Module 6
Refurbishment of 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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Guide to using Module 6

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 6 focuses on the refurbishment of district heating systems, with particular attention to legacy high-temperature systems, district-heated housing estates and the transition toward more efficient, flexible and low-carbon operation. It introduces the historical development, technical characteristics and typical inefficiencies of older district heating systems, especially in contexts where large-scale systems were originally designed under different energy price, comfort and efficiency assumptions.

The module examines refurbishment measures at both network and building level. It covers building-side and secondary system improvements, single-pipe heating system refurbishment, hydraulic balancing, compact and modular substations, apartment-level substations, heat consumption measurement and billing, low-temperature district heating, predictive maintenance, digital tools and economic aspects of refurbishment.

The module combines technical explanations with real-world case studies and applied learning activities. The guidebook includes case studies of urban district heating development and refurbishment, while separate supporting activities allow learners to diagnose a hypothetical legacy district heating system, develop a refurbishment strategy and analyse economic decision-making in a district heating retrofit scenario.

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 refurbishment exercise and economic case study 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 district heating systems, building services, substations, hydronic systems and energy efficiency.

Main topics covered in the module

- Historical development of legacy district heating systems
- High-temperature district heating systems and their limitations
- Refurbishment of district heating systems in housing estates
- Building-side and secondary system refurbishment
- Single-pipe heating system refurbishment
- Hydraulic balancing and variable-frequency pumps
- Compact and modular substations
- Apartment-level substations and individual heat supply solutions
- Heat consumption measurement and billing
- Transition to low-temperature district heating
- Integration of renewable and low-exergy heat sources
- Predictive maintenance, monitoring and digital tools
- Business models and economic aspects of district heating

- Tariff structures, motivational tariffs and heat-as-a-service models
- Urban district heating refurbishment and development case studies
- Refurbishment strategy design and prioritisation

Learning outcomes of Module 6

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

Upon completion of this module, learners should be able to:

- explain the historical development, structure and operational characteristics of legacy district heating systems;
- identify common sources of inefficiency in district heating networks, buildings, substations and control systems;
- analyse hydraulic balancing challenges and evaluate appropriate technical solutions for improving heat distribution;
- assess refurbishment measures at both building and network level, including insulation upgrades, substation modernisation and advanced control strategies;
- evaluate the benefits and technical requirements of low-temperature district heating systems and renewable heat integration;
- explain the role of heat metering, billing and tariff structures in supporting efficient district heating operation;
- compare district heating business models and financing approaches in refurbishment contexts;
- develop and justify refurbishment strategies that improve energy efficiency, reduce heat losses, enhance user comfort and support district heating decarbonisation.

Main tasks and activities

The module combines conceptual learning, case-study analysis, practical refurbishment planning and assessment. The case studies included in the guidebook demonstrate how refurbishment concepts are applied in real-world district heating projects. Through the analysis of practical examples, learners examine technical solutions, implementation challenges, achieved benefits and lessons learned from modernisation initiatives. The case studies help bridge the gap between theory and practice by showing how refurbishment measures can contribute to improved system performance, user comfort and sustainability.

The module is also supported by a separate practical refurbishment exercise. In this activity, learners evaluate a hypothetical legacy district heating system and develop a refurbishment strategy. They identify technical problems, analyse their causes and impacts, propose modernisation measures and prioritise interventions based on technical, economic and operational criteria. This learning-by-doing activity encourages critical thinking, problem-solving and the practical application of refurbishment concepts introduced in the module.

In addition, the module includes an economic classroom case study focusing on district heating retrofit decision-making. This activity allows learners to examine business models, tariff structures, financing options, stakeholder perspectives and sensitivity scenarios in a realistic refurbishment context.

Learning outcomes are supported by a module-level self-check quiz and a reusable question bank. The assessment materials evaluate learners' understanding of district heating refurbishment principles, modernisation technologies, hydraulic balancing, substation upgrades, low-temperature district heating concepts and economic decision-making. The assessment focuses on the ability to interpret technical challenges, compare alternative solutions and apply engineering reasoning to realistic district heating scenarios.

Estimated workload

This module represents approximately 7 learning hours, including lectures, practical exercise, case-study work, independent 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 teaching unit,
- a set of selected lecture materials,
- a blended learning component,
- a practical refurbishment exercise package,
- a case-study and decision-making package,
- or a supplementary resource for existing courses.

