Module 3
Heat Production

Part of the SHaKE Educational Package on District Heating and Cooling Systems

Guidebook

Reusable teaching resource for higher education and professional training

Version: 1.1
Date: June 2026
https://www.shakeproject-dhc.eu/

Project
Sharing Heat and Knowledge on Energy Communities (SHaKE)
Erasmus+ KA220-HED Cooperation Partnerships in Higher Education
Project No.: 2023-1-HU01-KA220-HED-000160219

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EU funding acknowledgement and disclaimer
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Acknowledgement
This publication has been developed as part of the SHaKE project. The consortium would like to thank all educators, researchers, professionals and stakeholders who contributed to the development, review and improvement of the educational materials.

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Suggested citation:
Universitat Jaume I de Castellón and Budapest University of Technology and Economics. Module 3: Heat Production. SHaKE Project, 2026.
https://www.shakeproject-dhc.eu/

Guide to using Module 3

This module is part of the SHaKE educational package developed to support the teaching of district heating and cooling (DHC) systems in higher education and professional training contexts.

Module 3 focuses on heat production technologies for district heating networks. It combines renewable and low-carbon heat sources, waste heat utilisation, heat pump technologies, combined heat and power (CHP), and the economic and environmental assessment of heat production systems.

The guidebook is primarily intended as a reusable teaching resource for educators, lecturers and trainers. It can be used to support lectures, blended learning activities, classroom discussions, practical assignments, case-study work and continuing professional development training. The accompanying presentation slides, question bank, self-check quiz, practical exercise and case-study materials are designed to help educators adapt the content to their own teaching context.

Students and professionals may also use the module for independent study, especially if they already have basic knowledge of thermodynamics, heat transfer, energy systems, district heating and building services engineering.

Main topics covered in the module

- Primary energy supply and municipal heat production strategies
- Biomass combustion, energy recovery from waste and biogas production
- Solar district heating and thermal energy storage
- Geothermal district heating and cascade utilisation of thermal water
- Waste heat classification, capture and utilisation technologies
- Heat exchangers and active waste heat recovery technologies
- Thermodynamic principles and technologies of heat pumps
- Heat pump applications for waste heat upgrading and district heating
- Combined heat and power (CHP) systems and integration into district heating networks
- Economic and environmental assessment of heat production systems
- Policy instruments, market trends and future considerations for low-carbon heat production

Learning outcomes of Module 3

The module is designed to support the development of the following skills and competences. Upon completion of this module, learners should be able to:

- identify and classify heat production technologies used in district heating networks;
- explain the role of renewable and low-carbon heat sources in decarbonising heat supply;
- compare biomass combustion, gasification, biogas, solar thermal and geothermal heat production options;
- identify, classify and quantify waste heat sources based on origin and temperature profile;
- explain the thermodynamic principles governing heat pump operation;
- evaluate heat pump technologies for heat production and waste heat upgrading;
- describe the operating principles and district heating integration of CHP systems;
- compare technological configurations based on efficiency, cost and environmental impact;
- analyse real-world case studies to assess the feasibility and benefits of integrating renewable heat, waste heat recovery, heat pumps and CHP into district heating systems.

Estimated workload

This module represents approximately 8.4 learning hours, including theoretical assimilation, practical application, case analysis, independent research and assessment.

Educators may adapt the workload depending on the level of the course, the selected materials and the teaching format. The module can be used as a complete teaching unit, a set of selected lecture materials, a blended learning component, a practical exercise package, a case-study package or a supplementary resource for existing courses.

Activities and Learning Hours

Activity Type	Time Allocation	Description
Theoretical Assimilation	4.0 h	In-depth study of lecture materials and critical reading of technical articles and policy documents.
Practical Application	1.0 h	Technical exercises involving efficiency calculations, thermodynamic simulations and economic analyses.
Case Analysis	0.5 h	Critical evaluation of real-world implementations focusing on renewable energy and CHP systems.
Independent Research	2.5 h	Autonomous literature review and environmental impact assessment.
Evaluation	0.4 h	Continuous assessment and final technical project or assessment task to consolidate the acquired knowledge.
Total Learning Hours	8.4 h	

Target groups

This guidebook is primarily intended for educators, lecturers and trainers who wish to use or adapt the SHaKE materials in their own teaching or training activities.

- higher education lecturers in engineering, building services, energy systems, district heating and cooling, HVAC and sustainable energy systems;
- trainers involved in professional or continuing education on district heating and cooling systems;
- educators developing blended, modular or practice-oriented learning activities;
- academic staff seeking reusable teaching resources on sustainable district energy systems;
- students, researchers and professionals interested in renewable heat production, waste heat recovery, heat pumps and CHP in district heating networks.

For independent use, basic prior knowledge in the relevant engineering fields is recommended.

Recommended use by educators and trainers

Module 3 can be used flexibly as a complete teaching unit or as a set of selected teaching resources. Educators may combine the materials according to the level of the course, the available teaching time and the intended learning outcomes.

Teaching need	Suggested Module 3 resource
Introducing the topic	Use the module overview and introductory slides to present the scope, key concepts and relevance of heat production in district heating networks.
Preparing learners before class	Assign selected guidebook sections as pre-reading for flipped classroom or blended learning activities.
Supporting lectures or seminars	Use the presentation slides to explain renewable heat sources, waste heat recovery, heat pumps, CHP and economic or environmental assessment.
Checking understanding	Use selected questions from the question bank for discussion, short in-class checks, formative assessment or LMS-based quizzes.
Developing applied engineering skills	Use the practical exercise for group work, homework, thermodynamic calculation tasks, economic comparison or project-based learning.

Supporting case-study work	Use the case-study materials to discuss real-world examples of renewable heat, waste heat recovery, heat pumps and CHP integration.
Supporting independent review	Direct learners to the module-level self-check quiz after they have studied the relevant materials.
Adapting to local teaching contexts	Select, combine or modify the guidebook sections, slides, questions, exercise and case studies according to the curriculum, participant level and professional context.

Recommended pathway for independent learners

Students and professionals using the module independently may follow the sequence below.

Review the introductory presentation

Familiarise yourself with the main concepts, terminology and structure of the module.

Study the guidebook materials

Read the detailed explanations, engineering principles and case examples presented in the guidebook.

Watch the module video

Use the short supporting video as an orientation to the module's main topics and learning focus.

Complete the self-check quiz

Test your understanding of the key concepts and technical principles covered in the module.

Attempt the practical exercise

Apply the acquired knowledge through engineering-oriented calculation, comparison or assessment tasks.

Review the case studies

Analyse selected real-world examples and reflect on their technical, economic and environmental transferability.

Available supporting materials

The supporting materials include:

- presentation slides for the module subtopics;
- a reusable question bank and answer key;
- a module-level self-check quiz;
- a practical engineering exercise;
- case-study materials;
- and a short supporting module video.

Table of Contents

1. Renewable Heat Production

1.1 Primary Energy Supply of Municipalities

One of the key questions in the development of district heating systems is determining the most appropriate primary energy source — both for current needs and for the long-term future. The selection of the primary energy supply strongly influences not only the efficiency and environmental performance of the local energy system, but also the energy security and economic stability of the municipality.

In Hungary, the extensive natural gas network has played a dominant role in heat supply for several decades. Its well-established infrastructure and reliability have made it the most convenient and widely used energy source for both residential and district heating purposes. However, the growing emphasis on sustainability, the decarbonization targets of the European Union, and the volatility of fossil fuel prices highlight the need to gradually reduce dependency on natural gas.

When a municipality hosts an industrial site with significant primary energy consumption, there is a mutual interest in developing a shared energy strategy. Coordinated energy planning allows for the optimization of resources, reduction of overall energy costs, and improved utilization of local energy potentials. In such cases, integrated energy systems — combining industrial processes, municipal heat networks, and renewable or waste energy sources — can create substantial environmental and economic benefits.

A particularly valuable opportunity lies in the use of industrial waste heat. Many industrial facilities release considerable amounts of low- or medium-temperature waste heat into the environment. By capturing and integrating this energy into district heating networks, municipalities can significantly reduce primary energy demand and carbon emissions while improving overall system efficiency.

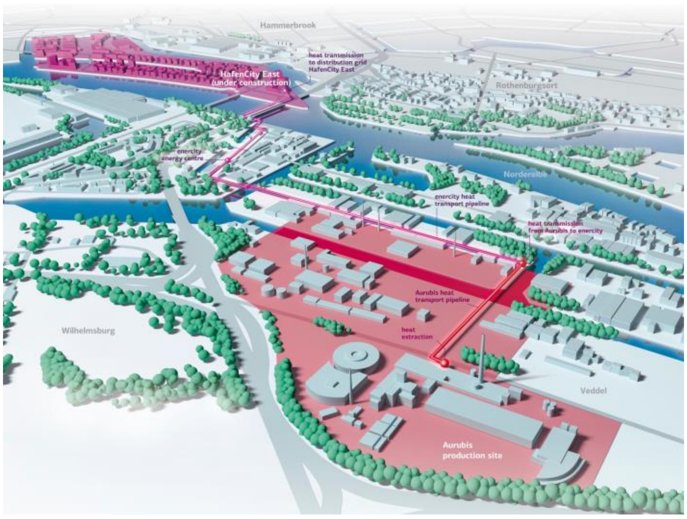

Figure 1. District heating system for Hamburg's HafenCity East [1]

In Hungary, the share of natural gas in the national primary energy supply remains significantly higher than the average across the European Union. While the EU as a whole has seen relatively stable natural gas consumption in recent years, Hungary has experienced a gradual decline. This reflects both energy efficiency improvements and the growing role of alternative energy sources.

Energy Type	Units	EU 28			Hungary		
		2000	2006	2012	2000	2006	2012
Primary energy, G	PJ	72,362	76,698	70,485	1,051	1,150	986
Final energy, F	PJ	45,769	49,984	48,388	662	754	622
F/G	%	65	65	66	63	66	63
Natural gas, Fg	PJ	17,832	18,490	16,495	406	481	349
Fg/G	%	24.6	24.1	23.4	38.6	40.8	35.4
Renewables, U	PJ	4,377*	5,242	7,746	39*	52	74
U/G	%	4.9	4.2	11.0	3.7	4.2	4.2

* Data for 2003.

Figure 2. Energy consumption data for the European Union and Hungary [2]

As shown in Figure 2, the share of natural gas within household energy consumption is notably higher than its share in the total primary energy use. This highlights the strong dependence of Hungarian households on natural gas for space heating and domestic hot water production — a legacy of the extensive residential gas network established in previous decades.

The most significant reduction in natural gas consumption has occurred in the field of electricity generation. The shift towards renewable power generation, along with improvements in energy efficiency and the modernization of power plants, has contributed to this trend. Nevertheless, natural gas continues to play a key balancing role in the energy system, ensuring flexibility and security of supply during peak demand periods or when renewable production fluctuates.

1.1.1 SOLID FUEL ASSESSMENT

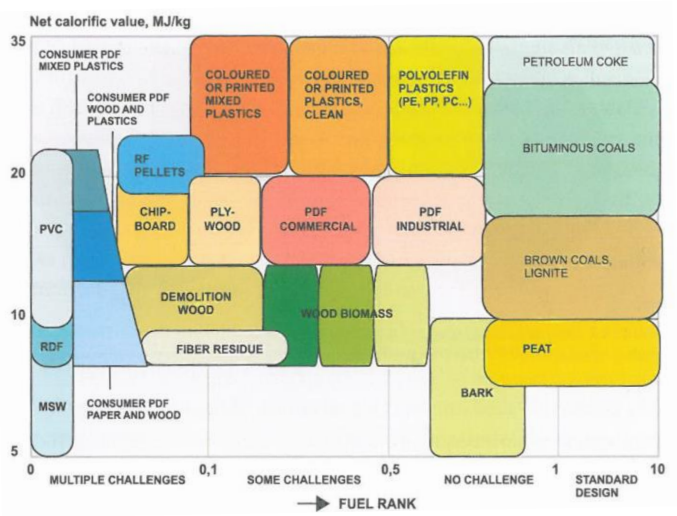

Figure 3. Solid fuel ranking based on heating values and challenges imposed on boiler design [3]

Figure 3 illustrates the relationship between the calorific value and the composition of various solid fuels. In general, fuels with high moisture content exhibit a lower calorific value, as a significant portion of the energy released during combustion is used for water evaporation rather than heat production.
Certain waste-derived fuels, such as PVC, RDF (Refuse-Derived Fuel), or MSW (Municipal Solid Waste), can present additional challenges. These materials often contain chlorine and other halogenated compounds,

which may lead to the formation of hydrogen chloride (HCl) and dioxins during combustion. Even in very small concentrations, these substances are toxic and require careful emission control and flue gas cleaning. Another important consideration is ash formation. Depending on the chemical composition of the fuel, the resulting ash can vary widely in both quantity and characteristics. Some types of ash may be highly corrosive to boiler components, requiring the use of resistant materials and regular maintenance. In other cases, however, the ash is relatively inert and poses minimal operational or environmental risk.

Overall, the assessment of solid fuels must take into account not only the calorific value but also the moisture content, chemical composition, and potential environmental impacts. These factors together determine whether a particular solid fuel is technically and economically suitable for use in district heating systems.

1.1.2 Biomass Combustion and Energy Recovery from Waste

In district heating systems, lower-quality biomass and certain types of waste can also serve as valuable energy sources. Their utilization supports local energy independence, reduces fossil fuel consumption, and contributes to the circular economy by recovering energy from materials that would otherwise require disposal.

Energy recovery from biomass can be achieved through two main technological pathways: combustion and gasification.

Combustion is the most common and technically mature method. It is primarily applied to solid, dry biomass — such as wood chips, pellets, or agricultural residues — to produce heat directly. In district heating systems, this heat can be used either for direct heat supply or in combined heat and power (CHP) plants, where both electricity and thermal energy are generated.

Gasification, on the other hand, is suitable for wet biomass, organic sludge, or other feedstocks that are less ideal for direct combustion. In this process, the material is partially oxidized at high temperatures, producing a raw gas (often referred to as producer gas or syngas). This gas can be utilized locally for heat and power generation, typically in combination with gas engines or microturbines. Alternatively, upgraded biogas can be sold as a fuel gas, contributing to decentralized energy markets.

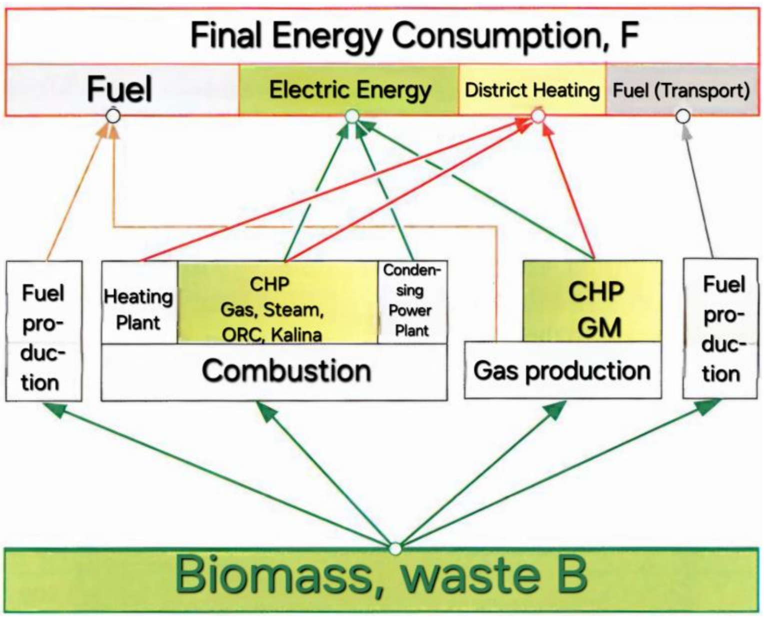

Figure 4. Biomass and waste energy conversion flowchart [2]

1.1.3 Combustible Biomass Potential in Hungary

Combustible biomass includes materials of forestry and agricultural origin, as well as certain fractions of municipal solid waste (MSW) that are suitable for energy recovery. In Hungary, the potential for biomass utilization is influenced by the country's relatively low forest cover and specific land-use conditions.
Hungary's forest coverage is approximately 20%, which is only about half of the European Union average. The total estimated tree stock amounts to around 360 million cubic metres, with an annual growth (gain) of approximately 13 million cubic metres.

If roughly half of this annual increment were to be used for energy purposes, it could provide a primary energy source of about 60–70 petajoules per year (PJ/a). This represents a significant renewable energy potential, especially for regional or municipal district heating systems, where locally available biomass can be utilized efficiently and sustainably.

While forestry biomass constitutes the largest share of the domestic potential, agricultural residues (such as straw, corn stalks, and other by-products) and biogenic waste fractions from municipal solid waste can also contribute to the renewable energy mix. Their integration into district heating systems not only enhances energy security but also reduces greenhouse gas emissions and supports rural economic development.

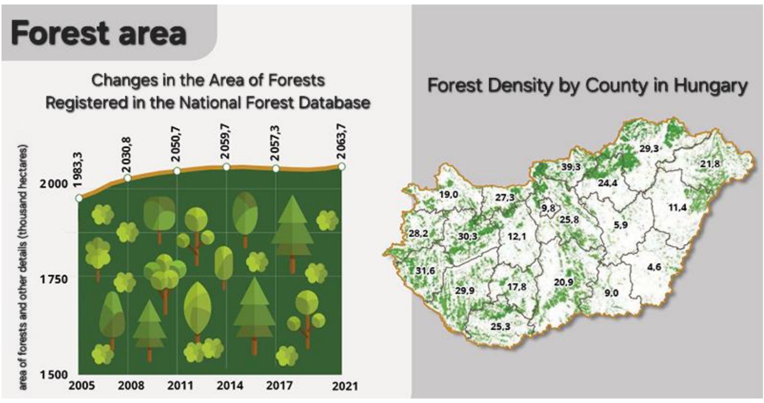

Figure 5 Forest density in Hungary [4]

Within the Hungarian biomass potential, several types of plant-based fuels play a significant role in renewable energy production. These include firewood, wood chips, and agricultural residues such as wheat straw. Each has distinct characteristics and is suitable for different scales and technologies of heat production.

Firewood accounts for approximately 40% of total logging in Hungary. Due to its accessibility and moderate energy density, it is most practical for use in individual heating systems, particularly in rural areas. At a moisture content of around 15%, the calorific value of firewood ranges between 15,000 and 16,000 kJ/kg, providing an efficient and reliable local heat source when properly dried and stored.

Wood chips are typically used as fuel in larger boilers or centralized heating plants, including district heating systems. Their calorific value depends strongly on moisture content: about 8,000 kJ/kg at 50% moisture, and up to 16,000 kJ/kg when dried to 10% moisture. The annual available quantity of wood chips in Hungary is estimated at 1–1.4 million tonnes, corresponding to an energy potential of roughly 10–18 petajoules (PJ) per year.

Wheat straw represents another important renewable fuel source. Approximately 1.5 million tonnes of straw can be utilized energetically each year. With a moisture content of around 18%, its calorific value is approximately 13,000 kJ/kg, translating to an energy potential of about 20 PJ per year.
When all plant-origin fuels are considered together — including forestry biomass, wood-processing residues, and agricultural by-products — the total renewable primary energy potential is estimated at 70–90 PJ annually. This indicates that biomass can make a meaningful contribution to Hungary's renewable energy

portfolio, particularly within local and regional district heating systems where fuel transport distances can be minimized.

Bio-briquettes and bio-pellets are modern forms of processed biomass fuels that offer higher combustion efficiency and greater convenience compared to raw firewood. They are produced by binder-free compression of dry biomass materials such as sawdust or agricultural residues, with the natural lignin acting as a binding agent. The resulting high density (1.0–1.3 t/m³) allows for efficient storage, transport, and use in automated small-scale heating systems. Their uniform quality and low moisture content enable clean, controllable, and efficient combustion, providing a practical and sustainable alternative to traditional solid fuels.

Energy plantations provide another efficient and sustainable source of biomass for heating systems. These fast-growing plants, reaching 2–3 m in height, are harvested on a 2–3 year cycle using specialized machinery that also shreds the canes, which are typically 2–3 cm in diameter. While their rapid growth can help bind harmful compounds, some species may pose risks such as soil degradation or corrosion in combustion plants. After cutting, the plants resprout from their roots, ensuring a continuous and renewable supply of biomass for district heating or other energy applications.

Lower-quality combustible biomass can also be effectively utilized in district heating plants ranging from 100 kW to several megawatts. Successful integration requires careful planning and coordination at the municipal level, including biomass procurement, assessment of local availability, and cost determination. Common feedstocks include local woodworking residues and biomass from nearby forest holdings.

Freshly cut biomass typically contains around 50% moisture, which significantly reduces its calorific value. To ensure efficient combustion, the moisture content should be lowered to 15–20%, which can be achieved through controlled drying processes. In practice, this often involves drying the biomass between heating seasons during the summer, allowing for optimized fuel quality and consistent operation of the heating system.

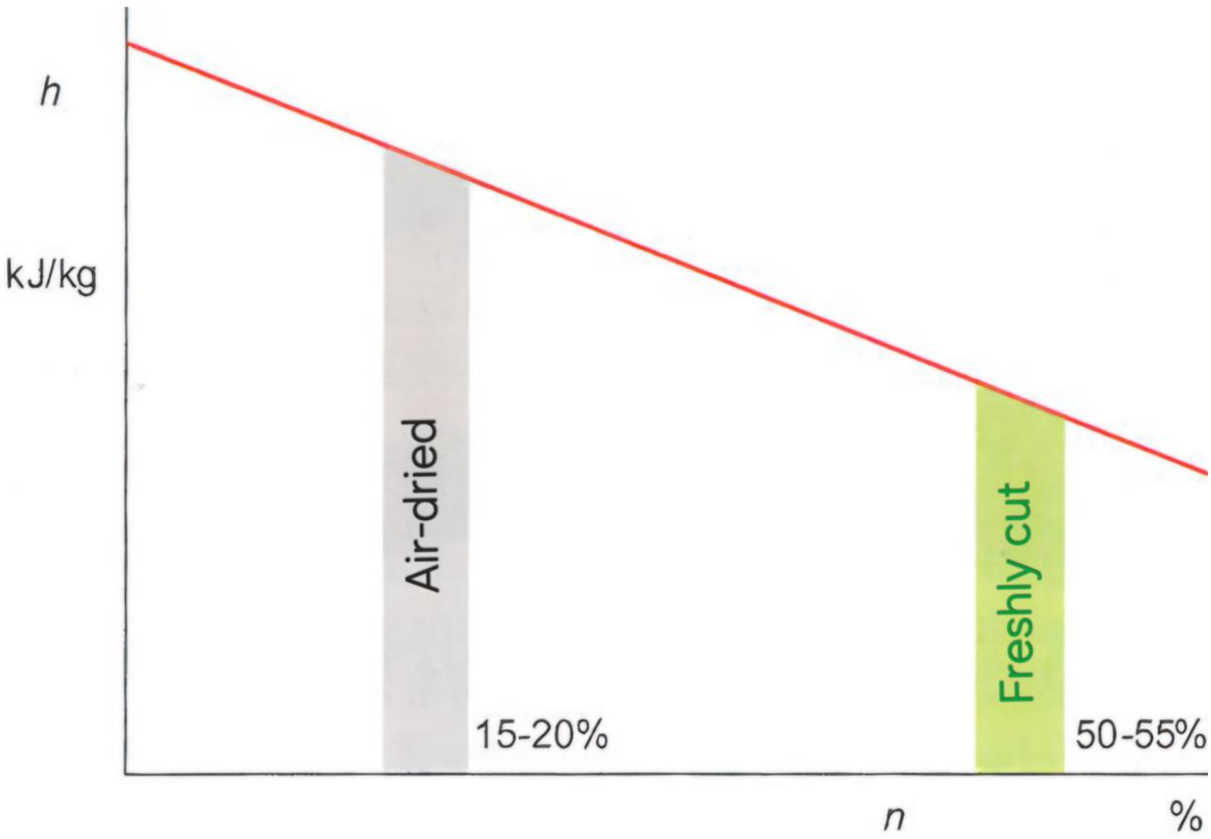

Figure 6 Specific energy of biomass depending on moisture content [2]

1.1.4 Wood chip and straw-fired heating block at Pécs Power Plant

A remarkable example of large-scale biomass utilization in Hungary is the Pécs Power Plant, where a former coal-fired power station was successfully converted into a biomass-based combined heat and power (CHP) plant through a two-stage modernization process. The conversion retained the original steam turbines and steam parameters of the old plant, ensuring efficient integration of new technologies into the existing infrastructure.

In the first phase, a wood chip-fired boiler with a steam capacity of 185 t/h was installed. It produces steam for an extraction-condensing turbine with an electrical output of 50 MW.

In the second phase, a straw-fired boiler was added, providing 137 t/h of steam. Outside the heating season, this unit operates with a 35 MW extraction-condensing turbine, while during the heating period, it is connected to a 27 MW backpressure heating turbine to supply district heat.

The district heating system of Pécs serves approximately 31,000 apartments and 450 public institutions, with an annual heat demand of around 1,600 TJ. Of this, about 62% is supplied by the straw-fired unit, and 32% by the wood chip-fired unit. Altogether, the biomass facilities deliver 94% of the city's renewable heat and electricity, while natural gas combustion accounts for the remaining 6% of the heat demand.

The Pécs Power Plant stands as a prime example of how existing fossil-based infrastructure can be transformed into a sustainable, renewable energy system, combining local biomass resources with efficient district heating technologies.

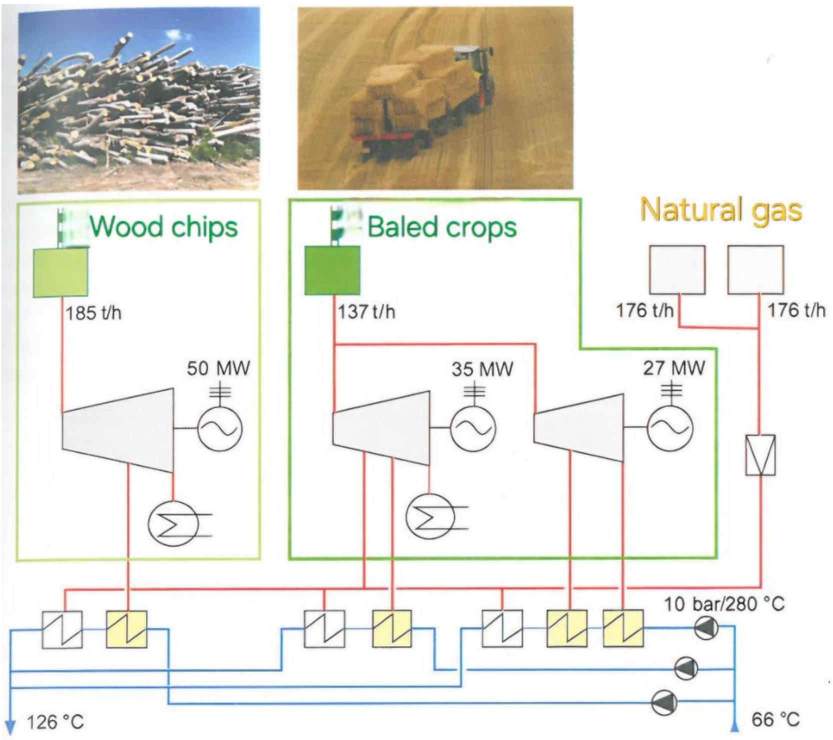

Figure 7 Combined heat and power generation system at the Pécs power plant [2]

1.2 GASIFICATION OF BIOMASS

1.2.1 The Potential of Domestic Biogas Production

Biogas production offers an effective way to utilize soft biomass that cannot be directly used for combustion. In Hungary, significant amounts of such organic materials are available every year. For example, approximately 700,000 tonnes of sewage sludge are produced annually, while Hungarian agriculture generates around 7.5 million tonnes of biodegradable waste suitable for gasification or anaerobic digestion. Currently, about 40 domestic biogas plants are in operation, processing nearly 3 million tonnes of organic raw materials per year.

Organic Material	Amount (million $t/year$)	Biogas Production (billion $m^3/year$)	Natural Gas Equivalent (billion $m^3/year$)
Animal-origin Waste	43	1.6	1.1
Municipal Waste	10	0.7	0.5
Energy Crops (1000 thousand ha)	30	3.3	2.2
Total	**83**	**5.6**	**3.8**

Figure 8. Biogas produced from various organic materials and quantities equivalent to natural gas [2]

The production of biogas is based on the anaerobic fermentation of organic matter — a process that takes place in an oxygen-free environment. During this process, microorganisms such as fungi and bacteria decompose complex organic compounds (carbohydrates, fats, and proteins) into simpler molecules. In the acid-forming phase, these intermediate products are converted into acids (such as acetic and lactic acid), alcohols, aldehydes, hydrogen, carbon dioxide, and other gaseous components.
Through further microbial reactions, these substances are transformed into biogas, which primarily consists of methane (CH_4) and carbon dioxide (CO_2). The resulting biogas can be used for heat and power generation, or after purification, it can be upgraded to biomethane and injected into the natural gas network or used as vehicle fuel.

1.2.2 The Process of Biogas Production

The technological process of biogas production consists of several key stages, each serving a specific role in the conversion of organic matter into usable energy. The typical process flow includes the following steps:

1. Receiving of liquid biomass – collection and delivery of substrates such as manure, sewage sludge, or other liquid organic materials.
2. Receiving of solid biomass – intake of solid feedstocks like crop residues, food waste, or energy crops.
3. Pre-storage – temporary holding of the feedstock to ensure continuous and uniform feeding of the digester.
4. Pre-fermentor – the initial stage of anaerobic digestion, where the biomass begins to decompose under controlled conditions.
5. Post-fermentor – the secondary fermentation chamber, where the remaining organic matter continues to break down and the majority of biogas is produced.
6. Final storage – the treated digestate is stored before being used as fertilizer.
7. Gas tank – collection and intermediate storage of the produced biogas.
8. Gas scrubber – cleaning and conditioning of the raw biogas by removing impurities such as hydrogen sulfide, carbon dioxide, and water vapor.

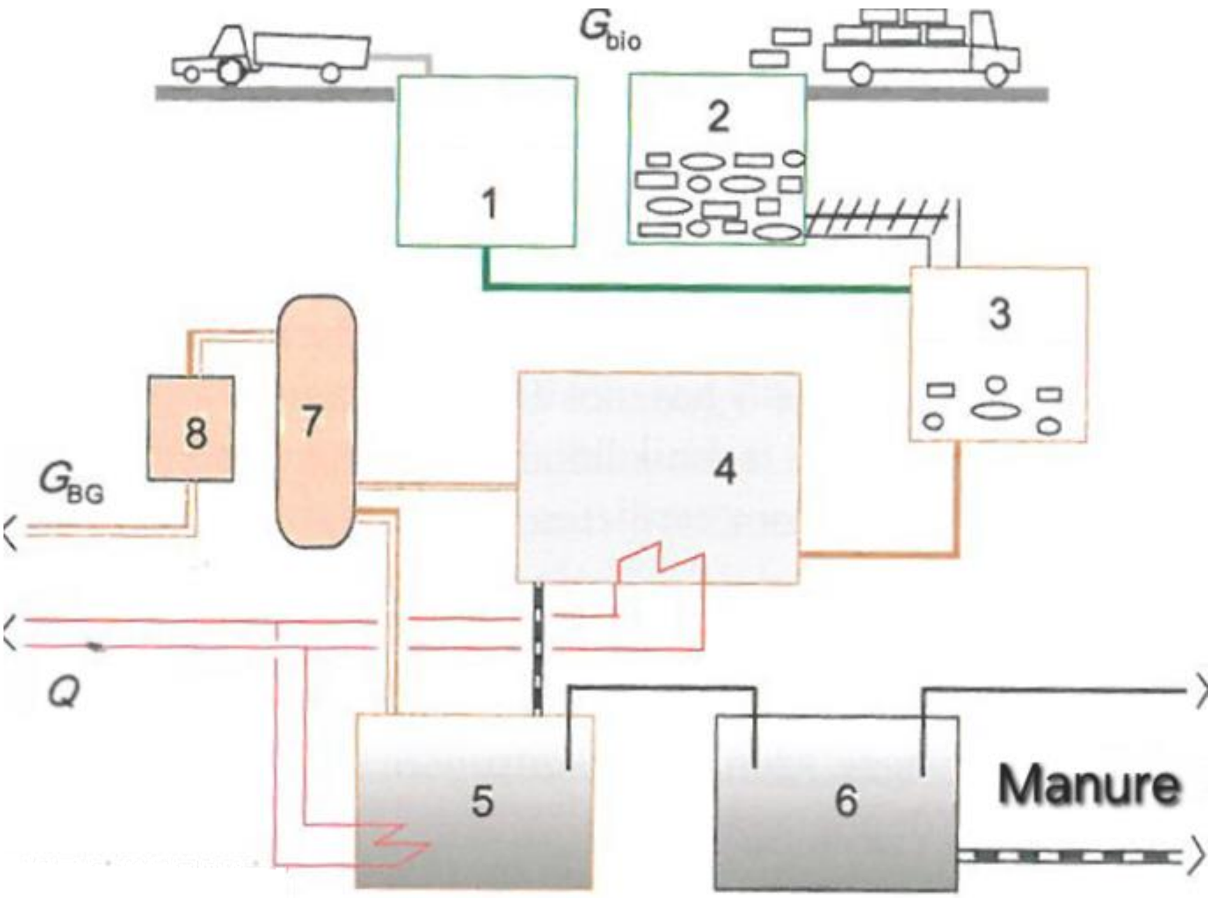

Figure 9. The process of biogas production [2]

During the fermentation process, the number of pathogenic microorganisms in the biomass significantly decreases, the material becomes less odorous, and the remaining digestate serves as an excellent nutrient-rich fertilizer for agricultural use. Thus, biogas technology not only contributes to renewable energy production but also provides an environmentally beneficial waste management solution.

