Module 1
Introduction to District Heating Systems

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

Guidebook

Reusable teaching resource for higher education and professional training

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Project

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Guide to using Module 1

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 1 provides a comprehensive introduction to district heating systems and their role in sustainable energy communities. It introduces the historical development of district heating, from early steam-based networks to modern low-temperature and fifth-generation energy-sharing systems. The module explains the main system components, including heat production, distribution, transfer, consumption and district heating substations, while also highlighting the advantages and challenges of centralised heat supply.

Special attention is given to the integration of renewable and alternative heat sources, including geothermal energy, solar thermal energy, waste-to-energy technologies and waste heat recovery. European examples are used to illustrate how district heating systems can support the transition towards low-carbon urban energy 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, introductory case-based work and continuing professional development training. The accompanying presentation slides, question bank, self-check quiz, module video and practical exercise are designed to help educators adapt the content to their own teaching context.

Students and professionals may also use the module for independent study. As an introductory module, it is suitable for learners who are new to district heating systems, as well as for those who wish to review the basic terminology, system structure and technological development of district heating before moving on to more specialised SHaKE modules.

Main topics covered in the module

- District heating systems and their role in urban energy supply
- Advantages and disadvantages of district heating
- Heat production and centralised heat supply
- District heating in Europe
- Historical development and generations of district heating
- First-generation steam distribution systems
- Second-generation hot-water distribution systems
- Third-generation warm-water distribution systems
- Fourth-generation low-temperature smart district heating
- Fifth-generation ambient-temperature energy communities
- Functional subsystems of district heating networks
- District heating substations and hydraulic connection types
- Heat exchanger technologies in substations
- Renewable energy integration in district heating
- Geothermal energy and solar thermal energy
- Waste-to-energy in district heating
- Waste heat recovery from industry, data centres and municipal infrastructure
- Future trends in fourth- and fifth-generation district heating networks
- Policy and economic considerations for sustainable district heating development

Learning outcomes of Module 1

The module is designed to support the development of the following skills and competences:

- understand the historical development and evolution of district heating systems from first-generation steam networks to fifth-generation energy communities;
- identify the main components and subsystems of district heating networks, including heat production, distribution, transfer, consumption and substations;

- compare different district heating technologies and generations in terms of efficiency, operating temperatures, infrastructure and renewable energy integration;
- evaluate the advantages, limitations and sustainability impacts of district heating systems in different regional and urban contexts;
- analyse the role of renewable energy sources, waste heat recovery and energy communities in supporting the transition to low-carbon district heating systems;
- apply introductory district heating concepts to a practical municipal planning scenario.

Estimated workload

This module represents approximately 6.7 learning hours, including lectures, exercises, case-study work, self-study 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 introductory teaching unit,
- a set of selected lecture materials,
- a blended learning component,
- a practical exercise package,
- a preparatory module before more specialised SHaKE modules,
- or a supplementary resource for existing courses.

Activities and Learning Hours

Activity Type	Time Allocation	Description
Lectures	3 h	Introduction to district heating systems, advantages and disadvantages, heat production and sources, European context, district heating generations, substations, renewable heat sources, waste-to-energy and waste heat recovery
Exercises	0.5 h	Practical activity based on comparing district heating generations, evaluating renewable and alternative heat sources, and preparing a recommendation for a municipal heating modernisation scenario
Case Studies	0.5 h	Discussion of European and real-world examples related to geothermal district heating, waste-to-energy, waste heat recovery and energy community concepts
Self-Study	1.5 h	Independent reading, review of guidebook sections, preparation for the self-check quiz and revision of key module concepts
Assessment	0.2 h	Multiple-choice assessment questions evaluating understanding of the main district heating concepts, technologies and applications
Total Learning Hours	**6.7 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.

The primary target groups are:

- higher education lecturers in engineering, building services, energy systems, district heating and sustainable urban energy systems;
- trainers involved in professional or continuing education on district heating and district energy systems;
- educators developing blended, modular or practice-oriented learning activities;
- academic staff seeking reusable teaching resources on sustainable district energy systems;
- trainers and lecturers working with topics related to district heating, renewable heat integration, energy communities, substations and urban energy infrastructure.

The materials may also be used by students, professionals and independent learners who wish to study selected topics individually. As this is an introductory module, no advanced prior knowledge of district heating is required, although basic familiarity with building services, thermodynamics or energy systems is useful.

Recommended use by educators and trainers

Module 1 can be used flexibly as a complete introductory 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 1 resource
Introducing the topic	Use the module overview and introductory slides to present the basic concept of district heating and its relevance for sustainable urban energy systems.
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 district heating principles, advantages and disadvantages, heat production, European context, generations, substations, renewable heat sources and waste heat recovery.
Checking understanding	Use selected questions from the question bank for discussion, short in-class checks, formative assessment or LMS-based quizzes.
Developing applied reasoning	Use the practical exercise for classroom work, group activities, homework assignments or short written reports on district heating modernisation.
Supporting discussion of sustainability	Use the sections on renewable energy, waste-to-energy, waste heat recovery and fifth-generation energy communities to initiate discussion on decarbonisation and future district heating systems.
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 and exercise 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.

Step	Suggested activity
Review the introductory presentation	Familiarise yourself with the main concepts, terminology and structure of district heating systems.
Study the guidebook materials	Read the explanations of district heating principles, system generations, substations, renewable heat sources and waste heat recovery.
Watch the module video	Use the module video and its attached assessment questions to explore one selected topic, concept or practical aspect of the module.
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 by comparing district heating technologies and heat sources in a municipal modernisation scenario.
Review the question bank	Use the questions for revision, discussion or preparation for assessment.

Available supporting materials

The available learning resources and assessment materials include:

- presentation slides for the module topics;
- a reusable question bank;
- a module-level self-check quiz;
- a module video with attached assessment questions;
- a downloadable practical exercise based on a municipal district heating modernisation scenario;
- assessment questions designed to support self-study, classroom discussion and formative evaluation.

The practical exercise may be used for group work, homework assignments, short written reports, classroom discussion or introductory project-based learning. It asks learners to compare district heating generations, evaluate renewable and alternative heat sources, and formulate a recommendation for a municipality seeking to modernise its heating infrastructure.

1 Table of Contents

1 Introduction to District Heating Systems

Historically, district heating evolved as a response to both economic and safety concerns. Early adopters sought to improve fuel utilization, centralize combustion emissions away from populated areas, and reduce the hazards associated with maintaining multiple high-pressure steam boilers in residential buildings.