Activities and Learning Hours

Activity Type	**Time Allocation (Hours)**	**Description**
Lectures	3 h	Introduction to legacy district heating systems, refurbishment measures, building-side systems, substations, low-temperature transition, metering, business models and case studies
Exercises	1 h	Practical refurbishment exercise based on the diagnosis and modernisation of a legacy district heating system
Case Studies	0.5 h	Discussion of selected real-world district heating refurbishment and urban development case studies
Self-Study	2 h	Independent reading, review of lecture materials and preparation for the exercise or assessment
Assessment	0.3 h	Module-level self-check quiz and/or selected questions from the question bank
Total Learning Hours	**appr. 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 and related fields,
- trainers involved in professional or continuing education on district heating and cooling,
- 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 refurbishment, building energy systems, urban energy infrastructure and energy efficiency.

The materials may also be used by students, professionals and independent learners who wish to study selected topics individually. For independent use, basic prior knowledge in the relevant engineering fields is recommended.

Recommended use by educators and trainers

Module 6 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 6 resource
Introducing the topic	Use the module overview and introductory slides to present the relevance of district heating refurbishment, legacy systems and the transition toward low-temperature operation.
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 refurbishment measures, hydraulic balancing, substation modernisation, low-temperature district heating, metering, business models and case studies.
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 refurbishment exercise for group work, homework, project-based learning or guided engineering discussion.
Supporting economic and strategic decision-making	Use the economic case study to discuss ownership models, tariffs, financing strategies, stakeholder perspectives and sensitivity analysis.
Supporting case-study discussion	Use the real-world examples in the guidebook to compare different approaches to district heating refurbishment and urban network development.
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, practical exercise and case study 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 the module.
Study the guidebook materials	Read the detailed explanations, engineering principles and refurbishment concepts presented in the guidebook.
Review the real-world case studies	Compare how refurbishment and urban district heating development are approached in different contexts.
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 refurbishment exercise	Apply the acquired knowledge by diagnosing a legacy district heating system and proposing a prioritised refurbishment strategy.
Review the economic case study	Explore how business models, tariffs, financing and stakeholder interests influence district heating retrofit decisions.
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 practical refurbishment exercise based on the diagnosis and modernisation of a legacy district heating system,
- an economic classroom case study on district heating retrofit decision-making, business models, tariffs, financing and stakeholder perspectives,
- activity slides supporting the economic case study.

The practical exercise and the economic case study may be used for group work, homework assignments, short technical or economic reports, oral presentations, poster work or classroom discussion. Educators may select one or both activities depending on the level of the learners, the available teaching time and the intended learning outcomes.

Tartalomjegyzék

1.1 Introduction

District heating (DH) systems are a critical piece of urban energy infrastructure: they centralize heat production and distribute thermal energy through a network of insulated pipes to multiple end users, enabling economy-of-scale generation, easier integration of large heat sources and—potentially—lower urban emissions than individually heated buildings. However, many European DH networks were built decades ago under design assumptions and energy price regimes that differ markedly from today's decarbonization goals. The need to modernize and refurbish existing systems is therefore urgent: refurbishment not only restores lost efficiency but also enables the integration of low-exergy heat sources, smart controls and new business models that together can transform DH into a core technology for low-carbon cities. This chapter synthesizes the technical, economic and institutional dimensions of refurbishing district heating systems.

1.1.1 Historical context and the challenge posed by legacy systems

Many DH systems, particularly across Eastern Europe and former Soviet countries, were designed in an era of relatively inexpensive primary energy and were optimized for large residential blocks with poor thermal envelopes. These "high-temperature" systems typically operated with supply temperatures in the range of 100–130 °C and return temperatures around 60–70 °C, used large-diameter insulated pipes, and often relied on central fossil-fuel plants or large combined heat-and-power (CHP) units. Such design parameters were appropriate for the high heat demand and limited building insulation of the time, but they create friction with today's objectives: these systems incur high transmission losses, are inefficient with modern low-energy buildings, and are poorly matched to low-exergy heat sources (e.g., geothermal, ambient heat, industrial waste heat or large heat pumps).

Early district heating systems pose a major challenge compared to today's expectations. Due to high flow temperatures and insufficient pipe insulation, they operate with high heat losses, which continue to deteriorate over time. Furthermore, these systems have very limited connectivity to low-exergy heat sources such as solar collectors, geothermal heat, or heat pumps. Such systems incur high maintenance costs, which reduces their efficiency. On the consumer side, more and more buildings are renovated, which reduces the amount of energy needed to be transported, thus making pressure control essential. For this reason, it is less suitable for modern, low-energy buildings and residential communities.