1.2.3 Process of Wastewater Treatment and Biogas Production

In municipal wastewater treatment, the organic content of urban wastewater is first thickened to form a concentrated sludge. This thickened sludge is then directed into an anaerobic digestion system, where it undergoes biological gasification in the absence of oxygen. As a result, energetically valuable biogas and stabilized solid residue (digestate) are produced.

The treated and diluted wastewater can be made suitable for agricultural use after undergoing appropriate purification, deodorization, and disinfection. In cases where the treatment process is not fully comprehensive, the partially treated effluent can still be used for irrigating energy crops, contributing to circular resource utilization.

The solid digestate, after drying, may serve either as an organic fertilizer or as a fuel, depending on its composition and energy content. Through this integrated approach, wastewater treatment plants can function not only as waste disposal facilities but also as renewable energy producers, contributing to sustainable energy and nutrient management within municipalities.

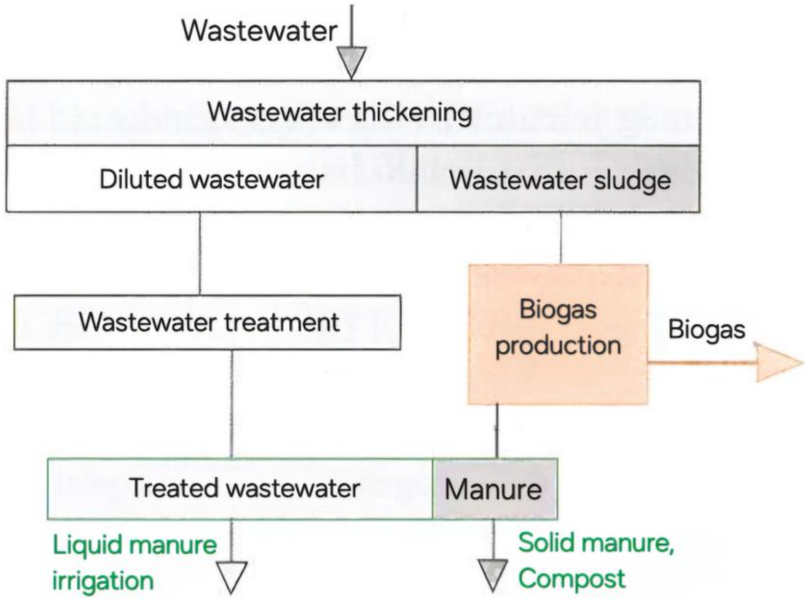

Figure 10. Process of wastewater treatment and biogas production [2]

1.2.4 The Güssing Biomass Power Plant

The Güssing Biomass Power Plant in Austria is a notable example of thermal gasification of wood to produce synthesis gas (syngas) for energy generation. The plant employs an advanced fluidized bed gasification system, allowing efficient conversion of solid biomass into combustible gas.

Figure 11. The Güssing Biomass Power Plant [5]

The gasifier consists of two main zones:

1. Burning zone: In this section, bed material and air circulate, providing the necessary heat for the gasification process. The circulation ensures uniform temperature and stable operation.
2. Gasification zone: Wood feedstock is introduced here. The superheated steam (~850°C) generated in the burning zone fluidizes the biomass, promoting rapid thermal decomposition and the formation of syngas.

This dual-zone arrangement enables efficient thermal conversion of wood into a combustible gas mixture suitable for combined heat and power (CHP) generation, while maintaining high process stability and low emissions. The Güssing plant serves as a benchmark for modern biomass gasification technologies and demonstrates the potential of locally sourced wood for sustainable energy production.

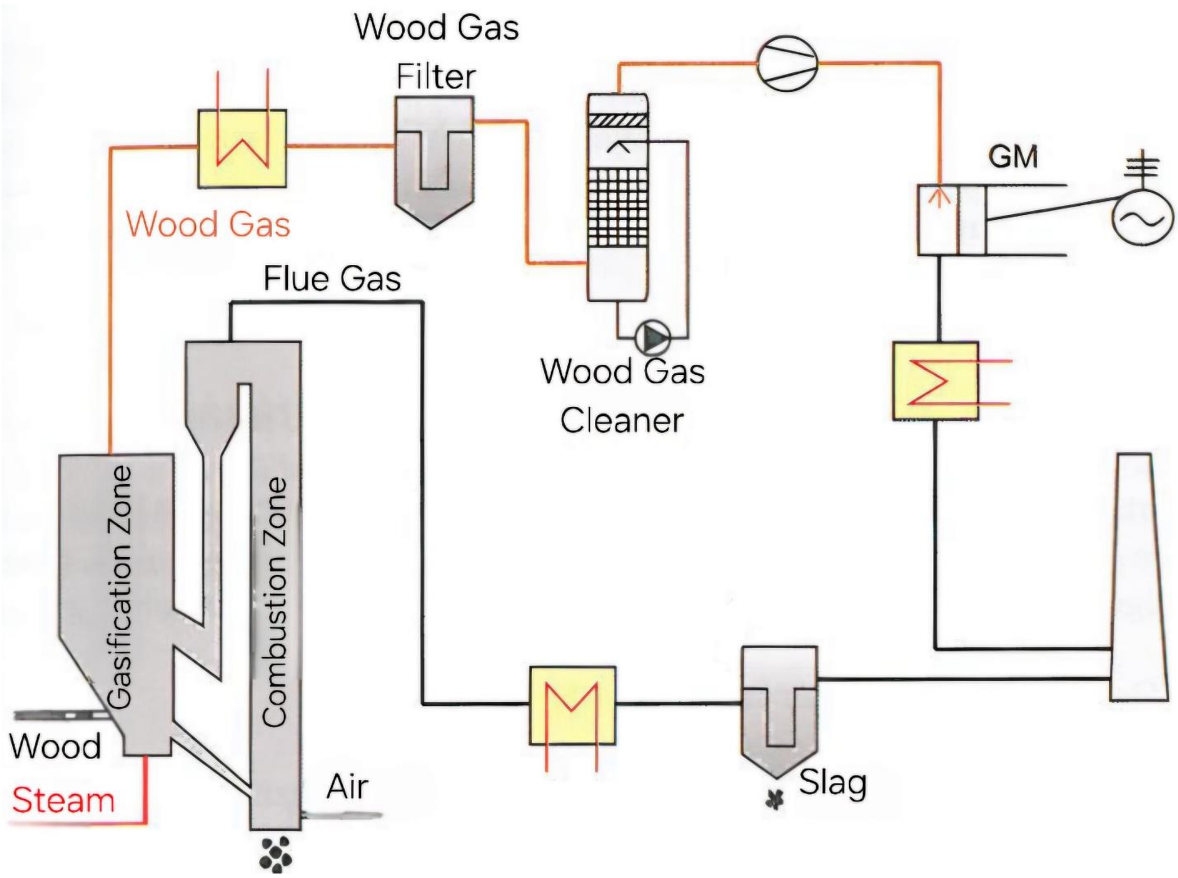

Figure 12. The process flowchart of the Güssing Biomass Gasification power plant [2]

1.2.5 Landfilling of Municipal Solid Waste and Landfill Gas Production

Municipal solid waste (MSW) landfills undergo aerobic decomposition initially, followed by anaerobic processes as oxygen becomes depleted. During the anaerobic phase, landfill gas is generated, which typically consists of 40–60% methane (CH_4) and 40–60% carbon dioxide (CO_2). In addition, trace amounts of carbon monoxide, nitrogen, hydrogen sulfide, volatile fatty acids, mercaptans, and water vapor are present.

Landfill gas can be extracted and utilized as an energy source, with typical yields of 2–3 m^3 per tonne of waste per year. The operational and environmental management of a landfill site, including gas extraction, is a long-term process, as site closure and stabilization can take 20–30 years. Proper capture and utilization of landfill gas not only provides a renewable energy source but also reduces greenhouse gas emissions and odor problems associated with waste disposal.

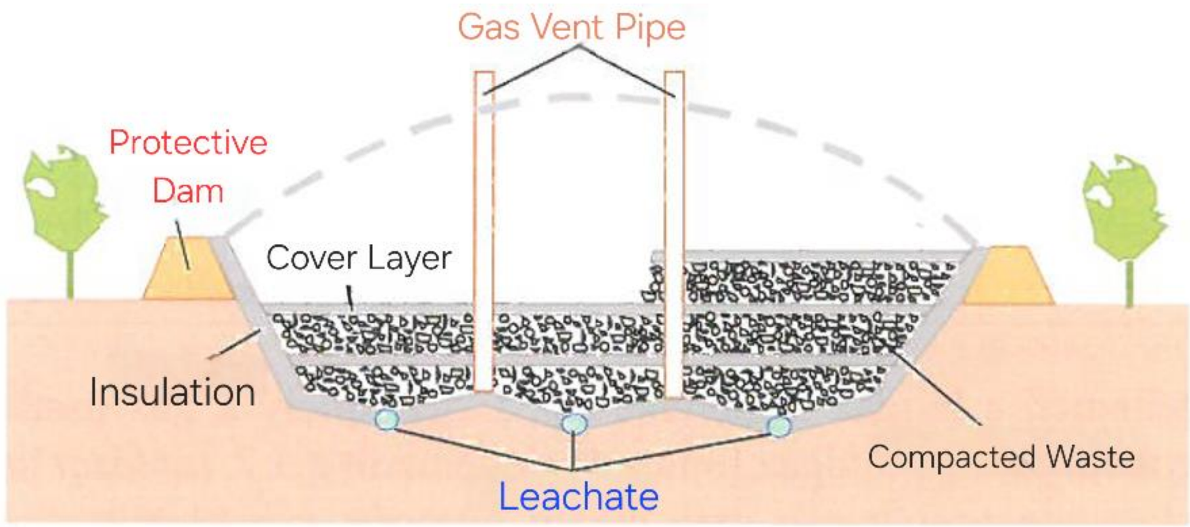

Figure 13. Landfilling of municipal solid waste, landfill gas production [2]

The table summarizes the typical biogas yields obtained from different types of organic substrates, illustrating the relative energy potential of agricultural residues, sewage sludge, and other biodegradable materials.

Organic Material	Biogas Yield (m^3/t)	Organic Material	Biogas Yield (m^3/t)
Pig manure	340–550	Grass	280–550
Cattle manure	90–310	Reed	170
Poultry manure	310–620	Clover	430–490
Horse manure	200–300	Potato waste	280–490
Sheep manure	90–310	Sugar beet leaves	400–500
Stable manure	175–280	Sunflower leaves	300
Wheat straw	200–300	Agricultural waste	310–430
Corn stalks	380–460	Plant seeds	620
Rapeseed straw	200	Leaves	210–290
Rice straw	170–280	Algae	420–500
Flax	360	Sewage sludge	310–740
Hemp	360	Landfill waste	40–300

Figure 14. Biogas Yield from Various Organic Materials [2]

This table presents a comparative overview of the main properties and composition of biogas, landfill gas, and natural gas, highlighting differences in methane content, energy density, and suitability for heat and power generation.

Component	Biogas	Landfill Gas	Natural Gas
Methane (%)	50--70	45--55	94--98
Carbon Dioxide (%)	17--42	30--35	0.0--3
Nitrogen (%)	0--1	15--25	0.3--4
Density (kg/m³)	1.1--1.15	1.15--1.20	0.8--0.9
Calorific Value (kJ/m³)	18,000--25,000	15,000--17,000	32,000--40,000

Figure 15. Comparison of Biogas, Landfill Gas, and Natural Gas [2]

1.2.6 Combined heat and power production with a biogas-fueled engine

Biogas can be effectively utilized in decentralized combined heat and power (CHP) systems using gas engines. These engines are available in a wide range of capacities, from a few kilowatts up to several megawatts, making them suitable for small community installations as well as larger industrial applications.

Many biogas engines are containerized, allowing for easy on-site installation and integration into existing infrastructure. These units typically include the gas engine, electric generator, and necessary connection equipment, along with heat exchangers to capture the thermal energy produced during operation. By simultaneously producing electricity and usable heat, biogas-fueled CHP systems maximize the energy value of organic waste while supporting local energy independence and sustainability.

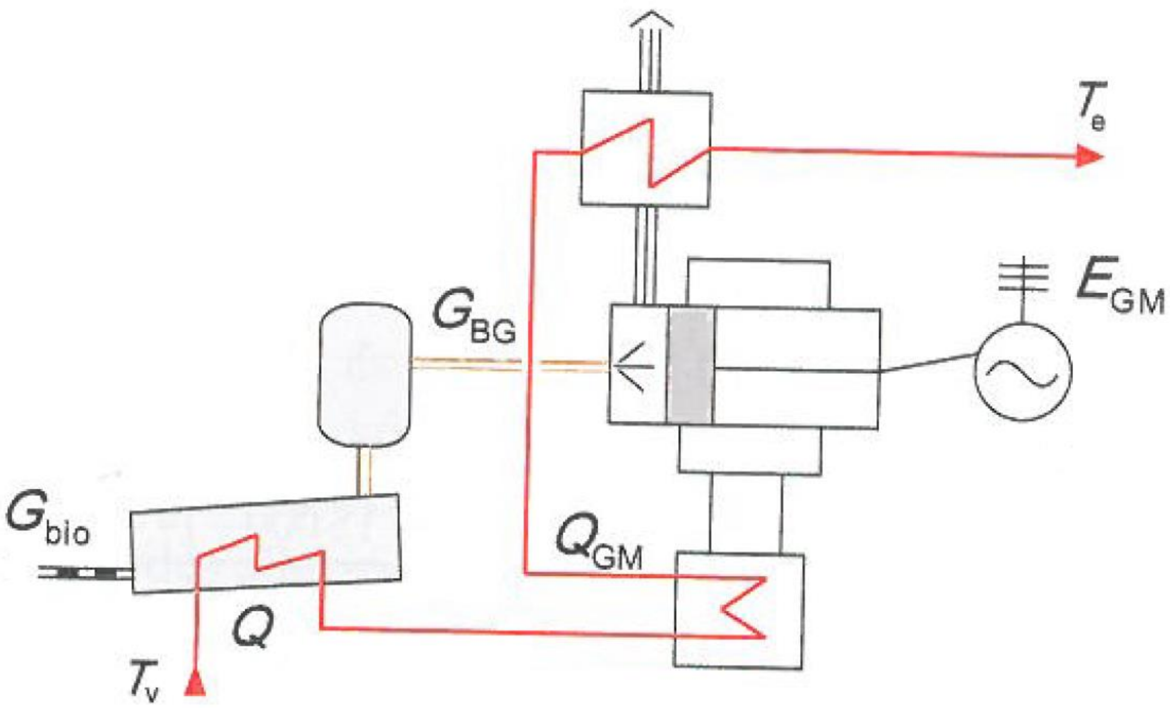

Figure 16. Combined heat and power production with a biogas-fueled engine [2]

1.2.7 Comparison of biomass combustion and gasification for energy production

When comparing biomass combustion and gasification for energy production, the choice largely depends on the heat demand and desired energy distribution. Combustion is more suitable for applications requiring high heat output, as it achieves an overall efficiency of about 80%, delivering approximately 12 GJ of heat from 1 ton of biomass. However, its electricity-to-heat ratio (E/Q) is relatively low at 0.25, meaning it prioritizes thermal energy over power generation.

In contrast, gasification is recommended for lower heat demands or when a higher share of electricity is needed. Although the total heat output is lower (around 6.8 GJ), gasification offers a better electricity-to-heat ratio of 0.79, making it more efficient for combined heat and power (CHP) systems. Additionally, gasification produces biogas (about 400 m³ per ton of biomass) and can utilize byproducts such as manure, enhancing its versatility.

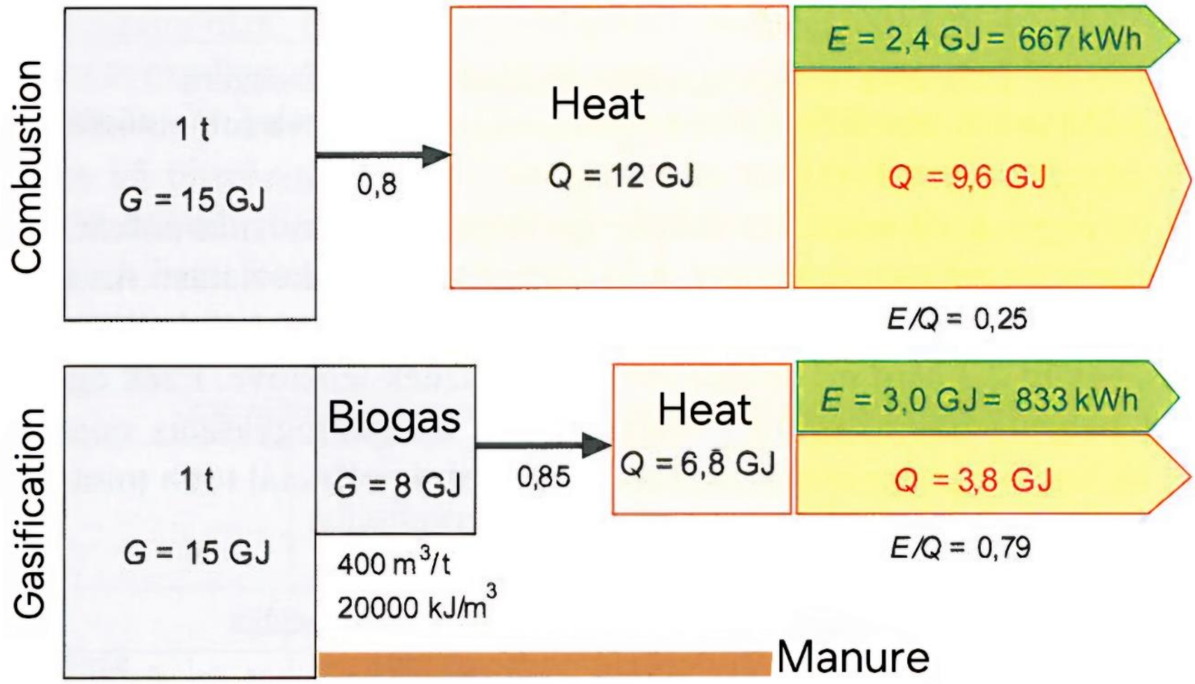

Figure 17. Comparison of biomass combustion and gasification for energy production [2]

1.3 SOLAR DISTRICT HEATING

1.3.1 Flat-plate collector

Flat-plate collectors are one of the most common technologies used in solar thermal systems for district heating. They consist of an insulated box with a transparent cover and an absorber plate that captures solar radiation and transfers heat to a working fluid. These collectors are typically installed in large arrays to achieve the required thermal output for district heating networks.

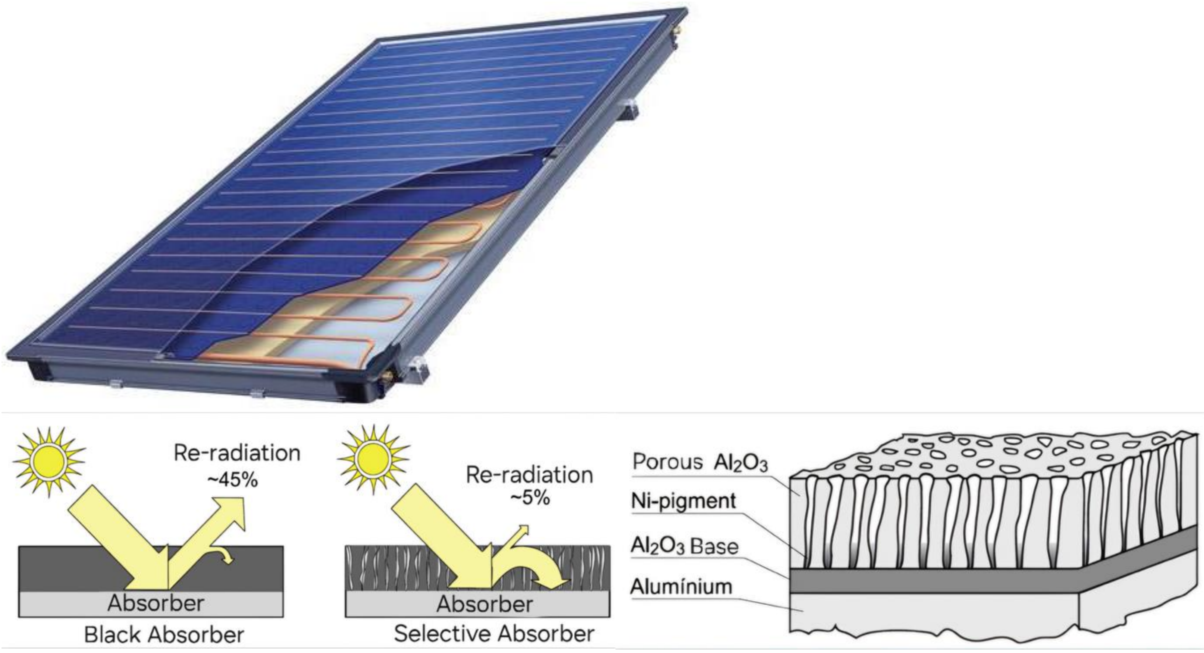

Figure 18. Flat-plate collector and absorber [6]

1.3.1.1 Connection Configurations: Series vs. Parallel

When multiple collectors are combined, they can be connected either in parallel or in series, each configuration having distinct hydraulic and thermal characteristics:

Parallel Connection

In a parallel arrangement, the fluid flow is divided among the collectors. This results in: Lower pressure drop across the system, which reduces pumping energy requirements. Lower flow rate per collector, which can slightly affect heat transfer efficiency. Parallel connection is often preferred when minimizing pressure losses is critical.

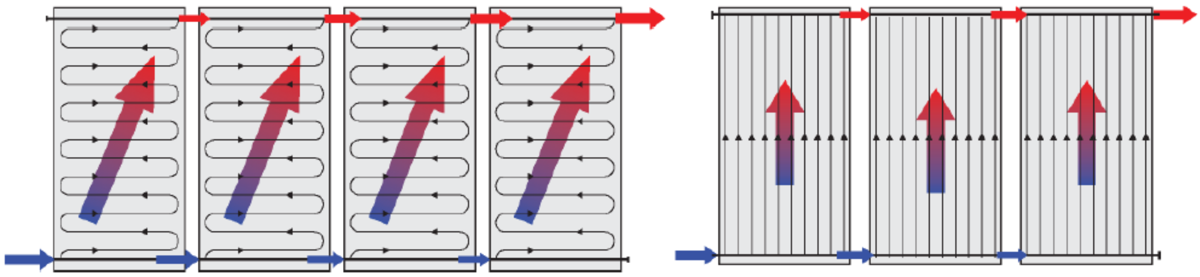

Figure 19. Parallel connection of solar collectors [6]

Series Connection

In a series arrangement, the fluid passes through each collector sequentially. This leads to: Higher pressure drop, requiring more pumping power. Higher flow rate through the entire circuit, which can improve heat transfer but increases hydraulic resistance. Series connection is typically used when higher outlet temperatures are desired.

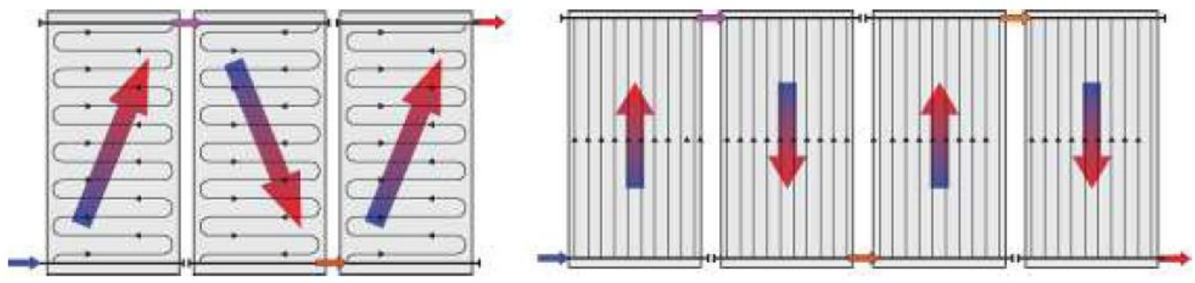

Figure 20. Series connection of solar collectors [6]

Proper regulation is essential to maintain optimal performance. Flow balancing valves and differential pressure controllers are commonly used to ensure uniform distribution and prevent overheating in individual collectors.
Collectors are not always equivalent in performance. Variations in orientation, shading, and manufacturing tolerances can lead to differences in thermal output. Therefore, system design should account for these factors to achieve uniform efficiency.

1.3.2 "Sydney tube„ vacuum tube

Sydney tubes are a type of vacuum tube collector widely used in solar thermal applications. They feature a thermos-style double-walled glass tube, where the space between the walls is evacuated to minimize heat losses through conduction and convection. This design ensures high thermal efficiency even in colder climates.
The absorber surface is adhered to the inner side of the inner glass wall, allowing direct exposure to solar radiation. A heat-conductive sheet is required to transfer the absorbed heat effectively to the working fluid.

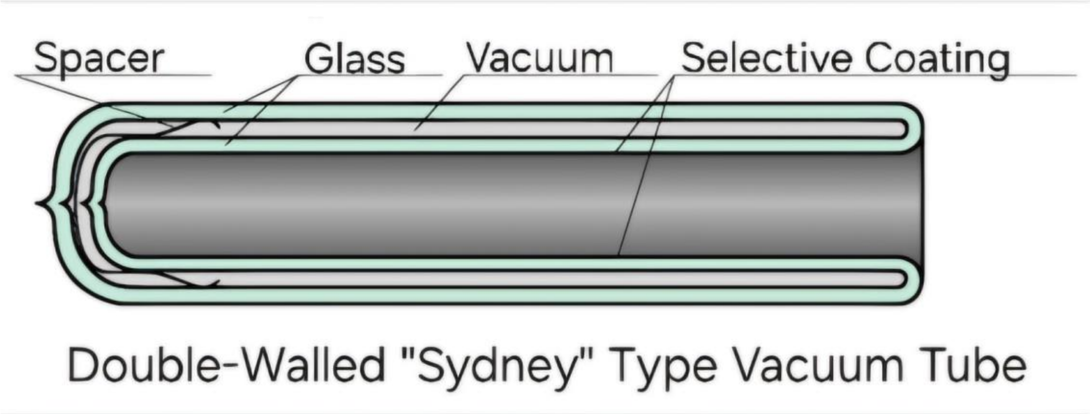

Figure 21 Structure of a Double-walled Sydney type vacuum tube [6]

An optional Compound Parabolic Concentrator (CPC) mirror can be installed behind the tubes to maximize the utilization of solar radiation by reflecting additional sunlight onto the absorber.
Vacuum tube collectors are particularly advantageous in systems requiring higher operating temperatures or where ambient conditions lead to significant heat losses in flat-plate collectors.

Figure 22 Double-walled Sydney type vacuum tube collector [7]

1.3.3 Heat Pipe Vacuum Tube

Heat pipe vacuum tubes represent an advanced design for solar thermal systems, combining high efficiency with reliable heat transfer. Each tube contains a plate absorber inside the vacuum envelope, which captures solar radiation and transfers heat to a sealed heat pipe.

Key Features:

- Plate absorbers are installed within the vacuum tubes to maximize solar energy absorption.
- The absorber has a slightly adjustable tilt angle, allowing optimization of solar incidence within the tube.
- The heat pipe design requires installation at an angle to ensure proper phase change and heat transport from the evaporator to the condenser section.
- Special attention must be given to thermal expansion at glass-metal junctions to prevent mechanical stress and maintain vacuum integrity.

Heat pipe collectors are ideal for applications requiring high outlet temperatures and efficient heat transfer over long distances, such as large-scale solar district heating systems.

1.3.4 The Challenge of Large-Scale Solar Heat Production: Storing Performance Peaks

One of the most critical challenges in large-scale solar heat production is the management of performance peaks. Solar thermal systems are inherently dependent on weather conditions, which means that periods of high solar radiation can lead to significant heat surpluses. If this excess energy is not properly managed, it can cause operational issues such as overheating, increased pressure in the network, and reduced system efficiency.

The most common solution is thermal energy storage, which allows surplus heat to be stored during peak production and released when demand is higher or solar input is lower. Large-scale storage systems, such as stratified hot-water tanks or pit thermal energy storage (PTES), are essential for balancing supply and demand in district heating networks. However, these systems require substantial investment, space, and careful integration into the overall hydraulic design.

In addition to storage, smart control strategies and predictive algorithms play a key role in optimizing system performance. By forecasting solar availability and heat demand, operators can adjust flow rates, storage charging, and auxiliary heat sources to maintain stability and efficiency.

Managing performance peaks is therefore not only a technical challenge but also an economic and operational one. Effective solutions ensure that solar district heating remains reliable, cost-effective, and sustainable.

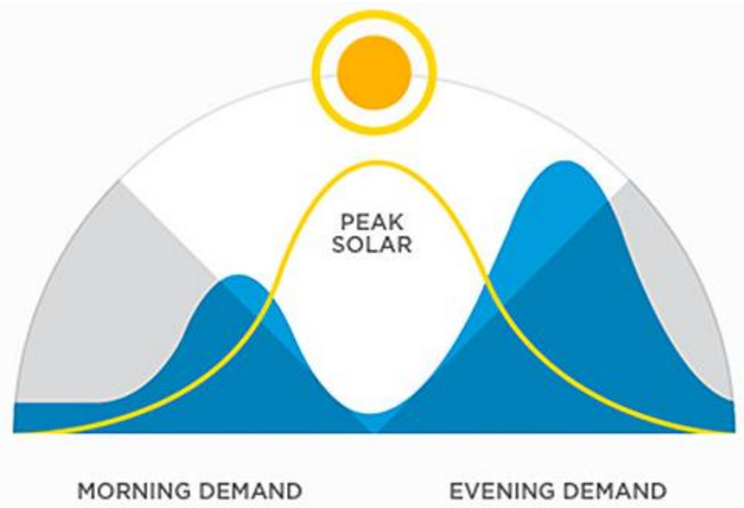

Figure 23. Differences between consumption and production over time [8]

1.4 Geothermal District Heating

Geothermal energy offers a reliable and sustainable heat source for urban district heating systems. Its application depends primarily on the temperature of the thermal water, which determines the technology and integration method:

High-temperature thermal water (>80 °C): This category allows direct heat supply to district heating networks without additional temperature boosting. It is the most efficient option, as the water can be circulated directly to consumers after heat exchange.

Medium-temperature thermal water (40–80 °C): At these temperatures, partial direct use is possible, but often heat pumps are required to raise the temperature to meet network standards. This approach combines geothermal energy with auxiliary technologies for optimal performance.

Low-temperature thermal water (<30 °C): Direct use is not feasible at this level. Instead, heat pump systems are essential to upgrade the heat to a usable temperature. Although this requires additional electricity, the overall system remains highly sustainable due to the renewable nature of the source.

The flexibility of geothermal energy utilization makes it a cornerstone of urban energy strategies, enabling cities to reduce fossil fuel dependency and greenhouse gas emissions.

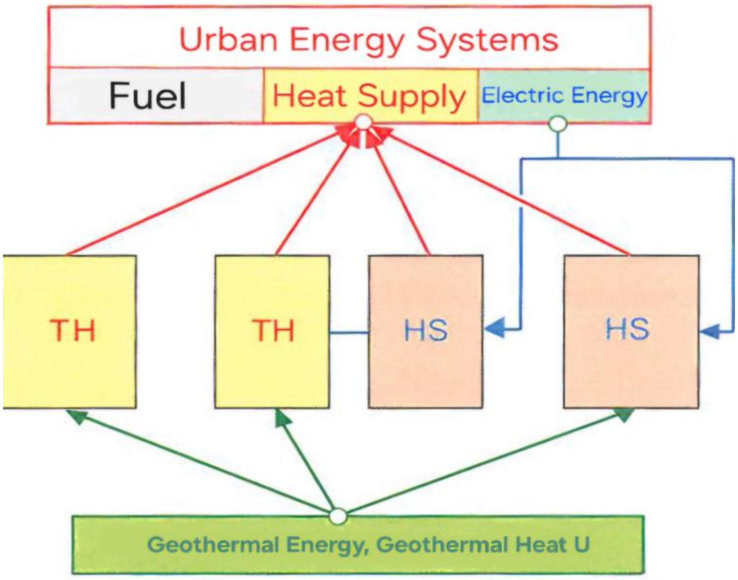

Figure 24 Utilization of Geothermal Energy in Urban Energy Systems [2]

1.4.1 Integration Methods in Geothermal District Heating

Geothermal energy systems can be designed for multipurpose utilization, ensuring that the thermal water is used as efficiently as possible. One of the most effective strategies is cascade utilization, where the same water serves multiple applications in sequence. For example, high-temperature water may first supply district heating, then be used for industrial processes or wellness facilities before reinjection. This approach maximizes energy recovery and economic viability.

