and lack of system interoperability	Development of IoT, AI, and home energy management solutions	High risk of premature ageing of implemented technologies
Environmental	Reduction of total energy demand and implicitness of emissions	Limited impact if not applied on a large scale	Direct contribution to achieving energy efficiency and climate goals	If measures are insufficient, pressure increases on the supply side
Legal	Clear European framework (EPBD, minimum performance standards)	Implementation of rules may be costly for property owners	EU directives support the obligation for progressive renovations	Possible sanctions for buildings that do not meet future standards

The integrated analysis underscores that demand-side measures—centred on enhancing energy efficiency and reducing consumption at the building level—are shaped by a complex and interdependent configuration of political, economic, social, technological, environmental, and legal factors.

These multidimensional influences determine not only the feasibility and pace of implementing such interventions, but also their long-term effectiveness and scalability within district heating and cooling systems. By recognising the systemic interactions among these drivers, the analysis provides a more comprehensive foundation for designing coherent strategies that support the transition toward higher energy performance, reduced environmental impact, and a more resilient built environment.

Political dimension. A generally supportive political framework exists, reinforced by national and European programmes dedicated to renovation and energy efficiency. However, the reliance on governmental priorities and the availability of public funding constitutes a significant vulnerability. The stability and continuity of policy measures are critical prerequisites, as changes in government may lead to the interruption or discontinuation of subsidy schemes.

Economic dimension. Small- and medium-scale investments, characterised by rapid payback through reduced energy bills, represent a major strength. However, vulnerable households often lack sufficient financial resources, which limits the large-scale adoption of demand-side measures. Access to green loans and dedicated subsidies provides significant opportunities, yet an unstable economic context—marked by inflation and fluctuating income levels—may reduce purchasing power and weaken public interest in renovation-related investments.

Social dimension. The increase in thermal comfort and the active involvement of users constitute key advantages of demand-side measures. However, changes in consumption behaviour require education, awareness, and sustained engagement from end users. Social inequalities may limit the ability of vulnerable groups to access the benefits of energy efficiency, thereby widening existing gaps during the green transition.

Technological dimension. The availability of accessible technologies—such as individual meters, thermostatic valves, and smart home solutions—creates favourable conditions for the digitalization and optimization of energy consumption. Nevertheless, fragmented system integration and a lack of interoperability remain significant barriers. The development of IoT and artificial intelligence–based solutions offer promising prospects, yet the risk of rapid technological obsolescence calls for stronger standardization and continuous adaptability.

Environmental dimension. Demand-side measures contribute directly to reducing energy demand and associated emissions, thus supporting the achievement of decarbonization and energy-efficiency targets. Their overall effectiveness, however, depends on large-scale implementation and on complementarity with measures applied on the supply side. Without sufficient uptake, pressure on the energy system remains high.

Legal dimension. The European framework is clear and coherent, with directives such as the EPBD establishing minimum performance standards and mandating progressive building renovations. The implementation of these requirements, however, may impose significant costs on property owners, while non-compliance could lead to future penalties.

The integrated analysis highlights that the effectiveness and sustainability of Demand Side Management measures within the energy transition process are conditioned by a systemic interdependence among political, economic, social, technological, and regulatory factors. In particular, the stability of the political framework and the predictability of support mechanisms, equitable access to financial resources, and the level of education and active engagement of end users constitute decisive elements for ensuring coherent and effective implementation of demand-side interventions. At the same time, the intelligent integration of emerging technological solutions—combined with strict alignment to European regulations and standards—represents a fundamental prerequisite for strengthening the resilience and flexibility of district heating and cooling systems.

By aligning these dimensions within a unified strategic framework, it becomes possible to design integrated and adaptive policies aimed at modernizing urban energy infrastructure, optimizing the energy performance of buildings, and reducing environmental impact. Taken together, such measures contribute to accelerating the transition toward a sustainable and climate-neutral energy model, in accordance with the objectives of the European Green Deal and national decarbonization agendas.

5.2 Supply side measures

In the context of the accelerated energy transition and the intensified decarbonisation objectives established at the level of the European Union, the optimisation of District Heating and Cooling systems has become a strategic component in the transformation of urban energy infrastructures. To meet current requirements for energy efficiency, emission reduction, and the integration of renewable energy sources, DHC systems require a holistic approach in which supply-side interventions are implemented complementarily to demand-side measures. While demand-side optimisation focuses on reducing overall consumption and increasing flexibility in usage profiles, supply-side measures target improvements in the efficiency of thermal energy production, conversion, transport, and delivery processes[21].[22]

From the perspective of modernising DHC systems, supply-side measures constitute an essential structural element due to their direct potential to reduce primary energy consumption and to limit distribution network losses. These measures also enable a higher degree of integration of variable renewable energy sources and contribute to enhancing the operational flexibility of DHC infrastructures—an increasingly critical requirements given the growing penetration of electrification and the variability of renewable energy generation. The modernisation of production units [23], the transition from fossil fuels to low-emission energy carriers[24] [25] the recovery of industrial and urban waste heat [26] [27]the implementation of high-efficiency cogeneration[28], and the deployment of advanced thermal energy storage[29] [30] capacities form the core pillars of supply-side optimisation.

Through the integrated implementation of such interventions, DHC infrastructures can evolve towards fourth- and fifth-generation systems [31] [32] [33]characterised by lower operating temperatures, increased interoperability, advanced digitalisation, and enhanced adaptability to dynamic operational conditions. Moreover, strengthening the supply-side component contributes to improving system resilience, reducing dependence on fossil fuels, and ensuring operational stability under conditions of significant fluctuations in both demand and generation.

Therefore, supply-side measures represent not merely a set of technical actions but a fundamental prerequisite for the sustainable transformation of district heating and cooling systems, enabling their transition towards a modern, flexible, energy-efficient model aligned with long-term climate neutrality objectives.

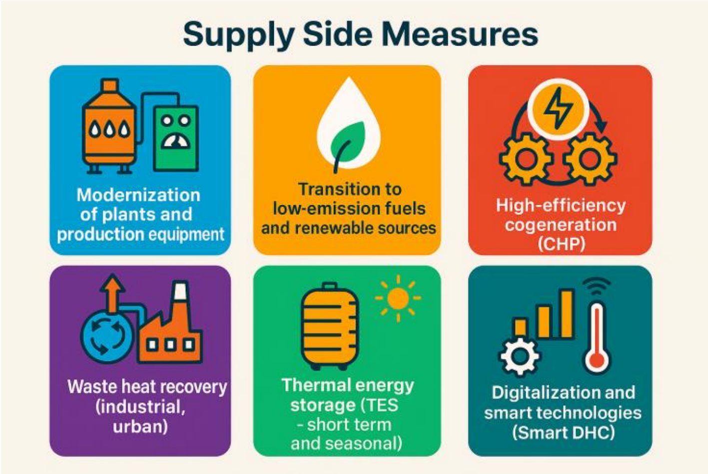

Figure 5-2 Supply side measures

Modernization of Heat Generation Plants and Thermal Equipment

The modernization of heat generation plants and thermal energy production equipment represents one of the most effective and immediate measures for improving the performance of district heating systems. A significant share of existing plants in Central and Eastern Europe operate with outdated technologies, characterized by low efficiencies, high thermal losses, and elevated operational costs. In this context, technological upgrade interventions play a fundamental role in reducing primary energy consumption and enhancing the reliability of heat production processes.

The main modernization directions include the replacement of outdated District Heating Production Units with new-generation systems offering higher efficiencies, the adoption of modulating burners, and the installation of economizers for recovering residual heat from flue gases. The upgrade of auxiliary installations—such as pumping systems, electrical equipment, and automation infrastructure—also contributes to reducing electricity consumption and optimizing the overall operation of the system. The integration of advanced control systems (SCADA, IoT, predictive algorithms) ensures continuous monitoring of key parameters and enables dynamic adjustments in plant operation in response to demand fluctuations.

By implementing these measures, operators can achieve a significant reduction in losses, extend the service life of equipment, and obtain a general improvement in energy efficiency, contributing directly to the decarbonization and modernization objectives of DHC systems. The table below summarizes key technical interventions aimed at improving the efficiency and performance of heat generation units and auxiliary systems in DHC plants.[23] [34][35]

Table 5-7 Technical Interventions to Improve the Efficiency of Heat Generation Units and Auxiliary Systems in DHC Plants

Category	Technical Measure	Parameters / Details	Impact on Performance
Heat Generation Units	Modulating burners	Continuous control, modulation 10–100%	Reduction of fuel consumption by 5–12%
	Economizers / flue gas heat recovery	Recovery of flue gas heat (ΔT 80–120°C)	Increase in efficiency by 3–7%
	Advanced thermal insulation	$\lambda \leq 0.030$ W/mK	Reduction of radiant heat losses by 30–50%
	Optimization of air–fuel ratio (O_2 trim control)	Oxygen sensors, automatic combustion control	Reduction of emissions and improved combustion efficiency
	SCADA-based automation and control for production units	Automatic regulation of temperature / pressure / flow	Operational stability and improved efficiency
Auxiliary Systems	Variable-speed pumps (VFD)	Dynamic load adaptation	Electricity savings of 20–40%
	Advanced water treatment systems	Desalination, degassing, filtration	Reduced corrosion and extended equipment lifetime
	High-efficiency heat exchangers	Optimized thermal transfer plates	Reduced losses and improved efficiency
	High-efficiency electric motors (IE3–IE4)	Modernized auxiliary equipment	Reduction of electricity consumption by 10–15%
	Predictive automation	Parameter adjustment based on historical data	OPEX optimization and failure prevention

Transition to Low-Emission Fuels and Renewable Energy Sources

Fuel switching represents one of the fastest and most effective pathways for decarbonizing urban district heating systems, fully aligned with the European objectives established through the Fit for 55 package and the Renewable Energy Directive (RED III). This transition targets the replacement of traditional fossil fuels—such as coal, heavy fuel oil, or natural gas—with low-emission alternatives or renewable energy sources capable of significantly reducing the carbon footprint of the sector.

An important direction is the conversion of coal-fired district heating plants to lower-carbon fuels such as natural gas or biogas, as well as the adaptation of existing infrastructure for the use of hydrogen blends (H_2 blending) of 10–25%, with the long-term perspective of transitioning to 100% hydrogen by 2030–2040. In parallel, sustainable biomass remains a feasible solution for regions with local availability, offering competitive operational costs and low net emissions across the entire value chain.

The integration of electrified technologies such as large-scale heat pumps—primarily supplied with renewable electricity—enables direct access to low-temperature resources such as geothermal water, aquatic sources, wastewater, or exhaust air, thereby reducing dependence on fossil fuels. Likewise, large-scale solar thermal systems provide a mature and scalable solution with minimal operational costs, particularly when combined with seasonal thermal storage.

Through the gradual implementation of these technologies, DHC operators can substantially reduce greenhouse gas emissions, enhance energy security, and advance toward the sustainable model characteristic of fourth- and fifth-generation district heating systems. [24] [25][36]

Table 5-8 Fuel Switching Options for DHC Operators

Initial Fuel	New Source	Advantages	Limitations
Coal	Natural gas / biogas	CO_2 reduction by 40–60%; lower pollutant emissions	Dependence on gas market fluctuations
Natural gas	Hydrogen (H_2 blending 20–25%)	Rapid decarbonization; partially compatible with modern burners	Requires system adaptations; high hydrogen cost
Any fuel	Large-scale heat pumps	COP 2.5–4; integration with renewable electricity surplus	High initial investment
Any fuel	Large-scale solar thermal	Minimal operational cost; stable renewable resource	Requires significant land area for collectors
Gas / biomass / biogas	Geothermal (direct use or via heat pump)	Stable operation; constant local resource	Depends on local geological potential; high drilling cost

Implementation of High-Efficiency Cogeneration

High-efficiency cogeneration (Combined Heat and Power – CHP) represents one of the most robust and versatile solutions for improving energy efficiency in urban district heating systems. By producing thermal and electrical energy simultaneously within a single process, CHP installations achieve overall efficiencies exceeding 85–90%, significantly reducing primary fuel consumption compared to separate heat and power generation. This characteristic makes cogeneration a key technology in the energy transition, offering operational flexibility as well as environmental and cost benefits.

Modern cogeneration installations include gas turbines in combined-cycle configurations (CCGT), large-scale reciprocating engines powered by natural gas, biogas, or hydrogen, as well as emerging technologies such as fuel cells (SOFC, PEMFC), which offer high efficiencies and low emissions. The selection of an appropriate technology depends on the size of the DHC system, consumption profile, fuel availability, and the required level of flexibility in relation to the electricity grid.

A major advantage of CHP lies in its ability to provide ancillary services to the electricity network (balancing, frequency regulation) by adjusting electrical output according to system needs, without compromising thermal supply. In addition, integrating CHP with thermal energy storage systems and variable renewable sources enables optimized operation under fluctuating demand conditions and contributes to overall emissions reduction.

By implementing high-efficiency cogeneration units, DHC operators can achieve significant reductions in operational costs, enhance infrastructure resilience, and progress towards a modern energy model aligned with decarbonization objectives. [8, 17]

Recovery of Waste Heat (Industrial, Urban, Commercial)

Waste heat recovery represents one of the most efficient and sustainable measures for decarbonizing district heating and cooling (DHC) systems by harnessing energy streams that are typically dissipated into the environment. Waste heat is generated in industrial processes, in energy-intensive commercial infrastructures, or in urban systems such as sewage networks, wastewater treatment plants, and HVAC systems of large buildings. Integrating these sources into DHC networks directly contributes to increasing overall system efficiency and significantly reducing fossil fuel consumption.

Industrial sources often provide medium- and high-temperature waste heat, enabling direct recovery through heat exchangers or thermodynamic cycles such as the Organic Rankine Cycle (ORC). These applications can cover a substantial share of local heat demand, particularly in areas with high industrial density. Urban and commercial sources—such as data centers, supermarkets, or hospitals—typically generate low- or medium-temperature heat that can be efficiently utilized through large-scale heat pumps, especially in fourth- and fifth-generation DHC networks.

The integration of waste heat requires careful assessment of local potential, proximity to the distribution network, and the temporal profile of heat flows. When combined with thermal energy storage systems, these sources can provide a stable and predictable contribution, reducing dependence on conventional production and enhancing operational stability.