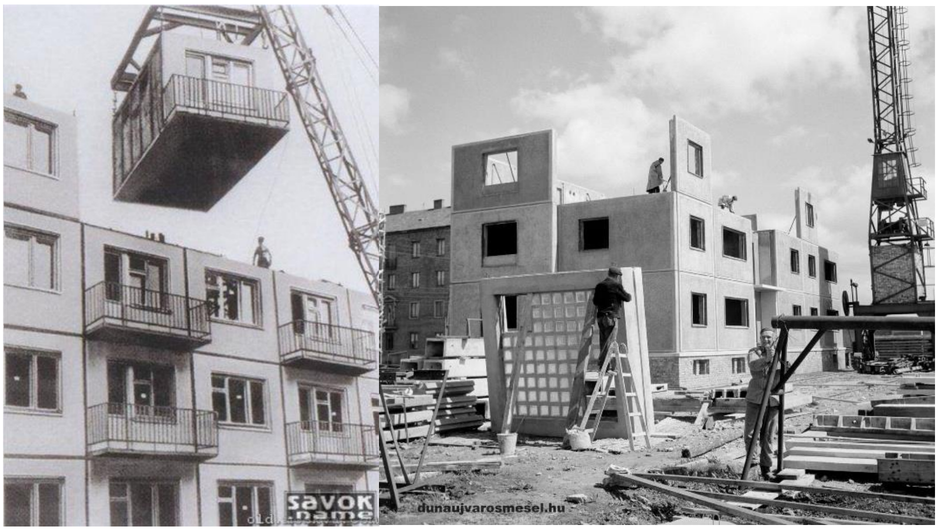


Figure 1. Construction of prefabricated buildings [1]

1.1.2 Technical anatomy of legacy (high temperature) district heating

Between the 1950s and 1990s, most Eastern European countries implemented large-scale prefabricated housing programmes to address severe post-war housing shortages, rapid industrialization, and urban population growth. Influenced by socialist planning principles, governments prioritized the rapid and cost-effective construction of standardized apartment blocks using factory-produced concrete panels (see Figure 1), enabling millions of housing units to be built within a relatively short period. While these developments significantly improved living standards by providing modern apartments with indoor plumbing, hot water, and district heating, construction speed and affordability were often prioritized over architectural quality, thermal performance, and long-term durability. As a result, many housing estates were designed as dense urban districts connected to centralized district heating networks, creating exceptionally high heat demand concentrations that initially favoured the economic operation of district heating systems. However, poor building insulation, inefficient windows, limited control of indoor temperatures, and aging network infrastructure led to substantial energy losses and excessive heat consumption. Consequently, many Eastern European district heating systems inherited a combination of favourable customer density and inefficient building stock, making energy-efficiency retrofits, building renovations, and network modernization key priorities in the region's ongoing energy transition.

Second-generation district heating systems were developed and widely deployed throughout the Soviet Union and Eastern Europe between the 1950s and 1980s to serve rapidly expanding prefabricated housing estates and industrial districts. These systems were designed within centrally planned economies where the primary objective was to provide reliable and universal heat supply at the lowest possible investment cost, rather than to optimize energy efficiency or consumer comfort. Heat was typically generated in large, centralized plants and distributed through high-temperature water networks with limited possibilities for local control, while apartments generally lacked individual heat metering or thermostatic regulation. As a result, indoor temperatures were often maintained well above comfort requirements, and occupants frequently regulated room temperature simply by opening windows during winter. Combined with poorly insulated buildings, high network temperatures, and aging distribution infrastructure, this operational philosophy resulted in substantial heat losses and excessive energy consumption. At the time, however, fuel prices were heavily subsidized, and energy security was prioritized over efficiency, making investments in advanced controls, insulation, or demand-side management economically unattractive within the prevailing planning framework. Following the political and economic transitions of the 1990s, rising energy prices, environmental concerns, and aging infrastructure fundamentally changed these conditions. Consequently, the modernization of district heating networks, installation of modern substations and controls, and thermal renovation of buildings became essential measures for improving efficiency, reducing operating costs, and ensuring the long-term viability of district heating systems in the region.

To design refurbishment interventions, it is essential to understand the anatomy and typical failure/inefficiency modes of high-temperature DH systems.

1. Heat production: Traditionally coal, oil or gas boilers and large CHP plants supply heat. These units often operate best at high return temperatures and are sized for peak demand rather than for variable modern loads. Modern decarbonization seeks to replace or complement these with biomass, waste heat recovery, heat pumps and renewables.
2. Transmission and distribution pipelines: Large-diameter pipework, as seen in figure 2, often heavily insulated when new but subject to aging and damage, runs through urban corridors. Heat losses from old pipelines can be substantial and increase operational fuel consumption. Aging joints, corrosion and thermal bridging are common refurbishment targets.

Figure 2. Overground DH pipelines [2]

3. Substations and heat exchangers: Older substations were often assembled on-site from many components; modern refurbishment favours factory-built prefabricated substations that are compact, modular and instrumented (flat-plate exchangers, variable-speed pumps, expansion vessels, control and metering). Apartment-level substations can enable per-flat temperature control, metering and the elimination of central DHW circulation loops.