This schematic illustrates how geothermal water can be used in a cascade system, where the same water serves multiple purposes in sequence. High-temperature water first supplies applications requiring higher heat levels, such as district heating, and then moves to lower-temperature uses like balneological (spa) services or horticulture/greenhouse heating.

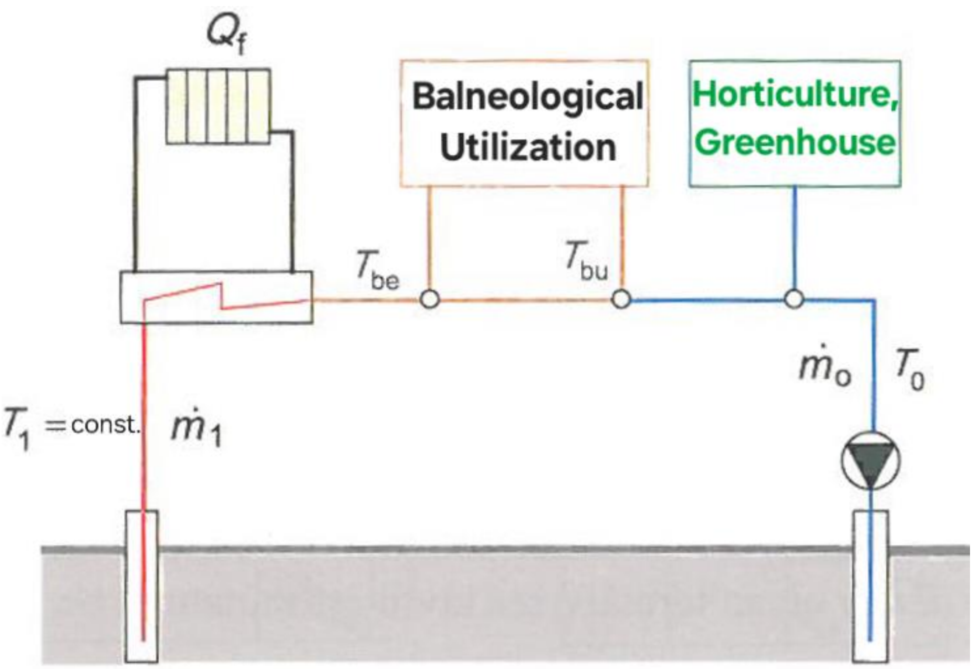

Figure 25. Multipurpose, Cascade Utilization of Thermal Water [2]

Geothermal district heating systems utilize thermal water extracted from deep underground reservoirs to supply heat to urban consumers. The process begins with production wells delivering water at a high temperature, which is then distributed through a network designed to serve multiple heating applications. To ensure stability and efficiency, the system incorporates a heat storage unit that acts as a buffer between production and consumption. This storage balances fluctuations in demand and maintains a consistent supply temperature.

From the storage, heat is transferred to various consumer circuits. Conventional radiator systems receive water at higher temperatures, suitable for space heating in residential and commercial buildings. For applications requiring lower temperatures, such as wall and floor heating, the system adjusts the supply to optimize comfort and energy efficiency. These configurations allow geothermal energy to integrate seamlessly into existing heating infrastructures.

The diagram also highlights key operational parameters. The supply temperature (T1) represents the heat delivered from the geothermal source, while the return temperature (T0) indicates the water temperature after heat delivery. The outlet temperature (T0) reflects the point at which water exits the consumer circuit. Heat flow rates quantify the energy supplied to different consumer groups, and the mass flow rate ensures adequate circulation throughout the system.

By combining heat storage, temperature control, and efficient distribution, thermal water district heating provides a sustainable solution for urban energy needs. It reduces reliance on fossil fuels, lowers greenhouse gas emissions, and supports the transition to renewable energy in densely populated areas.

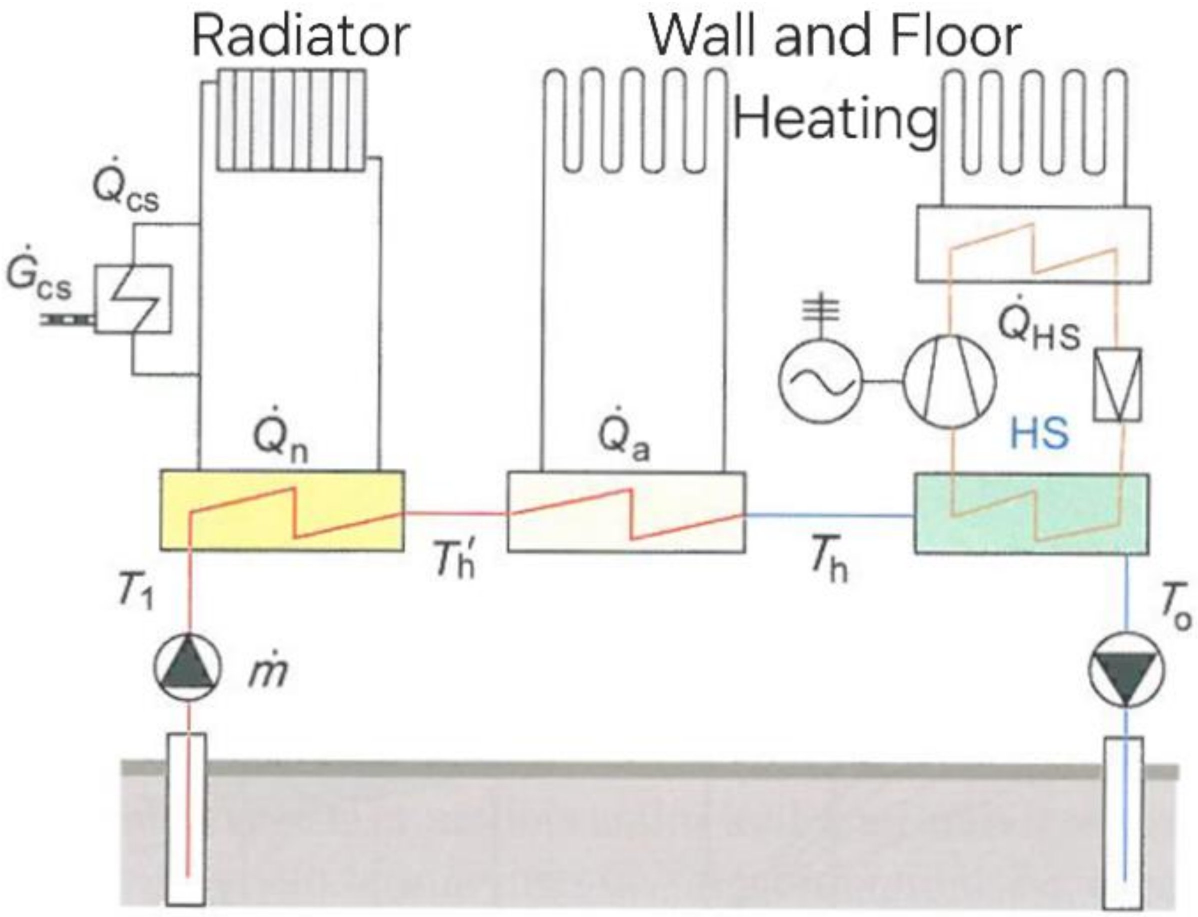

Figure 26. Thermal Water District Heating [2]

The Geinberg system in Austria demonstrates this principle. Thermal water is first applied for space heating, then for domestic hot water, and finally for spa and wellness services. By progressively lowering the temperature requirements at each stage, the system achieves optimal resource efficiency.

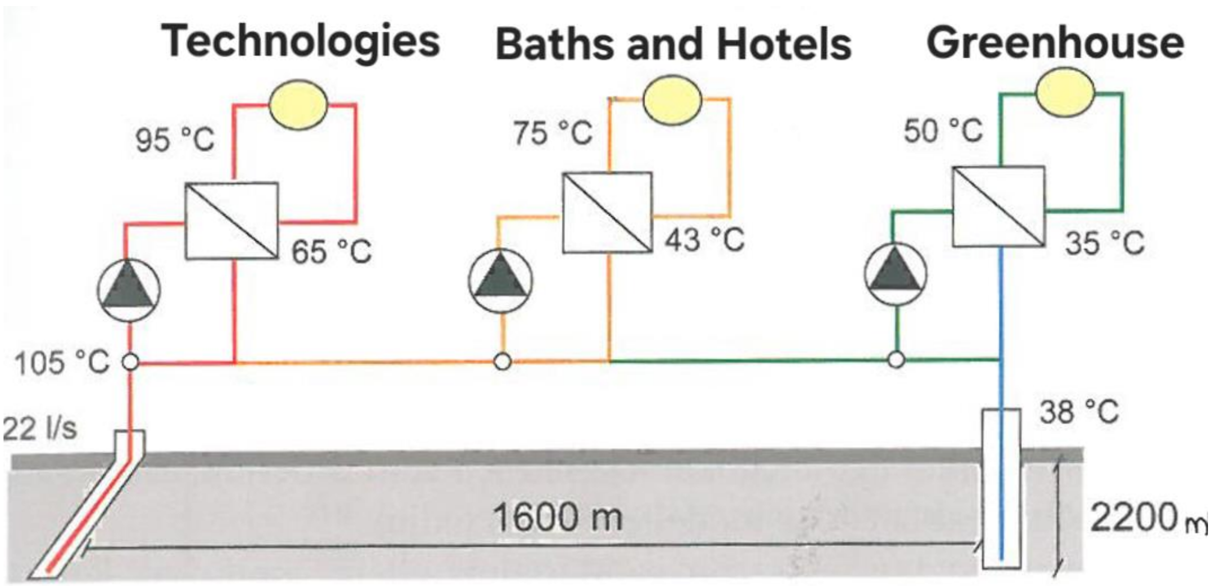

Figure 27. Cascade Connection of Thermal Water Utilization in Geinberg [2]

1.4.2 Consumer Connection Methods

Consumers can be connected to geothermal district heating networks in three ways:

- Direct connection: Geothermal water flows directly to the consumer's heating system. This is simple but only suitable when water quality is high and mineral content is low.
- Indirect connection: Heat exchangers separate geothermal water from the building's heating circuit, preventing corrosion and scaling. This is the most common method.
- Mixed systems: Combine direct and indirect connections, often used in large networks with diverse consumer requirements.

These configurations allow flexibility in system design, ensuring safety, reliability, and efficient heat distribution.

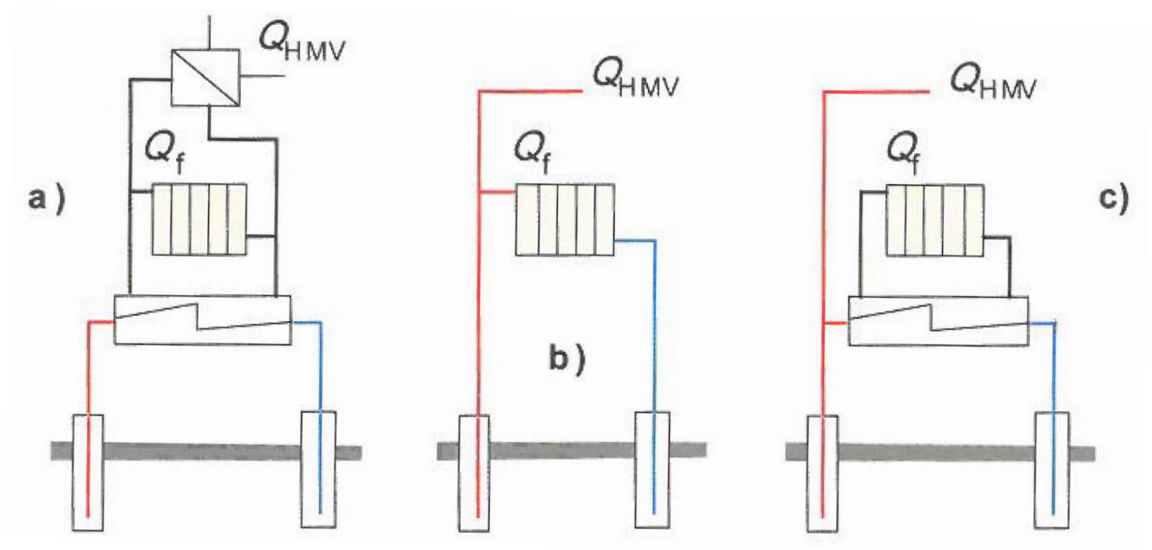

Figure 28. Connecting Consumers Directly (a), Indirectly (b), and in a Mixed Manner (c) to Geothermal District Heating [2]

1.4.3 The possibilities of utilizing water depend on the quality and yield of the water

The utilization of geothermal water depends largely on its quality, temperature, and yield, which determine the most suitable applications. High-mineral-content water can serve purposes beyond heating, such as medicinal and wellness uses, provided that its therapeutic properties are scientifically verified. These applications rely on the proven benefits of dissolved mineral salts and gases, making geothermal water an important resource for health tourism and spa facilities.

When geothermal water exhibits high enthalpy—meaning it has a high temperature and energy content—it can be used for electricity generation. This process typically involves production wells that bring hot water or steam to the surface, where it drives turbines in geothermal power plants. Such systems are common in tectonically active regions with abundant geothermal reservoirs.

For low-enthalpy geothermal water, where temperatures are moderate, the most practical application is district heating. These systems use the thermal energy directly or in combination with heat pumps to supply space heating and domestic hot water. Even water with relatively low temperatures can be upgraded through heat pump technology, making it suitable for urban heating networks.

By matching water characteristics with appropriate technologies, geothermal energy can be harnessed efficiently for multiple purposes—from electricity generation to heating and wellness—maximizing its economic and environmental benefits.

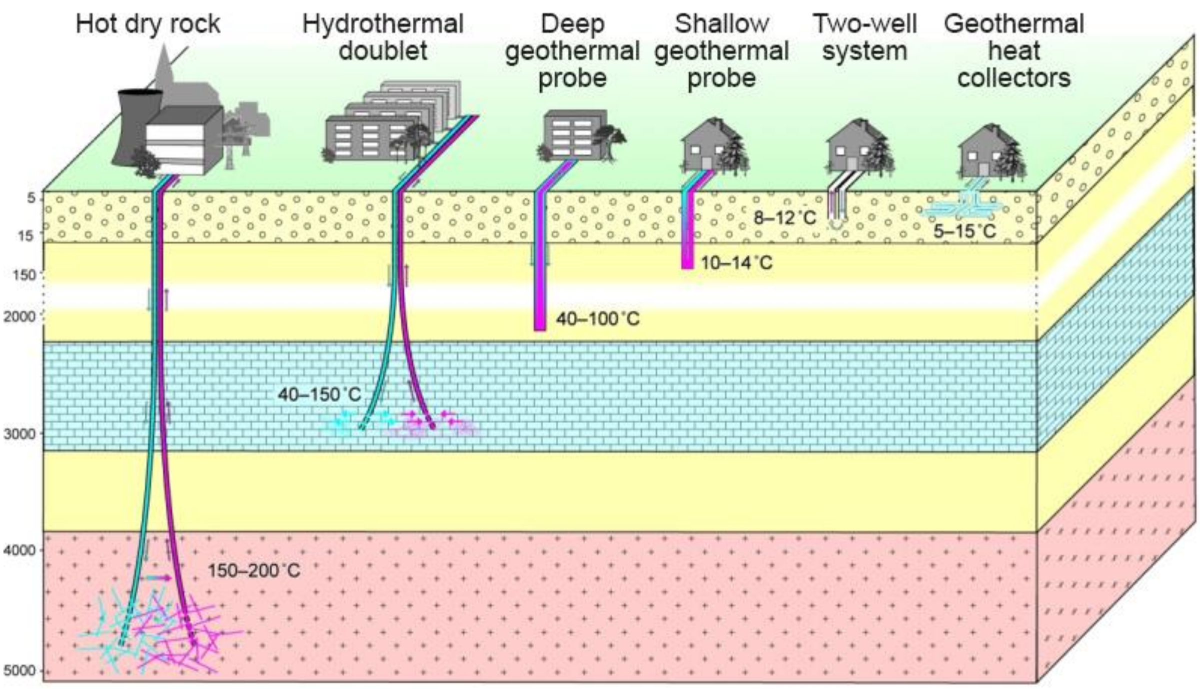

Figure 29. Different methods of utilizing geothermal energy depending on drilling depth and temperature [9]

1.4.4 Establishing a Geothermal District Heating System

Alongside biomass, geothermal energy is one of the most accessible renewable sources for district heating. Its ability to provide a stable and continuous heat supply makes it highly attractive for urban energy systems. However, establishing such a system involves significant challenges and requires careful planning.

The most critical barrier is the high investment cost, primarily due to drilling deep wells and constructing the necessary infrastructure. Beyond financial considerations, there is a risk of partial or complete project failure, which often stems from geological uncertainties. Accurate estimation of water yield and temperature is essential; if these parameters are miscalculated, the system may not deliver the expected performance.

Geothermal projects are typically located in tectonically active areas, where the geothermal gradient is favorable. While this increases the potential for high-temperature resources, it also introduces risks such as

earthquakes and, in some regions, volcanic activity. These factors demand rigorous site assessment and continuous monitoring to ensure safety and reliability.
Despite these challenges, successful implementation offers long-term benefits: reduced greenhouse gas emissions, stable energy prices, and a renewable heat source that supports sustainable urban development.

1.4.5 Challenges During the Implementation of a Geothermal System

Implementing a geothermal district heating system involves not only technical and financial challenges but also significant environmental and geological risks. One major concern is the chemical composition of geothermal groundwater, which may contain toxic substances such as arsenic. If not properly managed, these contaminants can migrate and pollute underground drinking water resources, posing serious health hazards. To prevent this, reinjection practices must be carefully designed and monitored to ensure that extracted water returns to the reservoir without affecting surrounding aquifers.
Another critical issue is induced seismicity, or human-triggered earthquakes, which can occur when large volumes of water are injected into deep geological formations. Notable examples include Basel (Switzerland), where a geothermal project caused measurable seismic activity, and Staufen (Germany), where reinjection led to ground uplift and structural damage to buildings. These cases highlight the importance of thorough geological assessments and continuous monitoring during operation.
Additionally, the presence of minerals such as anhydrite—a waterless calcium sulfate compound—can complicate drilling and reinjection processes. When anhydrite comes into contact with water, it can transform into gypsum, causing volume expansion and potentially leading to ground deformation. This phenomenon was a contributing factor in the Staufen incident, where the ground rose by several millimeters per year.
Addressing these challenges requires a combination of advanced engineering solutions, strict environmental safeguards, and risk management strategies. While geothermal energy offers substantial benefits for sustainable heating, its implementation must prioritize safety and environmental protection to ensure long-term viability.

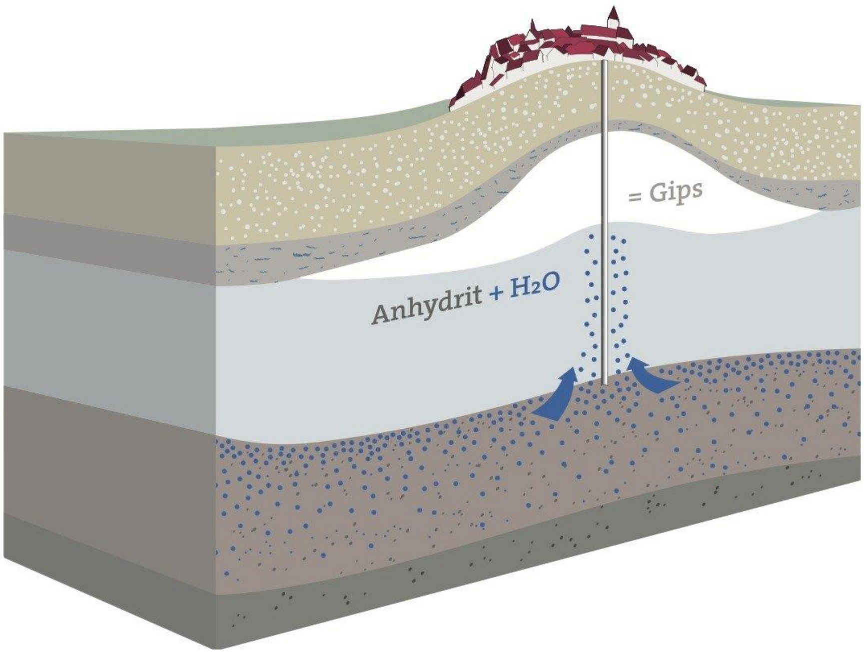

Figure 30. Difficulties caused by anhydrite in geothermal systems [10]

1.4.6 The Geothermal Gradient

The geothermal gradient describes how the Earth's temperature increases with depth beneath the surface. This rise in temperature is approximately 30 °C per kilometer in the upper layer of the Earth, known as the lithosphere. The gradient is not uniform; it varies depending on geological conditions. Areas with a thinner solid crust or tectonic activity exhibit higher gradients, making them particularly suitable for geothermal energy extraction.

For district heating, water temperatures between 40 °C and 90 °C are typically sufficient. Achieving 90 °C, which is considered the lower limit for geothermal electricity production, generally requires drilling to an average depth of 3 kilometers. The deepest geothermal wells currently reach depths of around 5 kilometers, accessing even higher temperatures for power generation.

Understanding the geothermal gradient is essential for planning geothermal projects. It determines drilling depth, influences investment costs, and helps identify regions with the greatest potential for renewable heat and electricity production.

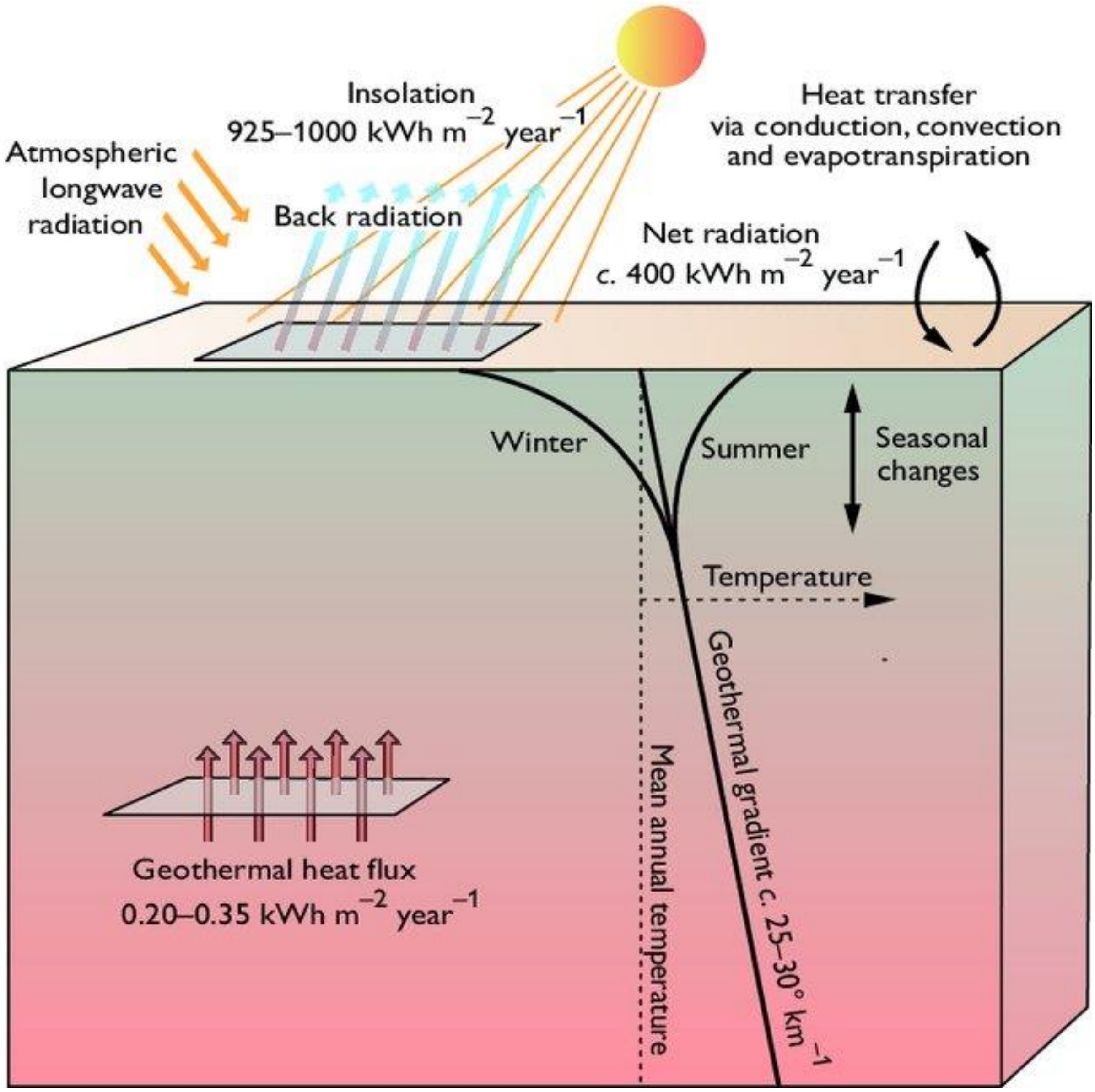

Figure 31. Schematic block diagram showing the geothermal gradient and magnitude of geothermal heat flux and insolation with average values for Denmark as well as the seasonal zone of fluctuation in temperature [11]

1.4.7 GeoDH Map – Geothermal Potential and District Heating in Europe

The GeoDH Map is an interactive tool that provides essential information for planning and implementing geothermal district heating systems across Europe. It combines three key datasets:

1.4.7.1 Estimation of Geothermal Heat Sources

The map identifies regions with significant geothermal potential, based on geological surveys and temperature gradients. This helps developers locate areas where drilling can yield sufficient heat for district heating.

1.4.7.2 Existing Geothermal District Heating Systems

Operational systems are marked on the map, offering insights into successful projects and best practices. These examples serve as benchmarks for new developments.

1.4.7.3 Heat Demand Map

By overlaying geothermal potential with urban heat demand, the map highlights areas where geothermal energy can be most effectively integrated into district heating networks.
The GeoDH Map covers 14 European countries actively involved in geothermal district heating projects: Italy, Germany, France, Netherlands, Ireland, United Kingdom, Slovakia, Slovenia, Czech Republic, Romania, Bulgaria, Poland, Denmark, and Hungary.
This tool supports strategic decision-making by aligning renewable energy resources with consumer needs, promoting sustainable heating solutions across Europe.

Figure 32 Heat demand map of Europe [12]

1.4.8 Geothermal Potential in Hungary

Hungary is among the European countries with significant geothermal resources, making it a key player in renewable heat production. According to data from the Hungarian Central Statistical Office (HCSO), in the year 2000 there were approximately 1,100 thermal water wells in operation. Of these,

- 286 wells had an outlet temperature of 30–40 °C,
- 179 wells provided 41–60 °C, and
- 121 wells delivered 61–90 °C.

Assuming a final cooling temperature difference of 15 K, the annual extracted heat was estimated at 30.4 PJ, equivalent to the heating value of 740,000 tons of crude oil.

By 2015, the number of wells had increased to 1,622, and the amount of thermal water extracted reached 24.608 million m³ per year, corresponding to 2,509 TJ of thermal energy. Current estimates for 2023 suggest that Hungary has between 1,750 and 1,800 wells, reflecting continuous growth in geothermal utilization.

To support planning and development, Hungary operates the National Geothermal System (OGRE), an online platform that provides detailed maps and data on geothermal resources, existing wells, and potential sites for new projects (OGRE Map). This system is an essential tool for integrating geothermal energy into district heating networks and expanding renewable heat supply across the country.

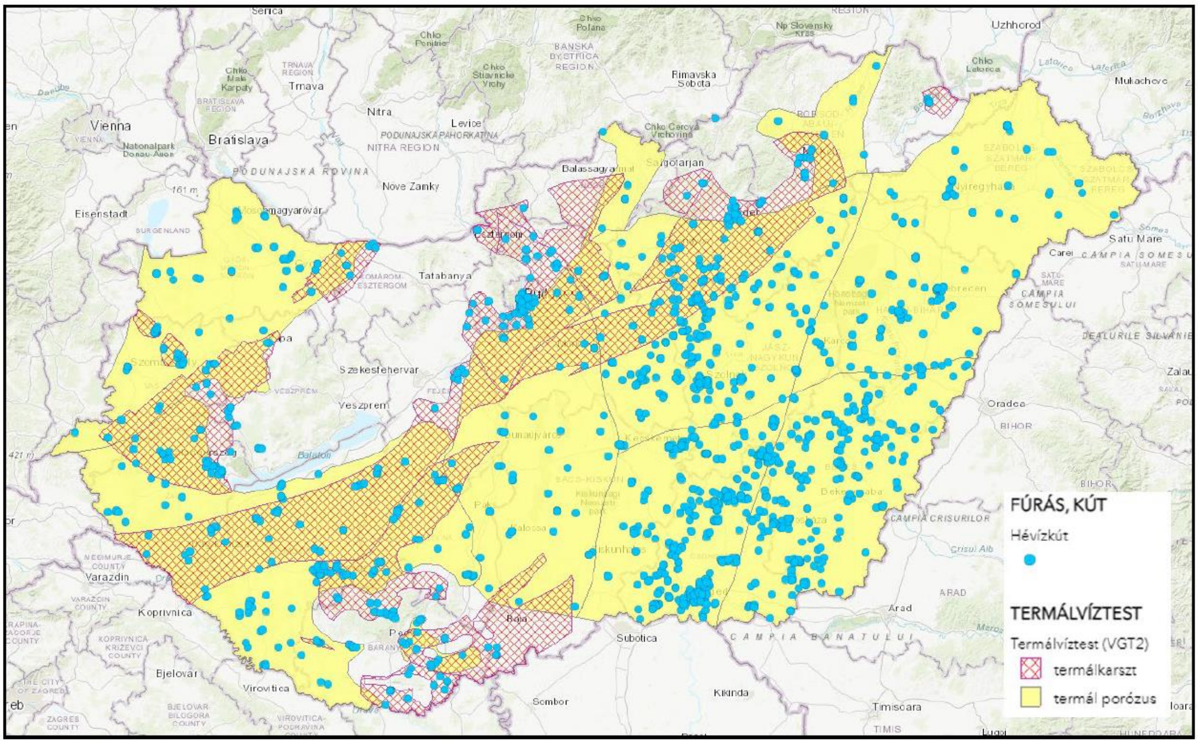

Figure 33. Thermal groundwater body and active wells in Hungary [13]

The next map shows the geographical distribution of thermal wells used for balneological, agricultural, and district heating purposes. It highlights the historical development of geothermal district heating networks in southern Hungarian cities such as Hódmezővásárhely, Szeged, Makó, Szentes, and Kistelek, where such systems began to emerge in the late 1960s.

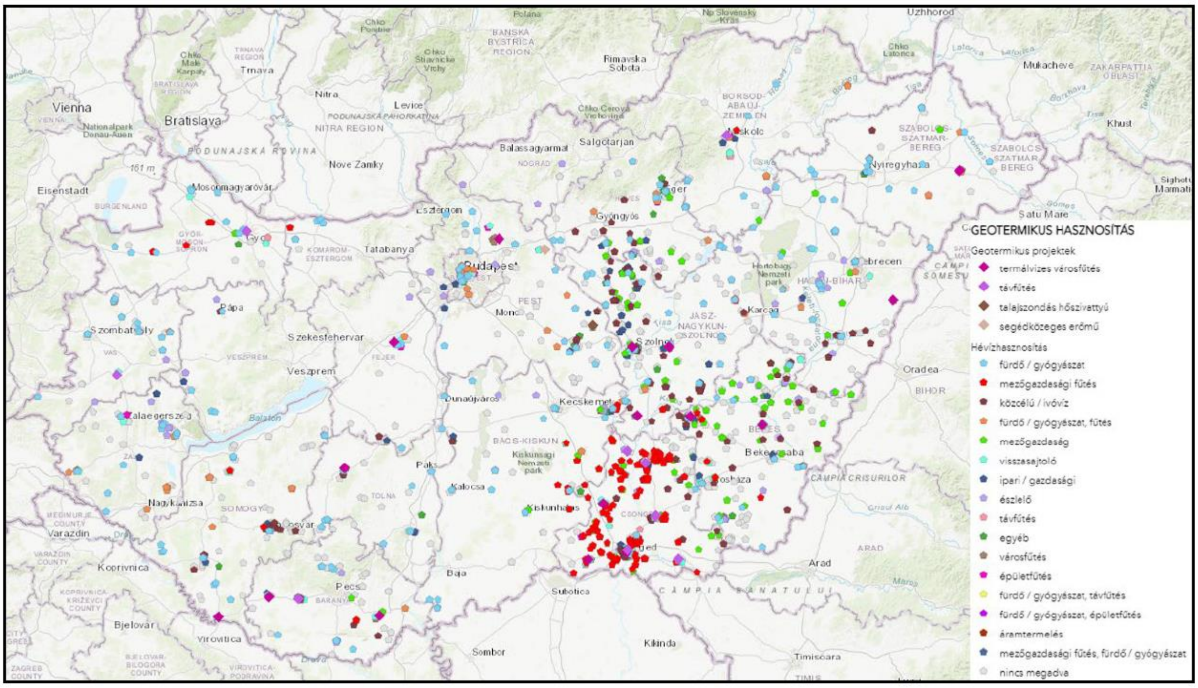

Figure 34. Types of thermal water use in Hungary [13]

The following chart provides an overview of how geothermal energy is currently used across different sectors in Hungary. The largest share is attributed to balneology, accounting for 352 MW_t, followed by agriculture and industry with 325 MW_t, and building heating with 220 MW_t. Geothermal heat pumps represent a smaller portion, contributing 42 MW_t.