By capturing and reusing waste heat, DHC systems can make substantial progress toward energy efficiency and decarbonization objectives, transforming the unavoidable losses of other processes into valuable resources for the community. [26] [27] [37][38]

Table 5-9 Types of Waste Heat Sources

Type of Source	Examples / Origin	Advantages	Limitations
Industrial – medium and high temperature	Metallurgy, cement, chemicals, steam processes, flue gases	High temperature → direct recovery; high potential; stable heat flow	Requires proximity to the DHC network; investments in heat exchangers and filtration
Industrial – low temperature	Food industry, textiles, machinery cooling	Constant heat flux; excellent for integration with large heat pumps	May require temperature upgrading; variable source quality
Urban (public infrastructure)	Wastewater, treatment plants, metro tunnels, urban ventilation systems	High availability; seasonal stability; local resource	Low temperature → dependence on heat pumps; requires access to infrastructure
Commercial	Data centers, supermarkets, hospitals, large buildings with HVAC systems	Constant source; medium temperature (30–80°C); exploitable in 4GDH/5GDH	Requires commercial agreements; dispersed heat flows, uneven distribution
Cooling processes	Industrial refrigeration systems, commercial chillers	Available in dense urban areas; rapid valorization	Low temperature; limited potential for individual sources

Thermal Energy Storage (Short-Term and Seasonal)

Thermal Energy Storage (TES) represents a central component in the modernization and flexibilization of urban district heating and cooling systems, being essential for the integration of variable renewable energy sources, the optimization of plant operation, and the reduction of peak loads. By using storage systems, DHC networks can temporally decouple production from consumption, enabling more efficient utilization of generation assets and a significant reduction in operational costs. [29] [30] [39]

Short-term storage solutions primarily include aboveground or underground hot-water tanks with volumes ranging from a few hundred to several tens of thousands of cubic meters. These systems are used for daily balancing, allowing heat generation units to operate at optimal loads and avoiding frequent start–stop cycles. In addition, short-term TES facilitates the integration of variable renewable sources (wind, photovoltaics) by converting surplus electricity into thermal energy via large heat pumps or electric boilers.

Seasonal storage, implemented through systems such as pit thermal energy storage, borehole thermal energy storage, or aquifer thermal energy storage, enables the transfer of thermal energy across seasons. This capability is particularly valuable for integrating large-scale solar thermal systems, which produce substantial surplus heat during summer and require storage infrastructures capable of maintaining elevated temperatures over long periods.

By implementing TES, DHC operators can reduce the demand for fossil-fuel-based generation capacity, improve system stability, and progress toward low-emission operational models characteristic of fourth- and fifth-generation district heating systems.

Table 5-10 Types of Thermal Energy Storage

TES Type	Technology	Characteristics / Typical Parameters	Advantages	Limitations
Short-term TES	Hot-water storage tanks	Volume 200–50,000 m^3; temperatures 70–95°C; low losses	Daily balancing; mature technology; low cost per kWh	Requires dedicated space; short-term storage only
Seasonal TES	Excavated and insulated underground thermal pits	Volume 10,000–200,000 m^3; temp. 75–95°C	Excellent for integrating large-scale solar thermal; low large-scale cost	Requires large land areas; depends on geotechnical conditions
Seasonal TES	Vertical geothermal boreholes for thermal storage	30–200 boreholes; depths 30–150 m; annual cycles	Integrable in urban areas; long service life	High initial investment; efficiency depends on soil conditions
Seasonal TES	Storage in underground aquifers	Temperature 5–25°C; very high storage capacity	High efficiency; cost-effective for large systems	Requires suitable aquifer; hydrogeological and regulatory constraints
High-density TES	Phase-change materials (PCM)	High energy density; fixed phase-transition temperatures (solid–liquid)	Compact; ideal for limited space; low thermal losses	High cost; more complex design

Minimizing Heat Losses in Transport and Distribution Networks

Minimizing heat losses in transport and distribution networks represents one of the most important measures for improving overall efficiency in urban district heating systems. In many European networks—particularly those built before the 1990s—thermal losses can exceed 25–40%, directly affecting operational costs, service reliability, and the economic competitiveness of the system. Modernizing distribution infrastructure is therefore essential for achieving energy efficiency targets, supporting decarbonization efforts, and enabling the integration of renewable energy sources.

Table 5-11 Technical Measures for Minimizing Heat Losses in Transport and Distribution Networks

Category	Technical Measure	Description / Parameters	Impact on Performance
Pipelines	Replacement of canal pipes with pre-insulated pipes	Generation II–III pre-insulated pipes; polyurethane insulation	Reduction of heat losses by 30–60%
	Pre-insulated pipes with integrated sensors	Leak and moisture detection	Increased service life and reduced failures
	Rehabilitation of defective pipeline sections	Replacement of local segments with high losses	Reduction of local losses by 20–40%
	Optimization of pipe diameters	Adjustment based on actual design flow	Reduction of hydraulic and thermal losses
	Use of high-performance insulation foams	$\lambda \leq 0.024$ W/mK	Reduced radiant losses and increased thermal stability
Pumping stations	Variable-frequency pumps	Automatic control of pressure and flow	Reduction of electricity consumption by 20–40%
	High-efficiency electric motors (IE4–IE5)	Modernization of auxiliary equipment	Reduction of electricity consumption by 10–15%
Operating temperature	Low-temperature operation	60–70°C instead of 90–110°C	Reduction of thermal losses by 15–25%
	Advanced temperature/pressure control	SCADA systems with optimization algorithms	Stable operation and increased efficiency
Monitoring	IoT systems for leak detection	Temperature, pressure, and humidity sensors	Rapid localization → reduced losses and fewer failures

One of the most effective technical measures is the replacement of old canal-type pipelines with modern pre-insulated pipes, characterized by significantly lower thermal losses and increased resistance to corrosion. Second- and third-generation pre-insulated pipe technologies enable heat loss reductions below 10%, while ensuring a network lifetime of more than 30–40 years. Optimizing operating pressures and temperatures is another critical aspect, achieved by adopting low-temperature operation strategies specific to 4th-generation DHC systems.

In parallel, the modernization of pumping stations through the implementation of variable-frequency pumps can reduce electricity consumption associated with heat transport by 20–40%. The integration of real-time monitoring systems—based on IoT sensors, SCADA platforms, and leak-detection algorithms—enables rapid fault identification and efficient intervention, thereby reducing operational costs and minimizing the impact on end users.

By implementing these measures, operators can ensure efficient, flexible, and resilient operation of DHC networks, accelerating the transition toward modern 4th- and 5th-generation heating and cooling systems.[40] [41][42]

Digitalization of Systems and Adoption of Intelligent Technologies

Digitalization represents a fundamental pillar in the modernization of urban district heating and cooling systems, enabling the shift from reactive operation to predictive, optimized, and efficiency-oriented management. By integrating intelligent technologies, operators can monitor and control network conditions in real time, anticipate consumption variations, and manage heat production and distribution in a more flexible and efficient manner. This transformation is a defining element of 4th- and 5th-generation DHC systems, characterized by low supply temperatures, extensive integration of renewable energy sources, and a high degree of automation.

Modern SCADA systems, combined with IoT platforms, enable continuous collection of critical data on temperatures, flows, pressures, and network losses. The analysis of these data through advanced Machine Learning algorithms provides capabilities for early leak detection, automatic operational optimization, and reduction of auxiliary equipment energy consumption. Furthermore, digital twins—digital models of the network—allow operators to simulate operational scenarios, assess the impact of planned investments, and optimize maintenance strategies.

At the consumer level, the use of intelligent meters and advanced billing systems based on real consumption facilitates demand flexibility and supports the implementation of dynamic pricing mechanisms. These tools contribute to system balancing and increase transparency in the relationship with end users.

By adopting intelligent technologies, DHC systems become more efficient, more resilient, and better adapted to future energy requirements, providing the necessary conditions for decarbonization, economic optimization, and large-scale integration of renewable energy sources. [43] [44]

Table 5-12 Digital Technologies and Intelligent Solutions for Modern DHC Systems

Category	Technology / Solution	Description / Functionalities	Impact on Performance
Monitoring	IoT sensors for temperature, pressure, and flow	Real-time measurement; data transmission via LPWAN/5G	Rapid detection of anomalies and optimization of flow conditions
	Sensors for leak and moisture detection	Early identification of underground leakages	Reduced failures and thermal losses
Operation and Control	Advanced SCADA systems	Integrated control of plants and distribution networks	Stable operation; improved overall efficiency
	Automated pump control	Dynamic adjustment of pressure and flow rate	Reduction of electricity consumption by 20–40%
	Network temperature optimization algorithms	Real-time adjustment according to demand	Reduced losses and optimized load management
Digital Modelling	Digital Twin for the DHC network	Full digital model of the infrastructure	Improved planning, simulation, and operational decision-making
	Advanced hydraulic and thermal simulations	In-depth analysis of flow and temperature behavior	Identification of critical zones and network optimization
Metering	Intelligent heat meters	Real-time data; automated remote reading	Accurate billing, reduced consumption, increased user engagement
	Meter Data Management platforms	Big Data analytics for consumption and performance	Increased transparency and improved economic efficiency
System Integration	EMS/DERMS platforms for RES and CHP integration	Coordinated production–demand management; load forecasting	High flexibility and optimal integration of renewable sources

Supply-side measures play a strategic role in the modernization and decarbonization of district heating and cooling (DHC) systems, contributing directly to improved energy efficiency, reduced reliance on fossil fuels, and large-scale integration of renewable energy sources. The modernization of production units and thermal generation equipment enables higher efficiencies and more stable operation, while the transition toward low-emission fuels—including hydrogen, biogas, large-scale solar thermal energy, and high-capacity heat pumps—provides scalable pathways for reducing greenhouse gas emissions.

Table 5-13 Overview of Key Supply-Side Measures in DHC Systems

Category	Scope	Main Benefits	Limitations / Challenges	Relevance for 4th/5th Gen DHC
Modernisation of Heat Generation Units	Heat generation units, turbines, auxiliary systems	Higher efficiency; reduced fuel consumption	High investment costs; requires retrofitting	Very high
Fuel Switching to Low-Carbon Sources	Gas → H_2/blending; biomass; electrification	Rapid emission reduction; operational flexibility	Fuel availability; hydrogen cost	High
Renewable Heat Integration	Solar thermal, heat pumps, geothermal	Low operating cost; deep decarbonization	Depends on local resources; land requirements	Very high
High-Efficiency Cogeneration	Gas turbines, engines, fuel cells	Efficiency >85–90%; electrical flexibility	Fuel needs; emissions if natural gas is used	High (especially with biogas/H_2)
Waste Heat Recovery	Industrial, urban, commercial sources	Utilization of losses; large local potential	Requires proximity and temperature compatibility	High
Short-Term Thermal Energy Storage	Hot-water storage tanks	Daily balancing; low cost	Space requirements; limited storage duration	Very high
Seasonal Thermal Energy Storage	Underground pits, boreholes, aquifers	Solar thermal integration; seasonal decoupling	High investment; geological constraints	Critical for 5GDHC
Network Loss Reduction	Pre-insulated pipes, pumps, LT operation	20–60% loss reduction	Extensive field works	Fundamental
Smart Monitoring & Control	SCADA, IoT, sensors	Optimized operation; early fault detection; OPEX reduction	Requires full digitalization	Critical
Digital Twin & Data Analytics	Advanced modelling, simulations	Predictive optimization; better decision support	High complexity; initial cost	Essential for 5G-DHC

High-efficiency cogeneration remains a key technology for the optimal use of primary energy, delivering both electricity and heat with minimal losses, while waste heat recovery expands the available energy potential by capturing industrial, urban, and commercial thermal streams. Thermal energy storage, both short-term and seasonal, ensures operational flexibility and supports the integration of variable renewable sources.

Minimizing losses in transport and distribution networks is essential for improving overall system efficiency, while digitalization through SCADA platforms, IoT infrastructures, intelligent sensors, and Digital Twin technologies transform DHC networks into proactive, optimized, and resilient infrastructures.

Through the integrated application of these measures, DHC systems can progress toward 4th- and 5th-generation models characterized by high efficiency, low emissions, enhanced flexibility, and an increased capacity to adapt to the energy requirements of the future.

Integrated PESTEL–SWOT Analysis for Supply-Side Measures in DHC Systems

The integrated PESTEL–SWOT analysis provides a comprehensive perspective on the external and internal factors that influence the implementation of supply-side measures in the modernization and performance optimization of district heating and cooling (DHC) systems. This approach enables the correlation of macro-contextual dimensions—political, economic, social, technological, environmental, and legal—with the internal strengths and weaknesses of thermal energy generation, transport, and distribution infrastructures.

In this way, the analysis supports the identification of barriers and opportunities associated with the transition toward efficient and low-emission technologies, such as the modernization of heat generation units, the integration of high-efficiency cogeneration, the deployment of renewable heat sources, the recovery of waste heat, and the development of advanced thermal energy storage solutions. At the same time, assessing the organizational and technological capabilities of DHC operators helps outline feasible strategic directions aimed at reducing primary energy consumption, increasing operational reliability, and minimizing environmental impact.

Essentially, the analysis functions as both a diagnostic and planning tool, oriented toward optimizing the performance of DHC systems through supply-side interventions—namely by improving the efficiency of production, distribution, and monitoring processes, integrating renewable energy sources, and strengthening the resilience of urban energy infrastructure.

Table 5-14 SWOT - PESTEL analysis

PESTEL Factor	Strengths	Weaknesses	Opportunities	Threats
Political	Strong EU-level support for decarbonization; national commitments to phase out coal gradually	Long approval procedures for infrastructure works; dependence on continuity of national policies	Access to European funding programmes for DHC modernisation	Policy changes or political instability that may delay major investments
Economic	Long-term reduction of operational costs through efficiency improvements, RES and TES integration; increased system competitiveness	High CAPEX for plant modernisation, TES implementation and network rehabilitation	Decreasing costs for RES and large heat pumps; emergence of new business models (energy-as-a-service, waste-heat markets)	Volatility of gas and electricity prices; high cost of hydrogen
Social	Improved air quality and service reliability; stable heat costs for consumers	Possible discomfort during network construction works; need for skilled personnel	Public acceptance for clean solutions; increasing interest in using waste heat and local renewable sources	Resistance from communities affected by construction works; shortage of specialised workforce
Technological	Mature technologies (CHP, SCADA, pre-insulated pipes); rapid progress in large-scale heat pumps, thermal storage and digital twins	High complexity in integrating hybrid systems; interoperability issues	Accelerated digitalisation, IoT implementation, automation and predictive maintenance	Cybersecurity risks; rapid technology obsolescence; challenges in hydrogen integration
Environmental	Significant CO_2 reductions; valorisation of waste heat; increased efficiency of resource use	TES /geothermal projects may require suitable geological conditions and large land areas	Major contribution to climate targets; valorisation of renewable sources and residual heat flows	Environmental constraints for ATES/geothermal projects; stricter emission regulations
Legal	Strong EU regulations on energy efficiency, RES integration and DHC performance standards	Complex procedures for underground work, geothermal projects or connecting waste-heat sources	Harmonisation of EU legislation facilitates hydrogen integration and RES expansion	Possible delays in updating national regulations; additional costs for compliance with new standards

The integrated PESTEL–SWOT analysis highlights that the implementation of supply-side measures in DHC systems is strongly shaped by the interaction between external and internal factors. Although the European framework is highly supportive of decarbonisation, the modernisation of infrastructures requires substantial investments, technical expertise, and strategic coordination among stakeholders. Advanced technologies—cogeneration, thermal energy storage, heat pumps, digitalisation—offer significant opportunities for efficiency gains, yet their deployment depends heavily on the economic, social, and regulatory context. Overall, the successful transition toward 4th–5th generation DHC systems demands political stability, adequate financial resources, and strong institutional capacity for implementation.