From its origins in the late 19th century – with pioneers such as Birdsill Holly in the United States – to today's 4th and 5th generation low-temperature, renewable-integrated networks, DH has undergone substantial transformation.

1.1 Advantages and Disadvantages of District Heating

District heating offers a range of benefits that make it an attractive option for supplying thermal energy to residential, commercial, and industrial users. One of its key advantages lies in economic efficiency. By centralizing heat production, district heating systems could exploit economies of scale, which reduced the cost per unit of heat compared with multiple smaller, individual systems. This centralized approach also tends to result in lower service costs, as operation and maintenance activities are consolidated, requiring fewer resources and specialized staff than numerous decentralized systems would.

One of the main advantages is that DH allow to exploit renewable energies such as geothermal and heat waste such as incinerator which could not be possible by building. The EU aims for a fully decarbonized, zero-emission building stock by 2050, transforming Europe's largest energy consumer into a climate-neutral sector. District heating helps achieve this target, because a significant part of district heating consumers could not be supplied with renewable energy without a centralised heat supply system.

Another important benefit is improved air quality. By locating heat generation facilities outside densely populated urban areas, the direct exposure of residents to combustion products is minimized. Central plants are also better suited for precise performance control. Advanced automation systems and load forecasting tools can be implemented to match heat output closely to demand, ensuring efficient operation throughout the heating season.

Despite these advantages, district heating systems are not without drawbacks. One of the most significant challenges is transmission losses. As hot water or steam travels through distribution pipelines, some heat is inevitably lost, particularly in older networks or when heat must be transported over long distances. High initial infrastructure costs are another barrier, as constructing the necessary network of pipelines, substations, and control systems requires substantial capital investment. Additionally, district heating networks can be prone to single-point vulnerabilities; a disruption in the central heat source – whether due to equipment failure or fuel supply issues – can potentially affect the entire served area.

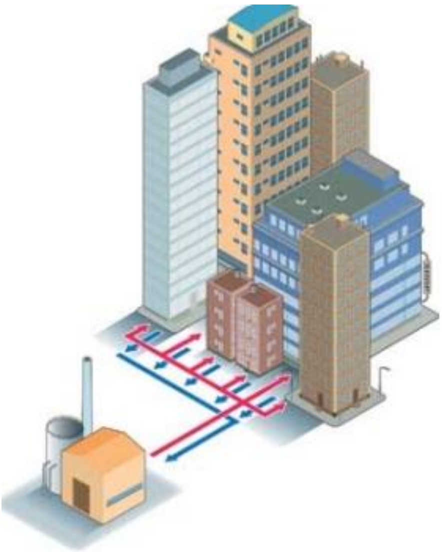

Figure 1. Illustrative figure of a district heating network (decentralizedenergy)

1.2 Heat Production and Sources

District heating systems can be supplied by a diverse range of heat sources, each offering distinct technical and environmental benefits. Dedicated heating plants are among the most common, typically using boilers fuelled by natural gas, biomass, or oil to generate hot water or steam for distribution. These plants are straightforward in design and operation, making them suitable for both small and large networks.

A more efficient approach is found in combined heat and power (CHP) plants, which generate electricity and capture the waste heat from this process for district heating. By making use of thermal energy that would otherwise be discarded, CHP systems can achieve much higher overall fuel efficiency compared to separate generation of heat and power.

Increasingly, networks are turning to renewable energy sources such as solar thermal fields, geothermal wells, and large-scale heat pumps. These options can significantly reduce greenhouse gas emissions while also lowering long-term fuel dependency. Another valuable source is waste heat recovery, which captures surplus heat from industrial processes, data centers, or waste incineration plants and redirects it into the district heating network.

Modern district heating systems often employ multi-source integration, combining several of these technologies within the same network. This approach not only enhances system resilience – by ensuring that heat supply can continue even if one source becomes unavailable – but also supports sustainability goals by allowing a greater share of renewable and recovered heat in the energy mix.

1.3 District Heating in Europe

The extent to which district heating has been adopted varies considerably across the world, reflecting differences in climate, urban planning traditions, and energy policy. In Northern Europe and Scandinavia, district heating has a long-established tradition. In countries such as Denmark, Sweden, and Finland, more than half of urban heating demand is often met through district heating networks. This prevalence is supported by cold climates, high population densities in urban centers, and long-term investment in centralized energy infrastructure.

In Western Europe, the uptake of district heating has accelerated in recent decades. Nations such as Germany, France, and the Netherlands have expanded their networks significantly, driven largely by decarbonization policies and a desire to reduce dependence on fossil fuels. The integration of renewable energy sources and waste heat recovery into district heating systems has become a central strategy for meeting national climate targets.

By contrast, many Eastern European countries inherited extensive district heating systems from the socialist era. These large-scale networks are capable of serving entire cities but often suffer from inefficiencies, heat losses, and outdated infrastructure. Modernization programs – ranging from pipeline insulation upgrades to the replacement of old boilers with renewable-based systems – are now a major focus for policymakers and utilities in the region.

Across Europe, policy frameworks such as the EU Energy Efficiency Directive (EED), along with national carbon reduction targets, play a central role in guiding the expansion and modernization of district heating. These policies encourage both improved system efficiency and a transition toward low-carbon and renewable heat sources, shaping the future of district heating across diverse regional contexts.

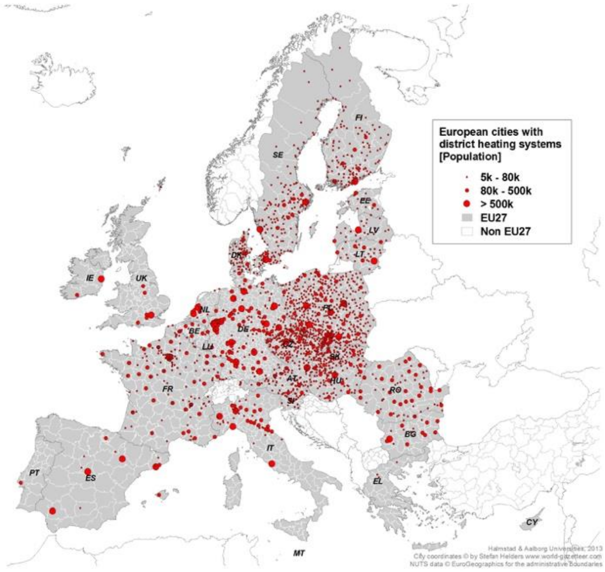

Figure 2. Map of DH penetration in Europe (wwwsolarthermalworldorg)

2 Historical Development: Generations of DH

The evolution of district heating technology is often described in terms of distinct "generations," each representing advances in heat distribution methods, temperature regimes, and system integration. While four generations are widely recognized, a fifth is now emerging as part of the energy transition.