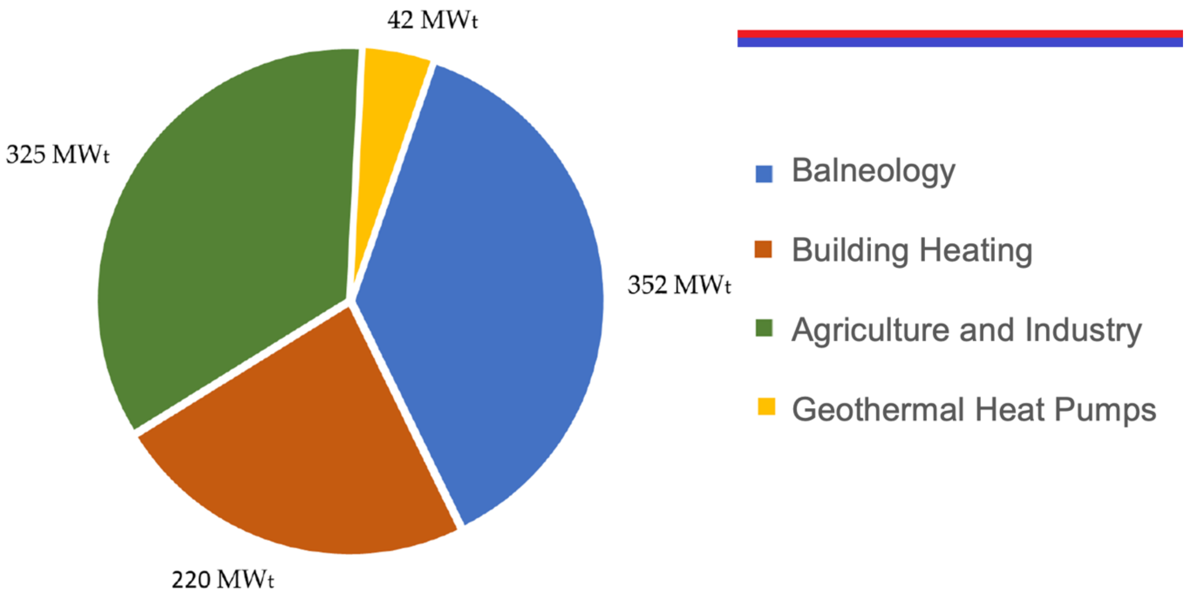

Figure 35. Geothermal energy used by different sectors in Hungary [14]

1.5 Utilization of Renewable Energy Sources in District Heating: Focus on Geothermal Energy

Geothermal energy represents one of the most promising renewable sources for district heating systems, particularly in regions with significant geothermal potential. The energy stored in the Earth's outer crust, down to a depth of approximately 10 kilometers, is immense—estimated to be sufficient to meet global energy demands for up to six million years, based on current consumption levels.

However, despite its theoretical abundance, the practical utilization of geothermal energy is subject to several limitations. One of the key challenges is the decline in thermal intensity over time. As geothermal reservoirs are exploited, the temperature and pressure of the source may decrease, potentially reducing the efficiency and economic viability of long-term operations.

Another consideration is the relocation or shifting of geothermal sources. Geological activity and changes in subsurface conditions can alter the accessibility or productivity of a geothermal field. This raises important questions regarding the economic feasibility of relocating infrastructure or developing new wells in response to such changes.

In Central Europe, several countries have already integrated geothermal energy into their district heating networks. The following diagram illustrates the number of district heating systems located near significant geothermal fields.

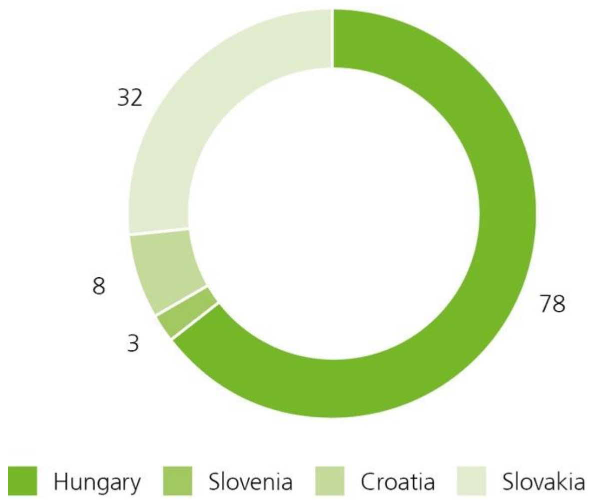

Figure 36. Number of District Heating Systems Near Significant Geothermal Fields [15]

1.5.1 Practical Aspects of Utilizing Thermal Groundwater in District Heating Systems

In geothermal district heating systems, heat is extracted from deep underground layers and transported to the surface via geothermal fluids. These fluids typically consist of: Water, Dissolved salts, Gases, Suspended solids.

Due to this complex composition, careful evaluation and testing are required before a geothermal well can be integrated into a heating network.

To assess the production characteristics of a geothermal well, a test pumping process is conducted. This involves cleaning pumping at 40%, 60%, and 80% of the expected water yield, each phase lasting for a minimum of 72 hours. During this period, key parameters are measured, including the resting water level and the height of the water column. Based on these measurements, the operational mode of the well can be determined:

- Positive Mode: The well operates independently, allowing geothermal fluid to flow freely to the surface without mechanical assistance.
- Negative Mode: The well requires artificial lifting, typically using pumps, because the static and operational water levels do not reach the surface naturally.

Over time, most wells tend to shift into negative operational mode due to declining pressure and reservoir changes, making artificial production essential for long-term use. There are two primary methods used to extract thermal water artificially:

1.5.1.1 Pump-Based Production

Pump-based systems are the most commonly used method today due to their efficiency and controllability. These systems typically involve:

- Multi-stage centrifugal pumps or submersible pumps installed directly into the well.
- Pumps equipped with radial or semi-axial impellers, integrated with an electric motor.
- Speed control systems that regulate pump performance to maintain desired flow rates and pressure levels.

Modern geothermal operations rely on automated and precise control of water extraction, ensuring energy-efficient and cost-effective performance. Submersible pumps are especially favored for their reliability and adaptability to varying operational conditions.

1.5.1.2 Compressor-Based Production

In compressor-based systems:

- Air introduction pipes are installed into the well.
- Compressed air is injected into the water column, reducing its density.
- This pressure differential allows the geothermal fluid to rise to the surface.

While this method can be effective, it has notable limitations:

- The extracted thermal water contains higher levels of dissolved oxygen, which may affect system components and water chemistry.
- It is unsuitable for wells with high sediment content, such as sand-carrying water, due to the risk of clogging and abrasion.

1.5.2 Increasing Water Flow

In geothermal district heating systems, maintaining or increasing water flow is essential for meeting growing thermal energy demands. Several technical interventions are available to enhance the yield of geothermal wells:

1. Acidizing: Acid treatment is used to dissolve mineral deposits and improve permeability in the rock formation surrounding the well. The process typically lasts at least 8 hours and can significantly increase water yield by clearing blockages and enhancing flow paths.
2. Explosive Stimulation: This method involves the detonation of insoluble explosives at great depths within the well. The shock waves fracture the surrounding rock, creating new flow channels. While effective, this technique requires careful planning and safety measures due to its invasive nature.
3. Layered Fracturing: High-pressure fluids are injected into the well to remove sand contamination and open up blocked layers. This hydraulic stimulation improves connectivity between the well and the geothermal reservoir, enhancing flow rates.
4. To evaluate the effectiveness of these interventions and the overall performance of the geothermal system, hydrodynamic testing is conducted. This involves: Measuring pressure, Assessing volume flow, Monitoring temperature variations. These tests provide a comprehensive understanding of the water supply system and help optimize operational parameters for long-term efficiency.

1.5.3 Degassing of extracted thermal water

Extracted geothermal water often contains separable gas components, which must be managed to ensure safe and efficient operation of district heating systems. The most common gases found in thermal water include: Carbon dioxide (CO_2), Methane (CH_4), Nitrogen (N_2)

1.5.3.1 Handling Low Methane Content

In cases where the methane concentration is low, the separated gas may be:

- Released into the atmosphere, following environmental regulations,
- Compressed and stored in dedicated tanks for potential later use,
- Reinjected into the cooled thermal water before it is returned to the reservoir.

These methods help minimize environmental impact and maintain system balance.

1.5.3.2 Utilization of High Methane Content

When the methane content is high, the separated gas can be utilized as an energy source. In such cases, the methane is typically:

- Collected and fed into gas engines,
- Used for on-site electricity generation or combined heat and power (CHP) applications.

This approach enhances the overall energy efficiency of the geothermal system and contributes to the use of renewable energy in multiple forms.

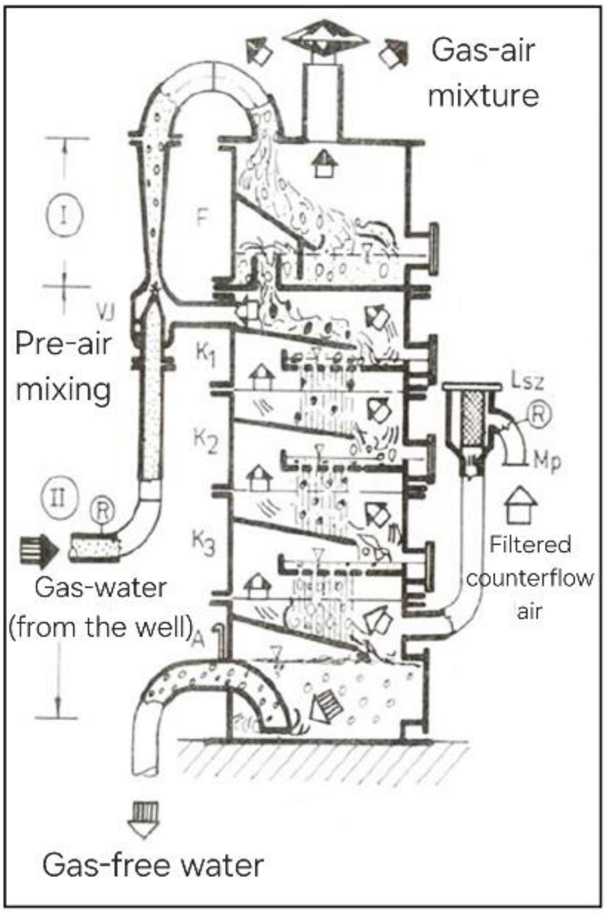

Figure 37. The process of degassing extracted thermal water [16]

1.5.4 Utilization of Thermal Wells in Hungary

Hungary has a long tradition of utilizing geothermal energy, particularly in the field of district heating and public infrastructure. One of the earliest documented uses dates back to post–World War I Budapest, where the palm house of the Botanical Garden was heated using hydrothermal energy.

Later developments saw the emergence of geothermal-heated residential buildings in Pest, especially in the vicinity of the Budapest Zoo and Botanical Garden. These early applications laid the foundation for Hungary's continued investment in geothermal technologies, making it one of the leading countries in Central Europe in terms of thermal well utilization.

Figure 38. Budapest palm house with geothermal heating [17]

1.5.4.1 The Geothermal District Heating System in Veresegyház

Veresegyház is a notable example of successful geothermal energy integration into municipal infrastructure. The development of the geothermal district heating system began in 1987, with the drilling of the first production well.

By 1992, the system expanded to include a thermal bath, followed by the connection of several public buildings, such as the local school, community center, and later the Mézesvölgy Primary School and the municipal swimming pool.

A major milestone was the construction of a reinjection well, which enabled sustainable operation. Between 2007 and 2010, additional public institutions were connected, and in autumn 2011, the system was significantly expanded with:

- New production wells,
- Nearly 1,500 meters of pipeline,
- Connection of approximately 45 large consumers.

One unique feature of the system is its impact on urban comfort during winter. While forward pipes are insulated, the return pipes are uninsulated and laid 1.5 meters underground. This design allows residual heat from the used thermal water to melt snow and ice on sidewalks, keeping pedestrian areas safe and accessible.

Figure 39. The Geothermal District Heating System before and after renovation in Veresegyház [18]

System Overview

- Total network length: 14.5 kilometers
- Consumers: Public institutions and industrial facilities
- Annual gas replacement: Approximately 2.2 million cubic meters

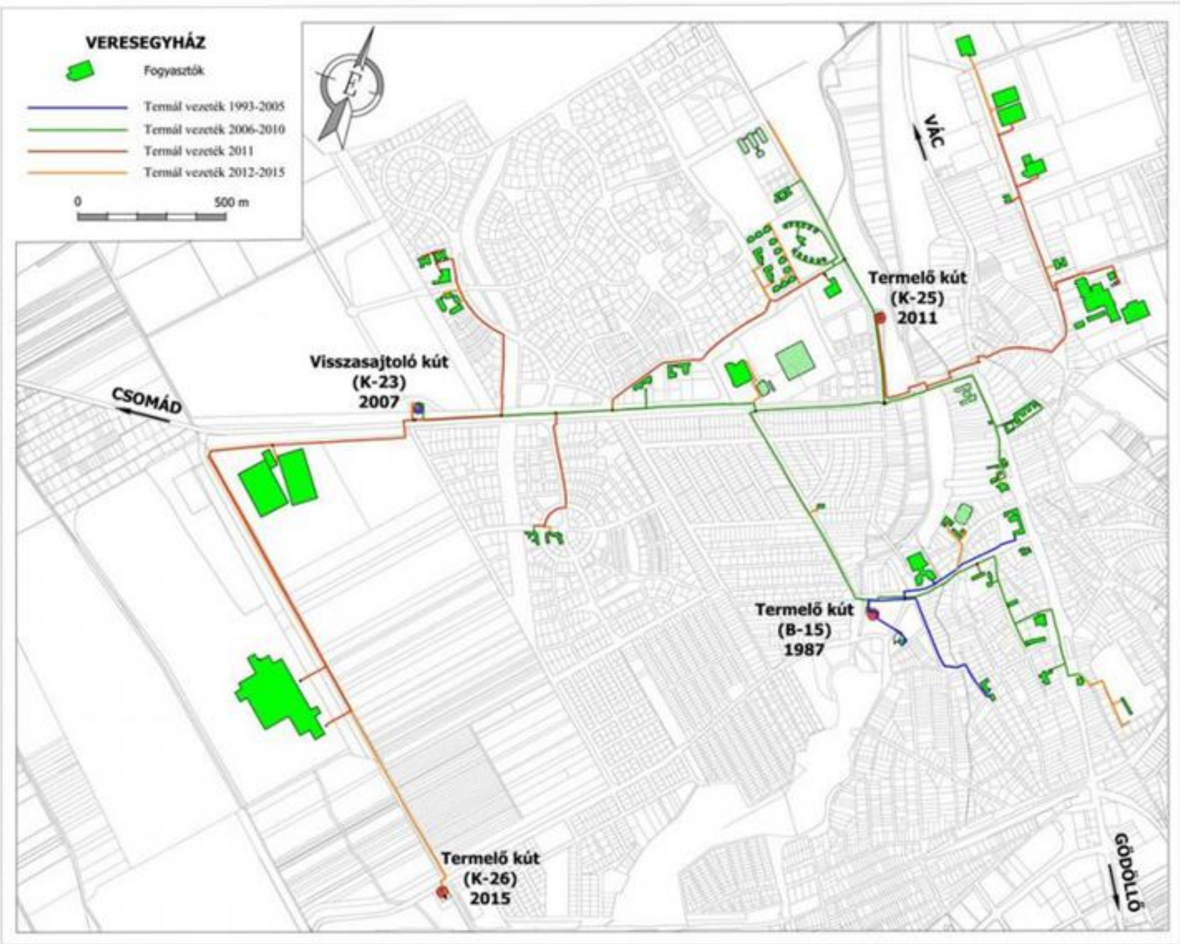

Figure 40. Extent and development of the thermal water pipeline network in Veresegyház until 2016 [18]

Financial Background

The project, with a total cost of around 650 million HUF, was made possible through 60% funding from the European Union and the Hungarian government. The municipality contributed the remaining 40% through co-financing, amounting to 385 million HUF in support.

This case demonstrates how geothermal energy can be effectively utilized not only for heating but also for improving urban living conditions and reducing fossil fuel dependency.

1.5.4.2 The District Heating System in Szeged

The city of Szeged operates one of the most ambitious geothermal district heating projects in Europe. The Szeged District Heating Company (SZETAV) provides heating and domestic hot water to 27,256 apartments, primarily located in 4–10 story residential buildings and 433 public buildings, including schools, kindergartens, and commercial units.

Since 2018, SZETAV and its partners have been implementing Europe's largest geothermal district heating renovation, transitioning from fossil fuels to renewable geothermal energy.

System Overview

- 23 heating circuits
- Boiler capacity: 1–12 MW per unit
- Total installed capacity: 204.17 MW
- Annual energy production: 843,700 GJ
- 239 heat centers
- 215 km of pipeline network

Until recently, the system relied entirely on imported natural gas, making SZETAV the largest local CO_2 emitter. The geothermal transition significantly reduces this environmental impact.

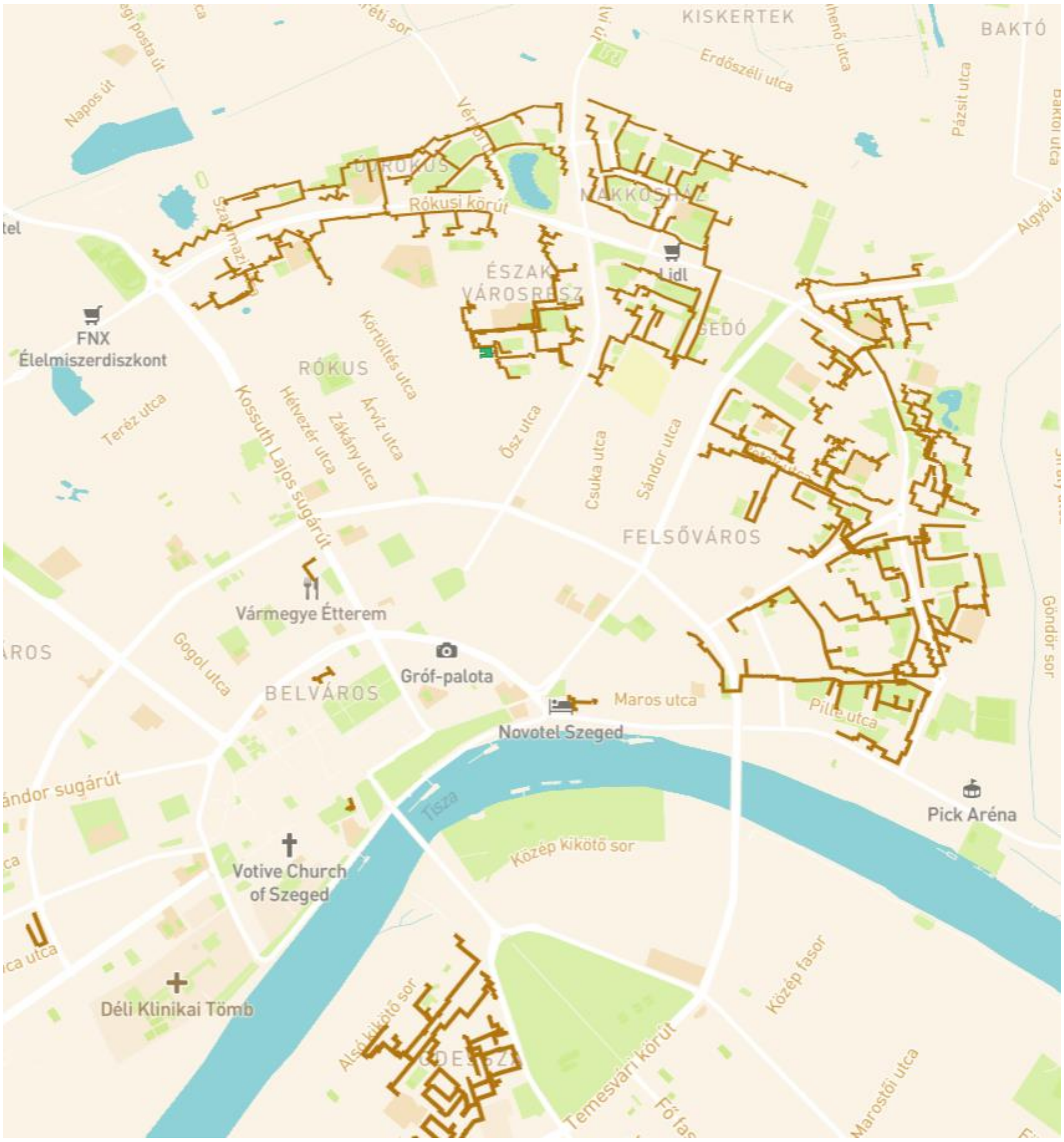

Figure 41. District heating system in Szeged[19]

Regional Geothermal Potential

Within a 50 km radius, 9 settlements utilize geothermal energy for district heating, based on medium enthalpy sources. Most systems follow a design with:

- 1 production well,
- 1–2 reinjection wells,
- Some systems also support balneological uses.

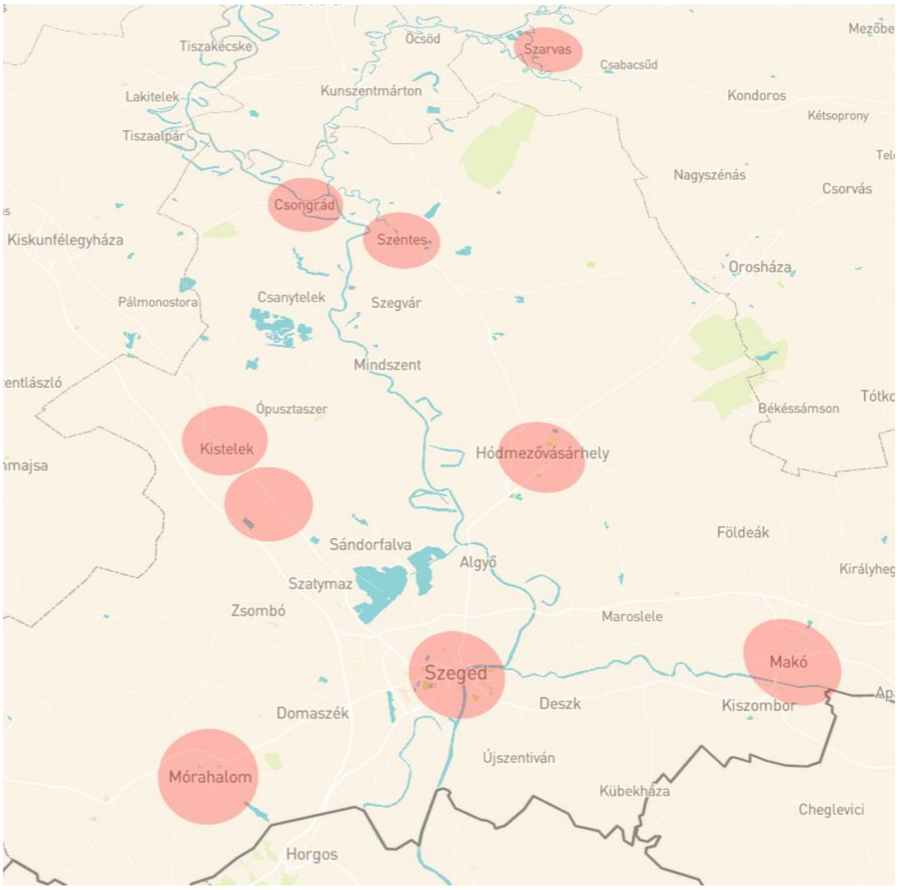

Figure 42. Geothermal systems installed in settlements in south-eastern Hungary [19]

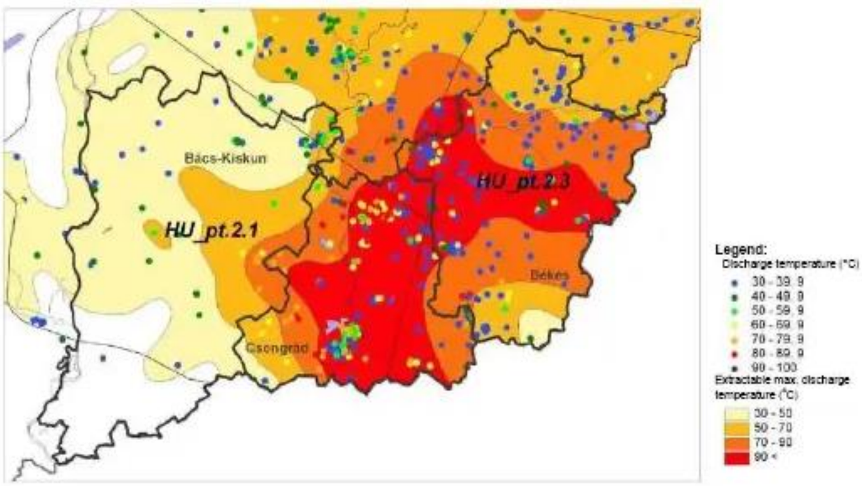

Figure 43. The temperature of the extractable thermal water in south-eastern Hungary [19]

Geothermal Development in Szeged

In various districts—Felsőváros, Odessa housing estate, Tarján, Rókus, and the city center—thermal wells are being drilled to depths of 1,700–2,000 meters. These wells produce 70 m^3/h of thermal water at temperatures of 90°C. A total of 27 new wells are being drilled, with two rigs operating continuously.

Energy Utilization

In Szeged's geothermal district heating system, thermal energy is extracted from deep wells and transferred to the heating network through heat exchangers. Importantly, the geothermal water itself does not enter the district heating system and is not used as domestic hot water. Instead, it serves solely as a heat source, ensuring that the water quality and system integrity are maintained. The system is designed to maximize efficiency while minimizing environmental impact. With the full implementation of geothermal heating, the city is able to utilize approximately 606,958 gigajoules (GJ) of thermal energy annually, replacing nearly 20 million cubic meters of natural gas.

Environmental and Economic Impact

The transition to geothermal energy in Szeged has resulted in substantial environmental and economic benefits. The system achieves an annual reduction of 595,887 GJ in natural gas consumption, representing an 82% decrease compared to previous usage. This translates to a savings of 17,525,718 cubic meters of natural gas per year, or 68% of the city's former consumption. In terms of carbon emissions, the geothermal system contributes to a reduction of approximately 39,299 tons of CO_2 annually, which accounts for a 65% decrease in emissions from district heating. These figures highlight the effectiveness of geothermal energy in supporting sustainable urban development and reducing dependence on imported fossil fuels.

1.5.4.3 The District Heating System in Hódmezővásárhely

The city of Hódmezővásárhely has a long history of geothermal energy utilization. The first thermal well was drilled in 1954, originally for balneological purposes. In 1967, the B913 hospital well was deepened and repurposed for heating applications, marking the beginning of geothermal energy use in public infrastructure.

A significant milestone was reached in 1993, when a geothermal district heating system was officially developed. Over the following decades, the system expanded steadily. By 2016, a total of eight geothermal wells were in operation, providing a combined heat capacity of 23,957 kWh, equivalent to approximately 7,555 petajoules (PJ) per year.

This geothermal system contributes to substantial energy savings, replacing around 5 million cubic meters of natural gas annually. The transition to renewable geothermal energy not only reduces fossil fuel dependency but also supports environmental sustainability and long-term economic efficiency for the city.

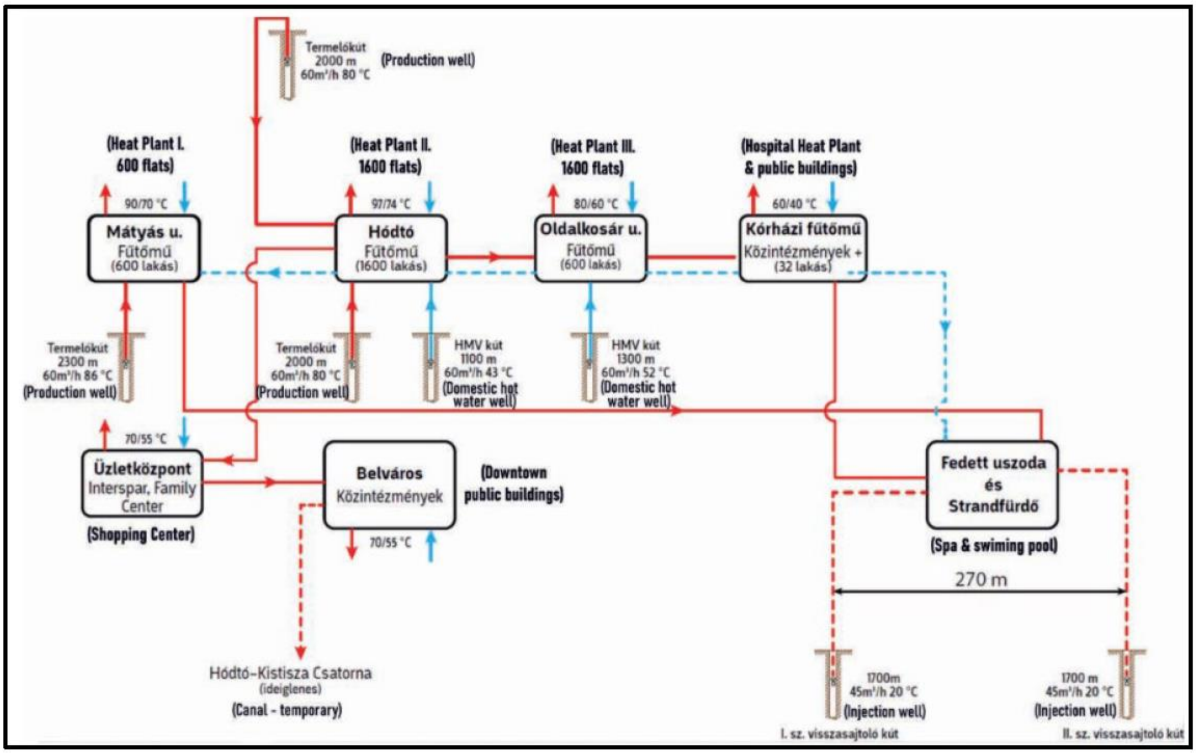

Figure 44. The District Heating System in Hódmezővásárhely [20]

1.5.4.4 Opportunities for Utilizing Geothermal Energy in Budapest

District heating plays a significant role in Budapest's energy landscape, accounting for approximately 10% of the city's final energy consumption and contributing to 8% of its total CO_2 emissions. Each year, the district heating system supplies 10–11 million gigajoules (GJ) of heat, covering roughly 30% of Budapest's total heat demand.

Despite this substantial coverage, the share of renewable energy within the system remains low. Currently, only 1–1.1 million GJ—about 10–11%—comes from renewable sources, primarily through waste incineration. In contrast, combined heat and power (CHP) generation dominates the system, providing 8 million GJ, or 70–75% of the total heat supply.

A key long-term strategic goal for Budapest is to reduce its dependency on imported natural gas, which remains the primary energy source for district heating. Geothermal energy presents a promising alternative, given Hungary's favorable subsurface conditions. While the geothermal gradient in Budapest is not exceptional, it is sufficient to support medium-enthalpy geothermal systems suitable for district heating.

However, several barriers hinder the realization of geothermal projects in the capital. The lack of funding and the current regulatory environment—which offers low return on investment—make such developments difficult without external financial support. Additionally, the operation of Budapest Spa and Thermal Baths Co. Ltd. (BGYH) poses a potential risk to geothermal projects, as overlapping subsurface usage could lead to resource conflicts.

For a geothermal district heating project to be viable in Budapest, several technical and economic conditions must be met:

- The district should not already have renewable heat production facilities.
- The geothermal source must allow for cooperation, particularly in terms of water temperature compatibility.
- Outside the heating season, there must be sufficient consumer demand to justify the use of large hot water storage systems.
- The production well, reinjection well, heat exchanger, and pipeline network must be cost-effectively located.
- The district's heat demand must be high enough to warrant the investment in renewable-based heating infrastructure.

If these conditions are met, geothermal energy could become a cornerstone of Budapest's sustainable heating strategy, contributing to lower emissions, reduced fossil fuel dependency, and long-term energy security.