Political dimension. The political dimension provides the main driver for DHC modernisation, supported by ambitious European decarbonisation targets and dedicated funding schemes. However, dependence on national governance stability and the pace of public policy adoption can delay the implementation of large-scale projects. Political shifts may alter energy priorities, while extensive bureaucracy can slow down investments. Thus, the political framework is favourable but fragile, requiring long-term continuity and predictability.

Economic dimension. From an economic perspective, the modernisation of DHC infrastructure promises substantial reductions in operational costs and increased competitiveness. However, the high upfront investment costs (CAPEX) for TES, heat pumps, or digitalisation may exceed the financial capacity of many operators. Energy market volatility complicates profitability forecasts, and the cost of hydrogen remains a major barrier. Although economic opportunities are significant, access to financing and risk management remain critical.

Social dimension. Socially, supply-side measures bring clear benefits: more stable services, cleaner air, and more predictable costs for consumers. However, extensive modernisation works can generate urban disruption, and social acceptance depends on transparent communication and community involvement. In addition, the shortage of specialised labour may slow down implementation. The social dimension is favourable but vulnerable to public perception and skill deficits.

Technological dimension. Although technologies such as modern CHP, digital twins, advanced SCADA, and TES are well established, their integration into existing—often outdated—systems is complex. Interoperability issues and the need for advanced expertise may lead to difficult implementations or suboptimal performance. Moreover, digitalisation increases exposure to cyber risks. Technologically, the potential is high, but requires careful management of compatibility and security.

Environmental dimension. The environmental impact is largely positive—reduced emissions, recovery of waste heat, and integration of renewable energy sources. However, certain TES, geothermal, or ATES projects may raise ecological, hydrogeological, or land-use concerns, requiring rigorous assessments. Furthermore, increasing climate pressures raise performance requirements, which can become a technical challenge. The environmental dimension supports the transition but demands rigorous planning.

Legal dimension. European regulations support modernisation, but at national level, authorisation processes are often slow and fragmented. Underground or geothermal projects may face bureaucratic obstacles. The rapid evolution of standards may impose additional costs on operators, and digitalisation requires strict compliance with data protection legislation. The legal dimension is a facilitator, but also a potential bottleneck if not efficiently harmonised.

The analysis of supply-side measures highlights that the modernisation of urban district heating and cooling systems depends on the coherent interaction among political, economic, social, technological, environmental, and legal dimensions. The stability of the political framework, access to financing, and the ability of operators to integrate advanced technologies are decisive elements for the effective implementation of low-emission solutions—from the modernisation of heat generation units and the integration of high-efficiency cogeneration to waste heat recovery and the development of thermal energy storage.

At the same time, digitalisation and the use of smart technologies are essential components for increasing operational flexibility and ensuring predictive infrastructure management. By integrating these interventions within a unified strategic framework, DHC systems can advance toward 4th and 5th generation models, characterised by high energy efficiency, enhanced resilience, and full alignment with European objectives for decarbonisation and sustainable development [45]

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6. Green Procurement in District heating and cooling systems

The basic concept of Green Public Procurement (GPP) is based on the integration of environmental criteria into the procurement processes for public products, services, and works [1].

According to the European Commission's Communication, GPP is defined as "*a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured*."[1]

GPP criteria can cover various environmental aspects, including but not limited to [2]:

- Resource efficiency
- Reduced Emissions and Efficiency
- Social Considerations
- Waste Management and Circular Economy
- Biodiversity Conservation

6.1 Definition and Objectives

Green procurement in the District Heating and Cooling (DHC) sector refers to the selection and acquisition of products, services, and technologies that support environmental sustainability throughout their entire life cycle from production and installation to operation and decommissioning.

It plays an important role in aligning DHC systems with national and international climate goals by reducing greenhouse gas emissions, promoting resource efficiency, and encouraging innovation in clean technologies.

To achieve these outcomes, green procurement focuses on several criteria [3]:

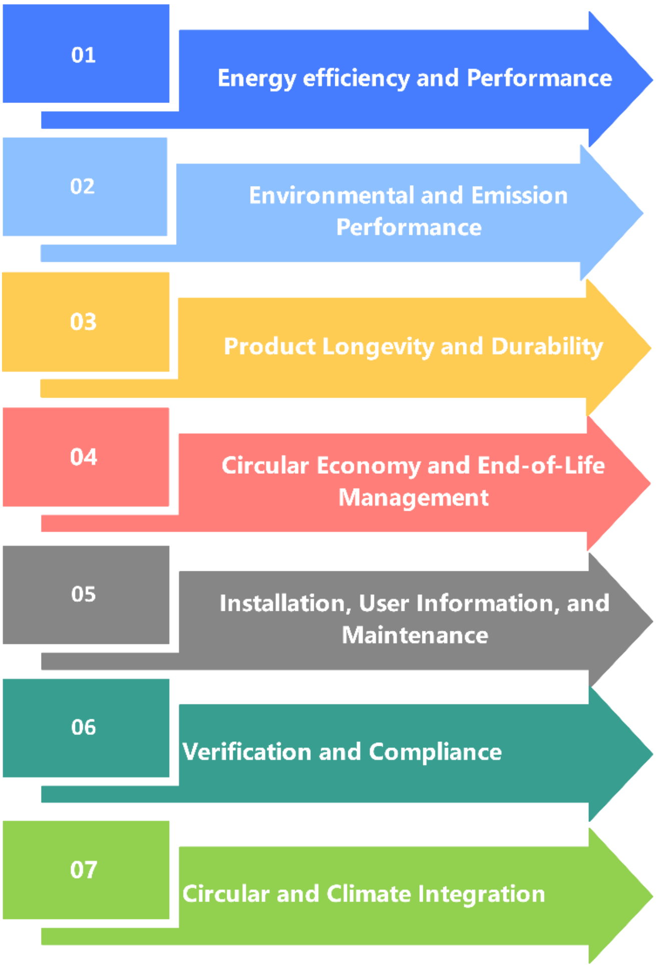

Figure 6-1Criteria for green procurement in district heating [3]

Energy Efficiency and Performance – Selecting systems with high energy efficiency ratings (high COP or SEER values) to minimize power consumption and operating costs.

Environmental and Emission Performance – Prioritizing low-GWP (Global Warming Potential) and zero-ODP (Ozone Depletion Potential) refrigerants, as well as systems that minimize direct and indirect emissions.

Product Longevity and Durability – Encouraging the use of robust materials and designs that extend equipment lifetime, reducing the need for premature replacement.

Circular Economy and End-of-Life Management – Promoting equipment that is recyclable, modular, and designed for easy disassembly, facilitating recovery and reuse of materials.

Installation, User Information, and Maintenance – Ensuring proper installation practices, comprehensive user documentation, and regular maintenance for sustained efficiency.

Verification and Compliance – Requiring adherence to recognized standards (e.g., ISO 14001, EN 14825, EU EcoDesign) and third-party certifications to verify environmental performance.

Circular and Climate Integration – Integrating procurement decisions with broader organizational climate strategies and circular economy objectives to support decarbonization and resource efficiency.

6.2 Application Areas in DHC

Green procurement can be applied across all components of a DHC system:

Generation Equipment

- Selection of boilers, cogeneration units or heat pumps with high efficiency and low emissions;
- Preference for systems compatible with renewable fuels (e.g., biomass, biogas, hydrogen)
- Procurement of solar thermal collectors and geothermal systems with verified sustainability criteria

Distribution Network Components

- Pipes with low thermal losses and long service life (e.g., pre-insulated, recyclable materials)
- Leak detection systems that reduce water and energy waste
- Equipment manufactured with low embodied carbon and minimal environmental impact

Customer Interface and Substations

- Heat exchangers and substations with modular, energy-efficient components
- Smart control systems to optimize end-use consumption
- Materials and products with environmental certifications

Construction and Installation

- Use of eco-friendly construction materials with low VOCs and recyclability
- Contractors adhering to environmental management systems
- Waste minimization and site impact reduction strate

6.3 Procurement Criteria and Standards

The successful implementation of green procurement in District Heating and Cooling (DHC) systems depends on the integration of clearly defined environmental and performance-based criteria within tender documents.

Energy Efficiency Ratings: Equipment and components should comply with relevant EU EcoDesign and Energy Labelling directives, ensuring high performance and low energy consumption. Energy efficiency should be demonstrated through standardized testing and certification, such as EN 14825 for seasonal performance and EN 14511 for chiller and heat pump efficiency.

Carbon Footprint Assessment: Tenderers should provide a Life Cycle Assessment (LCA) or equivalent documentation quantifying the total carbon footprint of products and services. Thresholds may be established to favor options with lower embodied and operational emissions, supporting climate-neutral system design.

Environmental Certifications Preference should be given to products and manufacturers holding verified environmental labels such as EU Ecolabel, Energy Star, Cradle-to-Cradle, or Environmental Product Declarations (EPD). These certifications demonstrate compliance with recognized sustainability criteria and lifecycle impact reduction.

Recycled Content and Material Efficiency

Procurement specifications should include minimum requirements for recycled content, material reusability, and recyclability of components and packaging. Design for disassembly and use of non-toxic, easily separable materials are encouraged to promote circular economy principles.

Sustainable Procurement Standards

Organizations should adhere to ISO 20400 – Sustainable Procurement, ensuring that environmental, social, and ethical considerations are embedded in the entire procurement process. In addition, suppliers may be required to demonstrate compliance with ISO 14001 (Environmental Management Systems) to ensure continuous improvement in sustainability performance.

Verification and Compliance

All environmental and efficiency claims must be supported by third-party verification, official documentation, or performance testing reports. Audits or supplier assessments may be conducted to confirm compliance with environmental and technical requirements.

6.4 Benefits of Green Procurement in DHC

The adoption of Green Procurement within District Heating and Cooling (DHC) systems offers a wide range of environmental, economic, and social benefits. By integrating sustainability criteria into purchasing decisions, public authorities and private operators can significantly enhance the overall performance, longevity, and resilience of DHC infrastructure.

Lower Operating Costs - Efficient technologies, durable materials, and optimized system designs result in reduced energy consumption and lower operational expenses throughout their life cycle. Green procurement encourages the selection of equipment with high efficiency ratings (e.g., COP, seasonal efficiency), minimizing electricity and fuel use while reducing maintenance needs.

Climate Impact Reduction-Green procurement supports compliance with national and EU climate objectives. By prioritizing low-emission technologies, renewable energy integration, and environmentally certified materials, DHC systems can significantly reduce greenhouse gas emissions and contribute to decarbonization goals.

Improved Asset Longevity and Reliability: Selecting high-quality, environmentally certified products extends the service life of assets and reduces the frequency of replacements. Durable, low-maintenance components lower lifecycle costs and improve the long-term reliability of heating and cooling networks.

Innovation and Market Transformation- Green procurement drives technological innovation and stimulates the market for sustainable products and services

Public Sector Leadership and Social Responsibility -Implementing green procurement demonstrates leadership in environmental governance and social responsibility.

Resource Efficiency and Circular Economy: Green procurement promotes resource efficiency by encouraging the use of recyclable materials, waste minimization, and product designs compatible with circular economy principles.

6.5 Implementation Challenges

While green procurement offers significant long-term benefits, several challenges may affect its implementation in District Heating and Cooling (DHC) systems:

- Higher Initial Costs – Some products may involve higher upfront investments, requiring lifecycle cost analysis to demonstrate long-term savings.
- Market Availability – The limited presence of local suppliers for advanced green technologies can restrict procurement options.
- Complex Evaluation – Assessing environmental performance and compliance often requires specialized technical expertise and reliable data.
- Policy Alignment – Procurement activities must remain consistent with regulatory frameworks, public procurement rules, and national or EU environmental policies.

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7. Standards and certifications

7.1 Role of Standardisation in DH

Definition: The process of developing and agreeing on technical specifications, norms, and procedures to ensure compatibility, safety, efficiency, and interoperability of systems and components.

Purpose: To create uniform rules and technical guidelines for design, materials, installation, operation, and maintenance of DH systems.

What it provide: Frameworks for technical design and performance; Common reference for manufacturers, operators, and policymakers.

Standardisation has an important role in the development, operation, and integration of district heating (DH) systems by ensuring *compatibility, safety, efficiency, and interoperability between different components*, *suppliers, and technologies* within the heating network.

District heating system design, operation, and maintenance are governed by a range of standards and certification schemes that guarantee quality, safety, efficiency, and environmental performance.

These standards underpin the entire lifecycle of District Heating systems, guiding procurement, design, installation, and regulatory compliance to ensure performance, reliability, and sustainability.

7.2 Standards for District Heating

Relevant standards for district heating are developed by international and regional organisations such as :

- ISO (International Organization for Standardization) (https://www.iso.org/standards.html)
- CEN (European Committee for Standardization (https://www.cencenelec.eu)

- and various national bodies.

Some of the relevant standards for district heating are [1–3]:

District Heating and Cooling Networks

- EN 13941-1:2019 / ISO 12576-1:2008 – Design and installation of pre-insulated bonded pipe systems for district heating.
- EN 13941-2:2019 – Design and installation of pre-insulated bonded pipe systems for district cooling.
- EN 253:2019 – District heating pipes – Pre-insulated bonded pipe systems with steel service pipes – Specification.
- EN 15698-1:2009 – Plastic piping systems for district heating and cooling networks – Classification, general requirements, and test methods.
- EN 14336:2004 + A1:2020 – Heating and cooling systems in buildings – Installation and commissioning requirements.
- EN 15316-4-5:2017 – Energy performance of buildings – Calculation of system energy requirements and efficiencies (district heating).
- EN 15316-4-7:2017 – Energy performance of buildings – District cooling generation systems – Efficiency calculation.
- EN 1434-1:2015 – Heat and cooling meters – General requirements, tests, and performance.

Boilers and Heat Generation Systems

- EN 303-5:2021 – Heating boilers for solid fuels and automatically stoked systems up to 500 kW – Requirements, testing, and marking.
- EN 15502-1:2021 – Gas-fired heating boilers – General requirements and test methods.
- EN 12952-1:2015 – Water-tube boilers and auxiliary installations – General requirements.
- EN 12953-1:2021 – Shell boilers – General requirements.

Cogeneration (CHP) and Fuel Cells

- EN 15316-4-4:2017 – Energy performance of buildings – Calculation of system energy requirements – Combined heat and power systems.
- IEC 62282 Series (2016–2022) – Fuel cell technologies – Safety, performance, and testing requirements.
- ISO 23551-1:2022 – Safety and control devices for gas burners and gas-burning appliances.