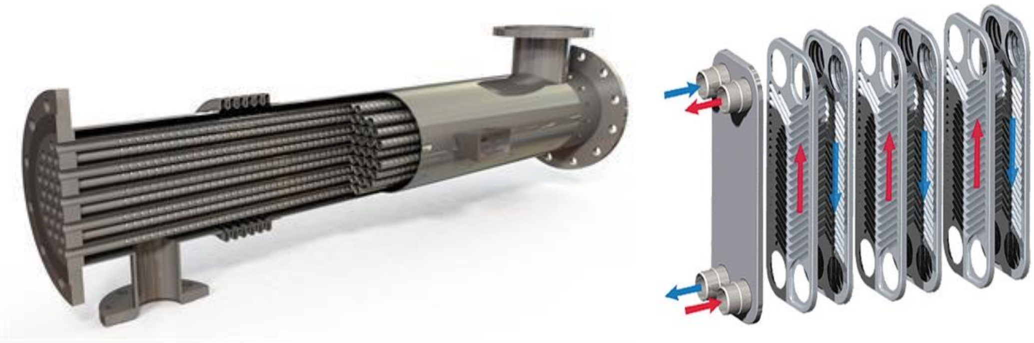


Figure 3. Shell and tube (left) [3], plate (right) [4] heat exchangers

4. Building-level distribution: Radiators, one-pipe systems, risers and internal hydraulics determine how effectively heat is delivered to rooms. Many Soviet-era panel buildings employed single-pipe (flow-through) heating topologies that complicate retrofit and fair billing. Hydraulic imbalance — where strings near the circulation pump get excess flow and others starve — is a pervasive problem remedied with balancing valves and pump control.
5. Control and measurement: Historically coarse thermostatic control, centralized start/stop regimes and lack of per-apartment metering harmed efficiency. Modernization introduces differential pressure control, thermostatic radiator valves, frequency-controlled pumps, electronic meters and remote data collection for better demand matching and billing.

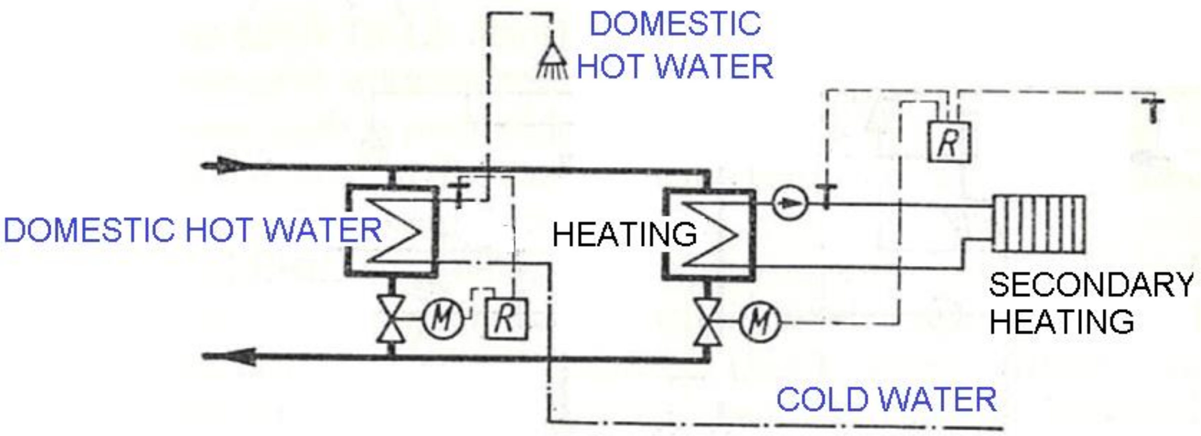


Figure 4. District heating heat centre with domestic hot water and heating circuit [5]

Understanding these technical elements frames the subsequent chapters on targeted refurbishment measures. Contemporary DH literature emphasizes that the future of DH is not simply “bigger boilers” but network–building integration, flexible low-temperature operation and intelligent control.

1.2 Measures at the building and secondary system level

The refurbishment of a district heating network does not stop at the pipes in the street; it must extend into the buildings themselves. A holistic approach to modernization involves several key strategies:

1.2.1 Thermal envelope upgrades

A fundamental step is reducing heat demand through insulation upgrades — better wall insulation, replacement of single-glazed windows with modern glazing, attic and roof insulation — which directly reduces peak loads and allows operation of the DH network at lower temperatures. The SHAKE draft stresses the primacy of building insulation for the success of low-temperature DH transitions.

1.2.2 Radiators, underfloor heating and system adaptions

When supply temperatures are reduced, building emitters must be compatible. Radiators with larger surface area or low-temperature-optimized underfloor heating are better suited to low-temperature supply. In refurbishment planning, radiator sizing, thermostatic valve upgrades and manifold changes are evaluated to ensure adequate indoor temperatures at lower inlet water temperatures.