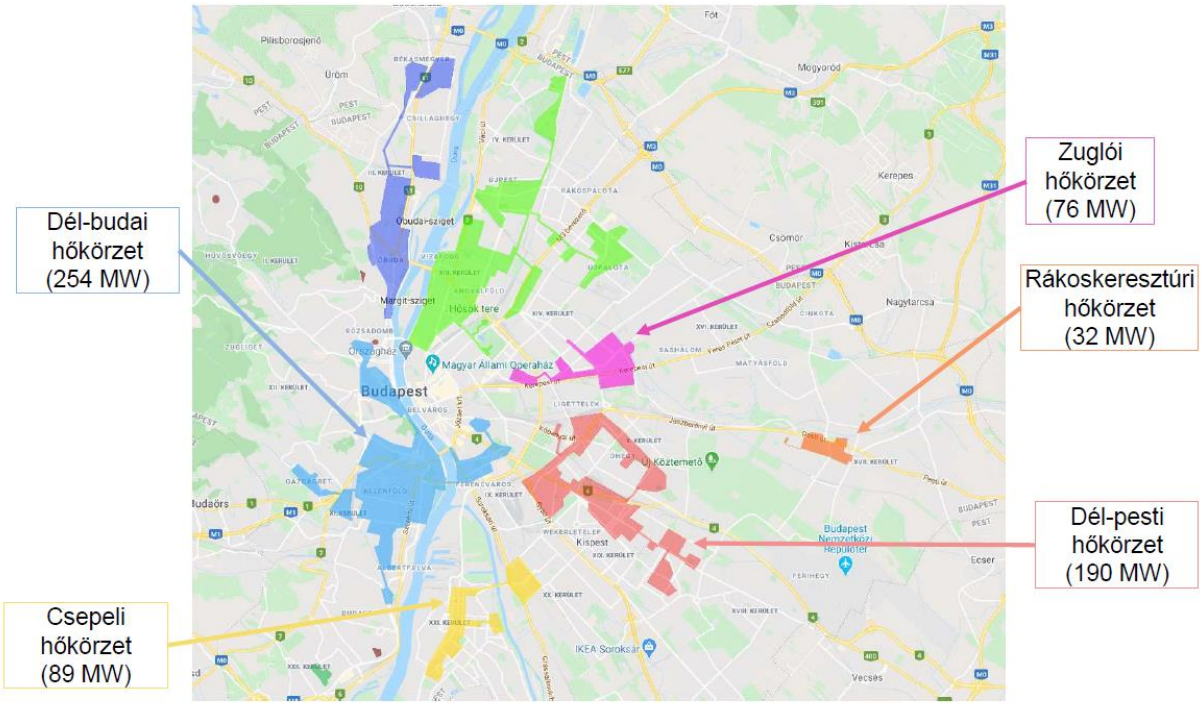

Figure 45. Districts Affected by Geothermal Permit Applications [21]

1.5.4.5 Budapest Geothermal Project Under Preparation

A geothermal district heating project is currently under preparation in Budapest, targeting the Dél-Pesti (Kispest–Kőbánya) district heating network. The system is designed around a single production–reinjection well pair, with an estimated thermal water temperature ranging from 75°C to 90°C. The expected yield per well is 70–90 liters per second, equivalent to 250–320 cubic meters per hour, and the projected thermal capacity per well is between 4 and 12 megawatts thermal (MW_{th}), translating to 120–360 terajoules (TJ) annually.

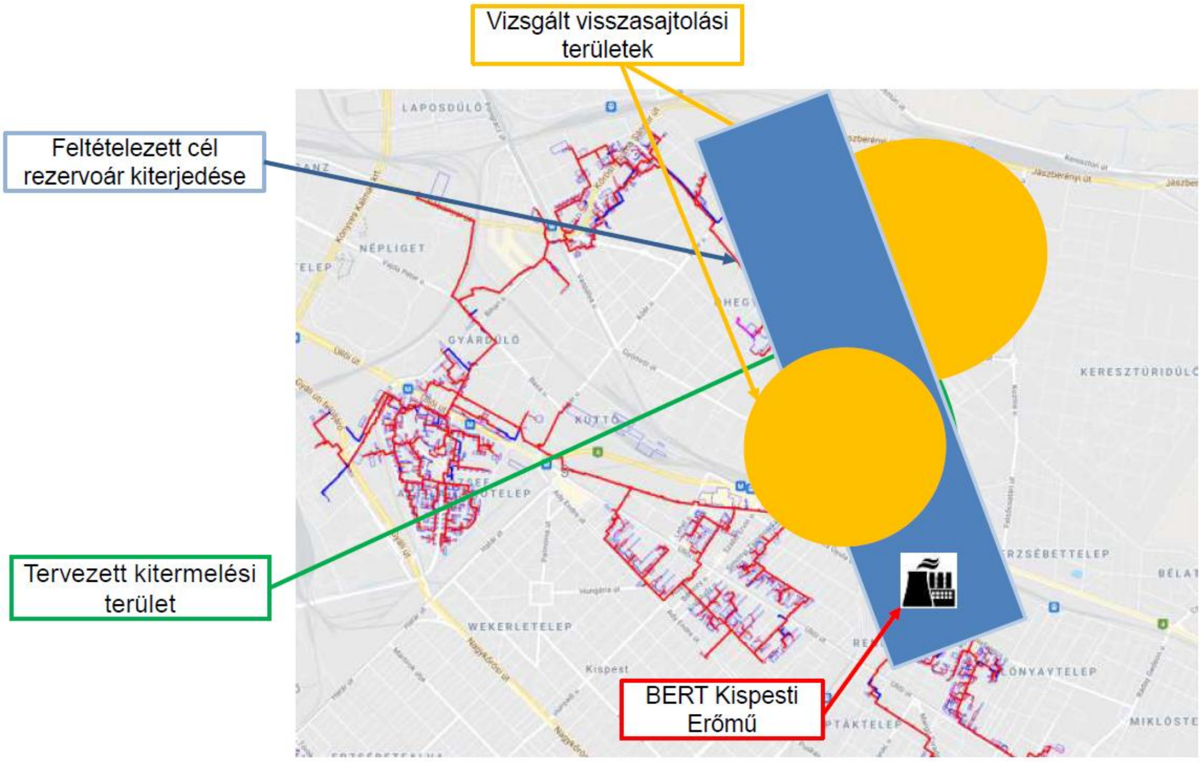

Figure 46. Planned Geothermal System for the Dél-pesti (Kispest) District Heating Area [21]

The implementation of this geothermal system could result in a CO_2 emission reduction of 6,700 to 20,200 tons per year, contributing significantly to Budapest's climate goals.

The project is being developed in cooperation with ArcticGreen Energy (AGE) Corporation, an Icelandic company specializing in green energy solutions. The geothermal source will act as a supplementary heat source, operating in series cooperation with the existing Kispesti Power Plant, which remains responsible for circulation, pressure maintenance, and final heat regulation.

The geothermal heat will be fed into the return pipeline (DN600), with the pipeline's flow capacity ranging from 300 to 800 m³/h during the heating season, and 250 to 400 m³/h in summer. Simulations have been conducted using a flow rate of 280 m³/h, with water temperatures of 75°C and 95°C, to assess system performance and integration feasibility.

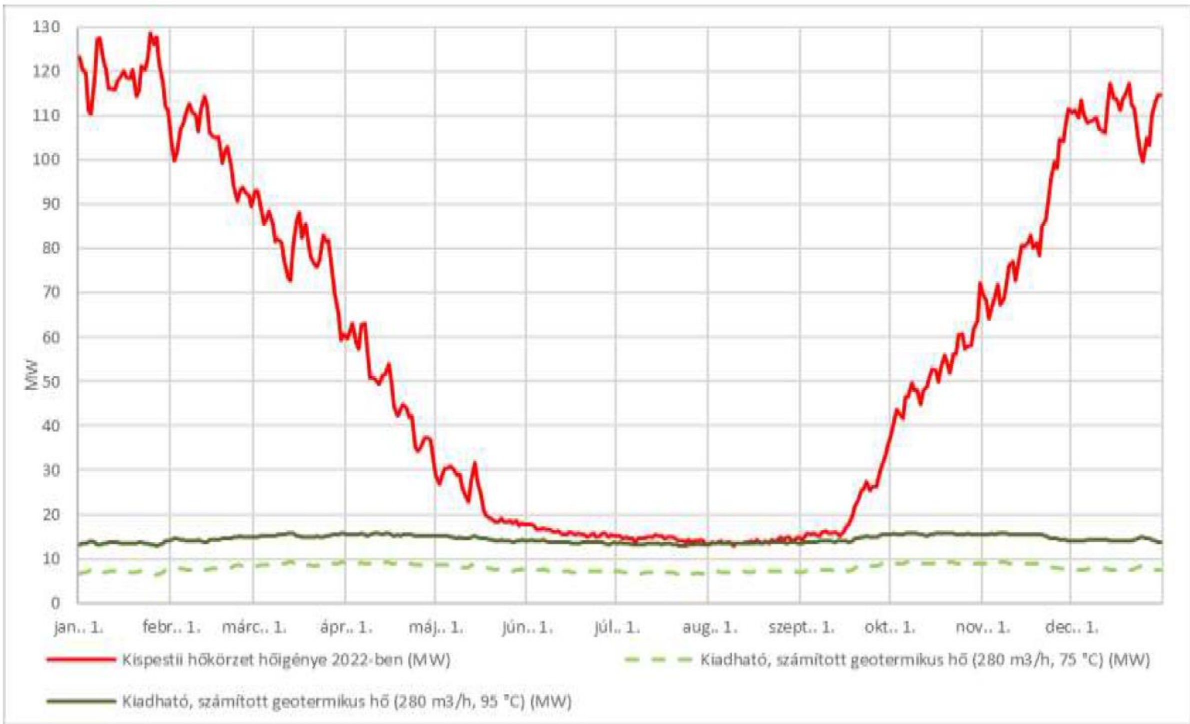

Figure 47. Heat demand in the Kispest district heating area and the output that can be supplied by geothermal energy [21]

This project represents a strategic step toward reducing Budapest's reliance on natural gas and increasing the share of renewable energy in urban heating systems. However, its success depends on careful planning, regulatory support, and effective cooperation between stakeholders.

1.5.4.6 Preliminary Geothermal Potential Calculated by INNARGI (Denmark) for Each Heat District

INNARGI, a Danish geothermal project development and operation company—part of the Maersk Group—has conducted a preliminary assessment of geothermal potential across several heating districts in Budapest. The company has extensive experience in developing geothermal district heating systems in Denmark, Germany, and Poland, and is now exploring opportunities in Hungary's capital.

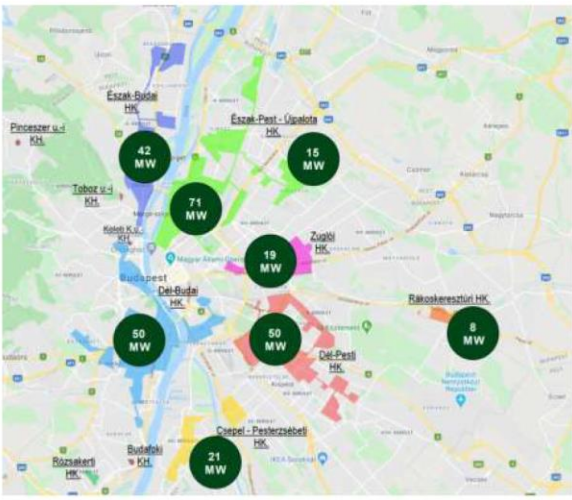

Figure 48. Calculated Geothermal potential for each heat district[21]

The current plan involves the establishment of two geothermal heat sources and their integration into Budapest's district heating network. Preparatory work is underway to identify and evaluate suitable locations across the following districts:

- Zugló heating zone
- South Pest (Kispest) heating zone
- South Buda
- South Buda (Kelenföld) heating zone
- Csepel heating zone

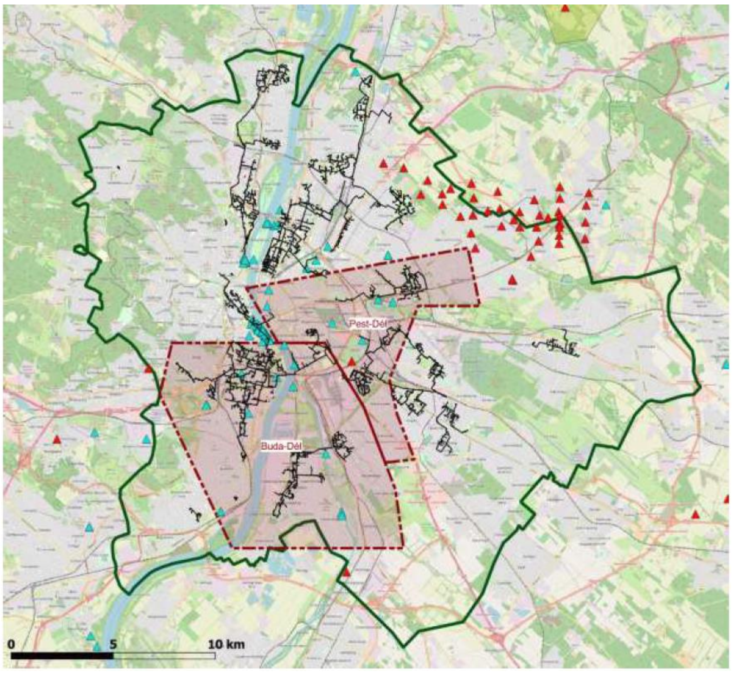

Figure 49. Budapest's district heating network [21]

Based on initial calculations, the total estimated geothermal capacity for these zones is approximately 90 megawatts thermal (MW_{th}), which corresponds to 1,900 terajoules (TJ) per year. If fully implemented, these systems could achieve a CO_2 emission reduction of up to 100,000 tons annually, significantly contributing to Budapest's climate and energy goals.

This assessment highlights the strategic importance of geothermal energy in decarbonizing urban heating systems and reducing reliance on imported natural gas. However, successful implementation will depend on regulatory support, financial investment, and coordinated planning across municipal and private stakeholders.

1.5.4.7 Rákoskeresztúr Geothermal Background

In 2010, FŐTÁV, Budapest's district heating provider, issued a tender for the procurement of geothermal heat energy to partially supply the Rákoskeresztúr district heating zone. The proposed development aimed to deliver 65 terajoules (TJ) of geothermal heat annually.

However, in 2011, changes in the national district heating pricing system—specifically the introduction of annual price setting—led the selected contractor to request a bank guarantee from FŐTÁV for the total projected income over the 15-year operational period. The financial burden of this guarantee rendered the investment unfeasible, and as a result, FŐTÁV abandoned the implementation of the geothermal heat generator in Rákoskeresztúr.

Despite this setback, the district remains a promising location for geothermal development. The current peak demand of the district heating system is 32 megawatts (MW), of which 4.5 MW is already supplied to municipal buildings and 3.3 MW represents new demand from municipally owned or maintained facilities.

The proposed geothermal system would include two wells, each drilled to a depth of 1,800–2,000 meters, with an estimated thermal capacity of 4 MW per well. Together, the wells could supply 8 MW of thermal power, equivalent to 170 TJ per year.
If realized, the project could achieve an annual CO_2 emission reduction of approximately 9,500 tons, contributing to Budapest's broader climate and energy goals. The Rákoskeresztúr case highlights both the potential and the challenges of geothermal integration in urban district heating systems, emphasizing the need for supportive financial and regulatory frameworks.

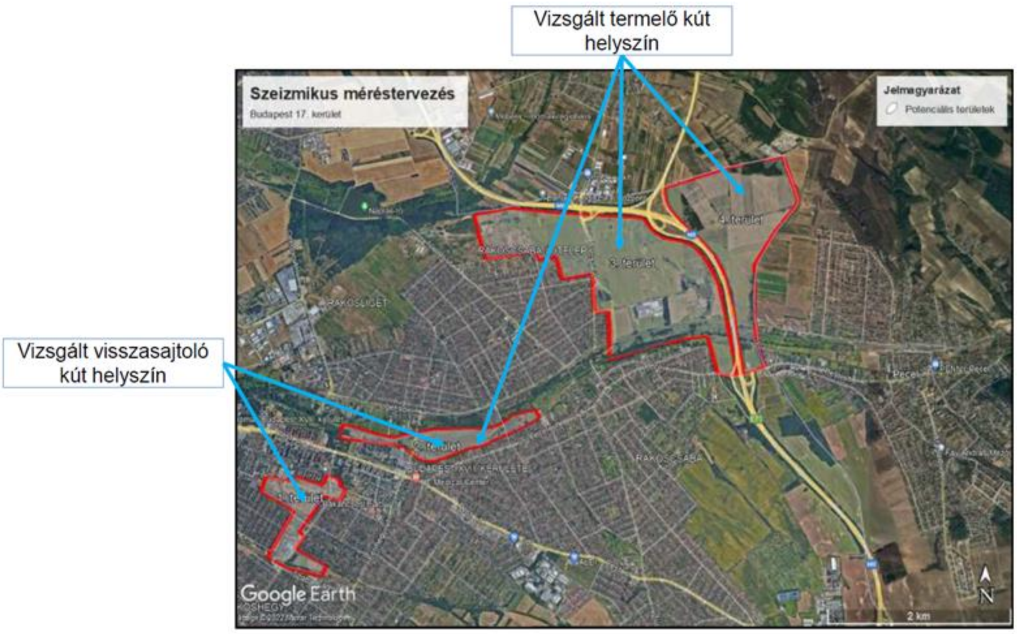

Figure 50. The currently envisioned Rákoskeresztúr geothermal project [21]

1.5.4.8 Renewable and waste energy in the FŐTÁV heat mix.

In 2022, the heat mix was dominated by natural gas, with 62% of the heat generated through cogeneration (CHP) and 27% through boiler-based systems. Only 11% came from waste-to-energy (W2E) cogeneration, indicating a limited share of renewable and alternative energy sources.
According to the conservative estimate for 2025–2026, the share of geothermal energy is expected to rise to 12%, while natural gas-based cogeneration and boiler heat would decrease to 55% and 20%, respectively. Waste-to-energy would slightly increase to 13%.
In the optimistic scenario for 2027–2028, geothermal energy could reach 20% of the total heat mix. This would further reduce the share of natural gas-based cogeneration to 48%, and boiler heat to 19%, with waste-to-energy remaining stable at 13%.
These projections suggest a significant shift toward renewable energy sources, particularly geothermal, in Budapest's district heating system. As noted in the diagram, this transition could result in CO_2 quota cost savings of at least HUF 400–500 million per year, underscoring both the environmental and economic benefits of diversifying the heat mix.

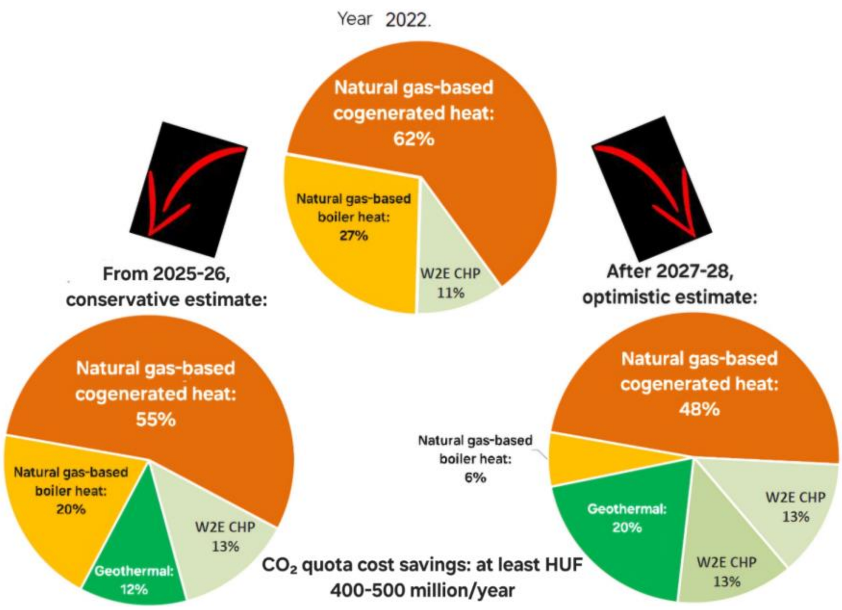

Figure 51. Renewable and waste energy in the FŐTÁV heat mix in 2022 and in the future [21]

2. Waste heat utilisation, and heat pump

2.1 Waste heat background

Waste heat refers to thermal energy that is generated but not effectively used in industrial, commercial, or residential processes. This heat is often lost to the environment through exhaust gases, cooling fluids….etc However, even though these heat streams are considered waste, they often contain large amounts of exergy and would be able to profit through one of the many waste heat usage technologies [1]. Intergovernmental Panel on Climate Change considers waste heat recovery technologies as a tool to improve the energy efficiency [2], decreasing the energy consumption of the industrial processes and therefore, the GHGs emissions. In this way, waste heat represents an opportunity to improve energy efficiency that often goes unexploited.

2.2 Waste heat classification

Waste heat can be categorized based on its **origin**, as different industrial, commercial, and natural processes generate excess heat at varying temperatures. Below is a classification based on key sources:

1. Industrial Waste Heat:
   a) Steel, cement, and glass manufacturing.
   b) Chemical and petroleum refining.
   c) Food processing and paper production.
2. Power Generation Waste Heat:
   a) Thermal power plants (coal, natural gas, biomass).
   b)Internal combustion engines and gas turbines.
3. Commercial and Residential waste heat:
   HVAC systems, refrigeration, and water heating.
4. Transportation Waste Heat:
   Engine exhaust gases and friction losses in vehicles.

Even Renewable Waste Heat could be considered as Waste Heat since even renewable energy systems generate waste heat, which can be recovered. Attending temperature level, waste heat can be classified into different temperature levels based on its usability and the potential for recovery. The classification typically falls into three or four categories (Fig. 52):

Low-Temperature Waste Heat (<100°C)

Examples: Exhaust from cooling towers and HVAC systems; Waste heat from industrial wastewater; Heat from refrigeration and air conditioning systems; Low-temperature flue gases (e.g., food processing, breweries).

Medium-Temperature Waste Heat (100°C – 300/400°C)

Examples: Exhaust gases from internal combustion engines and turbines; Waste heat from boilers, kilns, and drying processes; Chemical processing and refining operations; Steel and metal casting processes.

High-Temperature Waste Heat (>300/400°C)

Examples: Exhaust gases from steel, cement, and glass industries; Heat from metal smelting and refining; Flue gases from power plants and incinerators; High-temperature furnaces and reactors.

Ultra-low-grade (T_{amb}-60)	Low-grade (60-100 °C)	Medium-grade (100-400 °C)	High-grade (>400 °C)
• Data centers • Energy storage system • HVAC facility • Waste water sewage • Geothermal • Biologic descomposition • Solar thermal	• Internal combustion engine (jacket coolant) • Industrial process stream (manufacturing) • Hidrothermal • Anaerobic digestion	• Internal combustion engine (exhaust gas) • Power plant exhaustIndustrial process stream (chemical & food) • Geothermal (volcanic areas • Fermentation processes	• Industrial process stream (iron & steel) • Power plant exhaust (gas turbine) • Inceneration processes

Fig. 52. Waste heat classified by temperature level.

Finally, regarding waste heat, there is little data available. The US Department of Energy publishes a report on waste heat recovery in 2008 [3] stating that 20-50% of the energy consumed during industrial manufacturing processes is lost as waste heat, with about 60% being released as low-quality waste heat at a temperature below 230 °C. In 2009, Enova SF (a Norwegian government company responsible for promoting environmentally friendly energy production and consumption) also provides a temperature range distribution where 37% of the waste heat is above 140 °C and almost half of the remaining 63% is in the range 40-60 °C [4]. In a later study, [5] summarizes different data and collects the distribution by thermal powers in the form of waste heat and its distribution in temperatures for different sectors (including transport, industrial, commercial, residential and electrical), which is presented in a compact way in Fig. 53.

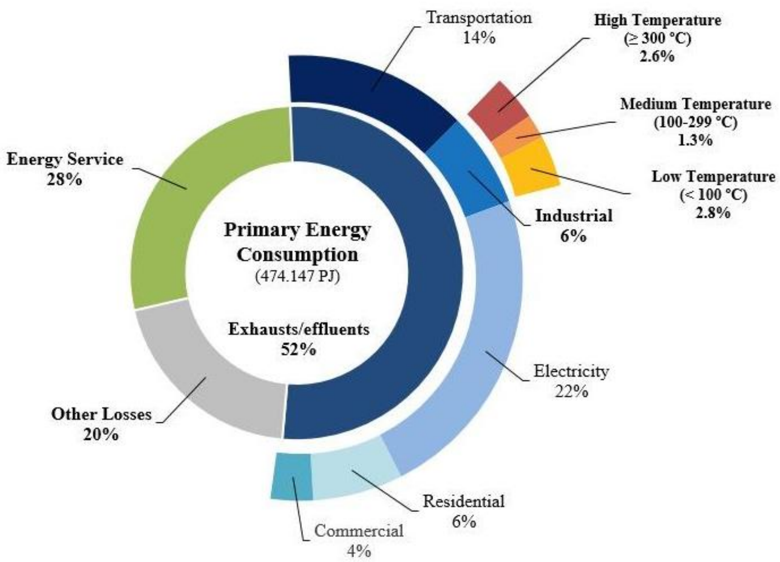

Fig. 53. Waste heat distribution by sector and temperature [5].

2.2.1 Technologies for capturing and utilizing waste heat

Waste heat can be either used directly, through passive use (simply using a heat exchanger) or transformed, through active technologies (transforming the temperature level or producing mechanical or electrical energy) as displayed in Fig. 54.

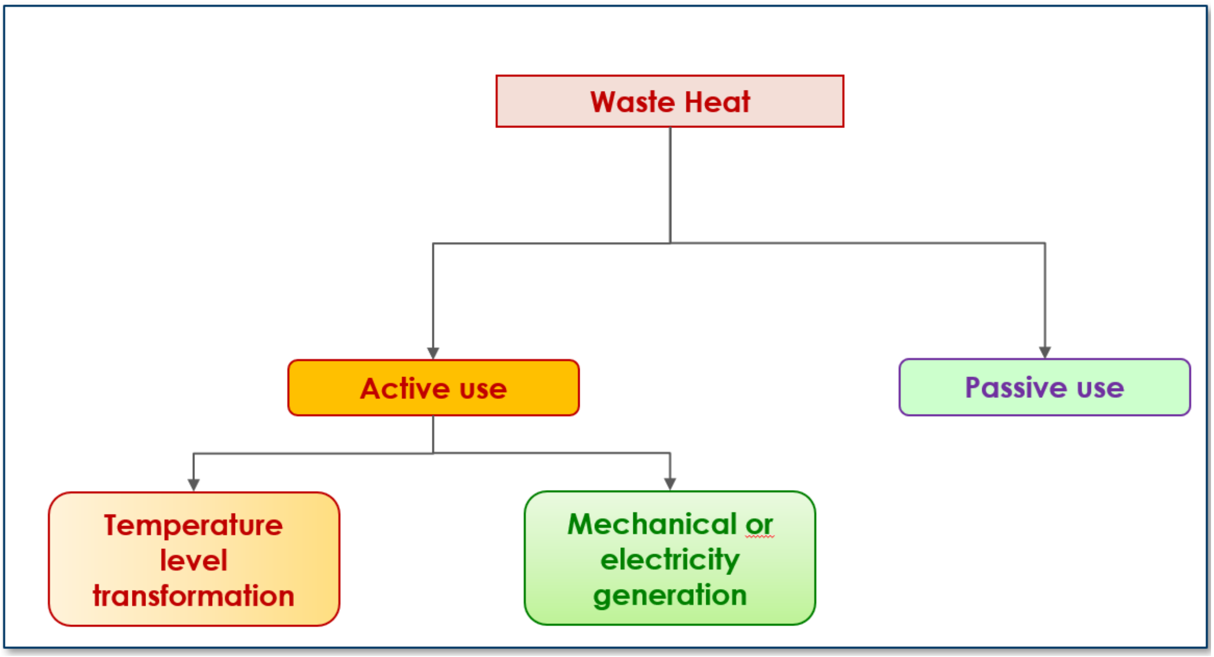

Fig. 54. Classification of technologies used for capturing waste heat.

2.2.1.1 Heat exchangers

The process that uses technologies to capture and use waste heat is known as waste heat recovery. And, in any case (passive or active use), it involves transferring waste heat to be revalued by producing heat or energy. In any case, the first step in waste heat recovery consists of a heat exchanger that captures the waste heat.

Heat exchangers are devices designed to transfer heat from one medium to another, usually without them mixing. They are widely used in various applications, such as heating, cooling, and energy recovery. The fundamental principle of a heat exchanger is to enable heat flow from a hotter fluid to a cooler one. There are several types of heat exchangers, but the most commonly used for heat recovery are the following [3,6]:

1. Plate heat exchanger
2. Shell and tube heat exchanger
3. Air-to-air heat exchangers
4. Finned tube heat exchangers/Economizers
5. Regenerative heat exchangers
6. Direct contact heat exchangers

1. Plate heat exchanger

A plate heat exchanger is a type of heat exchanger that uses metal plates that are stacked or brazed in parallel to each other, forming a hollow metallic shell to transfer heat between two fluids. These plates create a large surface area for efficient heat transfer while keeping the fluids physically separated. The main components are plates, gaskets or brazing, and frame (Fig. 55).

Advantages:

1. Highly efficient for heat recovery in industrial processes and HVAC systems.
2. Frequently used to recover heat from low to medium-temperature fluids.
3. Compact and offer a large heat exchange surface relative to their size.

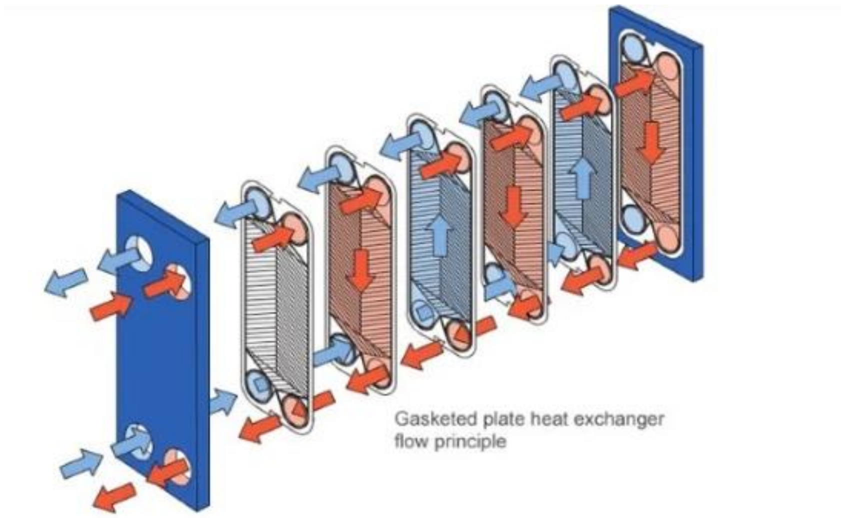

Fig. 55. Plate heat exchanger operation [7].

2. Shell and tube heat exchanger

A shell and tube heat exchanger (Fig. 56) operates by transferring heat between two fluids through a series of tubes contained within a cylindrical shell. One fluid moves through the tubes, while the other fluid circulates around the outside of the tubes inside the shell. The main components of this type of heat exchanger include the tubes, shell, baffles, and tube sheets.

Advantages:

1. Used in industrial applications for fluids at higher pressures and temperatures.
2. Robust and suitable for large flow volumes and more demanding conditions.
3. Can handle both liquids and gases, such as exhaust steam from industrial processes.

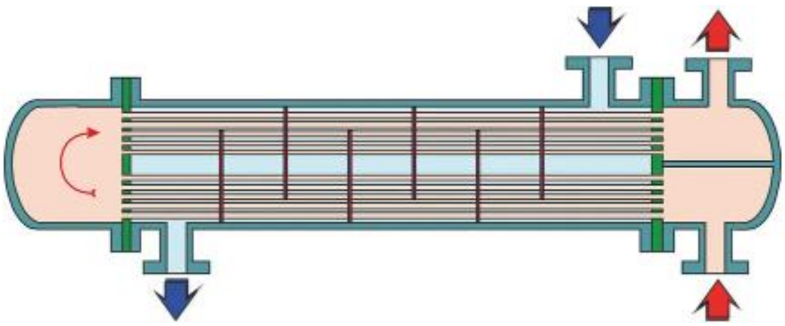

Fig. 56. Shell and tube heat exchanger operation [8].

3. Air-to-air heat exchanger (recuperator)

Air-to-air heat exchangers, often referred to as recuperators, are utilized to transfer heat between two separate air streams without mixing them. There are three main types commonly used for heat recovery:

1. Fixed Plate exchanger.
2. Rotary heat exchanger.
3. Heat pipe heat exchanger.

a) Fixed plate heat

This type is made up of several thin, flat plates arranged with small spaces in between. The exhaust air moves through alternating channels, while the fresh air travels through nearby channels in the opposite direction (counterflow) (Fig. 57).

Advantages:

1. It features a straightforward design with no moving parts.
2. It achieves high thermal efficiency in counterflow or crossflow setups.

Limitations:

It cannot transfer moisture; it only exchanges sensible heat (dry heat).

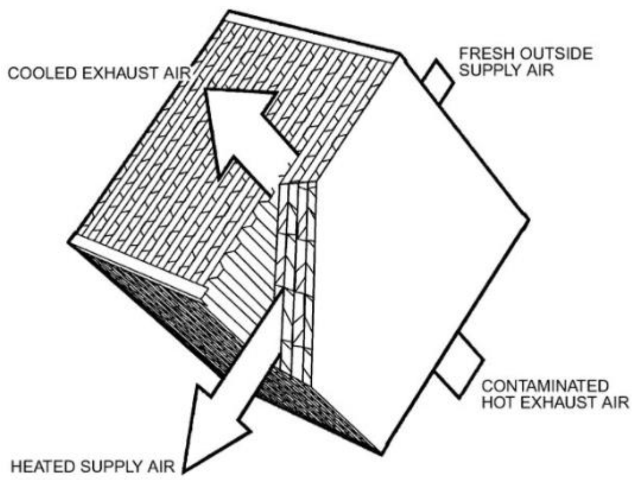

Fig. 57. Fixed plate heat [9].

b) Rotary heat exchanger

This type features a rotating wheel (or rotor) made from a heat-absorbing material, such as aluminum, that spins between the exhaust air and the fresh air streams. As the rotor turns, it captures heat from the exhaust air and transfers it to the incoming fresh air (Fig. 58).