Heat Pumps and Cooling Equipment

- EN 14511-1 to 4:2018 – Air conditioners, liquid chilling packages, and heat pumps – Terms, test conditions, and performance requirements.
- EN 14825:2022 – Air conditioners, chillers, and heat pumps – Seasonal performance and part-load testing.
- EN 16147:2017 – Heat pumps with electrically driven compressors – Testing and requirements for domestic hot water units.
- EN 378-1 to 4:2016 – Refrigerating systems and heat pumps – Safety and environmental requirements.
- EN 16798-3:2017 – Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems.
- EN 16798-17:2017 – Guidelines for inspection of cooling systems.

Control, Automation, and Communication

- EN 15232-1:2017 – Energy performance of buildings – Impact of building automation, controls, and building management.
- EN 12098 Series (2017–2020) – Control systems for heating systems (space heating, electrical heating, and heat generation).
- ISO 16484-5:2017 – Data communication protocol for building automation and control networks (BACnet).
- ISO/IEC 14543 Series (2010–2021) – Communication protocols for building automation (KNX).
- IEC 60870-5 and IEC 61850 Series (2016–2022) – Communication networks and systems for utility and energy automation.
- IEC 62974-1:2017 – Monitoring and control of energy systems – General requirements.
- CEN/TR 16355:2012 – District heating and cooling – Performance benchmarking and system optimisation.

Energy and Environmental Management

- ISO 50001:2018 – Energy management systems – Requirements with guidance for use.
- ISO 50006:2021 – Energy management systems – Measuring energy performance using baselines and indicators.
- ISO 14001:2015 – Environmental management systems – Requirements with guidance for use.

Hydrogen Integration in District Heating

- ISO 14687:2019 – Hydrogen fuel – Product specification.
- EN 17124:2018 – Hydrogen fuel – Product specification and quality assurance.
- ISO 19880-1:2020 – Gaseous hydrogen – Refuelling infrastructure – General requirements.
- EN 1594:2013 – Gas infrastructure – Pipelines for maximum operating pressure over 16 bar.
- EN 13445:2021 – Unfired pressure vessels – Design, fabrication, and inspection.

Digitalisation and Smart Energy Integration

- IEC 62974-1:2017 – Monitoring and control of energy systems – General requirements.
- IEC 61850-7-420:2021 – Communication networks and systems for distributed energy resources.

These standards cover design, materials, installation, commissioning, performance monitoring, and metering.

7.3 Certification Schemes

Definition: The process of verifying and proving compliance with established standards or requirements through testing, inspection, or auditing by an authorised third party.

Purpose: To demonstrate and confirm that a product, service, or system meets those standards and performs as intended.

What it provides:

- Proof of compliance through certificates or labels (e.g., Euroheat & Power (EHP) "Quality Label," ISO 9001 certification).
- Assurance for regulators, investors, and consumers.

Certification schemes are critical for ensuring the quality, efficiency, and sustainability of District Heating (DH) systems. Certification complements standardisation by verifying that products, services, or systems meet the established standards and regulatory requirements.

Product Certification:

This verifies that the physical components of the network meet technical and safety requirements, usually following European Norm (EN) or ISO standards.

Focus: Pipes (e.g., pre-insulated straight or flexible pipes), valves, heat meters, and substations (Heat Interface Units or HIUs).
Example : Euroheat & Power (EHP) Certification Programme [3] , which includes specific schemes like EHP001 for Straight Pipes, EHP002 for Flexible Pipes, and EHP004 for Eco-efficient Substations .
This ensures products comply with mandatory EN standards.

System Management Certification

These certifications focus on the overall management practices of the district heating operating company or system. The three most common and relevant international standards are provided by the International Organization for Standardization (ISO):

Table 7-1System Management Certification

Certification	Area	Relevance to district heating
ISO 9001	Quality Management (QMS) System-defines the general requirements for the development, implementation, and continual improvement of quality management systems to ensure that customer requirements are consistently met and service performance is maintained at a high level.	Ensures delivery of quality service, reliable processes, and customer satisfaction.
ISO 14001	Environmental Management System (EMS) ISO 14001 is the internationally recognized standard for environmental management systems. It provides a framework for organizations to design and implement an EMS, and continually improve their environmental performance	Helps manage and reduce the environmental impact of the DH operations
ISO 50001	Energy Management System (EnMS) ISO 50001 provides a framework of requirements for organizations to: • Develop a policy for more efficient use of energy • Fix targets and objectives to meet the policy • Use data to better understand and make decisions about energy use • Measure the results • Review how well the policy works, and • Continually improve energy management.	This is highly relevant as it focuses on systematically improving energy performance, reducing consumption, and increasing efficiency across the DH network and generation plants.

Personnel Certification: Personnel Certification is essential because even the best standards, products, and system designs can fail if the people implementing and operating them lack the necessary knowledge and skill. It bridges the gap between theoretical standards and practical application. Training and qualification of engineers, installers, and operators to ensure the correct application and implementation of standards, guaranteeing safe, efficient, and compliant operation of district heating systems.

Sustainability Certification: Labels and schemes that verify low-carbon, energy-efficient, or renewable-based district heating solutions, enhancing credibility for consumers and policymakers.

Sustainability Certification schemes are focused on verifying that a district heating solution is environmentally responsible and contributes to climate goals. These schemes provide concrete evidence that the system meets low-carbon, energy-efficient, or renewable-based criteria.

7.4 Benefits of Standardisation and Certification

For Utilities: Improved efficiency, reduced operational risks, and easier integration of renewable energy.

For Manufacturers: Market access, competitiveness, and credibility through conformity with recognized standards.

For Consumers: Increased trust in service reliability, billing accuracy, and environmental performance.

For Policymakers: Transparent benchmarks for regulation, public procurement, and monitoring progress toward climate goals.

References

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8. Contemporary Energy Trends

8.1 Energy and Its Associated Global Effects

8.1.1 Global energy consumption

The material presented in this document represents an analysis based on public data and information, regarding the current energy consumption of humanity and the global impact that the effects of this energy consumption present. The adjacent figure shows the curve of variation of global energy consumption between 1800 and 2023.

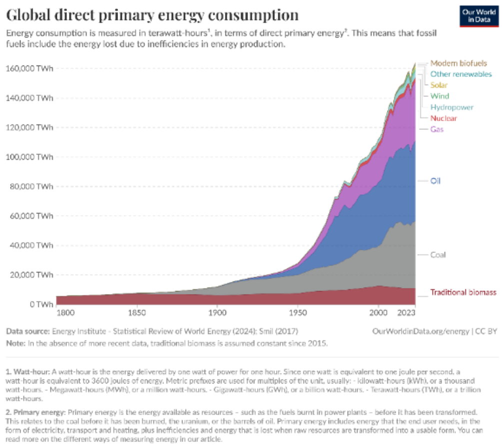

Figure 8-1 Variation of global energy consumption [1]

In 1800, global energy consumption was estimated at approximately 5,650 TWh/year. By 2019, this value had increased to 160,764 TWh/year (commonly rounded to 160,000 TWh/year), indicating a 28.11-fold increase over the course of 220 years. The first 100 years of this period (1800–1900) were characterized by a heavy reliance on biomass, which consistently accounted for more than 90% of the total energy supply. Coal represented the only other significant energy source during this timeframe.

The upward trend in the consumption of fossil fuels and even biomass is noteworthy, although in recent years there has been a slight downward trend in biomass. On the other hand, there is also an increase in energy production from nuclear fuels and renewable sources, but the share of these forms of energy is just over 7% and 7.47% respectively.

8.1.2 The relation between energy consumption, population and economic development

The accelerated growth in energy consumption worldwide is driven on the one hand by population growth and on the other hand by economic growth. The figures below show the curve for change of the world population in the last 12000 years, respectively the curve of change of the gross *domestic product (GDP*), at world level, in the last 2000 years.

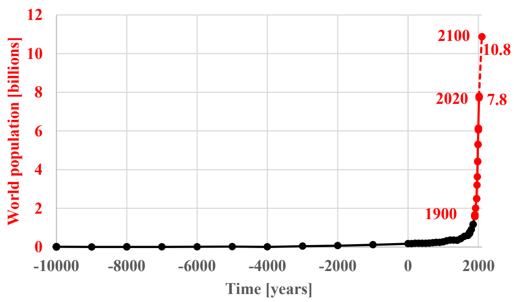

Figure 8-2World population variation (12000 years)[2]

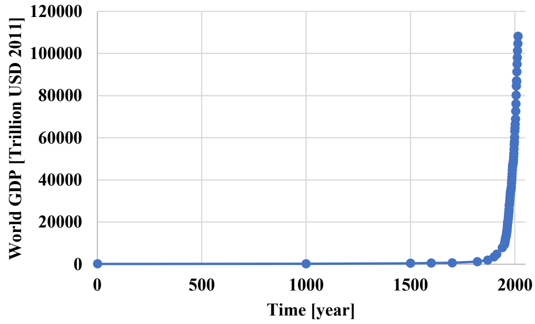

Figure 8-3 World GDP change (2000 years)[3]

On the graph of population change, the UN estimate of population growth up to 2100 is also included, and the values on the graph of GDP change are expressed in USD at the 2011 value.The next figure shows the curve of variation of energy consumption worldwide, starting with the year 1800 (period for which data are available), but related to the time scale considered for the last 2000 years.

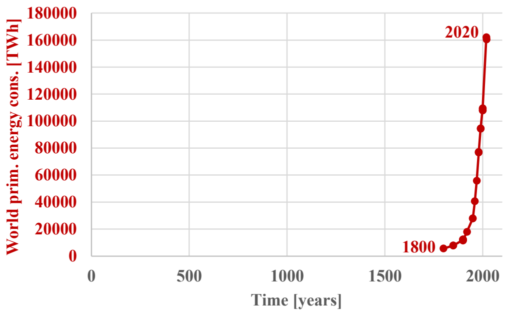

Figure 8-4Worldwide energy consumption variation (since 1800)[4]

A comparative analysis of global population, GDP, and energy consumption trends indicates that beginning around the year 1800, and continuing over the past 200–220 years, all three parameters have experienced rapid and sustained growth. This acceleration is strongly associated with the expansion of industrial activity, technological progress, and improved standards of living. The accompanying figure presents the global variation curves for population, GDP, and energy consumption over the period from 1800 to 2020. It is noted, however, that the GDP curve includes available data only up to August 2015.

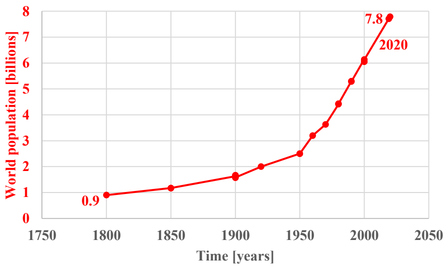

Figure 8-5 Curba de variație a populației la nivel mondial[5]

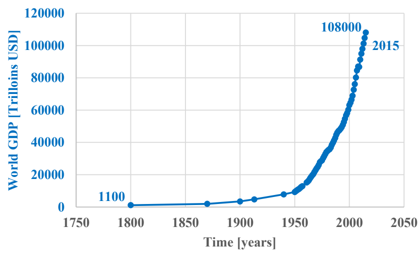

Figure 8-6 Curba de variație a PIB la nivel mondial [5]

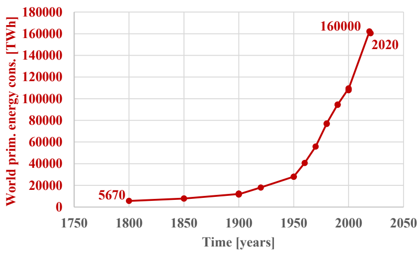

Figure 8-7 Curba de variație a consumului de energie la nivel mondial[5]

The population growth rate is lower than the GDP growth rate, and the growth rate of energy consumption is between the two, which confirms that both the number of inhabitants and the economic development through GDP influence energy consumption, but the share of economic development is higher.

- The population has increased 8.7 times (from 0.9 billion in 1800 to 7.8 billion in 2020).
- GDP grew 98.2 times (from $1100 trillion in 1800 to $108,000 trillion in 2015).
- Energy consumption increased 28.2 times (from 5670 TWh in 180, to 160000 TWh in 2020).

In view of this rapid and complex development, the question arises: ***Is the way human society develop sustainable?***

8.1.3 Energy consumption and CO_2 emissions

A direct and immediate effect of the production of energy from fossil fuels (*the share of these fuels – including biomass – in current energy production is 92.28 %*) is represented by CO_2 emissions, which result from the combustion of these fuels. In the accompanying figures, the evolution of the amount of CO_2 emitted annually into the atmosphere, at global level, compared to the period of the last 2000 years, respectively from the year 1750, is presented.

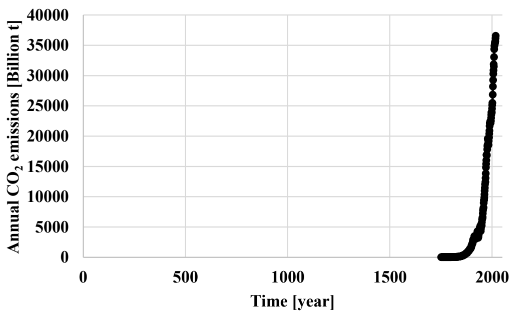

Figure 8-8 Global CO_2 emissions (2000 years)[5]

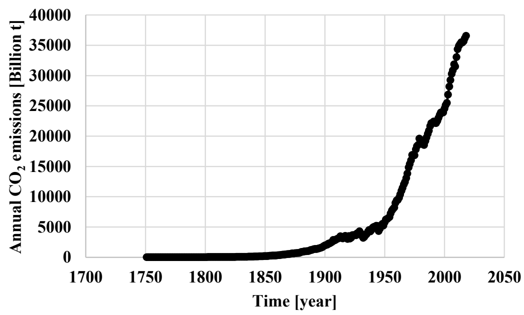

Figure 8-9 Global CO_2 emissions (since 1750)[5]

The level of CO_2 emissions has increased 3911 times (from 9.3 billion tons in 1970 to 36573 billion tons in 2018.The direct effect of the increase in the amount of CO_2 emitted into the atmosphere is the increase in the concentration of CO_2 as shown in the figure below. In 2024, the CO_2 concentration was 422.05 ppm.