1.2.3 Single-pipe system refurbishment

In single-pipe systems, the same water flow passes through multiple radiators in a sequence, as seen in figure 5. While cost-effective to install, these systems are notoriously difficult to regulate. Depending on the era and the specific design of the building, we typically encounter four main configurations. In single-pipe systems, the same water flow passes through multiple radiators in a sequence. While cost-effective to install, these systems are notoriously difficult to regulate. Depending on the era and the specific design of the building, we typically encounter four main configurations

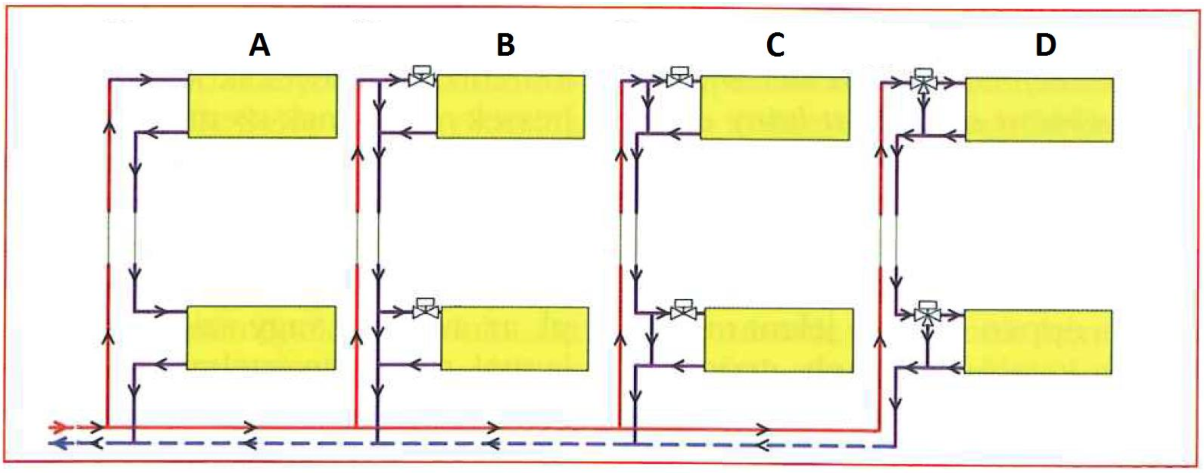


Figure 5. Renovation options for single-pipe heating systems on the radiator side [6]

Type A - Flow-through heating: The simplest and oldest form. The entire water mass-flow passes through every radiator in the string. If one resident turns off their radiator (which is often physically impossible without a bypass), the entire string stops.

Type B - Bypassed radiator: A bypass pipe allows a portion of the water to skip the radiator. This provides basic temperature control without stopping the flow to other apartments.

Type C - Shifted bypass with one-way valve: A more advanced version where the bypass geometry and a specialized valve help prioritize flow through the radiator or the bypass.

Type D - Shifted bypass with three-way valve: The most sophisticated legacy configuration, allowing for precise proportional mixing between the bypass and the radiator, improving thermal comfort.

1.2.4 The Hydraulic Imbalance Challenge

A significant hurdle in these systems is hydraulic pressure equalization. In a large-scale housing estate, the physics of fluid dynamics creates a natural "unfairness" in heat distribution:

The Proximity Problem: Heating strings located closer to the central circulation pump naturally receive a higher mass-flow because the path of least resistance is shorter.

Oversupply vs. Undersupply: As seen in figure 6, the "near" strings experience higher thermal performance (oversupply), leading to uncomfortably hot apartments and High Return Temperatures that decrease the efficiency of the entire district heating plant. Conversely, the "far" strings suffer from lower flow and persistent undersupply, leaving residents in those areas cold.

While the use of Variable Frequency Pumps (VFD) is a modern necessity—allowing the system to adjust the pump speed based on overall demand—a smart pump alone cannot fix an imbalanced network. It can change the total pressure, but it cannot ensure that the pressure is distributed equitably between the first and the last string.