2.1 First Generation: Steam Distribution

First-generation district heating systems were based on steam distribution, a concept introduced in the late 19th century in the United States. These systems delivered steam at high temperatures – often well above 100 °C – as the heat transfer medium. While effective in delivering large quantities of heat, they suffered from significant distribution losses, safety hazards due to high pressures, and corrosion in metallic pipes. Although largely replaced by modern alternatives, some steam-based networks remain in operation, such as the one serving Manhattan in New York City.

2.2 Second Generation: Hot Water Distribution

The second generation, dominant between the 1930s and 1970s – particularly in the Soviet Union – shifted to superheated water under pressures at which water is below boiling temperature as the transfer medium. These systems typically operated with supply temperatures between 120 °C and 200 °C, often above the atmospheric boiling point. While they reduced some of the safety risks associated with steam, they still suffered from poor control, high installation labor requirements, and substantial heat losses during transmission.

2.3 Third Generation: Warm Water Distribution

Third-generation district heating emerged in the 1970s, marking a significant improvement in efficiency and flexibility. These systems operated with warm water at supply temperatures below 100 °C and introduced pre-insulated pipes to reduce losses. Modular substations became standard, simplifying installation and maintenance. Lower temperatures also allowed for the integration of renewable energy sources and waste heat recovery, making these systems more environmentally sustainable.

2.4 Fourth Generation: Low-Temperature Smart District Heating

Building on these advances, the fourth generation focuses on low-temperature distribution – typically between 50 °C and 70 °C – and incorporates smart grid concepts. Renewable energy sources, large-scale heat pumps, and waste heat recovery play dominant roles. These systems are particularly suited to modern, well-insulated buildings with low heating demand, and their digital controls allow precise load management and optimization.

2.5 Fifth Generation: Ambient-Temperature Energy Communities

The emerging fifth generation takes the concept further by operating ultra-low-temperature or even ambient-temperature networks. In these systems, each building is equipped with a heat pump that raises the temperature to the required level. Bidirectional flow capability enables “energy communities,” where buildings can act as both consumers and producers – prosumers – sharing heat among neighbours and making the network a truly decentralized thermal grid.

3 District Heating Subsystems and Technologies

3.1 Functional Subsystems of District Heating

Heat Division – The controlled allocation of heat flows to different branches or zones within the district heating network, ensuring that each area receives the appropriate amount of energy.

Heat Transfer – The actual movement of thermal energy through the insulated distribution pipelines from the central source to consumer locations.

A district heating (DH) network comprises four essential subsystems:

1. Heat Production – Centralized generation using boilers, CHP plants, renewable collectors, or waste heat recovery units.
2. Heat Division – The allocation and regulation of heat flow toward different branches of the network.
3. Heat Transfer – Transport of thermal energy via insulated pipelines to consumer areas.

4. Heat Consumption – The use of heat in buildings for space heating, domestic hot water (DHW), or industrial processes.

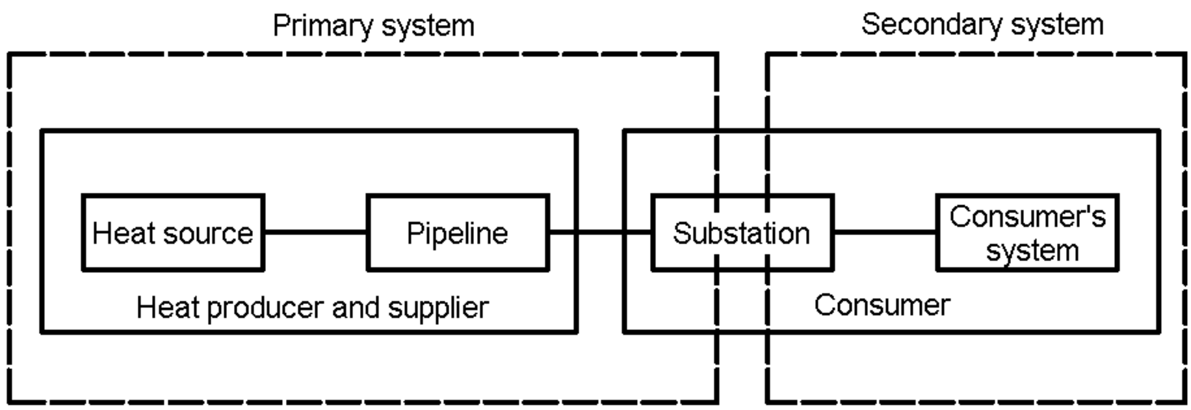

Figure 3. Functional subsystems of DH [14]

3.2 District Heating Generations in Detail

3.2.1 First Generation: Steam Distribution (Late 19th – Early 20th Century)

Birdsill Holly's pioneering prototype was constructed during the winter of 1878–1879 in Lockport, New York, supplying neighbouring estates with steam. While eliminating the need for individual boilers reduced explosion risks, early systems faced corrosion-related leaks, high distribution losses, and were prone to dangerous pipeline explosions that caused injuries and fatalities.