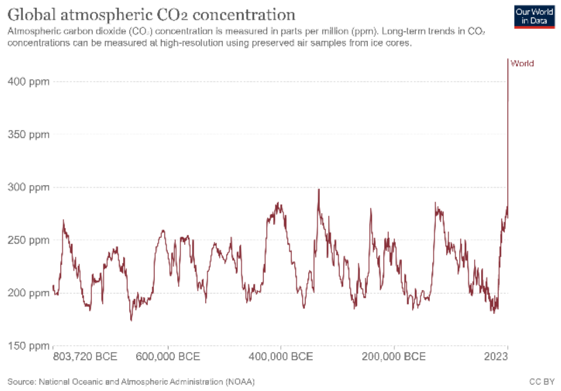

Figure 8-10 Global atmospheric CO2 concentration [6]

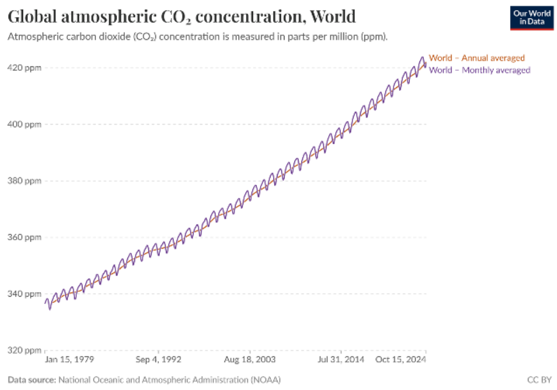

Figure 8-11 Global atmospheric CO2 concentration[7]

Measurement of the concentration of CO2 in the atmosphere is usually carried out in locations far from human activities, in isolated areas, where industrial development does not influence the results of the measurements. The next figure shows the locations of the World Meteorological Organization (WMO) stations where measurements were made in 2014, in the northern hemisphere. The figures also note the values recorded in April 2014. It is observed that all values exceeded 400 ppm, and this phenomenon happened for the first time in the history of measurements of the concentration of CO2 in the atmosphere.

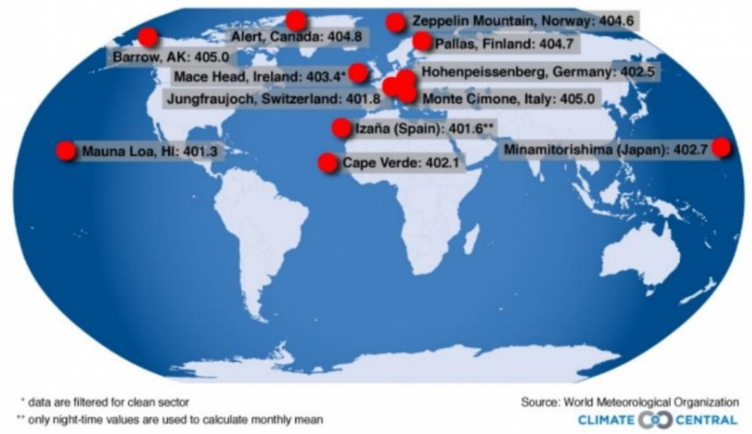

Figure 8-12Locations in the Northern Hemisphere where the concentration of CO_2 in the atmosphere is measured[8]

The figure the locations of all stations measuring the CO2 concentration in the atmosphere.

Figure 8-13 Locations where measurements of the concentration of CO_2 in the atmosphere are made [9]

The annual variations in CO_2 concentration are explained by the fact that every year, in the northern hemisphere that contains the vast majority of land, in the spring and summer period when the vegetation is green, plants absorb CO_2 from the atmosphere, through photosynthesis and thus the CO_2 concentration decreases, and in the autumn and winter period when the vegetation dries out, this process is no longer possible, and the concentration of CO_2 increases. The reduction of CO_2 concentration through photosynthesis carried out by vegetation is thus felt at a planetary level, and vegetation behaves like a "planetary" lung that performs an "exhalation" and an "inhalation" every year, and the concentration of CO_2 varies in accordance with this rhythm of "breathing" of the vegetation. The systematically recorded annual variation in the concentration of CO_2 in the atmosphere clearly reveals the importance of vegetation (i.e. green leafy plants and trees) in reducing the concentration of CO_2.

Correlation between CO_2 concentration and average atmospheric temperature

The correlation between CO_2 concentration and temperature is shown in the accompanying figure.

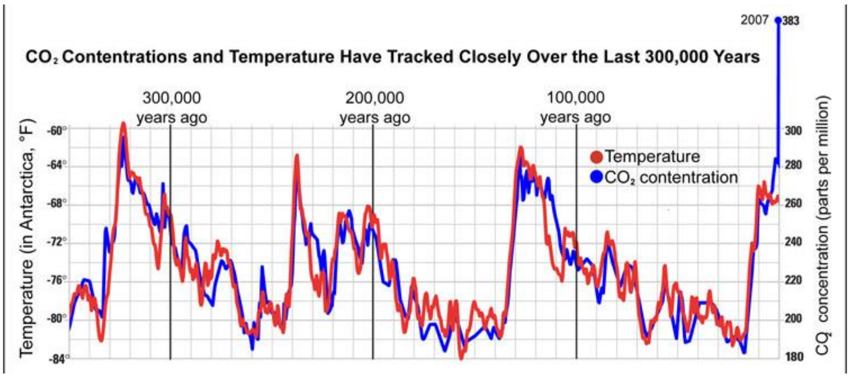

Figure 8-14 Correlation between CO_2 concentration and temperature, in the last 350000 years[10]

These curves, with consistent variations, suggest that there is a problem in terms of CO_2 emissions and suggest that there is a dependence between the concentration of CO_2 and the problem of global warming. The accompanying figure shows the variation of the average annual temperature on the globe, compared to the average temperature from 1850 to 2023.

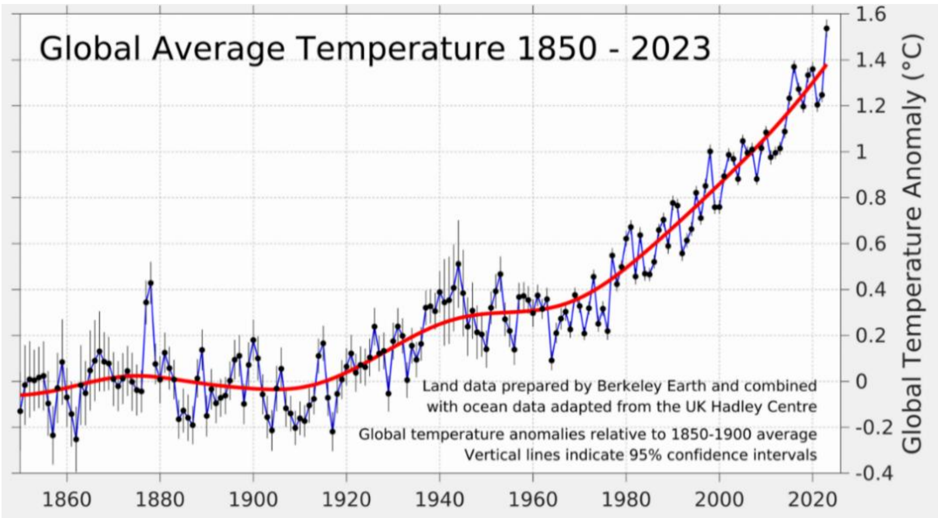

Figure 8-15 Variation of the world average annual temperature, compared to the average from 1850...1900 [11]

The adjacent figure shows the distribution of the local average annual temperatures in 2020 on the globe, compared to the average temperature in the period 1951 – 1980.

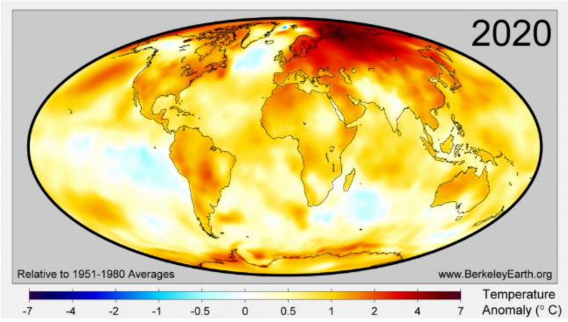

Figure 8-16 Worldwide distribution of local average annual temperatures in 2020[12]

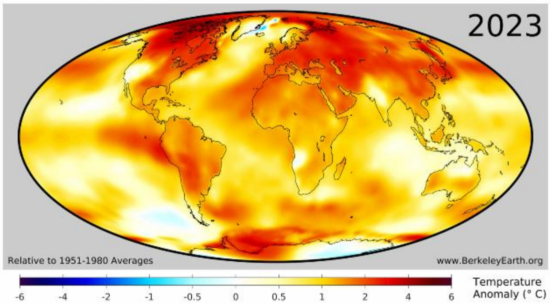

Figure 8-17 Worldwide distribution of local average annual temperatures in 2023[13]

Outside of small areas, practically all over the planet, the average annual temperature is higher than the average of the reference period, and the image is suggestive of the "global warming" of the planet, which is the most pronounced in the areas of the two poles.The accompanying figure shows the scenarios of variation in the average annual temperature of the atmosphere, correlated with the corresponding variations in CO_2 emissions.

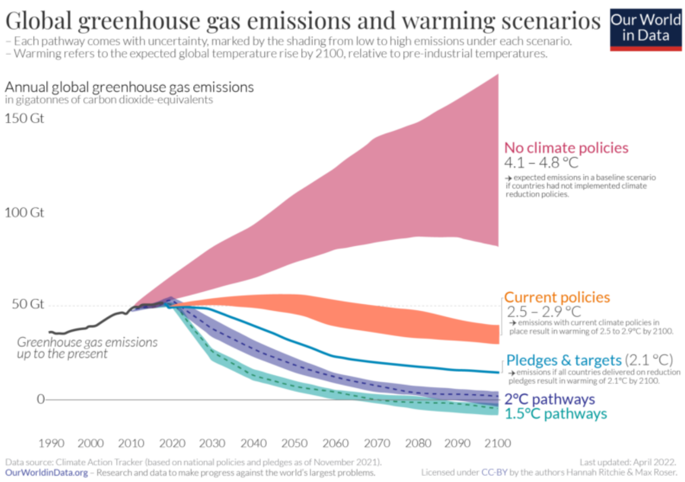

Figure 8-18 Scenarios of atmospheric temperature variation, correlated with variations in CO_2 emissions[14]

It is noted that:

- In the absence of measures to reduce CO_2 emissions, by the year 2100, the average temperature will increase by (4.1 – 4.8) °C.
- If current CO_2 emission reduction policies are maintained, the average temperature will increase by (2.5 – 2.9) °C.

- If the commitments are met and the announced CO_2 reduction targets are achieved, the average temperature will increase by 2.1 °C.
- Reducing emissions levels to close to 0 in 2100 will allow the average temperature to increase by 2°C.
- Reducing the level of emissions to zero by 2070, followed by reducing the concentration of CO_2 in the atmosphere (negative emissions), will allow the average temperature to increase by 1.5 °C.
- Due to the current remarkably high concentration of CO_2 in the atmosphere, the average temperature of the atmosphere will continue to rise, even if it is possible to fit into the most optimistic scenario.

The accompanying figures show the level up to which CO_2 emissions must be reduced, so that the average annual temperature does not rise above 1.5% and 2% respectively.

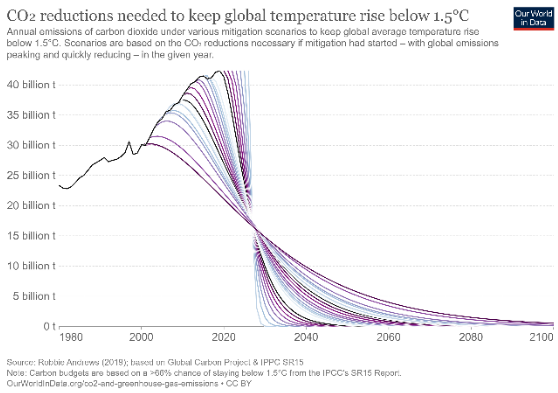

Figure 8-19 the level up to which CO_2 emissions must be reduced, so that the average annual temperature does not rise above 1.5%[15]

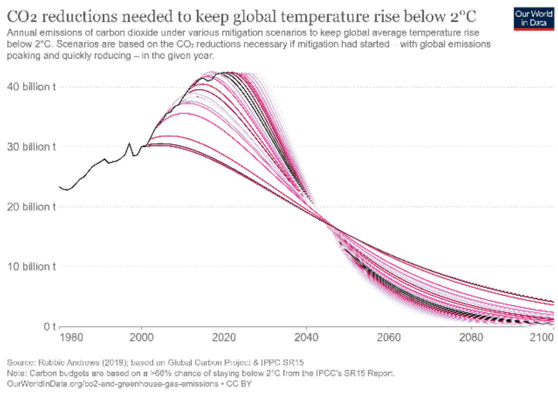

Figure 8-20 the level up to which CO_2 emissions must be reduced, so that the average annual temperature does not rise above 2%[16]

8.1.4 Effects of global warming. Rising ocean levels

Due to global warming, many localities located on the coasts of the oceans could become uninhabitable due to the rise in ocean water levels, caused by the melting of the ice at the two poles.15 coastal cities in the U.S. are set to be permanently flooded by 2050 due to rising ocean levels, and 10 of them are already at sea level.

Figure 8-21Miami.Simulation for ocean level rises by 2.4 m[17]

Figure 8-22New York. Manhattan. Simulation. 2014[18]

Figure 8-23Boston.Simulation. The extreme scenario[19]

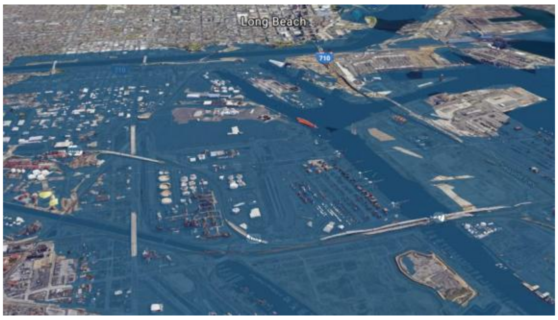

Figure 8-24Los Angeles.Simulation. The extreme scenario[20]

8.1.5 Effects of global warming. Reducing the amount of fresh (drinking) water

Water *stress* problems arise when the demand for water exceeds the amount available in each period and location, or when poor quality restricts its use. "*Water stress*" is determined by the deterioration of freshwater resources in terms of quantity (overexploitation of aquifers, drying up of rivers, etc.) and quality (eutrophication or transformation into swamps, pollution with organic matter, saline intrusion, etc.). A map of "water stress" is shown in the adjacent figure.