Advantages:

1. It transfers both sensible heat (temperature) and latent heat (moisture), which helps improve indoor air quality and comfort.
2. It operates with high efficiency, particularly in humid environments.

Limitations:

1. It contains moving parts, which requires more maintenance.
2. There is a possibility of some cross-contamination between the air streams.

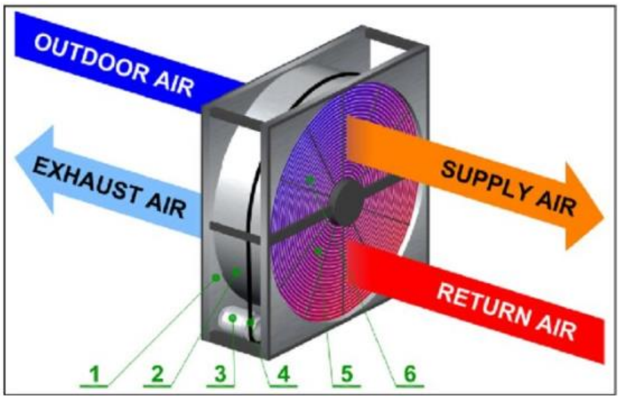

Fig. 58. Rotary heat exchanger [10].

c) Heat pipe heat exchanger

Heat pipes are sealed tubes that contain a refrigerant or working fluid. One end of the heat pipe is positioned in the exhaust air stream (hot side), where the fluid evaporates and absorbs heat. The resulting vapor then moves to the cooler end (incoming fresh air stream), where it condenses and releases the absorbed heat. The liquid then returns to the hot side through capillary action or gravity, and this cycle continues (Fig. 59).

Advantages:

1. They have no moving parts, which makes them very reliable.
2. They transfer sensible heat efficiently.
3. They can function at various temperatures and pressures by changing the working fluid.

Limitations:

1. They only transfer sensible heat.
2. They do not facilitate moisture transfer.
3. They require proper installation orientation to work effectively.

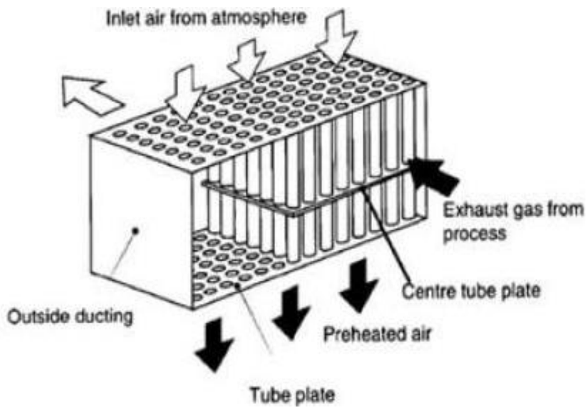

Fig. 59. Heat pipe heat exchanger [11].

4. Finned tube heat exchangers/Economizers

Finned tube heat exchangers are utilized to recover heat from low to medium temperature exhaust gases for heating liquids. They consist of a bundle of tubes through which feedwater circulates (Fig. 60).

Advantages:

1. They are commonly used in power plants or boilers to recover heat from exhaust gases and preheat feedwater, which improves thermal efficiency.
2. They are designed to capture residual heat from combustion gases.

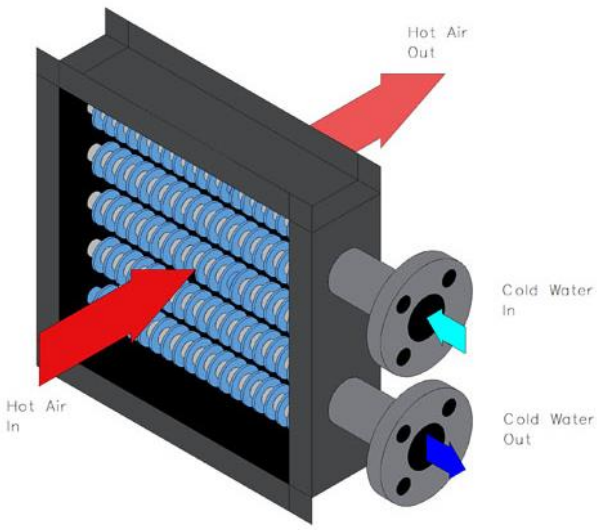

Fig. 60. Finned tube heat exchangers/Economizers [11].

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5. Regenerative heat exchangers

Regenerative heat exchangers temporarily store heat from one fluid and then transfer it to another fluid, facilitating heat recovery and enhancing energy efficiency. Unlike typical heat exchangers, where heat transfer occurs simultaneously between two fluids, regenerative heat exchangers use materials (such as metal or ceramic) to alternately absorb and release heat [12].

There are two main types of regenerative heat exchangers: static and dynamic. Each type operates in a slightly different manner, but the fundamental principle remains the same: storing heat from one stream and transferring it to another.

Advantages:

1. They are suitable for high-temperature applications, such as industrial furnaces or gas turbine systems.
2. They work by accumulating heat in a solid medium, which then transfers that heat to a working fluid.

6. Direct contact heat exchangers

Direct contact heat exchangers bring two fluids into direct physical contact, allowing heat to be transferred directly between them without a separating barrier. This contrasts with conventional heat exchangers, which have solid walls between the fluids. Heat transfer occurs through conduction and convection, and in some cases, phase changes such as condensation or evaporation can take place [13].

Direct contact heat exchangers are commonly used in situations where the two fluids are immiscible (they cannot mix) or when one of the fluids is a gas or vapor. They are particularly efficient for specific applications, such as cooling water with air or condensing steam.

Advantages:

1. In these exchangers, the hot and cold fluids come into direct contact, making them suitable for use in cooling towers or certain geothermal heat recovery systems.
2. They provide efficient heat transfer for specific applications where mixing of fluids is not a concern.

2.2.2 Waste heat revalorization

As mentioned before, heat exchangers are the most common technologies used for capturing waste heat. Once the waste heat is captured, it can be used directly **(reuse)** or several **active technologies** can be used to transform it into thermal energy at other temperature level or transform it into mechanical or electrical energy.

Reuse

Heat exchangers are utilized not only for capturing waste heat but also for making use of the heat that has been captured. They can be employed in either primary or secondary systems:

1. Primary Systems: In this setup, a heat exchanger transfers heat directly from the waste heat medium into the main medium for further transmission and use.

2. Secondary Systems: Here, heat is recovered from the waste heat medium into a transfer fluid (such as water or oil), which then moves to a secondary heat exchanger to heat the main medium for utilization.

Examples of reusing waste heat are:

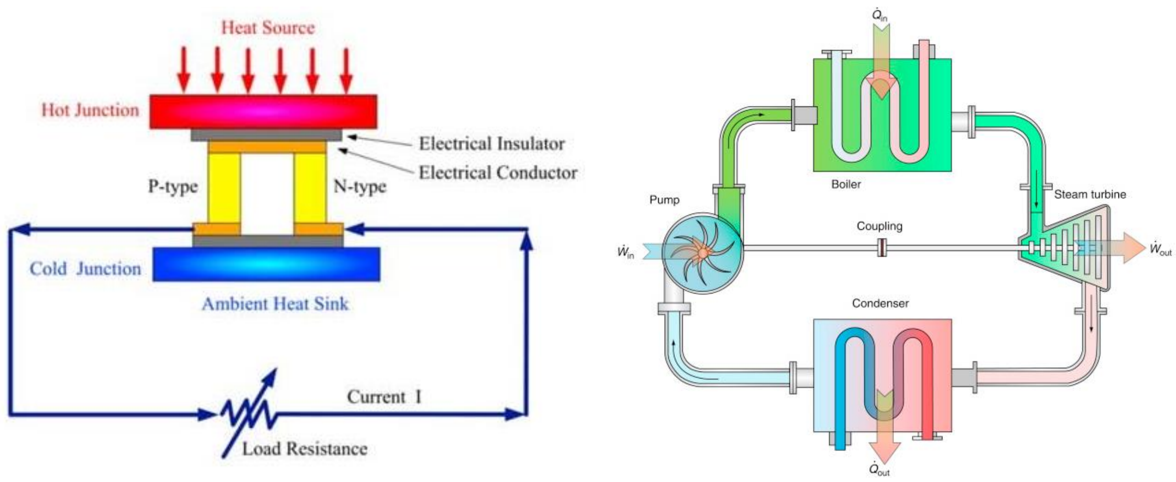
1. Heat recovery steam generators (HRSG): heat exchanger that captures and utilizes waste heat from hot exhaust gases to generate steam.
2. Economizers: heat exchanger that recovers waste heat from exhaust gases or process fluids to preheat water or air.
3. Heat recovery boilers: System that operates similarly to a gas boiler, but instead of using gas, it utilizes waste heat to heat a useful medium, typically water.

2.2.2.1 Active technologies

When we use the waste heat absorbed to activate a thermodynamic cycle, we say we are using waste heat recovery active technologies. In this way, we can use the heat to generate heat at another useful temperature level or we can use the heat to produce mechanical or electrical energy.

The utilization of waste heat can follow two main approaches. The first involves converting waste heat into mechanical or electrical energy through waste heat-to-power technologies. The most common systems are based on the Rankine cycle, either using water in the steam Rankine cycle (SRC) or organic fluids in the organic Rankine cycle (ORC). Thermoelectric generators are also employed for direct conversion of heat into electricity. The second approach involves using waste heat to produce thermal energy at a different temperature level. This includes technologies for generating cooling such as thermally activated refrigeration systems based on absorption or adsorption cycles and technologies for upgrading heat to a higher temperature, such as heat pumps. These heat pumps can be thermally driven (using absorption or adsorption cycles) or based on vapor compression mechanisms.

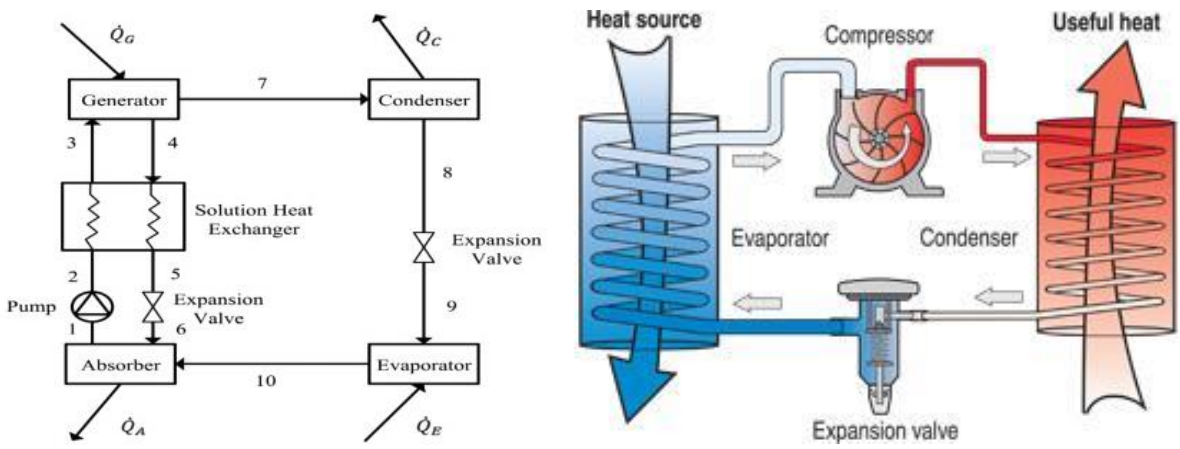
The most common technologies used are Rankine cycle also called steam Rankine cycle (SRC), general economically preferable when the source heat temperature exceeds 400 °C, and organic Rankine cycle (ORC) or Kalina cycle in moderate temperature ranges. Also, thermoelectric generators, with lower efficiencies but suitable for applications that require small amounts of power from a generator that requires minimal maintenance (Fig. 61).



a) b)

Fig. 61. Active technologies waste heat to power technologies, a) thermoelectric, b) Steam Rankine cycle [14,15].

Thermally driven or vapor compression cycles. Thermally driven technologies such as absorption and adsorption cycles can be used to generate cold (refrigeration systems) or obtain higher temperatures (heat pumps). Focusing on obtaining higher temperatures, vapor compression cycle is the most common technology (Fig. 62).



a) b)

Fig. 62. Active technologies waste heat to cold or heat, a) absorption cycle, b) Vapor compression cycle [16-18].

Thermodynamic principles for heat pump operation:

A heat pump operates based on fundamental thermodynamic principles. It transfers heat from a lower-temperature source to a higher-temperature sink using external energy, typically electrical or mechanical work.

Second Law of Thermodynamics (Clausius Statement): Heat naturally flows from a higher temperature to a lower temperature. A heat pump reverses this process by using external work to move heat from a cold to a hot reservoir.

First Law of Thermodynamics (Energy Conservation): The total energy within a system remains constant:

$Q_{in} + W = Q_{out}$

Q_{in} = Heat absorbed from the low-temperature source (evaporator)

W = Work input (compressor energy)

Q_{out} = Heat released at the high-temperature sink (condenser)

- Heat pumps

The ideal compression cycle is based on the concept of a heat engine that evolves cyclically between two heat sources at temperatures T2 > T1, extracting heat from the lower temperature medium (Q_1) and transferring heat (Q_2) to the higher temperature medium by virtue of the external work received.

The Carnot cycle will present the maximum possible performance of a heat pump evolving between two temperatures and consists of the reversible transformations outlined in the T-s diagram (Fig. 63).

1-2; an isentropic (adiabatic and reversible) compression takes place in the two-phase vapor zone of the diagram by means of the addition of work.
2-3; complete condensation of the vapor takes place by means of the reversible transfer of heat at constant pressure and temperature.
3-4; isentropic expansion from the saturated liquid point (3) to the pressure corresponding to the cold temperature, thereby producing a two-phase mixture (4) and a certain amount of energy transferred by the system.
4-1; partial vaporization of the liquid present in state (4), at constant pressure and temperature.

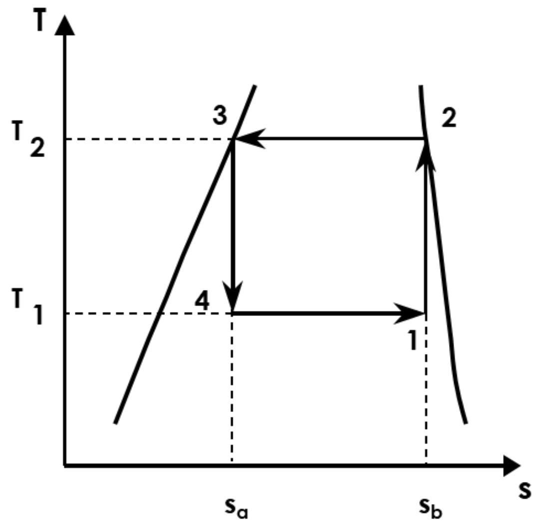


Fig. 63. Ideal (Carnot) cycle on T-s diagram [19].

The ideal Carnot cycle is not feasible, its equivalent ideal cycle involves a series of modifications: 1-2: Compression will be carried out on a gas, therefore at least point 1 must be saturated vapor in order to avoid liquid shocks.2-3: The compressor discharge gases will be cooled to saturation temperature and subsequently condensed in an ideal infinite surface exchanger.3-4: Isenthalpic expansion, of an irreversible nature, instead of that which occurred in the Carnot cycle, for reasons of simplicity and reliability.4-1: The two-phase fluid that reaches point 4 evaporates in an infinite exchanger until it reaches saturated vapor, closing the ideal cycle.

Thus, the equivalent ideal cycle represented in the Ph diagram would be as follows (Fig. 64):

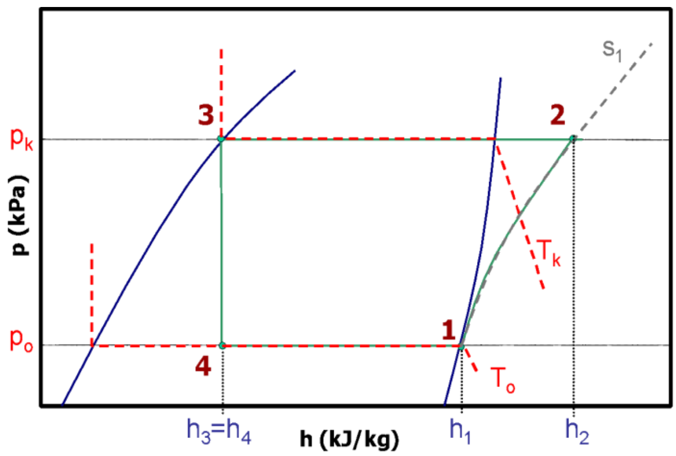


Fig. 64. Real cycle on T-s diagram [19].

Finally, the evaporation (T_e) and condensation (T_k) temperatures must be lower and higher than the temperatures of the corresponding sources (T_1 and T_2), with a superheating of the vapor at the compressor inlet and a subcooling of the liquid at the condenser outlet. In addition, the actual compression deviates from isentropic. Therefore, the compression cycle is as follows:

As has been observed, in vapor compression systems, it is necessary to bring a working fluid to boiling conditions at low temperature for the production of cold and to condensation conditions (or cooling) at high temperature for the production of heat.

Therefore, vapor compression systems employ several processes to complete a cycle that continuously achieves the desired objective (cold or heat). The main components of the system, in addition to the working fluid (refrigerant), are the evaporator, compressor, condenser, and expansion device (Fig. 65).

"The refrigerant is the substance that flows through the different elements of the system in a cyclical manner, absorbing heat at low temperatures in the evaporator and releasing heat at higher temperatures in the condenser. Generally, these processes involve a change in the state of the fluid."

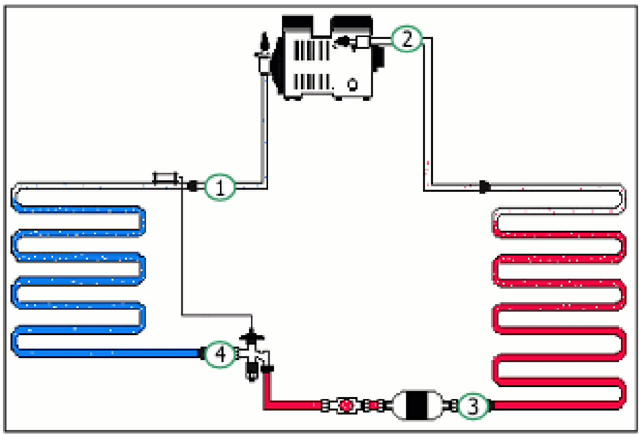


Fig. 65. Vapor compression cycle scheme [19].

1. Evaporator

It is a heat exchanger to which the refrigerant arrives as a biphasic mixture at low temperature. The liquid evaporates at the saturation temperature corresponding to the prevailing pressure in the evaporator, absorbing the latent heat necessary for its evaporation from the surroundings.

2. Compressor

The refrigerant arrives at the compressor in a vapor state (usually superheated vapor) at low pressure and temperature. The compressor mechanically draws in the vapors generated in the evaporator by creating a pressure lower than that of the evaporator, absorbing sensible heat along its path. Subsequently, these vapors are mechanically compressed, increasing their pressure and temperature.

3. Condenser

The refrigerant arrives at the condenser from the discharge of the compressor as superheated vapor at high pressure and temperature. Since the temperature of the surroundings will be lower than the saturation temperature of the refrigerant, cooling and subsequent condensation will occur. In this way, the latent heat absorbed in the evaporator and the heat absorbed during compression is transferred in the condenser to the surroundings (sensible heat of cooling and the latent heat of condensation that can be used for heating applications). The refrigerant leaves the condenser as a liquid (usually subcooled) and is directed toward the expansion device or accumulation tank.

4. Expander

The expander in a vapor compression cycle reduces the pressure and temperature of the refrigerant, which arrives in a saturated vapor or superheated state at high pressure from the condenser. As it passes through the expander, the refrigerant undergoes rapid expansion, causing a change of state that lowers its temperature and allows it to become a mixture of vapor and liquid. This process is crucial, as the refrigerant, now at low pressure and temperature, can absorb heat from the environment in the evaporator, thereby facilitating cooling and completing the vapor compression cycle.

- Heat pump technologies

1. Air-to-air heat pumps

Operation: These pumps operate by using a fan to draw in outdoor air, which then passes through an evaporator where it is warmed. The heated air is subsequently circulated indoors.

Efficiency: The efficiency of these pumps is measured by the Coefficient of Performance (COP), although this can fall below 1 in very cold conditions.

Common Uses: They are widely used in moderate climates for heating and cooling, often as part of air conditioning systems.

Maintenance: To maintain efficiency, it is essential to clean the filters and heat exchanger regularly.

2. Air to water heat pumps

Operation: Similar to air-to-air pumps, but instead of transferring the extracted heat to air, these pumps transfer it to water. This heated water can then be used for space heating via radiators or for providing domestic hot water.

Efficiency: These pumps are quite efficient, particularly when paired with low-temperature heating systems like underfloor heating.

Common Uses: They are suitable for heating in single-family homes and commercial buildings.

Maintenance: Routine inspections of both the pump and water circuit are necessary to prevent issues like corrosion or leaks.

3. Geothermal heat pumps

Operation: Ground-source heat pumps utilize a network of pipes buried underground (collectors) to extract heat from the ground or groundwater. This extracted heat is then transferred to the water circulating through the heating system.

Efficiency: These systems exhibit a high Coefficient of Performance (COP) since ground temperatures are more stable than air temperatures. They can achieve a COP of 4 or higher.

Common Uses: Ground-source heat pumps are ideal for new constructions in residential and commercial settings and in larger buildings.

Maintenance: They typically require less maintenance over time, but the initial installation costs can be higher due to the drilling required for the underground collectors.

4. Water-to-water heat pumps

Operation: Water-source heat pumps capture heat from water bodies, such as rivers or lakes, and transfer it to a water circuit for either heating or cooling purposes.

Efficiency: These systems are very efficient, particularly in environments where the water temperature remains relatively constant.

Common Uses: Water-source heat pumps are commonly employed in industrial facilities, large buildings, and district heating systems.

Maintenance: Regular monitoring of water quality and maintenance of the piping systems are necessary to ensure optimal performance.

5. Absorption heat pumps

Operation: Absorption chillers use a refrigerant and an absorbent (such as water or lithium bromide) instead of an electric compressor. They are powered by a heat source, such as natural gas, to facilitate their operation.

Efficiency: Absorption chillers can be less efficient than compression systems, but they are advantageous in applications where waste heat is readily available.

Common Uses: These chillers are commonly found in large buildings, industrial facilities, and cooling systems used in various industrial processes.

Maintenance: Regular maintenance is essential due to the complexity of the absorption system, ensuring reliable and efficient operation.

6. Hybrid heat pumps

Operation: Hybrid heating systems combine a heat pump with a gas boiler or another alternative heating system. The heat pump serves as the primary source of heating, while the boiler kicks in during low-temperature conditions when additional heat is needed.

Efficiency: These systems can achieve high efficiency by adapting to varying climatic conditions and optimizing energy use throughout the year.

Common Uses: Hybrid systems are particularly well-suited for climates that experience cold winters and hot summers.

Maintenance: Regular maintenance is required for both the heat pump and the boiler to ensure optimal performance and reliability.

7. Dual-service heat pumps

Operation: Heat pumps with reversible functionality can switch between heating and cooling as necessary. They utilize reversing valves to alter the flow of the refrigerant, allowing for both heating and cooling modes.

Efficiency: These systems are highly efficient, particularly in climates where heating and cooling are frequently required.

Common Uses: They are commonly used in spaces that need heating and cooling, such as commercial buildings and specific rooms within residential settings.

Maintenance: Regular maintenance is essential to ensure heating and cooling functions operate smoothly and efficiently.

8. Inverter heat pumps

Operation: Inverter heat pumps utilize inverter technology, which allows the compressor speed to adjust based on the heating or cooling demand. This enables the system to operate more effectively in response to varying conditions.

Efficiency: These systems deliver enhanced efficiency by running at different speeds, which helps to lower energy consumption compared to traditional systems.

Common Uses: Inverter heat pumps are commonly found in air conditioning systems and building heating applications.

Maintenance: They typically require less maintenance than conventional systems; however, the inverter technology can introduce additional complexity that may require more careful monitoring.

9. Waste heat pumps

Operation: Heat recovery systems capture wasted heat from industrial processes or refrigeration systems and repurpose it for heating applications.

Efficiency: These systems are highly efficient, effectively reducing energy waste and maximizing the use of available energy.

Common Uses: Heat recovery systems are commonly utilized in industrial settings as well as for heating in buildings.

Maintenance: To ensure optimal performance, these systems require careful design and regular monitoring to maintain the efficiency of the heat recovery process.

- Heat pumps classification: Attending to the production temperature

Heat pumps are classified based on the temperature of the heat they produce, which determines their suitability for different applications. The classification typically includes:

a) Low-Temperature Heat Pumps (<45°C):

Typical Supply Temperature: 30°C - 45°C (space heating)

b) Medium-Temperature Heat Pumps (45°C – 75/90°C)

Typical Supply Temperature: 45°C - 75°C

Applications:

1. Domestic hot water (DHW) production.
2. Radiator-based heating systems (retrofitting old buildings).
3. Process heating for food, textile, and chemical industries.

c) High-Temperature Heat Pumps (>75/90°C)

Typical Supply Temperature: 75°C - 150°C and more

Applications:

1. Industrial processing heating (drying, sterilization, and chemical processing).
2. District heating networks.
3. Steam production for power generation and industrial use.

- Heat pump application in waste heat

As previously mentioned, waste heat can be categorized into four temperature levels, with low-grade heat being the most suitable for heat pumps. Low-grade heat refers to heat at temperatures below 100°C. While these temperatures are often too low for direct use in industrial processes, they can still be valuable for space and water heating in residential and commercial buildings, or for improving the efficiency of certain industrial operations.

Heat pumps can utilize low-grade heat by raising its temperature to a more suitable level, depending on the specific requirements. Additionally, low-grade industrial heat can be captured from cooling water in industrial processes. The most common applications of heat pumps for waste heat recovery include:

1. Distilleries
2. Industrial laundries
3. Waste heat district heating
4. Supermarkets
5. Data centres

- Configurations and connections of heat pumps for various waste heat sources

1. Direct Connection to a Primary Circuit

Application: This approach is frequently used when the waste heat originates from a process involving a circulating fluid, like hot water or exhaust gases.

Configuration: The heat pump's heat exchanger is directly connected to the waste heat source circuit in this setup. This allows the waste fluid to flow through the heat pump's evaporator or condenser.

Advantages: This configuration reduces temperature loss and enhances efficiency, eliminating the need for intermediate heat exchangers.

Disadvantages: It necessitates complete compatibility regarding materials and temperatures between the pump and the heat source, which may restrict design options.

2. Intermediate Heat Exchanger (Indirect System)

Application: This method is beneficial when the waste heat fluid is corrosive, contains contaminants, or has temperatures that exceed the heat pump's equipment limits.

Configuration: An additional heat exchanger, such as a plate or tube type, is installed to transfer heat from the waste fluid to an intermediate fluid, which is then routed to the pump's evaporator.

Advantages: This setup safeguards the heat pump system from contaminants and enables temperature modulation.

Disadvantages: It introduces thermal resistance and necessitates extra maintenance.

3. Closed-Loop System with Secondary Heat Fluids

Application: This approach is perfect for gathering heat from various distributed waste sources, such as building ventilation air or several points in industrial processes.

Configuration: A secondary fluid circuit collects heat from these different sources and transports it to a heat exchanger linked to the heat pump.

Advantages: It enables heat collection from multiple sources and streamlines thermal management across distributed waste heat sources.

Disadvantages: This setup requires additional piping infrastructure and potentially extra pumping systems for the secondary fluid.

4. Storage Systems (Thermal Storage Tanks)

Application: This configuration is ideal for waste heat sources that exhibit variable or intermittent heat flow.

Configuration: In this setup, waste heat is stored in a thermal tank. The heat pump connects to this tank to absorb heat during peak demand or when the heat source is not operational.

Advantages: It maximizes waste heat utilization, particularly when the demand for the heat pump does not align with the availability of heat.

Disadvantages: It necessitates additional space for the thermal tank and requires precise control to optimize the processes of thermal charging and discharging.

5. Integration with Air or Gas Flows

Application: This configuration is designed for capturing waste heat from exhaust gases or ventilation systems.

Configuration: An air-to-water or air-to-refrigerant heat exchanger is connected to the heat pump's inlet, facilitating the transfer of heat from the gas flows.

Advantages: It efficiently captures both sensible heat (temperature-related) and latent heat (moisture-related) from the exhaust gases.

Disadvantages: Maintaining optimal thermal transfer efficiency can be complex due to the need for precise adjustments to the air or gas flow rates.

2.3 Selected urban waste heat sources for district heating

Waste heat represents a valuable yet often underutilized energy source within district heating systems. By capturing thermal energy that would otherwise be lost during industrial processes, power generation, or commercial operations, energy communities can significantly improve overall efficiency and sustainability. Integrating waste heat into district heating networks reduces primary energy consumption, lowers greenhouse gas emissions, and enhances the economic viability of the system.

2.3.1 Waste heat from data centres

Data centres are among the fastest-growing energy consumers in the digital economy. In 2010, global electricity consumption by data centres reached 350 TWh, accounting for more than 1% of worldwide electricity use. In Europe, consumption was 56 TWh/year in 2007 and was expected to rise to 104 TWh/year by 2020, driven by trends such as streaming services and the Internet of Things (IoT).

Cooling systems are essential for maintaining safe operating conditions for IT equipment, and they represent approximately 40% of the total energy consumption of a data centre. This cooling process generates significant amounts of waste heat, which can be recovered and utilised in district heating networks.

For example, a medium-sized data centre with 1 MW IT capacity emits around 3,700 MWh of heat per year through its cooling systems. This corresponds to approximately 0.46 MWh of thermal energy for every 1 MWh of electrical energy consumed. Larger facilities can reach 5 MW IT performance, while most centres operate below 500 kW, with many in the range of 500 kW to 5 MW.

Recovered heat from data centres can be integrated into district heating systems using heat exchangers and, where necessary, heat pumps to raise the temperature to the required level. This approach transforms a cooling necessity into a valuable energy resource, improving overall energy efficiency and reducing greenhouse gas emissions.

2.3.2 Waste heat from subway tunnels

Subway systems represent a significant source of low-grade waste heat, primarily generated during train braking and ventilation of subway cars. This heat, often dissipated into the surrounding environment, can be captured and integrated into district heating networks, especially in densely populated urban areas.

Globally, subway networks operate in 148 cities, covering approximately 11,000 km of lines and serving 151 million passengers per day. Within the European Union, there are around 50 medium and large cities with subway systems, totalling 2,800 km of lines and transporting 31 million passengers daily. The estimated waste heat potential from these systems ranges between 6.7 and 11.2 TWh per year.

Stations are typically spaced about 1 km apart, creating frequent opportunities for heat recovery. By installing heat exchangers in ventilation shafts or using heat pumps to upgrade the temperature, this otherwise lost energy can be transformed into a valuable resource for district heating, reducing primary energy demand and improving sustainability.

2.3.3 Waste heat from sewer networks using heat pumps

Urban sewer networks provide a stable and accessible source of low-grade heat that can be recovered for district heating. Wastewater typically maintains an annual average temperature of 10–15 °C, and in summer it can reach up to 20 °C, making it suitable for heat pump applications.

By installing heat exchangers in sewer systems and coupling them with heat pumps, cities can transform this latent energy into a valuable resource. In municipalities with more than 10,000 inhabitants, wastewater heat recovery can cover up to 5% of total heat demand, corresponding to an estimated 150 TWh per year across Europe. In Germany alone, this technology could supply 20% of the building stock with heating energy.

Several successful projects have already been implemented, including systems in Cologne and Nice, demonstrating the technical feasibility and economic potential of this approach. Wastewater heat recovery not only reduces primary energy consumption but also contributes to decarbonising urban heating systems.

The main components of a system that utilises wastewater heat loss are the following:

Wastewater sewer: A large underground pipe that carries wastewater from urban areas. It serves as the primary source of low-grade heat for recovery.

Wastewater: The actual water flowing inside the sewer, typically at 10–15 °C annually and up to 20 °C in summer, making it suitable for heat extraction.

Wastewater heat exchanger: A device installed in or near the sewer to transfer heat from the wastewater to a secondary water circuit without mixing the two fluids. This is the first step in capturing thermal energy.

Circulation pump: Ensures continuous flow of the secondary water circuit through the heat exchanger and toward the heat pump, maintaining efficient heat transfer.

Water-to-water heat pump: Upgrades the low-temperature heat from the wastewater to a higher temperature suitable for district heating. It uses a closed refrigeration cycle to achieve this.

2.3.4 Waste heat utilisation: the consumer becomes a prosumer

Waste heat recovery is transforming the way energy communities operate. Traditionally, consumers were passive recipients of heat supplied by centralised systems. Today, through technologies such as heat exchangers, heat pumps, and smart integration, consumers can become "prosumers" — both producers and consumers of thermal energy.