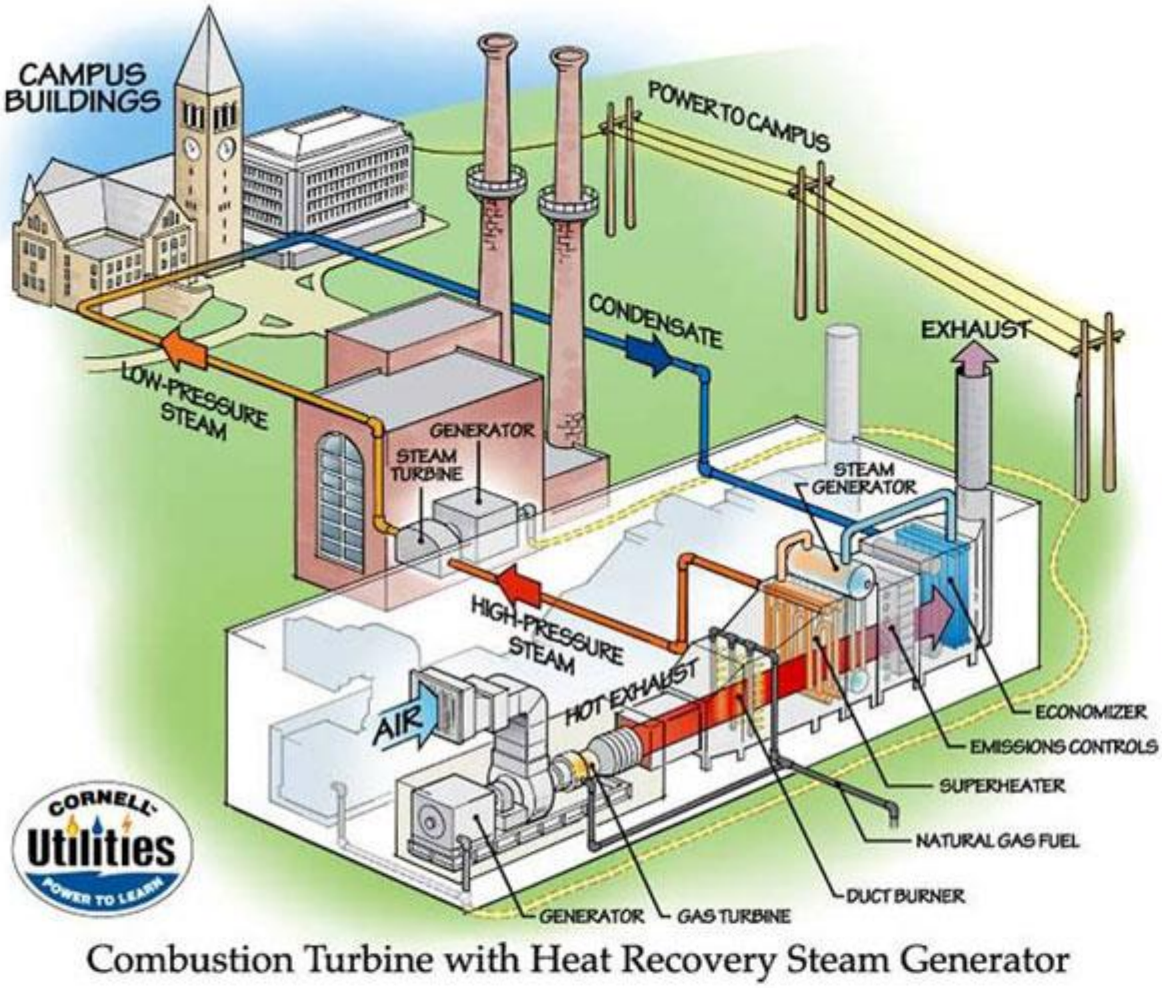

Figure 4. Illustrative figure of steam distribution (httpsfzbellowscom)

The earliest form of district heating, known as first-generation systems, relied on the direct transport of steam from a central plant to end-users via high-pressure pipelines. This approach was pioneered by Birdsill Holly, who developed one of the first operational prototypes in 1878–1879 in Lockport, New York. At the time, steam distribution offered clear advantages: it eliminated the need for numerous small-scale boilers in individual buildings, thereby reducing the risk of boiler explosions in densely populated urban areas. However, the technology also presented significant drawbacks. High thermal losses occurred due to very high distribution temperature and the limited effectiveness of insulation materials available in the period. Corrosion and leakage were persistent maintenance challenges, while safety hazards – including the potential for pipeline explosions – remained a concern. As technology advanced, steam-based systems came to be regarded as highly obsolete, with most having been decommissioned. Nevertheless, some continue to operate in niche cases, such as parts of Manhattan, and in certain European cities like Hamburg and Copenhagen, where historical systems have been reconstructed or preserved.

Figure 5. Historic steam DH network in Manhattan (Lizio-Katzen, dátum nélk.)

3.2.2 Second Generation: Hot Water Distribution (1930–1970)

In Hungary and other regions, distinctive overground pipelines with large U-bends were common. These structural loops absorbed the thermal expansion of long steel pipelines, preventing mechanical damage.

The second generation of district heating marked a shift from steam to pressurized hot water distribution, with supply temperatures typically exceeding 100 °C. These systems emerged in the 1930s and remained dominant until around 1970. Hot water was conveyed through steel pipelines, often installed within concrete ducts, which provided some protection from environmental exposure. This approach became particularly widespread in the Soviet Union and Eastern Europe, where large-scale urban heating schemes were constructed to serve entire cities. While effective in delivering high heat loads, these systems had notable limitations. Installation was highly labor-intensive, as duct construction and pipe welding required substantial on-site work. Operational flexibility was limited, making the integration of renewable or low-temperature heat sources impractical. Heat losses were also higher compared to later generations, especially in poorly insulated ducts. In some regions, such as Hungary, overground pipeline systems with distinctive U-bends were used to compensate for thermal expansion, a visual hallmark of mid-20th-century district heating networks.

Figure 6. Overground DH pipelines (mokshahu)

Figure 7. Underground DH pipelines with U-bends compensate thermal expansion [15]

3.2.3 Third Generation: Warm Water Distribution (<100 °C)

From the 1970s onward, the third generation introduced significant technological improvements aimed at increasing efficiency and reducing losses. Supply temperatures dropped below 100 °C, enabling the use of pre-insulated steel pipes that could be buried directly in the ground without the need for costly concrete ducts. This innovation reduced installation costs, minimized heat losses, and allowed faster network deployment. Another milestone was the introduction of prefabricated, modular substations, which replaced the large tube bundle heat exchangers of earlier designs with compact plate heat exchangers. These substations required less space, offered better thermal performance, and reduced on-site labor due to factory assembly. Lower supply temperatures also facilitated the integration of renewable energy sources such as solar thermal collectors and geothermal wells. In Eastern Europe, many old Soviet-era systems have since been retrofitted with third-generation technology to improve efficiency and reliability.

Figure 8. Prefabricated modular DH substation (left) (fotavhu), pre-insulated piping (right) (magyarepitok)

3.2.4 Fourth Generation: Low-Temperature Smart DH (50–70 °C) with renewable integration

The fourth generation builds upon the efficiency gains of its predecessor while aligning district heating with the requirements of energy-efficient buildings and a decarbonized energy system. Operating at supply temperatures between 50 °C and 70 °C, these systems achieve significantly reduced distribution losses and are optimized for integration with smart control systems. By using weather forecasts and real-time consumption data, operators can dynamically adjust heat output to match demand, enhancing both comfort and efficiency. Fourth-generation networks are sometimes integrated with intelligent power grids, enabling load balancing between electricity and heat production. The reduced temperature regime opens opportunities for extensive waste heat recovery from unconventional sources, including data center cooling systems, ventilation heat from metro systems, and wastewater heat extracted via heat pumps. A prominent example is the Aspern Smart City in Vienna, where renewable heat, combined heat and power (CHP) generation, and thermal storage are combined within a fully automated control framework.