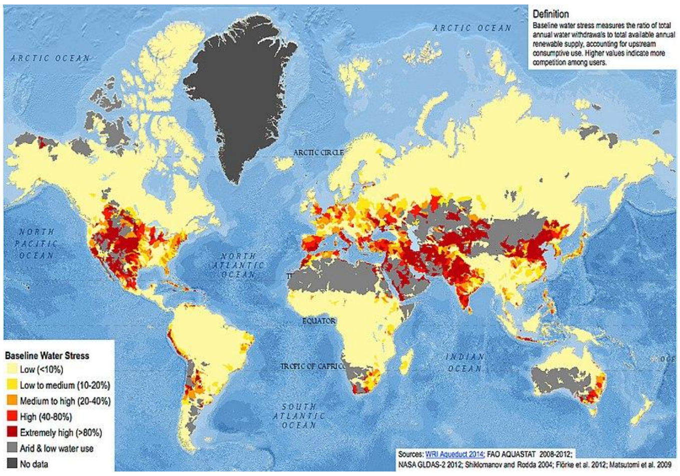

Figure 8-25 Map „*water stress*”[21]

Currently, 2.6 billion people (in 2018) are affected by the problem of insufficient drinking water.One of the reasons for the reduction in the amount of water available is the melting of glaciers in the mountains, which have a particularly important share among drinking water sources. For example, the glaciers of South Asia, located at an altitude of over 2000 m, supply water to the watersheds of large rivers (Indus, Ganges, Yellow, Brahmaputra, Yangtze), which provide water for 1.4 billion inhabitants representing 18% of the planet's population. About half of the planet's population, i.e. 4 billion people, suffer from severe water scarcity at least one month a year, and approx. half a billion people suffer from severe water shortages throughout the year. These data refer to the year 2017.

8.1.6 Effects of global warming. Ecological problems of ocean water warming

With global warming, because of the melting of ice in the polar regions, solar radiation manifests itself differently in the following aspects:

- is reflected to a lesser extent back into the atmosphere (the effect is due to ice and snow, and their surface is reduced)
- is absorbed to a greater extent by ocean water (which causes them to warm up further)

As a result of the increase in ocean water temperatures, important ecological problems arise, the biggest being the death of coral reefs, which are extremely sensitive to the increase in water temperature, which leads to the complete destruction of coral-based marine ecosystems.

Recommended technologies for energy production

The energy technologies that can be recommended must present:

- Specific emissions (relative to the unit of quantity of energy produced) of CO_2 should be as low as possible.
- Highest possible operational safety

It is obvious that ***to reduce CO_2 emissions, the consumption of fossil fuels must first be reduced***.

The accompanying figure shows both the level of specific emissions (relative to the unit of energy produced) of CO_2 and the degree of safety of using each energy source currently available.

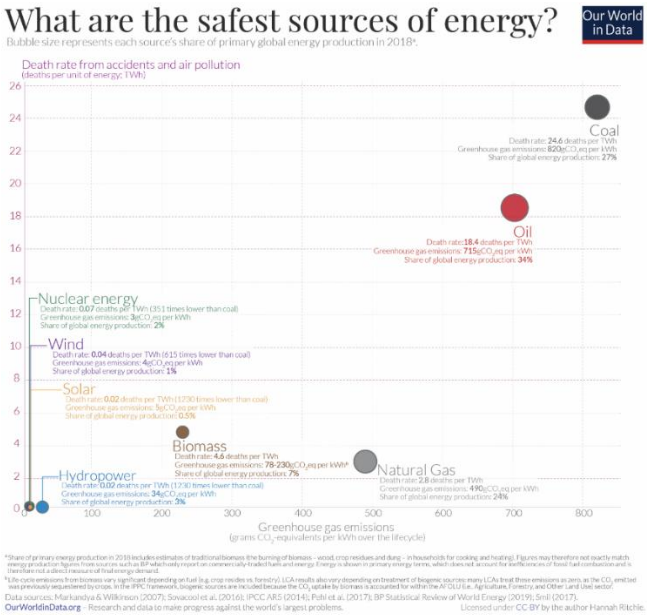

Figure 8-26The level of specific CO_2 emissions and the degree of safety of each energy source[22]

Both the highest levels of specific emissions and the rate of deaths due to accidents and pollution correspond to the use of coal and oil, with these fuels also corresponding to the highest shares in energy production: 27% and 34% respectively, i.e. 61% combined. Natural gas corresponds to the third level in terms of specific emissions, but a higher degree of safety, with the rate of deaths due to accidents and pollution lower.

Biomass has the fourth highest level of specific emissions (lower than natural gas), but a lower degree of safety of the industry compared to natural gas. The lowest levels of specific CO_2 emissions correspond to the use of renewable energy sources (water, sun, and wind), but also to nuclear energy. The same energy sources also present the highest safety. Surprisingly, nuclear energy is also part of the category of the safest energy sources, which is nevertheless associated with the problem of producing radioactive waste. Following the analysis of the information presented, ***the most appropriate solutions for reducing CO_2 emissions are represented using renewable energy sources (water, sun and wind), but also nuclear energy***.

8.1.7 Energy Consumption Required for Equipment Manufacturing

A particularly important and often debated issue, which must not be overlooked, concerns the significant amount of energy required for the manufacturing of equipment used to generate energy from renewable sources.

The example of photovoltaic collectors

For the construction of photovoltaic collectors, the following materials are primarily used:

- Series-connected photovoltaic cells (producing electricity)
- Low iron glass (thermally tempered to increase strength)
- Aluminum frame (which provides mechanical strength)

Indeed, ***the production of all these materials is energy-intensive*** (requires high energy consumption).

The production of these materials also causes ecological problems (especially in the case of photovoltaic cells and aluminum), for the extraction of the necessary raw materials:

- Quartz for Photovoltaic Cell Manufacturing
- Bauxite for Aluminum Fabrication
- fuels for the melting of these raw materials

Waste results in the manufacturing processes of these materials.

- In the case of photovoltaic cells, the silicon crystals actually used in their construction represent about 50% of the raw material used, and the rest represents losses, and production waste respectively.
- In the case of aluminum, caustic soda is used in the manufacturing process, and slag is produced by casting.

The manufacturing processes of these raw materials and materials are also associated with contamination or pollution of the technological water used in these processes.

The example of wind turbines

The construction of wind turbines requires energy-intensive materials and manufacturing processes, which also generate environmental concerns related to production impacts and waste management, similar to those associated with other industrial products.

A study examining the relationship between the energy produced over a turbine's lifetime and the energy required for its manufacturing—referred to as the Energy Return on Investment (EROI)—analyzed data from 119 turbines reported in 50 scientific publications (1977–2007). The results showed that wind turbines generate, on average, approximately 25 times more energy during their operational lifetime than is consumed in their production, with higher EROI values associated with turbines of greater installed capacity [23] The following table presents Energy Recovery Ratio (ERR) values for several energy-production technologies, as reported in the same study.

Power source	**"Energy Recovery Ratio" (ERR)**
Wind	25.2
Nuclear	15.8
Hydraulic	12.0
Geothermal	11.0
Solar (thermal)	9.0
Coal	8.0
Solar (PV)*	6.5

8.1.8 The issue of solar thermal systems for electricity production

Solar thermal power plants designed for electricity production are typically hybrid systems, supported by natural gas, which often supplies the majority of the generated electricity.

A representative example is the Ain Beni-Mathar plant in Morocco, which uses parabolic trough collectors covering 183,120 m², heating diathermic oil to 390°C. The plant includes two 150 MW gas turbines and a 172 MW steam turbine, resulting in a total natural gas–

based capacity of 472 MW. The solar field can provide approximately 130 MW of thermal energy, enabling the production of only 30–35 MW of electricity, equivalent to 7–7.5% of total output. At night, the plant operates solely on natural gas.

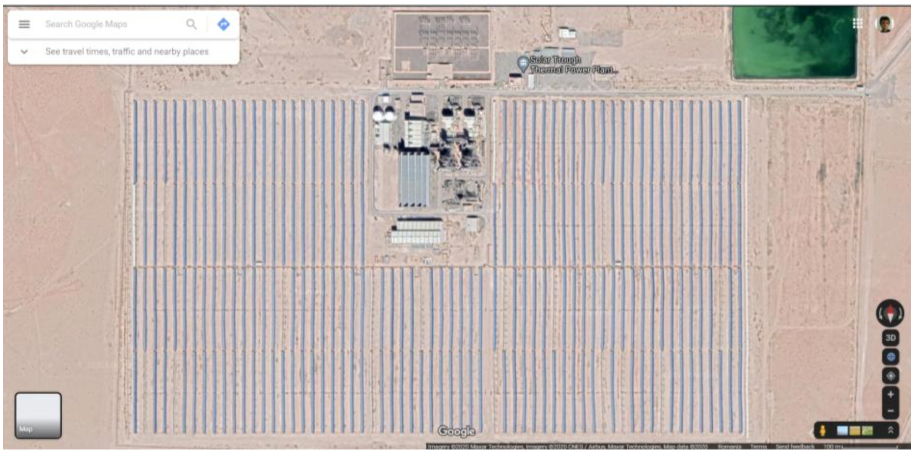

Figure 8-27 Site (location) of the solar thermal power plant in Ain Beni-Mathar, Morocco [24]

This example illustrates that most so-called *solar thermal* power plants function predominantly as **natural gas facilities**, with solar energy providing only a **minor supplementary share**.

8.1.9 Fusion, a promise for the future

Nuclear fusion is a reaction in which two or more atomic nuclei combine at extremely high velocities to form a heavier nucleus, releasing energy in the process. This reaction requires very high temperatures and pressures, such as those found in stars, where gravitational forces provide the necessary conditions. When nuclei lighter than iron undergo fusion, the reaction yields more energy than is required to form the new nuclear bonds, making fusion a potential energy-producing process.

Note: Fusion involving nuclei heavier than iron requires an external energy input, as more energy is needed to form stable nuclear bonds than the reaction can release.

The figure below illustrates the fusion reaction between **deuterium (^{2}H)** and **tritium (^{3}H)**, forming **helium-4 (^{4}He)** and releasing a **neutron**, along with a significant amount of energy.

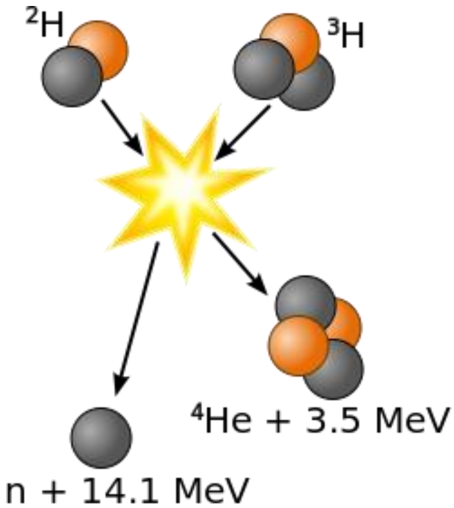

Figure 8-28 Fusion reaction diagram between deuterium (H^2) and tritium (H^3)[25]

The first artificial nuclear fusion experiment was carried out in 1932 by Mark Oliphant at the Cavendish Laboratory, University of Cambridge. In this experiment, accelerated deuterium atoms were used to bombard other deuterium atoms, resulting in the fusion of some nuclei and the formation of helium. The energy released was proportional to the mass deficit, in accordance with Einstein's equation $\boldsymbol{E = mc^2}$.

A major challenge in achieving controlled artificial fusion is the requirement for extremely high temperatures—approximately 100 million K, about six times the temperature at the Sun's core. Under these conditions, hydrogen exists not as a gas but as plasma, which no solid material can withstand, making magnetic confinement the most feasible solution. International cooperation on fusion research expanded after 1950, once studies in the United Kingdom, the United States, and the USSR confirmed that controlled fusion had no military application. By the 1970s, global research largely shifted toward tokamak technology—developed in the USSR—which uses a toroidal magnetic field to confine and stabilize plasma. One of the most significant international research initiatives in this field is ITER (International Thermonuclear Experimental Reactor), developed collaboratively by the EU, USA, Japan, Russia, China, South Korea, and India. The ITER reactor is designed to produce 500 MW of energy output while requiring approximately 50 MW of input power to sustain fusion, serving as a large-scale experimental platform to demonstrate the feasibility of commercial fusion power.

The figures below illustrate the operating principle and a 3D model of the ITER tokamak reactor.

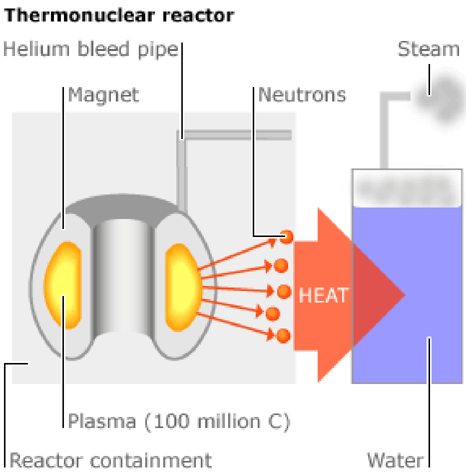

Figure 8-29 Outline of the operating principle of ITER[26]

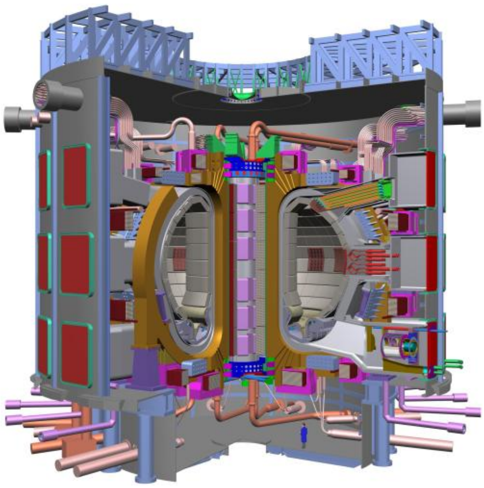
Figure 8-30 Virtual image of the ITER fusion reactor[27]

Currently, MIT University in Boston and spinoff company Commonwealth Fusion Systems are collaborating on a new type of nuclear fusion reactor, called the *Smallest Private-Funded Affordable Robust Compact (SPARC).* The innovative element of the project is the use of magnets made of *high-temperature superconducting magnets*, which became available long after the start of the ITER project. In addition, these magnets can develop a much stronger magnetic field (21 Tesla, compared to 12 Tesla in the case of ITER magnets). It is supposed to produce at least 2 times more energy than it will consume to maintain the fusion reaction, but it is estimated that it will produce 11 times more energy.The accompanying figures show a virtual image of the new SPARC reactor and a link to an interview with the director of the MIT Plasma Laboratory.