By utilising waste heat from sources such as data centres, subway tunnels and sewer networks, buildings and facilities contribute actively to the district heating network. This approach reduces primary energy demand, lowers greenhouse gas emissions, and enhances system resilience. It also creates economic opportunities, as prosumers can offset energy costs or even generate revenue by supplying surplus heat.

The transition from consumer to prosumer represents a paradigm shift in district heating: from a one-way supply model to a collaborative energy ecosystem. Waste heat utilisation is not only a technical solution but a cornerstone of sustainable urban energy strategies.

3. Combined heat and power (CHP)

3.1 Introduction to CHP systems

CHP, also known as cogeneration, is an efficient method of generating electricity and heat simultaneously from the same energy source. Unlike conventional systems where electricity and heat are produced separately, CHP systems recover the waste heat from electricity generation to provide useful thermal energy, such as steam or hot water, for industrial processes, heating, or cooling [20]. CHP are classified in two types:

a) Head-End Cogeneration Cycle (Topping Cycle)

Description: In this type of cycle, electricity is generated first (at the "head" of the cycle) and the excess heat produced during this process is then used for heating purposes (at the "tail" of the cycle) (Fig. 66).

Process:

The fuel (such as natural gas or biomass) is burned in a prime mover, like a gas turbine or an internal combustion engine, to generate electricity.

The hot exhaust gases produced by the engine or turbine are then captured and used to produce steam or hot water for heating applications.

This cycle is typically used in industrial settings or district heating systems, where there is a constant demand for both electricity and heat [21].

Advantages: This type of cycle maximizes the use of high-temperature exhaust gases, producing electricity first and utilizing the remaining energy for heating. It is more efficient when the demand for electricity is high, and the heat generated can be fully utilized.

Common Applications: It is commonly used in industrial processes, large-scale buildings, and district heating systems.

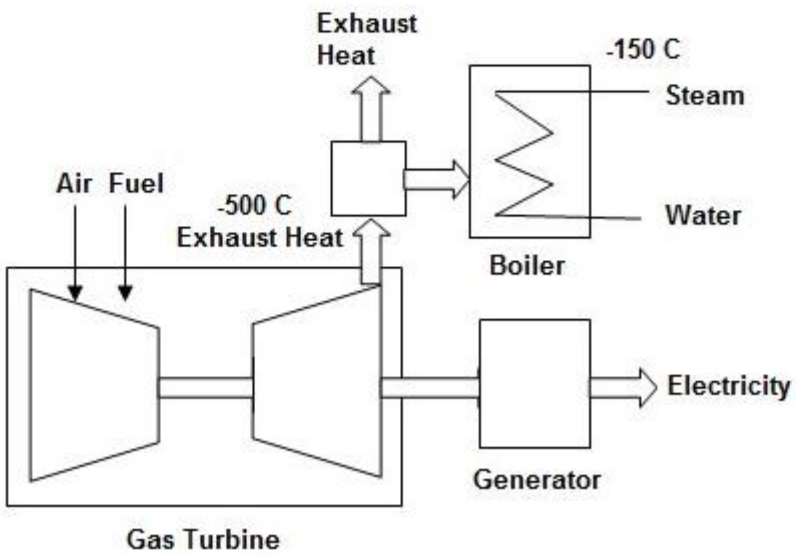


Fig. 66. Head-end cogeneration cycle [19].

b) Tail-End Cogeneration Cycle (Bottoming Cycle)

Description: In a tail-end or bottoming cycle, the heat is produced first (at the "tail" of the cycle), and the electricity is generated by utilizing this heat later in the process (Fig. 67).

Process:

The system begins by producing heat, typically through a conventional heat source such as a boiler or industrial waste heat.

This heat is then used to produce steam, which drives a steam turbine to generate electricity. In some cases, this can also be combined with a secondary cycle for additional electricity generation.

The process is less common than the head-end cycle but is sometimes used in facilities where heat is the primary requirement, and electricity generation is secondary [21].

Advantages: It is ideal for processes where a significant amount of waste heat is available, and the primary goal is heat generation, with electricity being a byproduct. It can also be useful in facilities where heat recovery from industrial processes or waste heat is readily available.

Common Applications: It is often used in waste-to-energy plants, where the heat from the waste incineration process can be used to generate electricity.

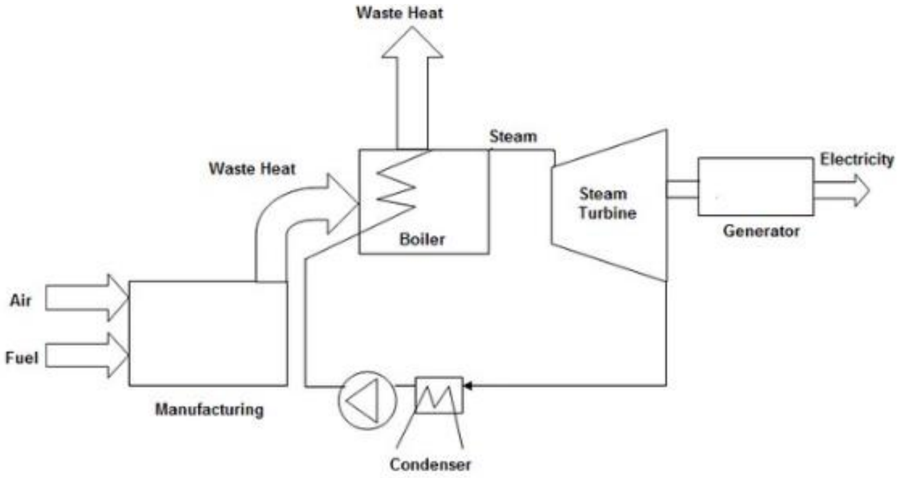


Fig. 67. Tail-end cogeneration cycle [19].

Key Differences

1. **Head-End Cogeneration** focuses on generating electricity first, followed by using the exhaust heat for heating, while **Tail-End Cogeneration** focuses on heat production first, with electricity generated as a secondary benefit.
2. **Efficiency**: Head-end cogeneration is often more efficient in systems where there is a significant demand for both electricity and heat, as it ensures that electricity is produced from the highest temperature source. Tail-end cogeneration can be more beneficial in systems where waste heat recovery or heat demands are the priority.

The electrical energy generated usually represents 30–40% of the fuel's energy content. Even in the most advanced power plants, this reaches a maximum of approximately 60% (European Commission, 2017).

Various CHP technologies have been developed, categorized into two main groups:

- Flexible Units:

These systems can adjust their power-to-heat ratio based on heat demand. They typically use steam turbines, where steam is partially extracted at specific points to provide heat. However, the extracted steam cannot be used for electricity generation, resulting in a trade-off between power and heat production [21]. These units can operate in:

a) **Full cogeneration mode**: Maximum heat generation.

b) **Full condensing mode**: Maximum electricity generation with no useful heat. Operation depends on the specific heat demand.

Different CHP technologies:

1. Combined cycle gas turbine with heat recovery, including a steam condensing extraction turbine– flexible power-to-heat ratio.
2. Combined cycle gas turbine with heat recovery without a condensing extraction turbine.
3. Steam back pressure turbine.
4. Steam condensing extraction turbine - flexible power-to-heat ratio.
5. Gas turbine with heat recovery.
6. Internal combustion engine.
7. Microturbines.
8. Stirling engines.
9. Fuel cells.
10. Steam engines.
11. Organic Rankine cycles.

Reciprocating Engines

Size Range: 10 kW to 10 MW

Applications: universities, hospitals, water treatment facilities, industrial facilities, commercial buildings, and multi-family dwellings.

Gas Turbines

Size Range: 1 MW to 300 MW

Applications: hospitals, universities, chemical plants, refineries, food processing, paper, military bases.

Microturbines

Size Range: 30 kW to 330 kW (modular packages exceeding 1 MW)

Applications: multifamily housing, hotels, nursing homes, waste water treatment, gas & oil production.

Fuel Cells

Size Range: 5 kW to 2.8 MW

Applications: data centres, hotels, office buildings, waste water treatment

Fig. 68 displays the range power of the CHP technologies mentioned before.

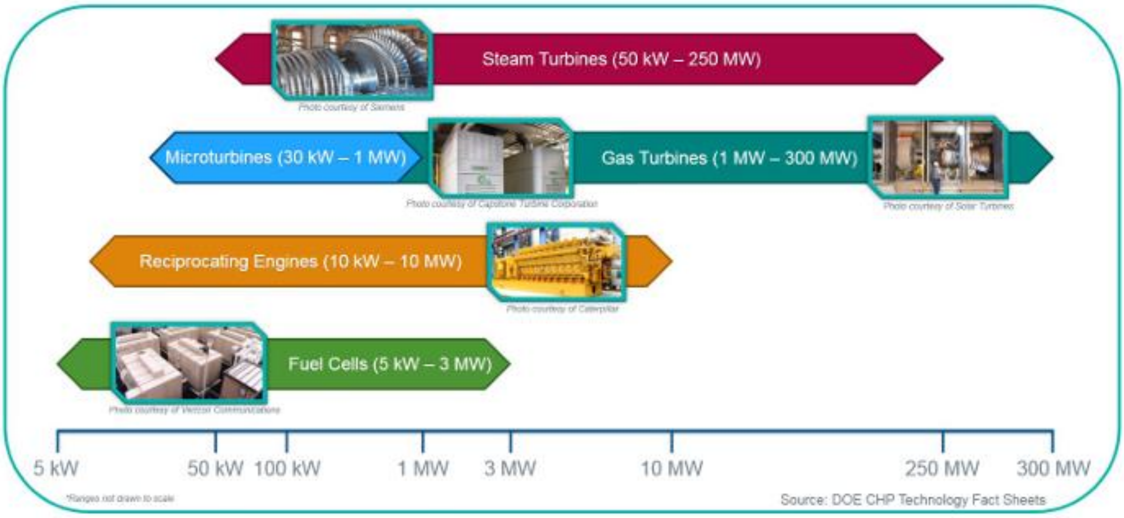


Fig. 68. Power range of the CHP technologies [22].

Standard Setup of a CHP Installation (Based on Commission Decision 2008/952/EC) [23]

The main components required to operate a steam-driven CHP installation (1-5 technologies) include (Fig. 69):

1. A boiler to generate steam.
2. A turbine that converts the steam into kinetic energy.
3. A generator to transform the kinetic energy into electrical energy.
4. A heat exchanger to deliver useful heat to a district heating network.
5. In industrial applications, exhaust gases can often be used directly for heating purposes.

Additional boilers are often installed as backup or to support the system during periods of high heat demand, such as in winter. These boilers are not considered part of the CHP units.

In some cases, the boiler supplying steam to the CHP unit can serve a dual purpose, producing steam for both the CHP unit and, for example, industrial customers (dual-purpose boiler).

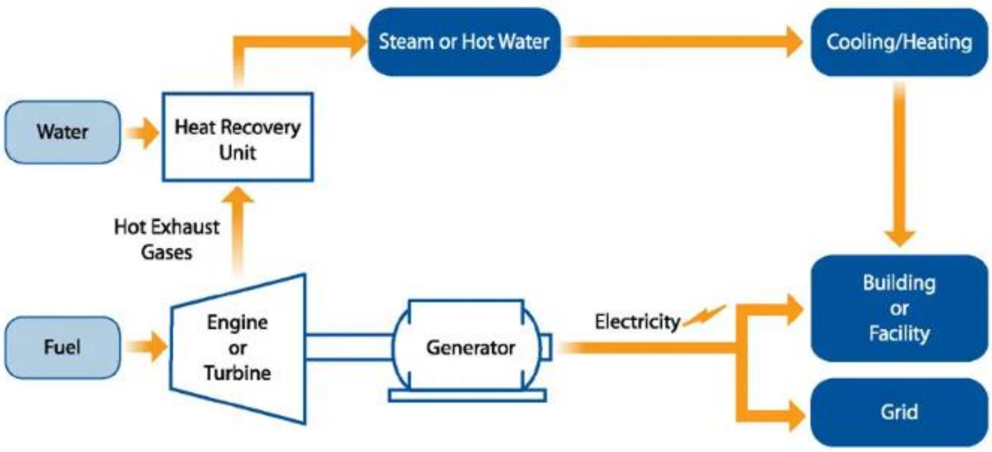


Fig. 69. Main components of the CHP cycle [22].

Main parameters (Eqs. (1-5))

Electrical power ($\dot{P}_e$): $$\dot{P}_e = \frac{\dot{Q}_{fuel} \times \eta_{generator}}{Inlet\ temperature\ of\ fluid} \quad (1)$$

Thermal power ($\dot{Q}_t$): $$\dot{Q}_t = \dot{m} \times C_P \times (T_{out} - T_{in}) \quad (2)$$

Overall efficiency (η_x): $$\eta_x = \frac{\dot{P}_e + \dot{Q}_t}{\dot{Q}_{fuel}} \times 100 \quad (3)$$

Heat-to-electricity ratio (C/E): $$\frac{C}{E} = \frac{\dot{Q}_t}{\dot{Q}_e} \quad (4)$$

Load factor: $$FL = \frac{p_{avarage}}{p_{max}} \quad (5)$$

3.2 The role of CHP systems in heat production and their integration into various technologies such as DHN

CHP systems play a significant role in heat production by simultaneously generating electricity and useful thermal energy from a single fuel source. This dual production enhances energy efficiency by utilizing the heat that would otherwise be wasted in conventional power generation methods. In heat production, CHP systems can supply heat to industrial processes, commercial buildings, or district heating systems. This allows for greater efficiency compared to traditional boilers, as heat that would otherwise be wasted in electricity generation is used for heating water or air. Additionally, by generating electricity on-site, CHP systems reduce losses associated with long-distance electricity transmission [24].

CHP efficiencies

a) If a CHP unit using a technology 3 and 5 to 11, achieves an overall efficiency of 75% or higher, it can be assumed that it operated in full cogeneration mode during the observed or measured period. Thus, all electricity measured at the generator clamps is considered CHP electricity.

b) If a CHP unit using a technology listed 1, 2, and 4 achieves an overall efficiency of 80% or higher, it can be assumed that it operated in full cogeneration mode during the observed period. Therefore, all electricity measured at the generator clamps is considered CHP electricity.

c) If the overall efficiency of the CHP unit falls below these minimum thresholds, it can be assumed that the unit did not operate in full cogeneration mode during the observation period. Consequently, both CHP electricity and non-CHP electricity were likely generated.

Integration Process into DHN (Fig. 70)

1. Heat Recovery: In a CHP system, the excess heat produced from generating electricity is captured and used for heating purposes. This recovered heat is then fed into the DHN. Connecting the CHP system to the network can provide heat to district residential, commercial, or industrial users.

2. Heat Exchange Units: A heat exchanger transfers the heat energy from the CHP system's hot fluids (such as exhaust gases or coolant) to the district heating water circulating through the DHN. The heat exchanger ensures that the thermal energy is efficiently transferred without mixing the two fluid streams.

3. Load Balancing: DHNs typically have varying demands for heat depending on the time of day or season. The integration of CHP systems can help balance this load. During periods of high demand, the CHP system can increase its heat output, while during low demand periods, it can reduce heat generation and focus more on electricity production.

4. Energy Storage and Buffering: To further enhance the integration, heat storage systems (such as thermal energy storage tanks) may be used. These systems store excess heat when production exceeds demand and release it when demand exceeds the available heat from the CHP system. This improves the flexibility of the DHN and ensures a steady heat supply.

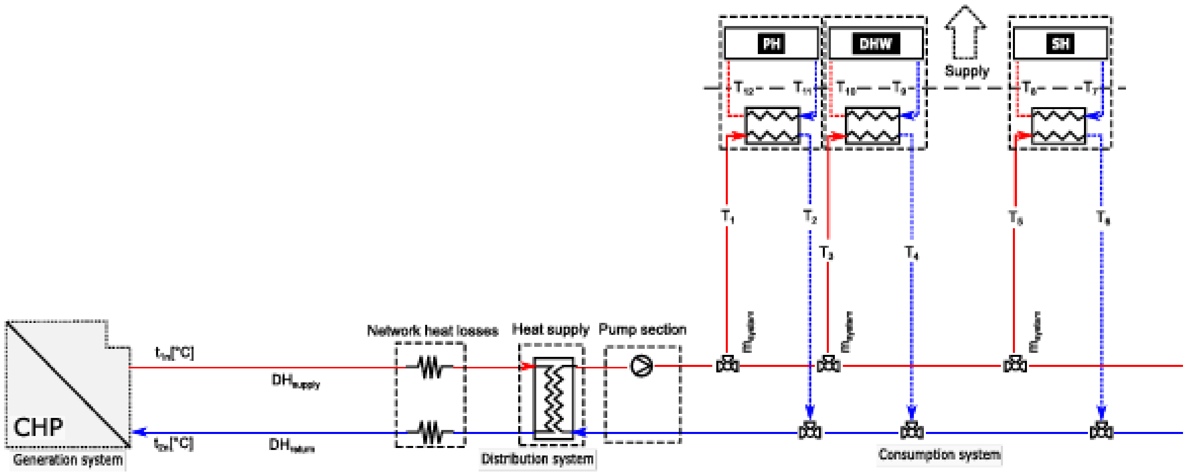


Fig. 70. Main components of the CHP cycle [25].

Advantages of CHP technology

General Advantages of Cogeneration:

1. **Energy Efficiency**: Cogeneration allows the simultaneous production of electricity and useful heat, increasing the overall efficiency of the system and reducing fuel consumption.
2. **Emission Reduction**: By improving efficiency, the system reduces the emissions of pollutants, contributing to sustainability.
3. **Flexibility**: Cogeneration systems can adapt to different fuel types and energy needs.
4. **Energy Security**: Diversifying energy sources and generating energy locally improves supply security.
5. **Reduced Operating Costs**: The higher efficiency in resource use can lower long-term operational costs.

In the Context of DHN (District Heating and Cooling):

1. Energy

Higher Efficiency: Cogeneration allows for more efficient use of the waste heat from electricity production, improving the overall performance of the heating and cooling system.

Optimization of Thermal Load: The simultaneous production of heat and electricity allows for better adjustment of thermal load based on demand.

2. Environmental

Emission Reduction: By using residual heat from power generation, the need for additional fossil fuels for heat production is reduced, lowering CO_2 emissions.

Efficient Resource Use: Cogeneration optimizes the use of energy sources, contributing to the transition to more sustainable systems.

3. Economic

Energy Cost Savings: By combining electricity and heat production in a single process, the total cost of energy supplied to a DHN can be reduced.

Economic Incentives: Many cogeneration systems receive fiscal incentives or subsidies for their energy efficiency, improving the investment's profitability.

3.3 Operational and technical challenges of integrating CHP to DHN

Flexibility in Operation:

Demand Variability: DHNs often experience variable heat demand throughout the day, seasons, and even across different regions of the network. CHP systems, however, are typically designed for continuous operation at full load. Managing this mismatch requires sophisticated control strategies and backup systems to ensure adequate supply.

Grid Interaction: CHP units need to be able to adjust output to match both heat demand in the DHN and power demand on the electricity grid, which can be difficult in real-time. This adds to operational complexity, especially when using renewable or intermittent power sources.

Integration with Existing Infrastructure:

Retrofit Challenges: Retrofitting a CHP system into an existing DHN can involve expensive upgrades to pipelines, heat exchangers, and storage tanks. The integration of a CHP system with older networks may require additional infrastructure, like expansion tanks, pumps, or pressure relief systems, to accommodate the heat generated.

Matching Temperature and Pressure: The temperature and pressure levels of the CHP output need to align with the specifications of the existing DHN. If there's a mismatch, additional equipment such as heat exchangers or pressure control devices might be necessary, which can increase system complexity and cost.

System Reliability:

Dependence on Both Heat and Power: CHP systems provide both electricity and heat, making them critical for both energy supplies. A malfunction in a CHP unit can disrupt both, affecting heating in winter months or causing power outages. Therefore, regular maintenance and high operational standards are essential to minimize downtime.

Redundancy and Backup: To improve reliability, DHNs must have backup heat sources or storage systems in place to ensure heating can still be provided in the event of a CHP failure. This requires additional capital and operational costs to maintain these backup systems.

Fuel and Emissions Control:

Fuel Supply and Availability: For CHP systems powered by fossil fuels, like natural gas, ensuring a stable and cost-effective supply of fuel is essential. For biomass-based CHP systems, the availability of sustainable fuel sources must be consistent. These supply chain dependencies can complicate planning and operations.

Environmental Compliance: Many regions have strict emission regulations, particularly regarding CO_2, NO_x, and particulate matter. CHP systems must be equipped with technology to control emissions, such as scrubbers, filters, or advanced combustion techniques. Managing these emissions in real-time, especially with variable demand, adds another layer of complexity. Additionally, integrating CHP with renewable energy sources like biogas or waste heat requires additional planning for fuel quality and emissions management.

Energy Efficiency

Improved Efficiency: CHP systems are typically much more efficient than separate heat and power generation. In conventional systems, energy is wasted when electricity is produced, and additional fuel is required for heat production. CHP utilizes this "waste" heat to meet heating demands, making it more efficient by recovering and using the thermal energy that would otherwise be lost.

Efficiency Gains: A typical CHP system can achieve overall efficiencies of 60-80%, compared to 35-45% for conventional separate production of heat and power. In district heating applications, the waste heat can be supplied to residential, industrial, or commercial buildings, reducing overall energy consumption.

Operational Flexibility: CHP can respond dynamically to heating demands, adjusting electricity and heat production to match load variations, further optimizing energy use.

Economy

Reduced Energy Costs: By generating both heat and electricity from a single fuel source, CHP systems reduce fuel consumption compared to separate production systems. This results in lower operational costs, especially when electricity and heat demand are high. The system may also benefit from economies of scale, further reducing costs.

Energy Security: For regions with unreliable power grids, CHP provides energy security by offering decentralized power generation. This can reduce dependence on external energy sources, stabilize energy prices, and provide savings over time.

Investment and Payback (Eq. (6)): The initial capital investment for CHP systems can be high, but they offer long-term savings through reduced energy costs and potential incentives. Payback periods typically range from 5 to 10 years, depending on system size, fuel type, and local energy prices.

$$Payback\ time = \frac{Initial\ investment}{Annual\ savings} \quad (6)$$

Case example (Epperson & Jane):

Gas turbine operates 7,800 hour/year, table 1 presents the economic data.

Total Annual Savings	1,650,000$
Estimated Capital Cost	9,075,000$
Simple Payback	5,5 years

Table 1. Economic data of case example Epperson & Jane.

Environmental Impact

Lower Carbon Emissions: By using waste heat and reducing the need for separate power plants, CHP systems can significantly reduce carbon emissions. The efficiency improvements reduce the total amount of fuel required, which directly translates into lower greenhouse gas emissions. For example, when using natural gas, a CHP system can reduce CO_2 emissions by 20-40% compared to separate heat and power production.

Cleaner Energy: CHP systems can be powered by a variety of fuels, including renewable ones like biomass or biogas, further decreasing their environmental footprint. Transitioning from coal or oil to cleaner natural gas or renewable biomass can drastically cut pollutants such as NO_x, SO_x, and particulate matter.

Energy Conversion Efficiency (Eq. (7)): CHP contributes to a more sustainable energy system by reducing fuel consumption, decreasing the overall environmental impact, and improving the efficiency of energy use across multiple sectors (power generation, heating, etc.).

$$E_{CO_2} = \frac{Q_{fuel} \times Emission\ factor}{Calorific\ value\ of\ the\ fuel} \quad (7)$$

4. Economics and environmental aspects of heat production district heating networks

4.1 Introduction

Considering the heating demand (Fig. 71) District heating production remained relatively similar to the previous year in 2022, meeting around 9% of the global final heating need in buildings and industry. As demonstrated by the best-performing networks, district heating offers great potential for the efficient, cost-effective, and flexible large-scale integration of low-emission energy sources into the heating energy mix. However, district heating's decarbonization potential is largely untapped, as fossil fuels still dominate district network supplies (such as Europe Fig. 72) globally (about 90% of total heat production), especially in China and Russia's two largest markets. Aligning with the Net Zero Emissions by 2050 (NZE) Scenario requires significantly stronger efforts to rapidly improve the energy efficiency of existing networks and switch them to renewable heat sources (such as bioenergy, solar thermal, large-scale heat pumps, and geothermal) [26].

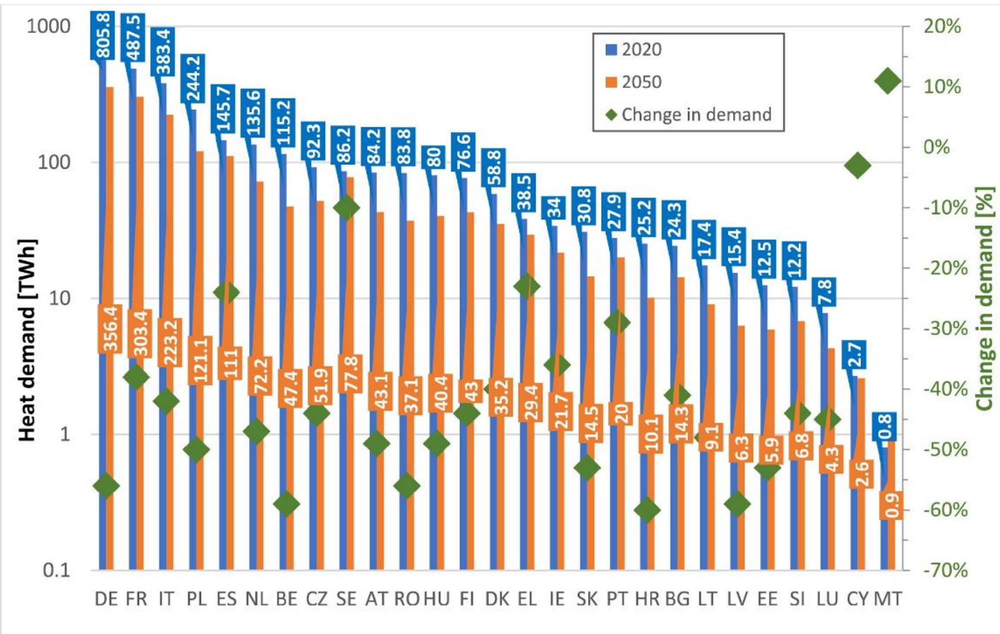


Fig. 71. Useful heat demand levels (TWh) in 2020 and 2050, and the relative changes in residential and tertiary sectors (secondary Y-axis) based on the best-case scenario [27].

In Europe, district heating has made significant progress in integrating renewable energy sources and improving energy efficiency. According to 2022 data, over 19,000 district heating networks across surveyed European countries supply heat to more than 77.3 million people. These networks have achieved a 42.6% share of renewable and waste heat sources. Countries like Finland and Denmark are leading in adopting these solutions. In Finland, district heating accounts for approximately 50% of the total heating market, with over 90% of apartment buildings connected to these networks.

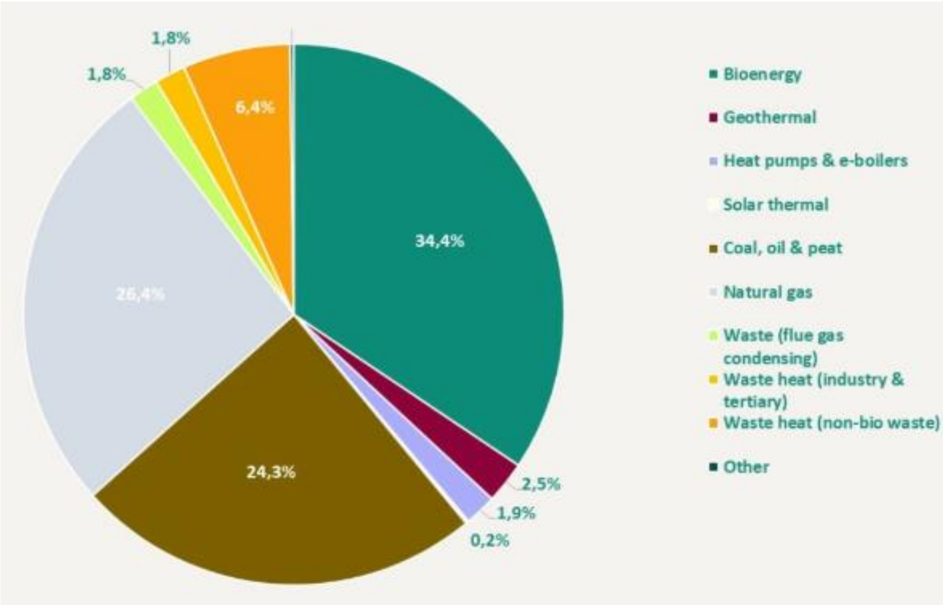


Fig. 72. Energy sources in European district heating in 2022 [27].

4.2 In-depth economic analysis of heat production systems

Economic Analysis - Introduction:

Definition: Economic analysis in heat production evaluates different technologies' cost-effectiveness, financial viability, and long-term sustainability.

Key Metrics [28]**:**

1. Capital Expenditure (CAPEX).
2. Operational Expenditure (OPEX).
3. Levelized Cost of Heat (LCOH).
4. Return on Investment (ROI).
5. Payback Period.

1. Capital expenditure (CAPEX):

Capital Expenditure (CAPEX) refers to investments made by a company in long-term fixed assets, such as buildings, machinery, and technology, which are essential for its operations and growth. These investments can be classified into two main categories:

Maintenance CAPEX: Investments aimed at maintaining or repairing existing assets to ensure proper functionality.

Expansion CAPEX: Investments focused on acquiring new assets or upgrading existing ones to increase production capacity or enter new markets.

Typical CAPEX components include:

1. Equipment
2. Installation
3. Infrastructure
4. System Integration Costs

2. Operating Expenditure (OPEX)

OPEX includes recurring costs for efficiently operating and maintaining a DHC system. The key components are:

1. **Energy/Fuel:** Costs are a significant expense influenced by fuel price fluctuations. Renewable sources offer more stable long-term costs.
2. **Maintenance:** Covers inspections, repairs, and unexpected interventions to ensure reliability.
3. **Labor Costs:** Salaries and benefits for operational staff, typically 30–50% of total OPEX.
4. **System Monitoring:** Software, analytics, and training for real-time performance tracking, improving efficiency and reducing costs.

3. Levelized cost of heat (LCOH):

The Levelized Cost of Heat (LCOH) is a metric that evaluates the average cost of producing heat over a heating system's lifetime. It contains all relevant expenses, including initial capital investment, operational and maintenance costs, and fuel expenditures, normalized over the total heat output. This metric enables a consistent comparison across different heating technologies and systems.

Definition & Formula:

The LCOH is calculated using the following formula (Eq. (8)):

$$LCOH = \frac{\sum_{t=1}^{n}\left(\frac{I_t+O_t+F_t}{(1+r)^t}\right)}{\sum_{t=1}^{n}\left(\frac{\dot{Q}_t}{(1+r)^t}\right)} \tag{8}$$

Where:

I_t = Investment expenditures in year t

O_t = Operations and maintenance costs in year t

F_t = Fuel costs in year t

$\dot{Q}_t$ = Heat produced in year t

r = Discount rate

n = Expected lifetime of the system

The formula mentioned before calculates the present value of total costs over the system's lifetime, divided by the present value of the total heat produced, providing a uniform cost per unit of heat generated.

Importance in Economic Evaluation

The LCOH is crucial for several reasons:

1. Technology Comparison: It offers a standardized method to compare the economic performance of various heating technologies, facilitating informed decision-making.
2. Investment Decisions: By understanding the LCOH, stakeholders can assess the long-term financial viability of heating projects, aiding in allocating resources to the most cost-effective solutions.

3. Policy Development: Policymakers can use LCOH analyses to design incentives and regulations promoting efficient and sustainable heating technologies.

4. ROI and Payback period

In the context of District Heating and Cooling (DHC) systems, evaluating efficiency metrics such as Cost per MWh of Heat Produced and Return on Investment (ROI) with Payback Periods is essential for assessing their economic viability and performance.

Cost per MWh of Heat Produced:

The cost per megawatt-hour (MWh) of heat produced in DHC systems varies based on factors such as energy sources, system efficiency, and regional economic conditions. For instance, a study on efficient DHC systems in the EU highlighted that the cost per MWh can differ significantly depending on the combination of heat sources and generation technologies.

Return on Investment (ROI) and Payback Periods:

Initial capital expenditures, operational costs, and revenue streams influence the ROI and payback periods for DHC systems. A report on cost drivers in district heating systems noted that Dutch DHC systems, for example, exhibit variations in cost per MWh produced, which can impact the overall ROI and payback periods.

Case Studies and Economic Comparison

South Korea [29]:

Larger district heating systems benefit from economies of scale, which reduce average costs as the system size increases. As a result, cost efficiency improves with the expansion of the system, making larger-scale implementations more economically advantageous.

CHP vs. Heat Pumps – Economic Performance:

CHP systems offer approximately 70% efficiency and lower operational costs, but they require high capital investment, typically ranging from $1,250 to $3,300 per kilowatt. Heat pumps also provide low operational costs, with efficiency depending on the coefficient of performance (COP) and the electricity source; however, they similarly involve significant upfront costs.

Europe:

District heating facilitates the large-scale integration of low-carbon energy sources, contributing to more sustainable energy systems. As these networks expand, they offer increased flexibility, improved efficiency, and greater cost-effectiveness.