3.2.5 Fifth Generation: Ambient Temperature Energy Communities

The fifth generation, currently in early adoption, represents a paradigm shift in district heating design. These networks operate at or near ambient ground temperature (around 10–25 °C), using decentralized heat pumps in individual buildings to raise the temperature for space heating or to provide cooling in summer. This configuration allows for bidirectional heat flows, enabling buildings to function as both consumers and producers – so-called prosumers – who can inject excess heat into the network for others to use. The ultra-low operating temperature virtually eliminates distribution losses and makes the system highly compatible with seasonal thermal storage and sector coupling strategies, linking heating, cooling, and power systems into a unified energy community. An example is the Paris-Saclay Network in France, where decentralized energy sharing and renewable integration form the backbone of the local heating and cooling infrastructure.

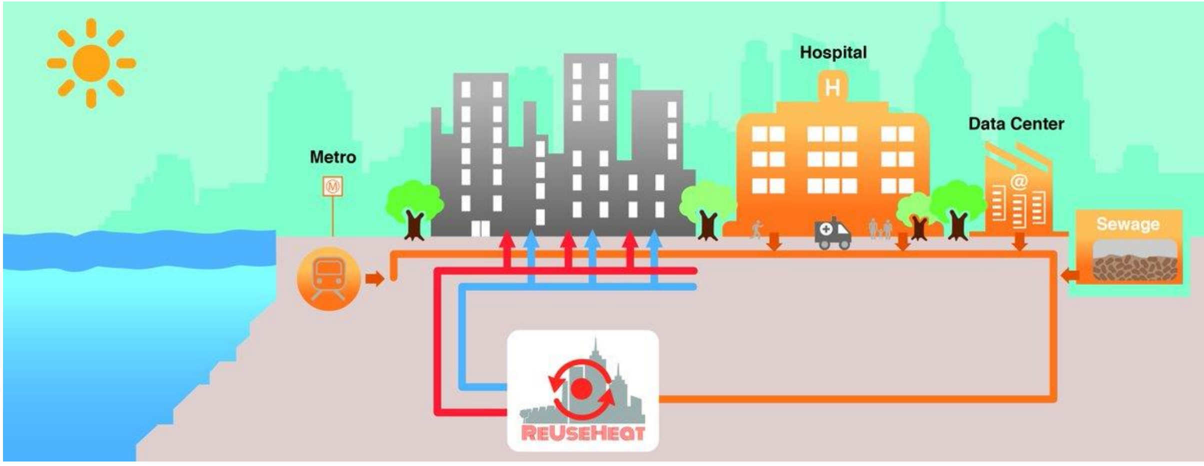

Figure 9. Concept diagram of 5th generation energy community (reuseheateu)

3.3 District Heating Substations

3.3.1 Role and Function

The district heating substation is the interface between the primary district heating (DH) network and a building's internal heating system. Its primary role is to transfer thermal energy from the distribution network to the building while controlling supply temperature, flow rates, and system pressures. Two main substation configurations are used in practice. In a direct substation, the building's heating circuit is hydraulically connected to the primary DH network, allowing hot water from the network to circulate directly through the building's radiators or heating loops. This arrangement is simple but places the building system under the same operating pressure and water quality conditions as the district network. In contrast, an indirect substation uses heat exchangers to hydraulically separate the building's circuit from the primary network. This configuration improves operational safety, reduces the risk of network-side water contamination, and provides greater flexibility in system design. A further variation is the indirect substation with variable flow control, which adjusts the primary flow rate in response to building demand, thereby improving energy efficiency.

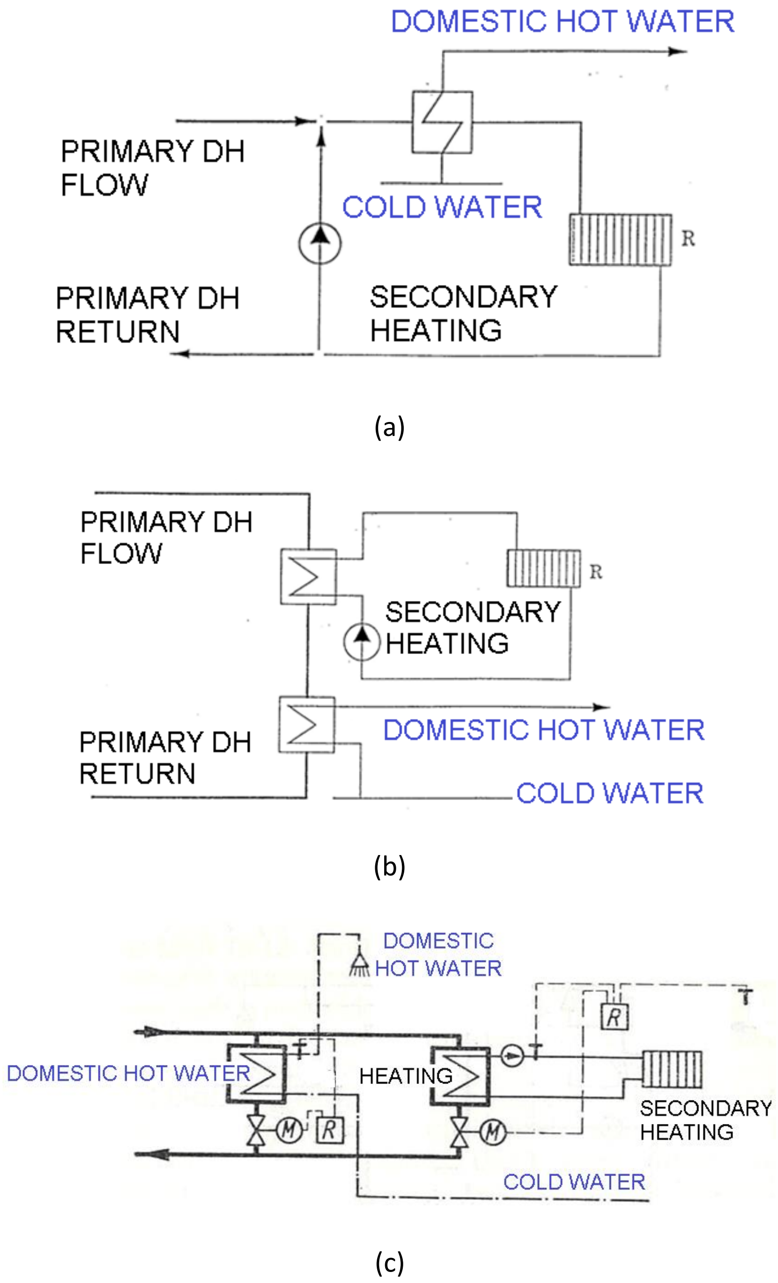

Figure 10. Hydraulic connection types to the primary district heating network. Direct (a), Indirect (b) Indirect with variable flow (c) (Kiss, 1997)