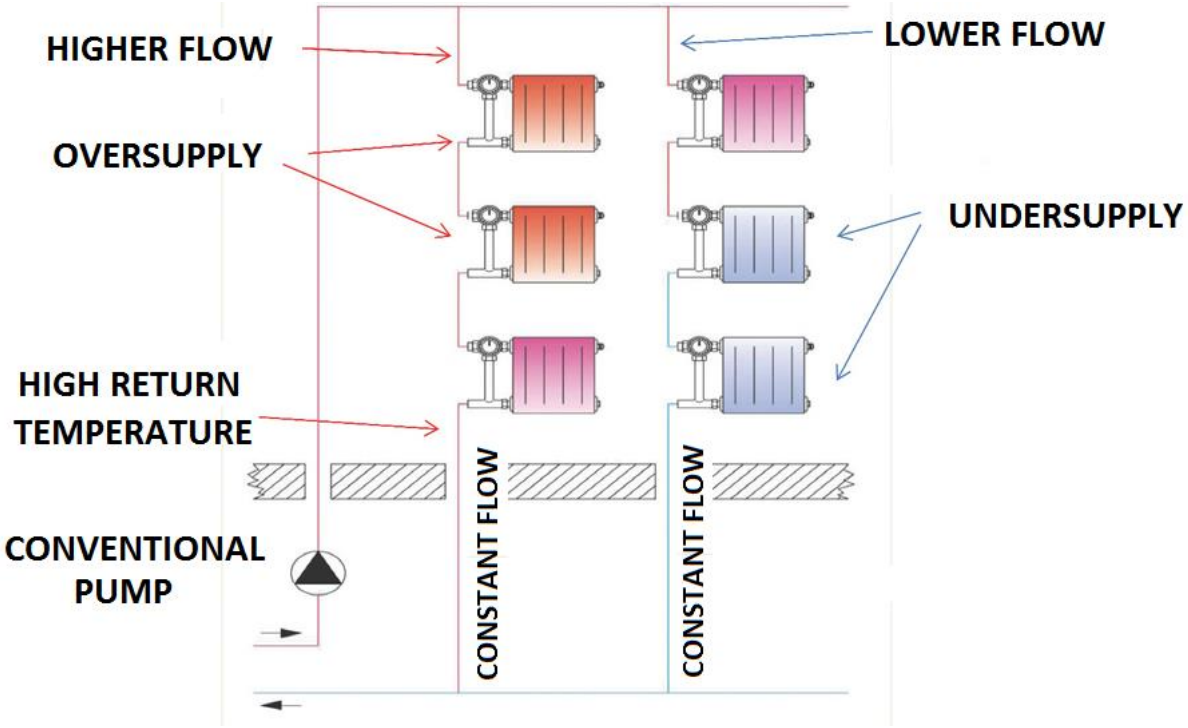


Figure 6. The lack of hydraulic pressure equalisation of heating strings [7]

1.2.5 The Solution: String-Level Balancing

The key to a successful refurbishment is the installation of balancing valves for each individual string, as seen in figure 7. This intervention transforms a chaotic network into a managed one through three primary functions:

- Pressure Compensation: Balancing valves create artificial resistance in the "near" strings, forcing the water to reach the furthest points of the network. This eliminates the "shortcut" effect.
- Flow Definition: Engineers can define and lock in the exact required flow for each string, ensuring that every apartment receives the heat it was designed for, regardless of its location.
- Measurement and Diagnostics: Modern balancing valves provide a measurement point. This allows technicians to verify the actual flow and pressure differences in real-time, moving from "estimated" performance to "measured" efficiency.

By implementing these building-level adjustments, the return temperature of the entire district heating network can be lowered, which is the fundamental prerequisite for integrating renewable energy and reducing operational costs.