Conclusion:

Scaling up DHC systems improves efficiency and reduces costs, supporting sustainable urban heating and cooling.

Cost Drivers in Each System

1. CHP Systems:

Fuel Costs: The price and availability of the primary fuel (ex, natural gas) directly impact operational expenses.

Capital Expenditure (CAPEX): High initial costs due to equipment, installation, and infrastructure requirements.

Maintenance Costs: Regular upkeep is necessary to ensure optimal performance, adding to operational expenses.

2. Heat Pumps:

Electricity Costs: Operational costs are influenced by electricity prices and the system's efficiency.

Installation Costs: Expenses related to equipment and setup can be considerable, especially for systems requiring extensive ductwork or ground-source installations.

Performance Variability: Efficiency can decrease in extreme temperatures, potentially increasing operational costs.

4.3 Environmental impact of heat production system

Environmental Impact-Introduction:

Environmental Impact Assessments (EIAs) are systematic processes designed to evaluate the potential environmental consequences of proposed projects or developments before they commence. The primary goal of an EIA is to ensure that decision-makers consider environmental impacts alongside economic and social factors, promoting sustainable development and minimizing adverse environmental effects [30].

Significance of Environmental Assessment [30]

Conducting an EIA is crucial for several reasons:

1. Informed Decision-Making: EIAs provide comprehensive data on potential environmental impacts, enabling stakeholders to make well-informed choices that balance development needs with environmental preservation.
2. Legal Compliance: Many jurisdictions mandate EIAs for specific projects to ensure adherence to environmental regulations and standards.
3. Public Engagement: The EIA process often involves public consultations, which foster transparency and allow communities to voice concerns and contribute to project planning.
4. Mitigation of Negative Impacts: By identifying potential adverse effects early, EIAs facilitate the development of strategies to avoid, minimize, or offset environmental harm.

Key Factors Analysed

An EIA typically examines a range of factors to assess a project's environmental footprint:

1. Project Scale and Nature.
2. Site Characteristics.
3. Potential Environmental Impacts.
4. Cumulative Effects.

5. Mitigation Measures.
6. Regulatory Framework.

Greenhouse Gas Emissions (GHG):

Greenhouse Gas (GHG) Emissions are a critical factor in evaluating the environmental impact of heating systems. Two prevalent technologies CHP systems and Heat Pumps differ significantly in their GHG emissions profiles.

CO_2 Emissions in CHP Systems:

CHP systems, known as cogeneration, simultaneously produce electricity and heat from a single fuel source, typically natural gas. This dual production process enhances overall energy efficiency compared to separate generation methods. According to the U.S. Environmental Protection Agency (EPA), a conventional 1 megawatt (MW) natural gas-fired CHP system can reduce CO_2 emissions by approximately 50% compared to traditional separate heat and power generation, equating to a reduction of about 4,100 tons of CO_2 annually [31].

However, the exact emissions depend on factors such as the type of fuel used, system efficiency, and operational practices. While CHP systems offer substantial CO_2 reductions relative to conventional methods, they are not entirely emission-free due to their reliance on fossil fuels.

Low/Zero Emissions with Heat Pumps

Heat pumps transfer heat using electricity, with their emissions depending on grid carbon intensity. In regions with low-carbon electricity, they can achieve near-zero emissions. Even carbon-intensive grids emit at least 20% less GHGs than gas boilers, reaching up to 80% reductions with cleaner grids (IEA). Advancements in refrigerants and grid decarbonization will further enhance their benefits, making heat pumps a key solution for low-emission heating [32].

Resource utilization:

Fossil Fuels: Finite resources requiring extraction and transport, causing environmental damage and high GHG emissions.

Renewable Electricity: Sustainably replenished sources (wind, solar, hydro, etc.) with lower emissions and a higher energy return over their lifetime.

Fig. 73 shows a comparison between fossil fuels and clean energy (renewable electricity) with a forecast until 2030.

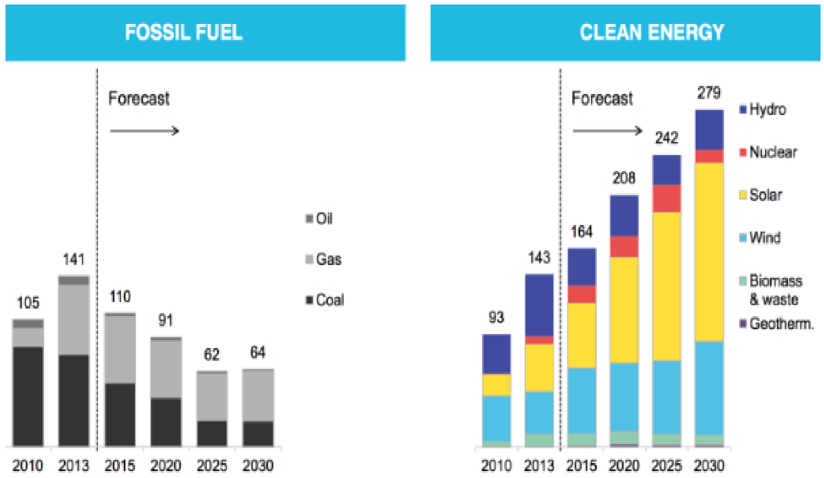


Fig. 73. Fossil fuel vs clean energy generation capacity forecast [33].

Efficiency & Sustainability:

Efficiency: Renewables convert energy with minimal losses, unlike fossil fuels, which suffer high extraction and conversion inefficiencies.

Sustainability: Renewable sources ensure long-term energy availability with minimal environmental impact, preserving resources for future generations.

Pollutants and Air Quality

NO_x, SO_x, Particulates from **CHP**: CHP systems, especially those using fossil fuels, emit pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter. While CHP systems are more efficient than separate heat and power generation, reducing overall emissions, they still contribute to air pollution. The exact emission levels depend on the fuel type and technology used.

Negligible Emissions from **Heat Pumps**: Heat pumps operate by transferring heat rather than generating it through combustion, resulting in minimal on-site emissions of NO_x, SO_x, or particulates. Their environmental impact is primarily influenced by the carbon intensity of the electricity used to power them. As electrical grids incorporate more renewable energy sources, the indirect emissions associated with heat pumps continue to decrease, making them a cleaner alternative for heating and cooling needs.

Lifecycle Assessment (LCA)

Lifecycle Assessment (LCA) (Fig. 74) evaluates the environmental impacts of a product or system throughout its entire lifespan, from raw material extraction to disposal. In heating technologies, LCA comprehensively compares CHP systems and heat pumps.

Assessing the Impact from Production to Decommissioning

CHP Systems: CHP units generate electricity and heat from a single fuel source, often natural gas or biomass. The LCA of CHP systems contains several stages:

1. Fuel Extraction and Processing
2. Manufacturing and Installation.
3. Operational Phase.

4. Decommissioning and Disposal.

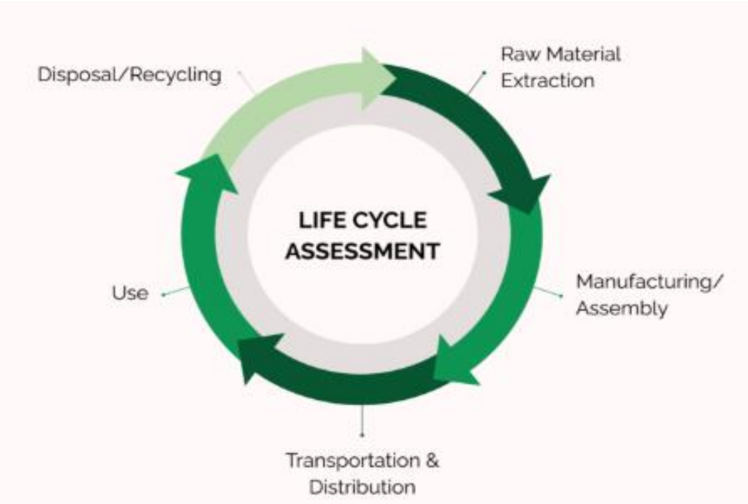


Fig. 74. LCA production cycle [34].

Heat pumps:

1. GWP: Heat pumps have a lower GWP, with cascade systems reducing it by 85.4% vs. gas furnaces.
2. Air Pollution: CHP emits NO_x and particulates; heat pumps have negligible direct emissions.
3. Efficiency: CHP reuses waste heat but depends on fuel; heat pumps (300–400% efficiency) are more sustainable with renewables.
4. Lifecycle Impact: Heat pumps have higher production impacts but offset them through cleaner operation.

Water Usage & Thermal Pollution

Water Consumption in CHP: CHP systems often require significant water for cooling processes. This usage can strain local water resources, especially in water-scarce regions.

Minimal Impact with Heat Pumps: Heat pumps generally have a lower water footprint and do not rely on water-intensive cooling processes. However, water-source heat pumps can cause localized thermal pollution by discharging heated water back into natural water bodies, potentially affecting aquatic ecosystems.

While CHP systems may exert pressure on water resources and contribute to thermal pollution, heat pumps typically present a more environmentally friendly alternative concerning water usage, with some considerations for specific types like water-source heat pumps.

Case study: Environmental Impact (CHP) [35]

A comparative environmental assessment was conducted on a CHP plant configuration for the Mexican oil and gas industry. The study evaluated three scenarios:

1. Case 1: Utilizing steam turbine generators with 58% efficiency.

2. Case 2: Implementing a gas turbine coupled with a heat recovery steam generator, achieving 87% combined efficiency.

3. Case 3: Incorporating post-combustion CO_2 capture into Case 2.

Results indicated that Case 2 reduced environmental impacts across all evaluated categories compared to the base case. Specifically, the Global Warming Potential (GWP) decreased from 626 kg CO_2e/MWh in the base case to 460 kg CO_2e/MWh in Case 2. Further, Case 3 achieved a GWP of 42 kg CO_2e/MWh, capturing approximately 1,075 tons of CO_2 daily with a 95% recovery efficiency.

Case study: Environmental Impact (Heat pump) [36]

A comprehensive environmental assessment was conducted on the retrofit of Hopkins Academy, a school in Massachusetts, transitioning from an oil-fired heating system to a ground-source heat pump. The study revealed significant environmental benefits:

1. **Energy Consumption:** The retrofit reduced the school's energy usage from approximately 5,120 gigajoules (GJ) to 1,580 GJ annually, a savings of about 3,540 GJ.
2. **Greenhouse Gas Emissions:** Annual GHG emissions decreased from 362 metric tons to 37 metric tons, reducing 325 metric tons.

The transition to a ground-source heat pump at Hopkins Academy also significantly decreased air pollutant emissions. Annual emissions were reduced by approximately 312 kilograms, dropping from 392 kilograms to 80 kilograms.

4.4 Market and industry trends, pricing, and market competition of CHP and Heat pumps

Market Trends – Introduction

Evolution of Heat Production Technologies: Heating methods have advanced significantly, transitioning from traditional coal-fired furnaces to modern, energy-efficient solutions. Early systems relied heavily on burning solid fuels, which were labour-intensive and environmentally taxing. The Industrial Revolution introduced steam and electric heating, enhancing efficiency and control. In recent decades, the focus has shifted towards sustainable technologies, with heat pumps emerging as a leading solution due to their ability to utilize renewable energy sources.

Growing Role of Heat Pumps: Heat pumps have gained prominence as a sustainable heating solution, with their share in global space heating rising to around 10% in 2021. This growth is driven by their high efficiency and compatibility with renewable energy sources. However, market dynamics can fluctuate; for instance, in 2024, European heat pump sales experienced a 23% decline, returning to pre-2022 levels, influenced by political uncertainties and economic factors. Despite these challenges, certain regions, like the UK, saw a 63% increase in sales, indicating varied adoption rates across different markets [37].

Growth of Heat Pumps

Driven by Decarbonization Goals: Heat pumps are essential in reducing greenhouse gas emissions, aligning with global decarbonization efforts. Their adoption can significantly lower CO_2 emissions, with potential reductions of at least 500 million metric tons by 2030, equivalent to the annual emissions of all European cars. In the United States, achieving a 50%- 52% reduction in household fossil fuel emissions by 2030 necessitates substantial growth in heat pump installations, with projected annual growth rates of 10%- 15% over the next decade [38].

Technological Advancements: Recent innovations have enhanced heat pump efficiency and expanded their applicability. Developments include variable-speed compressors that adjust to heating demands, improving energy efficiency and performance in various climates. Additionally, modern heat pumps can achieve higher heating capacities without requiring significant modifications to existing infrastructure, facilitating easier integration into homes and businesses. These advancements make heat pumps a more viable and attractive option for consumers, supporting their growing role in sustainable heating solutions. Fig. 75 presents insights about the heat pump market size.

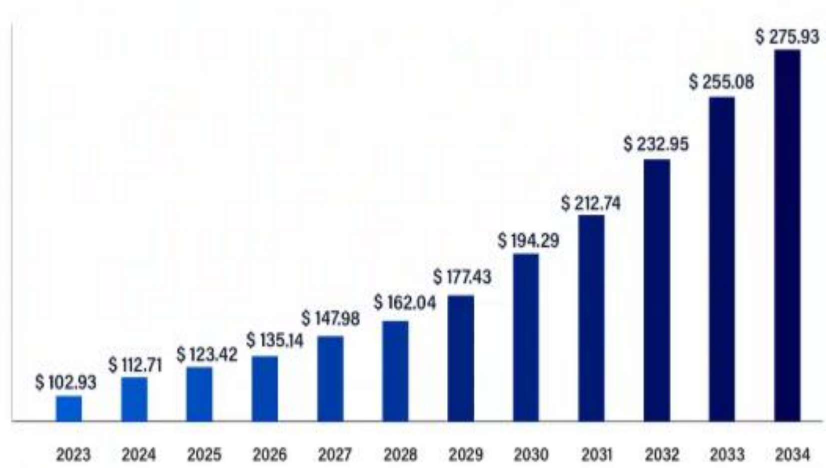


Fig. 75. Heat pump market size 2023 to 2034 (USD Billion) [39].

CHP Market Trends

Focus on Efficiency Improvements: CHP systems are increasingly recognized for their high efficiency, achieving operational levels up to 80%, significantly surpassing the approximately 50% efficiency of traditional separate heat and power generation methods. This efficiency is primarily due to simultaneous electricity production and sound thermal energy from a single fuel source, reducing energy waste. The industrial sector, in particular, is projected to experience a compound annual growth rate (CAGR) exceeding 6% by 2032 in CHP adoption, driven by the need for energy efficiency and reduced greenhouse gas emissions.

Integration with Renewables: Integrating CHP systems with renewable energy sources is becoming a strategic approach to enhancing energy resilience and sustainability. By combining CHP with technologies like heat pumps, which operate at low electricity prices due to surplus renewable energy, facilities can optimize energy use and stabilize power markets. This hybrid approach allows for flexible operation, where CHP plants can generate electricity and heat during peak demand. In contrast, heat pumps utilize excess renewable energy, improving overall system efficiency and reducing carbon emissions. Fig. 76 presents insights about the CHP market size [40].

Fig. 76. CHP market size 2024 to 2034 (USD Billion) [39].

Pricing Dynamics

Energy Prices and Their Impact: Fluctuations in energy prices significantly influence the adoption and operational costs of CHP systems and heat pumps. Between 2019 and 2022, retail energy prices experienced notable increases: electricity prices rose by 6%–14%, natural gas by 22%–46%, heating oil by 35%, and propane by 33%–50%. These shifts affect the cost-effectiveness of heating technologies, as heat pumps primarily rely on electricity, while CHP systems often utilize natural gas. Consequently, rising natural gas prices can make CHP systems less economical than heat pumps, whose competitiveness depends on stable or declining electricity prices.

Role of Technological Development: Technological advancements have a profound impact on the cost and efficiency of both CHP systems and heat pumps. For instance, integrating micro-CHP with electric heat pumps, thermal storage, and photovoltaic systems has demonstrated annual fuel-fired efficiencies greater than 130% for heating, cooling, and hot-water loads. These innovations enhance performance and reduce operational costs, making these systems more attractive to consumers. Economic analyses indicate that heat pumps are cost-effective, with a maximum payback period of 16 years, further incentivizing adoption [41-43].

Market Position

The competition between heat pumps (HPs) and CHP systems in the energy sector is shaped by their distinct operational characteristics and application scopes. Heat pumps, which leverage electricity to transfer heat from lower to higher temperature levels, are increasingly favored in low-carbon heating strategies. Their market position is strengthening due to advancements in efficiency, integration with renewable energy sources, and decarbonization policies.

Conversely, CHP systems, which simultaneously generate electricity and useful heat from a single fuel source, have traditionally held a strong position in industrial and district heating applications. Their high overall efficiency and ability to provide on-site power generation have sustained their relevance, particularly in areas with established gas infrastructure. However, the growing emphasis on reducing carbon emissions has challenged their market expansion, particularly when fossil fuels are the primary energy source.

Factors Influencing Competitiveness:

1. Energy Efficiency and Performance.
2. Carbon Footprint and Sustainability.
3. Energy Costs and Economic Viability.
4. Policy and Regulatory Framework.

5. Infrastructure and Grid Considerations.
6. Application-Specific Requirements.

Technological Innovations

High-Temperature Heat Pumps

High-temperature heat pumps (HTHPs) are emerging as a key innovation in the heating sector. Unlike conventional heat pumps, HTHPs can supply temperatures above 100°C, making them suitable for industrial applications and district heating networks. The development of advanced refrigerants, improved compressor technologies, and integration with waste heat recovery systems has enhanced their efficiency and feasibility. These innovations enable HTHPs to replace fossil fuel-based heating systems in industries such as food processing, chemical manufacturing, and paper production, contributing to decarbonization efforts.

Hybrid Systems (CHP + Renewables)

Hybrid systems combining CHP with renewable energy sources, such as solar thermal, biomass, and geothermal, present a promising pathway for increasing sustainability. These systems optimize energy utilization by integrating CHP's reliability with the intermittent nature of renewables. For instance, solar thermal collectors can supply additional heat during peak sunlight hours, reducing reliance on fossil fuels. Additionally, biomass-powered CHP units offer a carbon-neutral alternative to conventional gas-based CHP. By enhancing flexibility and reducing emissions, hybrid CHP-renewable systems are gaining attention for their role in achieving energy transition goals.

Industry Leaders and Case Studies

Key Market Players

The heat pump and CHP markets are led by several prominent companies known for their innovation and extensive product offerings:

1. **General Electric (GE)**: A major player in the CHP market, GE provides advanced technology and has a significant market share due to its high-efficiency and reliable CHP systems.

2. **Siemens Energy:** This German company is a leading provider of CHP solutions, offering a range of products that cater to various industrial applications.

3. **Veolia:** Based in France, Veolia is a key player in the CHP market, known for its comprehensive energy services and solutions.

4. **Wärtsilä:** A Finnish company, Wärtsilä is recognized for its innovative CHP systems and has a strong presence in the market.

5. **2G Energy:** This German company specializes in the production of CHP systems and is noted for its technological advancements in the field.

Successful Implementations

Several case studies highlight the effective deployment of heat pump and CHP technologies:

1. **Taber Aquafun Centre, Alberta, Canada:** The facility installed a 70kW micro-CHP solution, which was completed in two weeks with minimal disruption. This implementation has enhanced energy efficiency and reduced operational costs.

2. **Bornem – Barl'lo Project, Belgium:** This project demonstrates the use of heat pumps for both heating and cooling in nearly energy-neutral buildings, showcasing the potential of heat pumps in sustainable construction.
3. **Sixty Apartments Renovation, Turin, Italy:** A renovation project combined an air source heat pump with two gas boilers, successfully integrating these systems to minimize energy consumption, especially during mid-season.

4.5 Policy instruments and regulatory frameworks of CHP and heat pumps

Policy Instruments: Introduction

Importance of Policies in Heat Production [44]:

Policy instruments are essential in steering the heat production sector towards decarbonization and sustainability. They establish frameworks and incentives that promote the adoption of low-carbon technologies, enhance energy efficiency, and reduce greenhouse gas emissions. Effective policies can drive innovation, lower costs, and facilitate the transition to cleaner energy sources. Without robust policy support, market barriers may impede the deployment of renewable heating solutions, hindering efforts to combat climate change. In conclusion, policy instruments are essential in transforming the heat production sector globally. Tailored approaches considering regional disparities and challenges are essential to effectively promote adopting sustainable heating solutions and achieve overarching climate goals.

Global Context: Policies aim to limit warming to 1.5°C by decarbonizing heat production, varying by region based on economic and political factors.

EU Initiatives: The REPowerEU Plan targets 20 million heat pumps by 2026 and 60 million by 2030 to reduce fossil fuel reliance.

Global South Challenges: High borrowing costs hinder clean energy adoption; COP29 and G20 stress climate financing via carbon taxes and debt swaps.

Policies must be region-specific to drive sustainable heating adoption and meet climate goals.

Subsidies and Incentives in Energy Systems

Grants: Financial assistance provided by governments or organizations to support the development of renewable energy projects, such as wind, solar, and geothermal systems. These grants reduce the initial capital cost, making these technologies more accessible.

Tax Credits: Tax reductions owed by businesses or individuals investing in renewable energy technologies. Examples include the Investment Tax Credit (ITC) and Production Tax Credit (PTC), which incentivize the installation and operation of renewable systems.

Feed-in Tariffs (FiTs): Guaranteed payments or incentives paid to energy producers for supplying electricity to the grid. These tariffs are designed to encourage the development of renewable energy sources by ensuring a stable income for producers.

Impact on System Adoption

1. Increased Adoption Rates: Subsidies and incentives lower the financial burden on consumers and companies, driving quicker adoption of sustainable technologies.

2. Market Expansion: They encourage innovation and competition in the renewable energy market, leading to lower costs and more accessible options.
3. Long-term Sustainability: While initial support is crucial, the goal is to reduce dependence on subsidies over time as technologies become more competitive with conventional energy sources.

Further information about subsidies and incentives in Europe can be found at the "IEA (International Energy Agency) on renewable energy policies"

Carbon Pricing Mechanisms

1. **Emission Trading Systems (ETS):** Market-based approaches that allow companies to buy and sell allowances for carbon emissions. The total emissions are capped, and companies must hold allowances equivalent to their emissions. This creates financial incentives for reducing emissions.

   Example: The European Union Emissions Trading System (EU ETS) is the world's largest carbon market, covering industries like power generation and manufacturing.

2. **Carbon Taxes** are direct taxes imposed on the carbon content of fossil fuels. The goal is to increase the cost of carbon-intensive energy, thereby encouraging businesses and consumers to reduce their carbon footprints.

   Example: Countries like Sweden have implemented high carbon taxes, contributing to significant emissions reductions and a shift towards cleaner energy sources.

3. **Operational Costs:** ETS and carbon taxes influence business operational costs, especially in high-emission industries. The increased cost of carbon-intensive fuels can lead to higher operational expenses, but may also drive innovation toward cleaner, more efficient processes.

Impact on Businesses and Policy

1. **Incentivizing Emission Reductions**: These mechanisms encourage companies to invest in technologies that reduce emissions and transition to greener energy sources.
2. **Market Efficiency**: Carbon pricing creates a market-driven approach to lowering emissions, allowing for flexibility in how businesses achieve reductions.
3. **Revenue Generation**: Governments often use the funds generated through carbon pricing for reinvestment into renewable energy projects, climate adaptation, or other environmental initiatives.

Regulatory Frameworks in Energy Efficiency [45]

EU Directives:

RED II (Renewable Energy Directive II): Aimed at increasing the share of renewable energy in the European Union's overall energy mix. It sets binding targets for renewable energy usage, including in transport and heating, and encourages the use of biofuels, wind, solar, and other renewable sources.

Goal: Achieve at least 32% renewable energy in the EU by 2030.

EED (Energy Efficiency Directive): Establishes rules to help the EU reach its energy efficiency targets. It includes measures for improving energy use in buildings, transport, and industries.

Goal: Achieve a 32.5% improvement in energy efficiency by 2030.

National Energy Efficiency Standards: Each EU member state implements its own regulations, based on EU directives, to enhance energy efficiency in various sectors like buildings, transport, and industry. These standards ensure that national goals align with broader EU climate and energy targets.

Example: In Germany, the Energy Saving Ordinance (EnEV) sets standards for building energy performance.

International Policy Comparisons in Energy Systems [46]

Case Studies from Different Countries:

Germany: A leader in renewable energy policies, Germany's Energiewende (Energy Transition) emphasizes transitioning from fossil fuels to renewable energy sources. Policies such as feed-in tariffs, renewable energy auctions, and ambitious climate goals have made Germany one of the world's leading countries in renewable energy adoption.

Example: Germany's Renewable Energy Act (EEG), introduced in 2000, paved the way for massive growth in solar and wind energy.

China: As the world's largest emitter of CO_2, China has focused on expanding renewable energy to reduce emissions and improve air quality. The country leads in solar and wind energy capacity, with significant government support and incentives to grow these sectors.

Example: The 12th Five-Year Plan for Ecological Civilization outlined substantial investments in clean energy.

United States: The U.S. has diverse state and federal policies, including tax credits, clean energy standards, and renewable energy incentives like the Investment Tax Credit (ITC) and Production Tax Credit (PTC).

Example: The Clean Power Plan (CPP), although under review, aimed to reduce emissions from power plants.

International Policy Comparisons in Energy Systems

Lessons Learned from International Comparisons

1. **Policy Consistency and Long-term Commitment:** Successful transitions require stable, long-term policies to provide investors and industry players confidence.
2. **Flexibility and Adaptability:** Countries need policies tailored to their specific energy mix, resources, and economic conditions.
3. **Public-Private Partnerships:** Collaboration between governments, the private sector, and consumers has been key to accelerating renewable energy adoption.
4. **Public Support and Awareness:** Engaging citizens and ensuring broad public support are essential for the success of energy policies.

4.6 Future considerations

Future Considerations – Introduction

1. **Decarbonization:** Shifting to renewables (solar, geothermal, waste heat) faces infrastructure, investment, and storage challenges. For example, Geothermal integration requires advanced temperature control.

2. **Digitalization:** AI, sensors, and smart grids optimize heat distribution but raise cybersecurity and data privacy concerns.

3. **Energy Efficiency:** Growing demand requires new technologies to keep district heating cost-effective and sustainable.

Role of Innovation:

Technological Advancements: Innovation in heat pumps, thermal storage, and low-carbon technologies is critical in meeting future energy demand while reducing environmental impact.

Example: New advancements in heat pump technologies allow for better integration of renewable heat sources, making district heating systems more flexible and sustainable.

Business Models and Financing: New financing mechanisms, such as public-private partnerships (PPPs) and green bonds, are being explored to fund the transition of district heating networks. These models aim to reduce financial risk while promoting sustainable investments in renewable heat sources.

Decarbonization Goals

2050 Net-Zero Targets:

Many countries and regions, including the European Union and the United States, have committed to reaching net-zero emissions by 2050. For district heating systems, this means significantly reducing the reliance on fossil fuels and integrating renewable, low-carbon heat sources. Example: The EU's Green Deal outlines a roadmap to reduce emissions by at least 55% by 2030 and achieve net zero by 2050.Challenges and Opportunities: Achieving these targets requires large-scale investments in renewable technologies, upgrading existing infrastructure, and adopting innovative solutions like energy storage and smart grids [47].

Transitioning from Fossil-Based CHP:

Current State: Many district heating networks rely on fossil-based CHP plants, which use natural gas, coal, or oil to generate electricity and heat. These systems are major contributors to carbon emissions.

Transition Plan: A crucial part of the transition is the shift towards renewable energy sources, such as biomass, geothermal, and solar thermal energy. In addition, green hydrogen is gaining attention as a potential fuel for CHP plants.

Example: The Danish District Heating System is actively transitioning from fossil-based fuels to biomass and waste heat recovery, aiming for carbon neutrality by 2030.Technological Challenges: Upgrading fossil-based CHP plants to utilize renewable energy sources involves significant investment and technical expertise in new technologies, such as large-scale heat pumps and storage systems.

Grid Integration & Flexibility

Grid Integration & Flexibility in District Heating Networks

Demand-Side Management:

a. Definition: Demand-side management (DSM) refers to strategies that encourage consumers to adjust their energy consumption patterns in response to supply conditions or price signals. This is crucial for optimizing the integration of renewable energy into district heating systems.

b. Techniques:

Time-of-Use Pricing: Encouraging consumers to use heating during off-peak hours to balance supply and demand.

Thermal Storage: Storing excess heat during periods of low demand and releasing it during peak times, helping to stabilize grid fluctuations.

c. Benefits: DSM helps prevent grid congestion, reduces costs, and improves the efficiency of heat production and distribution. It can also reduce the need for backup fossil fuel-based generation.

Technological Advancements

Ultra-High-Temperature Heat Pumps:

Definition: Ultra-high-temperature heat pumps (UHTHPs) are designed to provide heating at significantly higher temperatures (above 100°C), making them suitable for district heating systems. They are key for integrating renewable heat sources into high-temperature applications, which traditionally rely on fossil fuels.

Applications: UHTHPs recover waste heat from industrial processes, geothermal energy, or even ambient air and heat residential and commercial buildings.

Benefits:

1. They reduce the reliance on fossil fuels, lowering carbon emissions.
2. Enable the integration of renewable and waste heat sources into the grid at higher temperatures.

Example: The Energiepark Mainz in Germany uses ultra-high-temperature heat pumps for district heating, achieving efficiencies of over 100%.

Advanced CHP with Biofuels & Hydrogen:

CHP systems generate both heat and electricity from a single energy source. To meet decarbonization goals, advanced CHP systems are increasingly being integrated with biofuels and hydrogen.

Biofuels: Biomass and bioenergy are renewable alternatives to fossil fuels, and when used in CHP systems, they provide low-carbon heat and power.

Hydrogen: Green hydrogen, produced using renewable electricity, can be used in CHP plants to generate heat and electricity without emitting CO_2, making it a key player in the transition to carbon-neutral district heating systems.

Benefits:

1. Biofuels reduce dependency on fossil fuels and support local agricultural economies.

2. Hydrogen enables a pathway for zero-emission district heating systems.

Example: The Hannover CHP Plant in Germany is exploring the use of hydrogen as a fuel source for its CHP units, contributing to the country's decarbonization efforts.

Climate Resilience

Impact of Climate Change: Changing weather patterns lead to fluctuating heating demands. Milder winters reduce demand, while extreme cold increases it.

Regional Variations: Northern Europe may see reduced heating needs, while other regions face unexpected peaks due to temperature extremes.

Long-Term Trends: Systems must adapt to handle milder and extreme conditions, requiring flexible, responsive energy solutions.

System Flexibility & Reliability:

Flexible Operations: Integrate renewables, use thermal storage, and adjust supply dynamically.

Grid Resilience: Ensure reliable backup capacity (ex, biofuels or hydrogen for CHP plants) to handle demand spikes.

Economic Resilience

Adapting to Market Fluctuations:

1. Diversify energy sources to reduce dependency risks.
2. Implement flexible pricing models to respond to energy market volatility.
3. Utilize energy storage and smart grid technologies for operational stability.

Long-Term Investment Strategies:

1. Prioritize technologies with scalable, future-proof capabilities.
2. Focus on lifecycle cost analysis rather than upfront costs.
3. Invest in infrastructure that aligns with decarbonization goals and policy incentives.

Future-Proof Heat Networks

Innovative Projects in Development:

Zero-Carbon District Heating in the UK:

Aiming for a net-zero carbon future, the UK is developing district heating networks that combine waste heat recovery, renewable energy, and smart grid technologies. One such project is London's "Green Gas for London", which utilizes biogas and waste heat for district heating systems to reduce carbon emissions and increase efficiency [48].

Key Features: Use of advanced heat pumps, renewable energy integration, and flexible control systems.

The Copenhill Project in Copenhagen:

Copenhagen aims to be the world's first carbon-neutral capital by 2025. The Copenhill project is a waste-to-energy plant that combines district heating with waste incineration. It generates electricity, steam, and heat from non-recyclable waste, providing heating to over 150,000 homes [49].

Amsterdam’s Smart Heat Network:

Amsterdam is developing a smart district heating network that utilizes thermal storage, solar thermal, and geothermal energy. The system integrates digital technologies to optimize heat distribution, ensuring energy efficiency and reduced carbon emissions.

Impact on the Future of Heat Networks

1. **Decarbonization:** These projects showcase the potential of combining renewable energy sources and innovative technologies to provide low-carbon, sustainable heating solutions.
2. **Resilience & Flexibility:** These networks are designed to withstand future climate challenges, ensuring a stable and flexible heat supply even in the face of unpredictable weather patterns or fluctuations in demand.
3. **Scalability:** Many of these projects are scalable, allowing for future expansion and adaptation to emerging technologies.

5. Conclusions

Economic & Environmental Aspects:

1. Economic: District heating systems reduce fossil fuel dependence, lower operational costs, and generate revenue via incentives and carbon credits.
2. Environmental: Adopting renewable technologies and waste heat recovery helps decarbonize heating and reduce carbon footprints.
3. Efficiency: Smart grids and advanced technologies improve system adaptability and energy efficiency.

Importance of Policies & Future Trends:

1. Policies: Supportive policies like subsidies, carbon pricing, and energy standards are essential for accelerating adoption.
2. Future Trends: Ultra-high-temperature heat pumps, CHP with biofuels and hydrogen, and smart grids will shape the future of district heating.
3. Climate Resilience: Flexibility in system design ensures reliability in changing climate conditions.

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