3.3.2 Heat Exchanger Technologies

Historically, tube bundle heat exchangers were the standard technology used in DH substations. While robust, these units are large, heavy, and require substantial installation space. They also tend to have lower heat transfer efficiency compared to modern designs. Over time, plate heat exchangers have become the preferred choice in most new installations. These compact units consist of multiple thin, corrugated plates arranged to create alternating channels for primary and secondary fluids. Their large surface area and turbulence-enhancing geometry provide high thermal efficiency in a small footprint. Plate heat exchangers are also easier to clean, maintain, and expand, making them well-suited to modular substation designs that can be adapted to changing load requirements.

4 Renewable Energy in District Heating

4.1 Geothermal Energy

Geothermal energy represents one of the most consistent and sustainable heat sources for district heating systems. Its principle involves extracting thermal energy from underground reservoirs, which can be transferred directly to the district heating network or upgraded to higher temperatures through the use of heat pumps. In Iceland, geothermal heat has been harnessed on a large scale, with the capital city, Reykjavik, meeting approximately 90% of its heat demand through geothermal district heating. Beyond space heating, the system's return pipes are also used for secondary applications such as snow and ice melting on roads and pavements. The key advantages of geothermal district heating include low operating costs and minimal CO_2 emissions once the infrastructure is in place. However, its feasibility depends heavily on specific geological conditions, limiting widespread application to regions with accessible geothermal resources.

In Iceland, surplus low-temperature geothermal water from DH return lines is even repurposed for pavement and road heating, melting snow and ice to improve winter safety.

Figure 11. Iceland geothermal power plant and district heating systems (nesjavellir)

Figure 12. After circulating through the building, the excess, low-quality geothermal heat is used for road de-icing (underfloor)

4.2 Solar Thermal

Large-scale solar thermal plants can also be integrated into district heating networks, offering a renewable and zero-emission source of heat, particularly in regions with high solar irradiance. Solar collectors – either flat-plate or evacuated tube designs – capture solar energy, which is then transferred to the district heating network or stored in large hot-water tanks for later use. Seasonal heat storage is often employed to balance the mismatch between peak solar availability in summer and peak heating demand in winter. A notable example is the Marstal Solar District Heating Plant in Denmark, which combines extensive solar collector fields with seasonal pit heat storage to supply a substantial portion of the town's heating needs. However, solar thermal systems face the challenge of matching supply to winter demand, which often necessitates hybridization with other heat sources such as biomass boilers or combined heat and power (CHP) units.

4.3 Waste-to-Energy (WtE) in DH

Waste-to-energy (WtE) systems are energy conversion technologies that recover useful heat and electricity from municipal solid waste that would otherwise be disposed of in landfills. In a typical WtE facility, waste is combusted under controlled conditions, releasing thermal energy that is used to produce steam. This steam can drive turbines for electricity generation while simultaneously supplying thermal energy to district heating networks through combined heat and power (CHP) processes. In addition to energy production, modern WtE plants contribute to sustainable waste management by reducing the volume of residual waste, recovering recyclable materials from combustion residues, and decreasing the environmental impacts associated with landfilling. As part of an integrated energy system, waste-to-energy technologies support resource efficiency, enhance energy security, and provide a reliable local heat source that can complement renewable energy technologies within district heating networks.

4.3.1 Vienna’s Spittelau Plant

The plant’s distinctive architectural redesign was undertaken by Austrian artist and architect Friedensreich Hundertwasser, making it an iconic landmark in Vienna.

- Designed by architect Friedensreich Hundertwasser after refurbishment in the 1990s.
- Performance:
  - Heat for 60,000 homes.
  - Electricity for 50,000 homes.
  - Processes 250,000 tonnes of waste annually.
  - Produces 120,000 MWh electricity and 500,000 MWh heat.
- Significance: Combines urban waste management with high-efficiency cogeneration.

Figure 13. Spittelau WtE plant, Vienna (wwwwienenergieat)

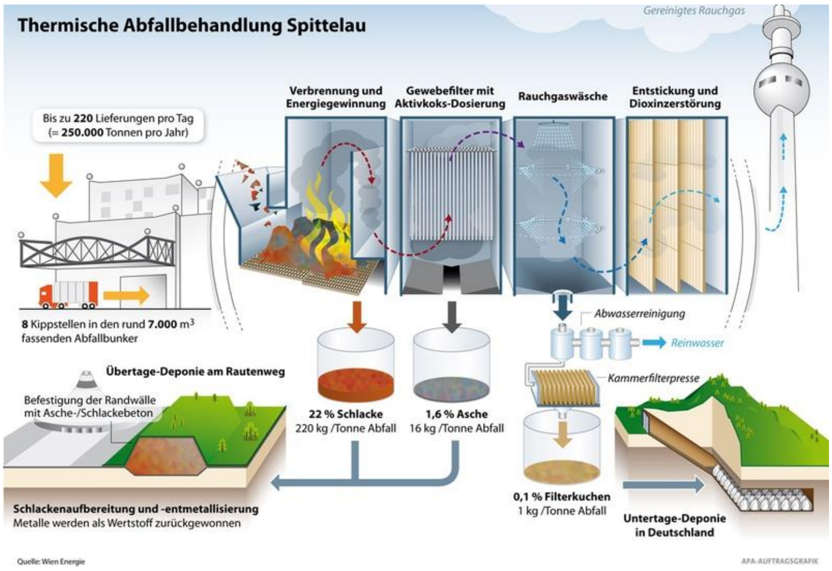

Figure 14. Scheme of operation of the waste thermal treatment plant in Vienna (wwwwienenergieat)

The Figure 15 shows the long-term trend depicts the significant expansion and structural transformation of Vienna's district heating supply between 1979 and 2006. While the total heat output increased dramatically over these three decades, the composition of energy sources shifted towards greater efficiency and sustainability. Simple heating plants (yellow), which once played a larger role, have been minimized to just 4.1%, while Combined Heat and Power (CHP) generation (red) has become the dominant technology, providing 61.3% of the total heat. Furthermore, the share of waste reclamation (black) has grown steadily to constitute nearly a quarter (24.8%) of the total supply, highlighting the city's strategic move towards circular economy principles and energy recovery.