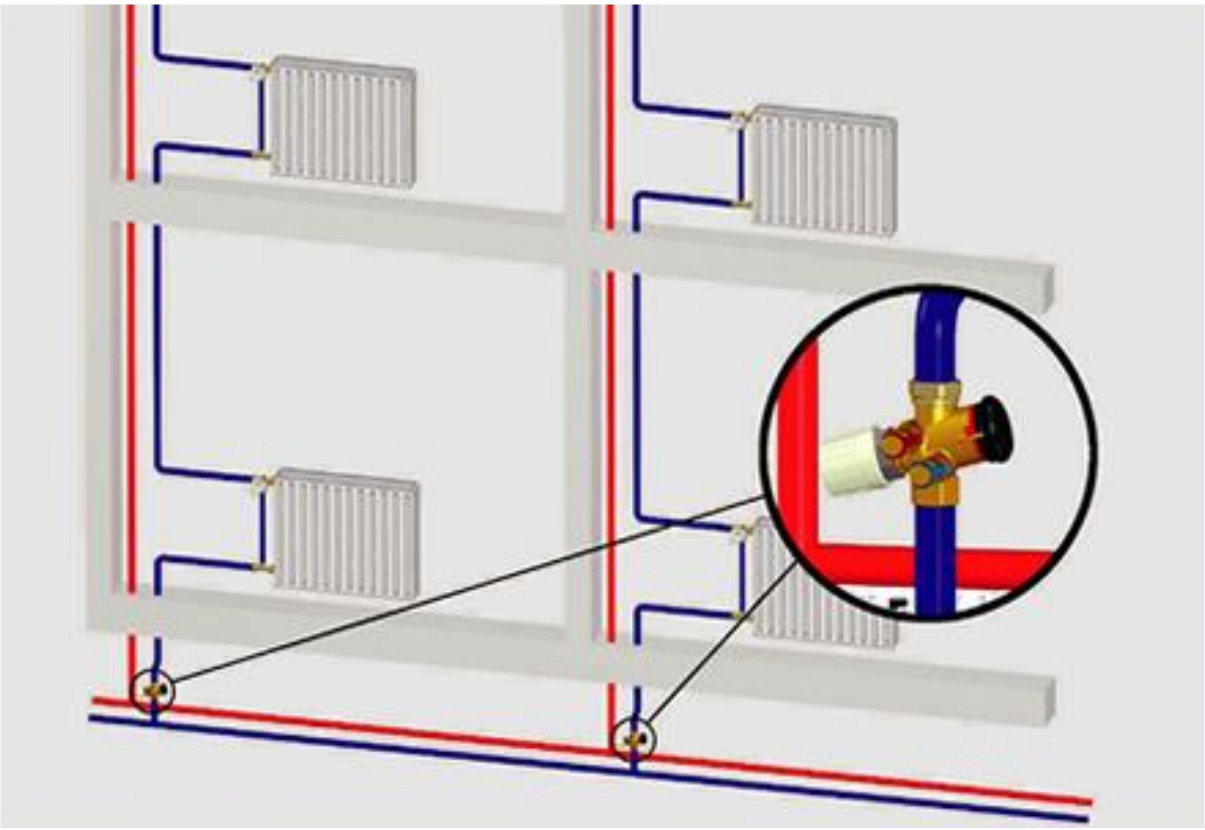


Figure 7. String-level balancing [8]

1.3 Substation modernization and per-apartment solutions

1.3.1 Refurbishment of DHC in Housing Estates

1.3.1.1 The Shift to Compact, Modular Substations

In the 2nd generation of district heating systems, substations were typically built in situ (on-site). This required extensive labour, custom pipework, and resulted in systems that were difficult to standardize or maintain. Modern refurbishment projects now utilize 3rd generation technology, characterized by prefabricated, modular substations, as seen in figure 8.

These units are factory-tested and arrive as "plug-and-play" solutions, available in various performance levels to match the specific needs of a building. A modern modular substation typically integrates all critical components into a single, compact frame:

- Flat-plate heat exchangers: Providing high thermal efficiency and rapid heat transfer.
- Variable frequency pumps: Automatically adjusting flow based on real-time demand to save electricity.
- Performance adjustment valves: Ensuring precise control over the heat medium.
- Expansion vessels: Managing pressure fluctuations safely within the system.

Figure 8. Compact, modular substation [18]

1.3.1.2 Apartment-Level Substations: Individualized Comfort

The most significant leap in resident satisfaction and system efficiency comes from the installation of apartment-level substations. A seen in figure 9. one of the most impressive features of these units is their compact design. They are often thin enough to be installed in a simple 150 mm wall recess, making them ideal for retrofitting into older "panel" buildings where space is at a premium. Key Advantages for Residents:

- Individual Control: Residents can start or stop their heating season independently and adjust their Domestic Hot Water (DHW) temperature to their personal preference.
- Transparent Metering: Both heat and water consumption are metered per flat, ensuring that residents only pay for what they actually use, which inherently encourages energy-saving behaviour.
- Hydraulic Stability: Each substation features differential pressure control, preventing fluctuations in the network from affecting the comfort level inside the apartment.