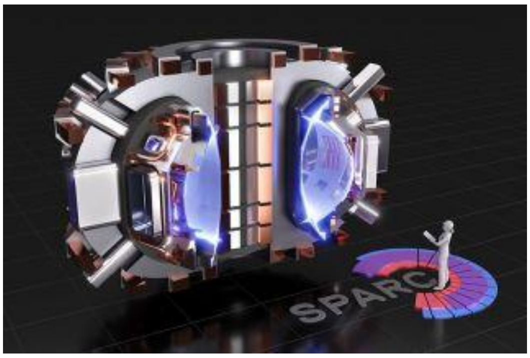

Figure 8-31Virtual image of the new SPARC reactor[28]

Thanks to the stronger magnets, the core diameter of the new type of reactor can be 3 times smaller than that of the ITER reactor (i.e. 2 m instead of 6 m), and the volume of the core can be 60 - 70 times smaller than that of the ITER reactor. These dramatic reductions in size are obviously accompanied by dramatic cost reductions, which is why it is estimated that the new project will be a success.Some of the great advantages of using the fusion reaction for energy production are:

- It does not produce CO2 emissions or other greenhouse gases
- The reaction produces heat that can be used to produce steam, and this can be converted into electricity by conventional technologies, without the need for changes to the electricity transmission system
- The technology is safe (the conditions for maintaining the fusion reaction are very difficult to maintain and any technical problem leads to cooling of the plasma and interruption of fusion reactions – uncontrolled propagation of fusion reactions is not possible, as in the case of the Chernobyl and Fukushima accidents)
- There are no military applications of controlled fusion reactions
- Does not produce radioactive waste

Final considerations

At present, humanity finds itself characterized in a moment by

- Rapid population growth
- accelerated development based on extensive exploitation of available resources
- increasing need for energy due to the two factors mentioned above
- The energy needed is produced by fossil fuel-based technologies
- existing energy technologies are characterized by high CO2 emissions
- The concentration of greenhouse gases in the atmosphere causes global warming
- The effects of global warming are increasingly visible and severe:
  - Rising sea levels
  - warming of ocean water with destructive (catastrophic) ecological effects
  - reducing the availability of drinking water
  - Increasingly frequent and devastating extreme weather events
- ***The current model of economic and social development of humanity is unsustainable***

One of the viable solutions to mitigate these effects is the use of renewable energy sources.A solution to solve the energy problem is represented by using nuclear energy by fusion.

8.2 Towards smart energy systems

The material presents a *vision on the transition from classic energy systems to a new energy concept*, which has emerged and is being implemented in Denmark (and gradually throughout the EU), respectively to ***intelligent energy systems (IES), which use 100% renewable energy sources***. This concept is promoted by the Aalborg University in Denmark, is based exclusively on existing technologies and has an *implementation horizon of **2050***.The following figure shows the simplified scheme of principle of classic energy systems, based on the use of fossil fuels.

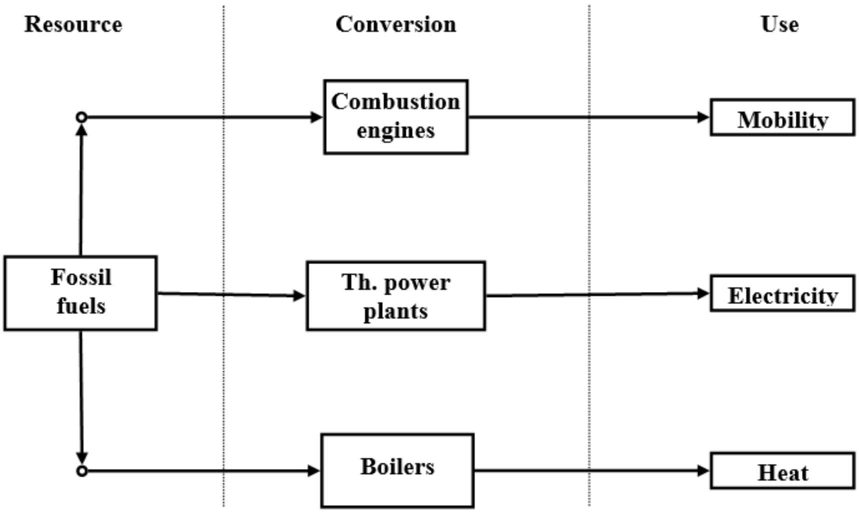

Figure 8-32 Schematic of principle of classic energy systems, based on fossil fuels

These systems are characterized by the fact that they are based entirely on (chemical) energy embedded in fossil fuels, mainly coal, oil and natural gas. The energy embedded in fossil fuels is released in the form of heat, through combustion, and this is converted into mechanical work (for mobility) or electricity.The classic technologies for converting chemical energy into fuels are characterized by CO_2 emissions, the most famous greenhouse gas, which is most responsible for global warming, one of the phenomena to combat which urgent efforts and measures are needed worldwide.There is very little flexibility in the use of the final forms of energy obtained. Thus, at most electricity is sometimes used to produce heat, but in principle, the use of the forms of energy obtained is individual and there are no interactions between the final forms of energy.One of the problems of classical energy systems is that in the context of population growth and economic activity, energy consumption also increases, so the consumption of fossil fuels also increases, in the context in which their availability is limited, so it is foreseeable that fossil fuel resources will be exhausted at some point, which is one of the reasons for replacing these systems.Classical energy systems were the basis of the development of human society, starting around 1760, with the period of industrial development and lasting until approximately the end of the twentieth century, around the 1990s.

Currently, in many countries of the world, and primarily in the European Union, there are plans and initiatives to reduce the use of fossil fuels, *in favor of renewable energy sources*, in all areas, which allows the transition to ***smart energy systems***.Directive 2010/27/EU of the European Parliament and of the Council on energy efficiency states: "*The Union is facing unprecedented challenges caused by* ***increasing dependence on energy imports and the low amount of energy resources****, as well as the* ***need to limit climate change*** *and overcome the economic crisis*".

8.2.1 The first stage of the transition to smart energy systems

The first step in the transition to energy systems based on renewable energy sources is to partially replace the use of fossil fuels with bioenergy fuels (biofuels).This measure began to be implemented around the 1990s.The next figure shows the first stage of transition to the IES.

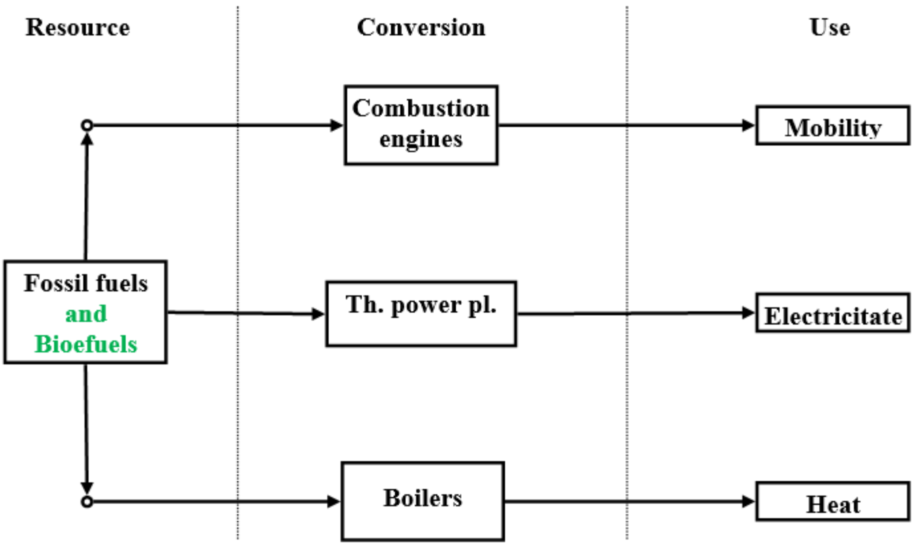

Figure 8-33Principle diagram of energy systems after the first stage of transition to IES

The solution to the use of bioenergy fuels is limited, because the areas available for energy crops are limited and because there is an unresolved dispute over the destination of agricultural land, i.e. for the cultivation of plants that produce food for a growing population, or for the cultivation of energy plants that contribute to reducing the pressure on the use of fossil fuels.

8.2.2 The second stage of the transition to smart energy systems

The second stage of the transition to energy systems based on renewable energy sources consists of ***reducing specific energy consumption*** in all areas. The accompanying figure shows the diagram of principle of the energy systems after the second stage of transition to the IES.

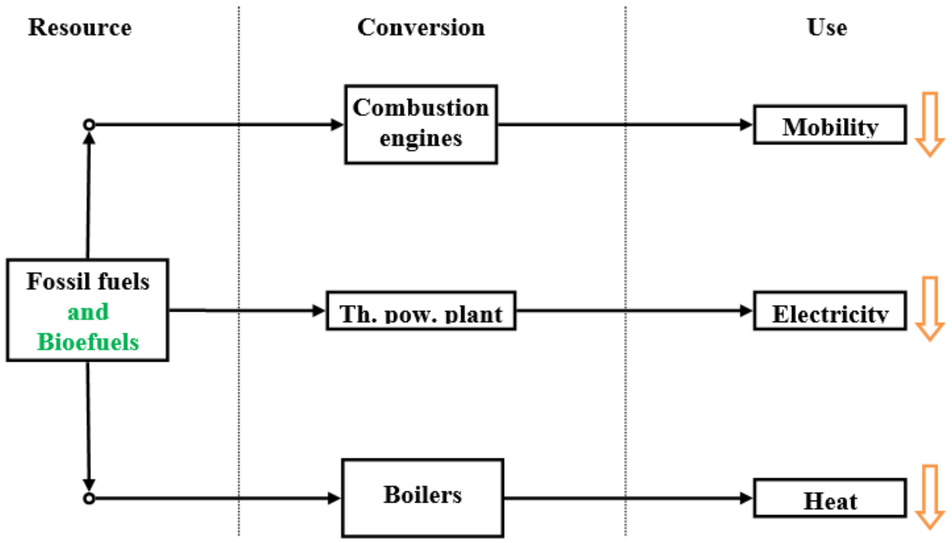

Figure 8-34Principle diagram of energy systems after the second stage of transition to the IES

This stage involves the efficiency of the use of electricity and mobility, but also the reduction of the heating needs of buildings, by about (40-60) %, compared to that characteristic for "classic" buildings. *Some of the technical or technological measures which serve this objective have already started to be implemented*.The reduction of electricity consumption can be and is achieved increasingly intensely using *increasingly energy-efficient systems and equipment, with lower and lower consumption*.

The reduction of energy consumption in the field of mobility, respectively of transport, is achieved by increasing the energy efficiency of the means of transport. In this area, the trend of increasing the global volume of mobility must be considered, so that in the future it is expected that the number and length of trips will increase.

The following figures are presented:

- energy losses from motor vehicles (less than 13% of the energy embodied in the fuel is used to move the vehicle), suggesting that *there is a high potential for efficiency in mobility*;
- the evolution of lighting systems, in terms of energy efficiency - currently, the most efficient solutions are those with LEDs (*Light-Emitting Diodes*).

Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings states: 'Buildings are responsible for 40% of total energy consumption in the Union. The construction sector is expanding, which will lead to increased energy consumption. Therefore, reducing energy consumption and the use of renewable energy in the buildings sector are important measures needed to reduce the Union's energy dependency and greenhouse gas emissions."

Several measures to increase the energy efficiency of buildings, aiming to reduce their energy consumption, are also provided for in Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings:

"*After December 31, 2018,* ***new buildings occupied and owned by public authorities*** *are buildings whose energy consumption is almost equal to zero*""*By 31 December 2020,* ***all new buildings*** *will be buildings with almost zero energy consumption*". In this context, practically after 2020, all buildings that are built in the EU must fall into the category "*Nearly Zero Energy Building (nZEB)*". The figure below shows a suggestive image for the energy consumption reduction targets for heating buildings.

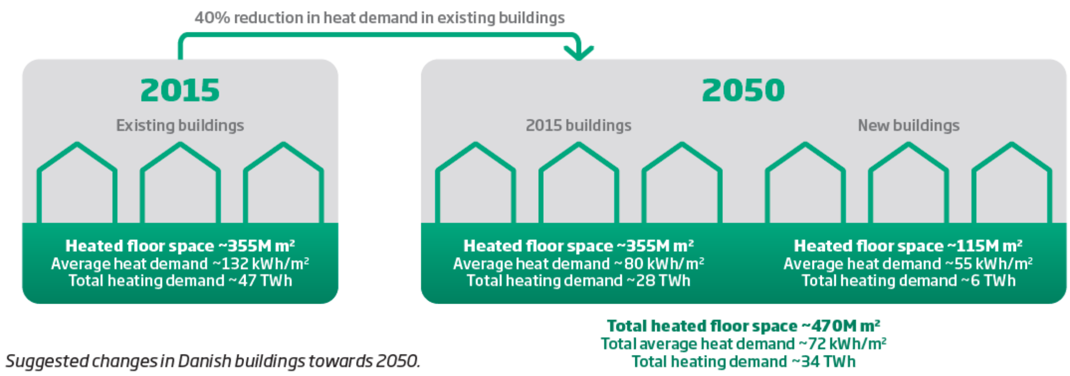

Figure 8-35 The trend of reducing energy consumption for heating buildings

The reduction in heat consumption is noteworthy:

- For existing buildings from 132 kWh/m2/year to 80 kWh/m2/year (≈40% reduction)
- For new buildings at 55 kWh/m2/year (≈60% reduction compared to 2015 level)

Some of the technical and technological measures that allow these low levels of annual heat consumption of buildings are:

- High-performance insulation of the exterior walls (equivalent to about 15-20 cm polystyrene);
- Use of high energy efficiency windows (three layers of glass and inert gas);
- Use of advanced mechanical ventilation and heat recovery systems;
- Use of low-temperature heating systems (fan coils or underfloor heating);

- Integration of energy systems based on renewable energy sources into the building

8.2.3 The third stage of the transition to smart energy systems

The third stage of the transition to energy systems based on renewable energy sources consists of ***the interconnection*** of electricity and heat production and distribution systems, as well as ***the use of new resources for heat production***.The accompanying figure shows the diagram of principle of the energy systems after the third stage of transition to the IES.