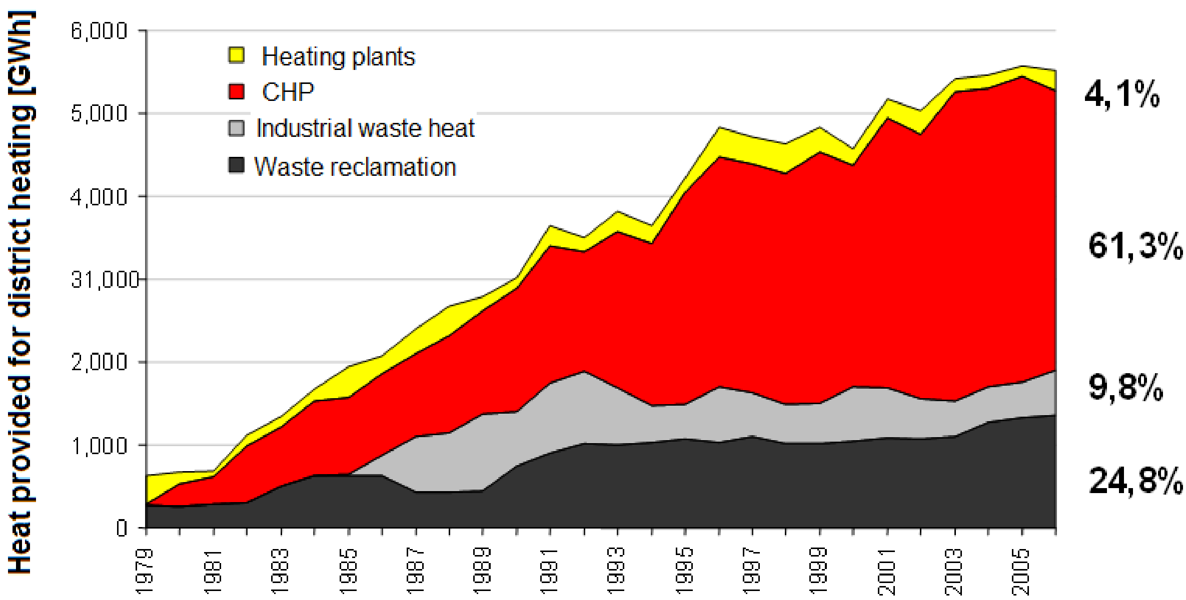

Figure 15. Evolution of heat sources provided for district heating in Vienna [14]

The Figure 16 illustrates the daily heat load profile of the Vienna district heating system throughout 2006, demonstrating how different energy sources are deployed based on seasonal demand. The gray base load remains relatively constant year-round, supplied primarily by cost-effective waste incineration and industrial waste heat, ensuring that summer hot water demand is covered by the cheapest sources. The red area represents the medium load, covered by Combined Heat and Power (CHP) plants; this layer scales significantly to meet the increased heating needs during colder months. Finally, the yellow peak load spikes appear only during the coldest days of winter, utilizing heat-only boilers as a flexible backup to bridge the gap when demand exceeds the capacity of the base and medium load producers.

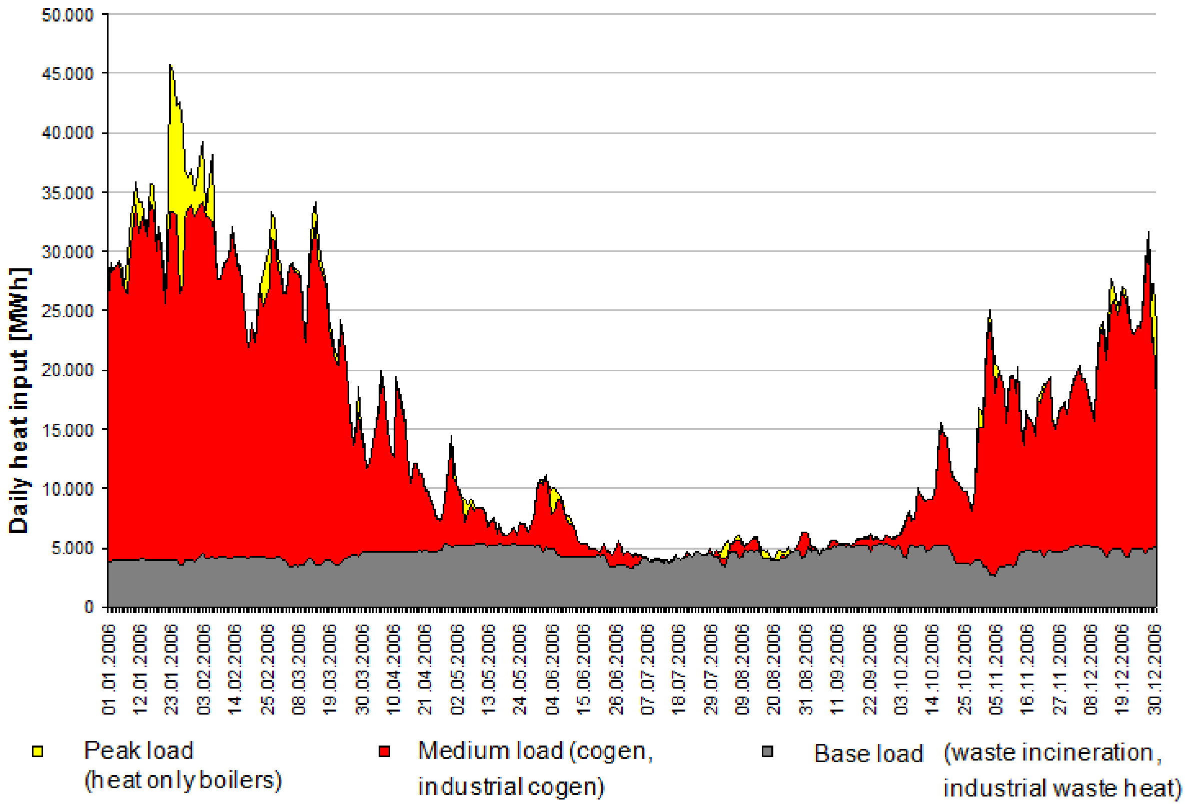

Figure 16. Production schedule changes during the year [14]

4.4 Waste Heat Recovery in District Heating

The recovery of surplus thermal energy from existing processes represents a highly effective strategy for improving district heating sustainability. By utilizing heat that would otherwise be discharged into the environment, waste heat recovery contributes to emission reduction, improves system efficiency, and reduces reliance on primary fuel sources. In fourth-generation district heating networks, the relatively low supply temperatures make it technically and economically feasible to integrate multiple forms of low-grade waste heat.

4.4.1 Industrial Waste Heat

Large industrial facilities – such as steel mills, oil refineries, and chemical plants – are major sources of recoverable waste heat. This heat, often in the form of low- to medium-temperature water or exhaust gases, can be transferred into the district heating network without additional fuel consumption, thereby reducing overall system emissions. A notable example is the Aurubis copper plant in Hamburg, Germany, where surplus heat from copper production is captured and fed into the local district heating system. This integration results in an annual reduction of approximately 20,000 tonnes of CO_2 emissions while displacing fossil-fuel-based heat generation.

4.4.2 Data Centers

In 2010, global data center electricity consumption reached around 350 TWh, exceeding 1% of total world consumption. In the EU, consumption grew from 56 TWh/year in 2007 to an estimated 104 TWh/year by 2020, with cooling systems accounting for approximately 40% of total energy use. Medium-sized data centres (1 MW IT capacity) can emit around 3,700 MWh/year of recoverable heat, equating to about 0.46 MWh_{th} of waste heat per 1 MWh_{el} consumed.

Data centers are another rapidly growing source of recoverable waste heat, due to their high and constant electricity consumption. In 2020, data centers within the European Union consumed an estimated 104 TWh of electricity, with much of this energy ultimately released as heat through cooling systems. The waste heat, typically at temperatures between 30 °C and 50 °C, can be captured using heat exchangers and upgraded via heat pumps for district heating use. The Stockholm Data Parks initiative exemplifies this approach, offering free cooling services to data centers in exchange for delivering their waste heat to the city's district heating network.

Figure 17. Server room suitable for waste heat utilization (reuseheateu)

4.4.3 Municipal Infrastructure

Across the EU, metro systems could theoretically supply between 6.7 and 11.2 TWh/year of waste heat. Worldwide, underground rail networks cover 11,000 km and serve 151 million passengers daily, creating significant low-grade heat recovery opportunities.

Urban transport systems can also serve as unconventional but valuable sources of low-grade heat. Metro systems, for example, release substantial amounts of heat through train braking systems, electrical equipment, and passenger occupancy. Across the EU, the theoretical recovery potential from metro systems is estimated at 6.7–11.2 TWh per year. In Paris, experimental projects are recovering waste heat from metro stations and transferring it to nearby residential and commercial buildings. Similarly, sewage networks represent a steady source of thermal energy, with wastewater temperatures typically ranging between 10 °C and 20 °C. In Cologne, Germany, sewage heat recovery systems supply approximately 5% of the local district heating demand, demonstrating the viability of integrating waste heat from municipal infrastructure into modern DH systems.

In Germany alone, sewage heat could theoretically meet 20% of the building stock's heating demand, with wastewater temperatures averaging 10–15°C year-round and reaching up to 20°C in summer.

5 Future Trends: 4th & 5th Generation Networks

5.1 4th Generation Goals

Fourth-generation district heating networks are designed to address both energy efficiency and climate objectives. A primary technical goal is to maintain low distribution temperatures – typically between 50 °C and 70 °C – thereby reducing heat losses, improving system efficiency, and enabling the integration of low-grade renewable and recovered heat sources. Increasing the renewable share of the heat supply is a central ambition, achieved through the incorporation of solar thermal energy, geothermal sources, and large-scale heat pumps powered by renewable electricity. Smart control systems play a crucial role, with advanced algorithms and AI-based forecasting used to optimize supply in real time based on weather predictions and consumption patterns. Additionally, sector coupling – the integration of district heating with electricity and cooling grids – offers further opportunities to balance energy flows, store surplus renewable electricity as heat, and enhance overall system resilience.

5.2 5th Generation Vision

The fifth generation of district heating represents a transformative vision for urban energy systems. These networks operate at ambient temperatures – often between 10 °C and 25 °C – and use bidirectional flow to enable heat exchange between buildings. Each connected building is equipped with a localized heat pump that can raise the temperature for space heating or provide cooling in warmer months, offering exceptional flexibility. A defining feature of fifth-generation networks is the creation of decentralized energy communities, in which every participant can function as both a heat consumer and a producer (prosumer). This model encourages local energy sharing and supports higher renewable integration. Furthermore, fifth-generation designs typically incorporate integrated seasonal storage solutions – such as borehole thermal energy storage, aquifer storage, or large pit heat storage – to capture surplus energy during low-demand periods for use during peak heating seasons. Together, these features create a highly adaptable, low-carbon heating model capable of supporting future sustainable cities.

Figure 18. Energy community schematic figure (ParisSaclay)

6 Policy and Economic Considerations

Case Study – Budapest's First DH System: The earliest municipal district heating scheme in Budapest served as a proof-of-concept for centralized urban heat supply. Today, the question of a municipality's primary energy supply involves balancing the role of Hungary's extensive natural gas grid with the integration of industrial waste heat sources, creating mutual benefits for both industry and urban consumers.

- EU Energy Efficiency Directive: Encourages efficient DH as part of decarbonization strategy.
- Carbon Pricing: Increases competitiveness of DH using low-carbon sources.
- Financing: Public-private partnerships, green bonds, and EU cohesion funds are key enablers for infrastructure upgrades.

7 Conclusion

District heating is a proven, adaptable, and increasingly vital component of sustainable urban energy systems. From the pioneering steam networks of the 19th century to smart, renewable-powered 5th generation grids, the technology has evolved to meet shifting environmental, economic, and social needs.

The future will see DH acting not just as a heating service, but as an integrated urban thermal infrastructure, enabling resilience, flexibility, and climate neutrality.

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