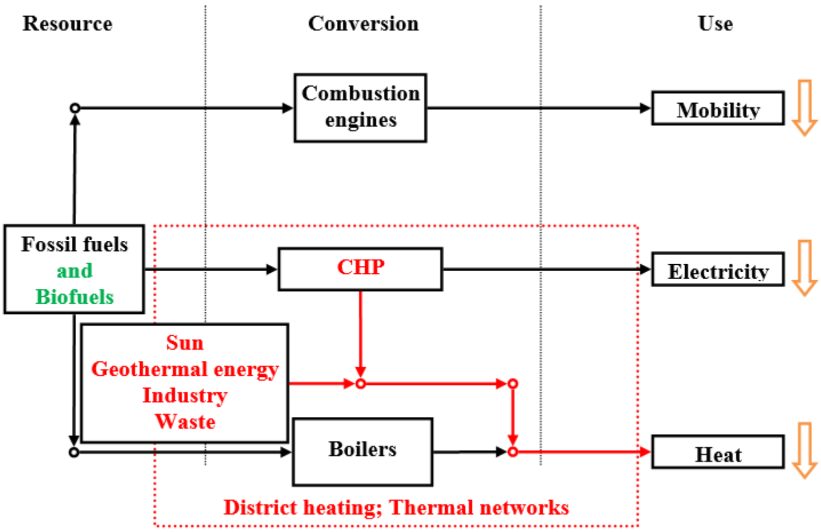

Figure 8-36 Principle diagram of energy systems after the third stage of transition to IES

The most important changes in the heat production and distribution system can be considered as follows:

- ***Abandonment of thermal power plants*** (based on the Steam *Rankine Cycle SRC* – typical for Europe or Asia) and other types of electricity production systems (based on gas turbines – typical for America), with energy efficiency of approx. (30-35) %;
- ***The use of cogeneration systems*** (combined production of electricity and heat), which allow operation with energy efficiency of around 90%. These systems can be based on several possible technologies: internal combustion engines; steam turbines – SRC, gas turbines, organic agent turbines (*Organic Rankine Cycle – ORC*);

- ***Extensive use of renewable or alternative energy sources*** for heat production (*sun; geothermal energy; waste energy from industrial processes; waste incineration*) and reduction of fossil fuel consumption;
- ***Heat distribution through district heating systems*** (*in areas characterized by high energy intensity – crowded/urban areas*

8.2.4 Fourth stage of the transition to smart energy systems

The fourth stage of the transition to energy systems based on renewable energy sources consists of **the integration of renewable sources of electricity production and interconnection with the system of use of thermal energy** through district heating systems, provided with large thermal storage systems, much cheaper than electricity storage systems. Due to the integration between renewable electricity production and the heat use system, the electricity production of wind and photovoltaic systems, although highly variable (daytime and seasonal), can account for around 20% of total electricity production. To this percentage, approx. (10-15) % of electricity needs from cogeneration, thus reaching the share of "renewable" electricity of (30-35) % of electricity consumption.

Heat storage is preferred over electricity because *the costs of heat storage systems are about 50 times lower than those of electricity storage*.

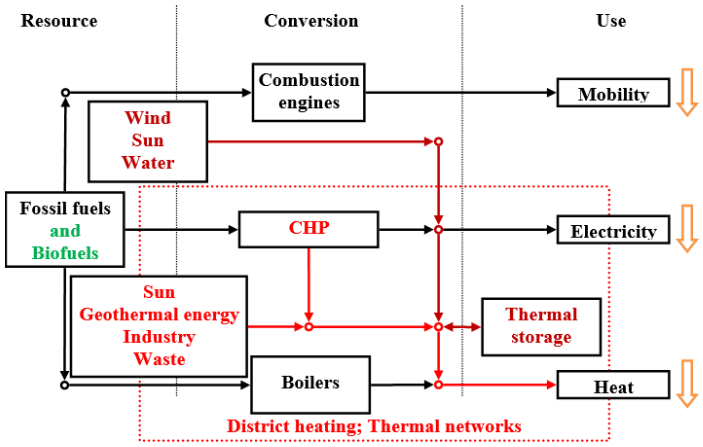

Figure 8-37 Outline of principle of energy systems after the fourth stage of transition to IES

This stage envisages the interconnection of the electrical and thermal networks, practically through heat storage systems (from the composition of district heating systems). Basically, these thermal storage systems have the role of taking over the fluctuations in electricity production, due to the variable nature of the renewable energy sources used to produce electricity. In this way, *electricity can be produced even when it is not needed in national energy systems, being converted into heat*. It should also be mentioned that at times when the electricity production capacities exceed the needs of the national networks (*for example at night*) and the price of electricity is low, so the cost of producing heat from electricity is also low (in Romania, although differentiated electricity tariffs at various times of the day are not practiced on an extended scale, On the electricity exchange, these tariffs vary considerably and decrease a lot during periods when the electricity requirement in the grid decreases).

8.2.5 The fifth stage of the transition to smart energy systems

The fifth stage of the transition to energy systems based on renewable energy sources consists of ***the integration of heat pumps***, for the interconnection of electricity production and heat distribution systems.Heat pumps use electricity to produce heat with very high efficiency. The thermodynamic parameter used to express the energy efficiency of heat pumps is the *coefficient of performance (COP),* which represents the ratio between the thermal power produced and the power consumed. COP has usual values for heat pumps, in the range (3-4), but there are conditions in which the values can be higher. The use of heat pumps with high thermal power (in district heating systems) and those with low thermal power (for individual systems), allows the use of electricity to produce heat even more efficiently, which will have the following effects:

- Increasing the share of electricity from renewable sources to about 40% of the need, in the form of heat, in seasonal storage systems, becomes very efficient;
- Dispensing with individual boilers (except in rare cases where the heated targets are in an area where there is a cheap source of bioenergy fuel).

The accompanying figure shows the diagram of principle of the energy systems after the fifth stage of transition to the IES.

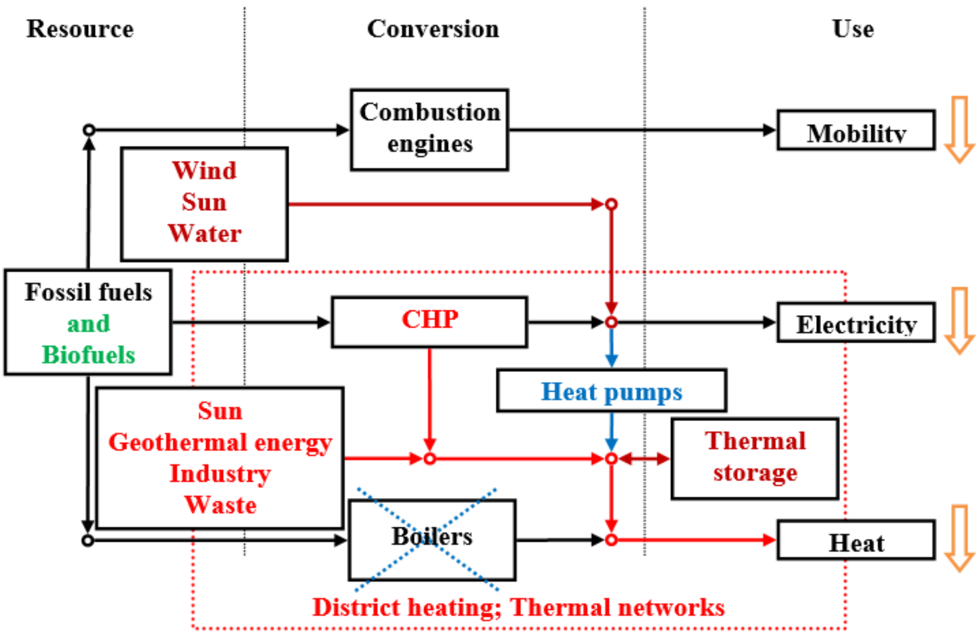

Figure 8-38Principle diagram of energy systems after the fifth stage of transition to IE

The attached figure shows two representative situations of interconnection.

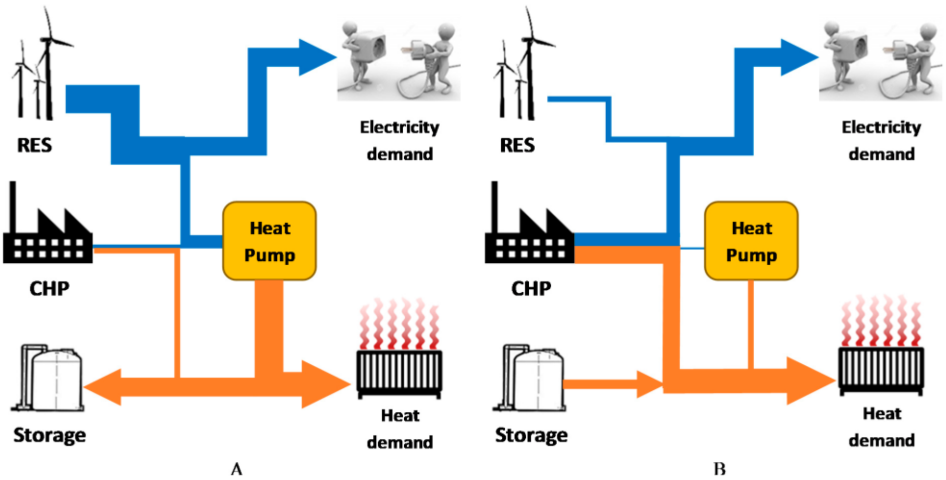

Figure 8-39 Flexible energy system thanks to multi-component networking
A. High availability of electricity from renewable sources; B. Low availability of electricity from renewable sources[29]

If the availability of electricity from renewable sources is high:

- Electricity consumers are fully powered by "renewable" electricity;
- The excess electricity is transformed into thermal energy, through the heat pump;
- The cogeneration system (which normally consumes fossil fuels, or bioenergy fuels if possible) is either shut down or operated at low power;
- The thermal consumers are supplied entirely from the heat pump production;
- The excess thermal energy is sent to the high-capacity (possibly seasonal) thermal storage system.

If the availability of electricity from renewable sources is reduced:

- "Renewable" electricity is consumed entirely by consumers;
- The difference in electricity (until the necessary coverage is covered) is produced by the cogeneration system (with fossil fuel consumption);
- The cogeneration system produces, in addition to electricity and heat, which is used entirely to supply thermal consumers;
- The difference in heat (until the necessary coverage is covered) is taken over from the large capacity thermal storage system (possibly seasonal).

8.2.6 Sixth stage of the transition to smart energy systems

The sixth stage of the transition to energy systems based on renewable energy sources consists of increasing the flexibility of the energy system, by *interconnecting the electricity system and mobility, through **electric cars***.It is estimated that by 2050, (70-80) % of cars will be electric and that their use will increase the share of electricity from renewable sources to (55-60) % of electricity needs, as they are equipped with batteries that represent electricity storage systems.The accompanying figure shows the diagram of principle of the energy systems after the sixth stage of transition to the IES.

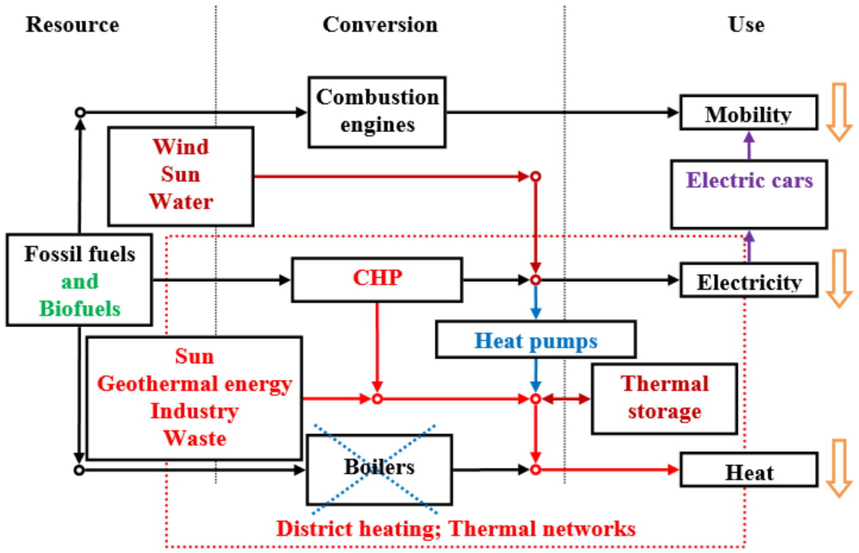

Figure 8-40Diagram of principle of energy systems after the sixth stage of transition to IES

In addition to increasing the flexibility of the electricity system and increasing the share of electricity from renewable sources, the use of electric cars allows the direct reduction of fossil fuel consumption and therefore the corresponding reduction of greenhouse gas emissions and fossil fuel imports, respectively the increase of energy security.

8.2.7 The seventh stage of the transition to smart energy systems

The seventh stage of the transition to energy systems based on renewable energy sources consists of *replacing liquid and gaseous fossil fuels for trucks, ships and airplanes with* ***synthetic fuels***.

Synthetic fuels (liquid or gaseous) can be obtained through various chemical reactions because of which a mixture of CO_2 and H_2 can be converted into hydrocarbons:

- Liquid hydrocarbons (ethylene / CH_2) are obtained by the Fischer–Tropsch process (discovered in 1925), at a temperature of (150-300) °C and a pressure between 1 and a few tens of bar;
- Gaseous hydrocarbons (methane / CH_4) are obtained by the Sabatier process (discovered in 1897), at a temperature of (300-400) °C and at high pressures;

The production processes of synthetic fuels consume electricity.The production and use of synthetic fuels allow *for a sharp increase in the interconnection between the national electricity system and mobility*, which leads to an even greater increase in the flexibility of the energy system.It is estimated that following the replacement of liquid and gaseous fossil fuels with synthetic fuels, approx. 80% of electricity needs can be covered by renewable energy sources.The accompanying figure shows the diagram of principle of the energy systems after the seventh stage of transition to the IES.

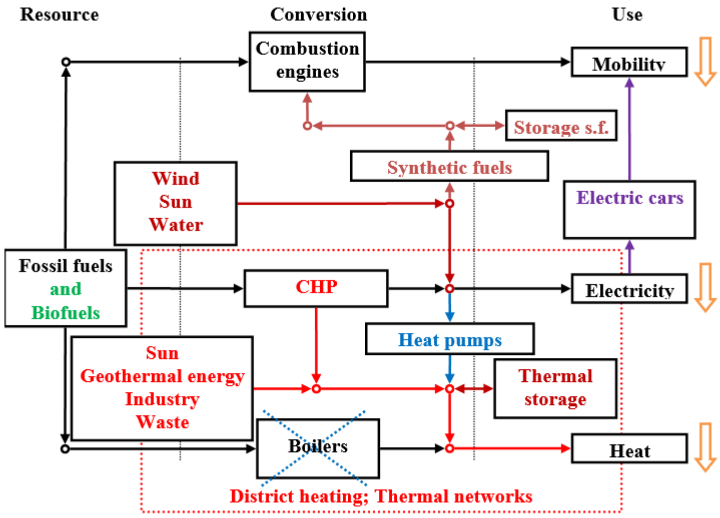

Figure 8-41 Diagram of principle of energy systems after the seventh stage of transition to IES

The use of synthetic fuels in the combustion engines of trucks, ships and airplanes, allows the direct reduction of fossil fuel consumption and thus the corresponding reduction of greenhouse gas emissions and fossil fuel imports, respectively the increase of energy security.Synthetic fuel storage can be achieved in existing fossil fuel storage systems.IES uses bioenergy fuels rationally, without excessive pressure on this type of fuel.The IES is almost 100% based on renewable energy sources and considerably reduces the consumption of fossil fuels (to the point of disposal), which saves the funds used for fossil fuel imports in the country implementing the system.The realization of the IES can only be achieved by implementing known technologies, without considerably increasing the cost of energy. The estimated increase in the cost of energy in 2050 is a maximum of 10%, compared to the current cost, but there are also optimistic scenarios in which the cost of energy remains at the current level.The transition to IES will be achieved through local investments, which will lead to an increase in the number of jobs compared to those in classic energy systems, based on fossil fuels (which is obvious, given the much greater complexity of IES).

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