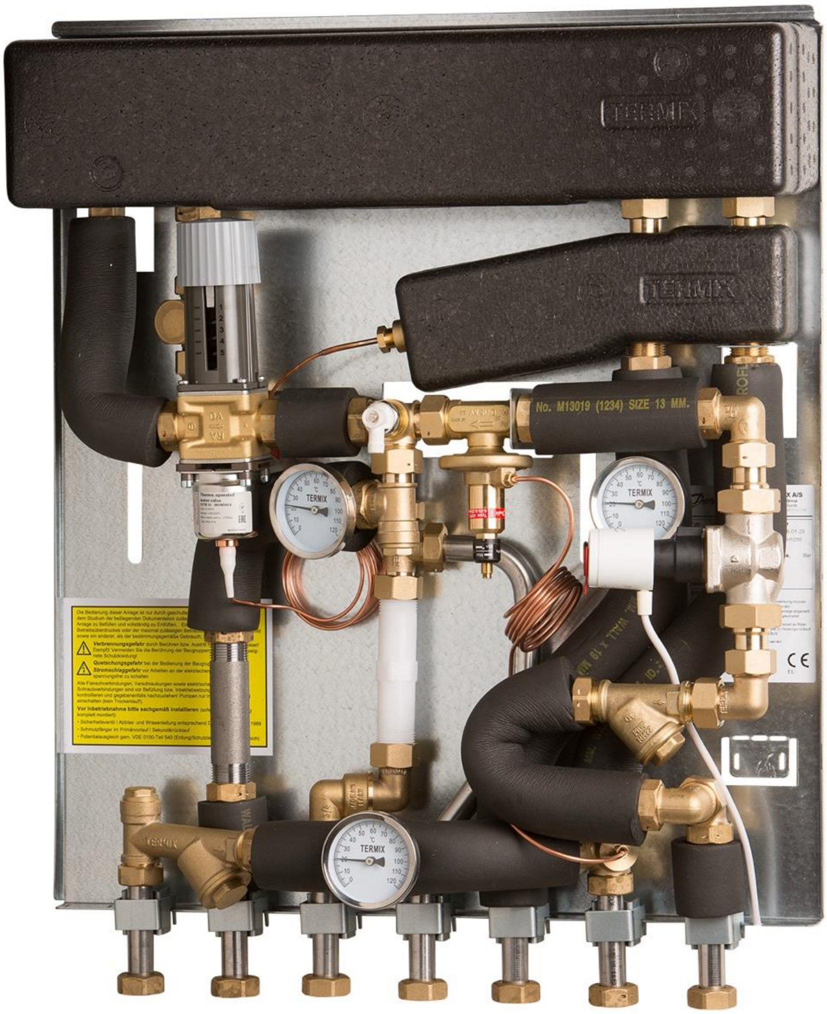


Figure 9. Apartment substation [9]

1.3.1.3 Enhanced Hygiene and System Simplicity

Beyond comfort, apartment-level substations fundamentally change the way we handle water. Traditional systems require a continuous DHW circulation circuit to ensure hot water is available at the tap instantly; however, these circuits are notorious for heat losses.

Because apartment substations produce hot water on demand through a local heat exchanger, the DHW circulation circuit is no longer required. This offers two major benefits:

Energy Efficiency: Eliminating the circulation loop significantly reduces standby heat losses throughout the building.

Health and Safety: By removing the need for large DHW storage tanks and long circulation pipes, the system drastically lowers the risk of Legionella contamination. Since water is not stored in a lukewarm state but heated only when needed, the system is inherently more hygienic.

1.3.2 Transitioning to Low-Temperature District Heating (LTDH)

The transition toward Low-Temperature District Heating (LTDH), often referred to as the 4th generation of heating technology, represents a fundamental paradigm shift in how we distribute energy across the urban landscape. Unlike legacy systems that relied on high-pressure steam or scalding water, LTDH operates with supply temperatures typically ranging from 35°C to 70°C, and in some ultra-low-temperature experimental networks, as low as 30°C. By maintaining return temperatures between 20°C and 40°C, the system creates a much narrower thermal gradient with the surrounding environment. This technical shift is not merely an incremental improvement; it is the prerequisite for a fully decarbonized energy sector, as it allows the network to act as a flexible "thermal bus" that can harvest energy from sources previously considered unusable.

The primary driver behind lowering these temperature levels is the dramatic reduction of thermal losses during distribution. In traditional high-temperature grids, the vast difference between the pipe temperature and the soil temperature leads to significant energy dissipation, which can be mitigated to some extend by insulating the pipes. By bringing the supply temperature closer to the ambient temperature of the ground, these losses are minimized, allowing the system to maintain high efficiency even when serving less dense areas. This efficiency is further enhanced by modern infrastructure designs that favor smaller pipe diameters and decentralized network sections. Smaller pipes not only reduce the surface area available for heat loss but also lower the capital costs and physical footprint of the network, making it easier to integrate into the existing "living fabric" of a city during refurbishment projects.

Perhaps the most transformative aspect of LTDH is its ability to integrate low-exergy and renewable energy sources. High-temperature systems are essentially "locked in" to combustion-based heat sources like coal or gas boilers, as it is energetically expensive to boost renewable heat to over 100°C. In contrast, an LTDH network is perfectly matched with the output of large-scale heat pumps, geothermal reservoirs, and solar thermal arrays. Furthermore, it allows for the recovery of industrial waste heat and even low-grade heat from non-traditional sources like data centres, sewage systems, or large commercial refrigeration units. This turns the district heating operator into an energy orchestrator, balancing a diverse portfolio of green heat sources that significantly reduce the carbon footprint of the entire building stock.

However, the successful implementation of Low-Temperature District Heating is inextricably linked to the performance of the buildings it serves. LTDH is most effective when paired with energy-efficient new builds or heavily retrofitted older building stock. For a building to remain comfortable while being supplied with 45°C water instead of 90°C, the demand-side efficiency must be addressed. This typically involves improving the building envelope through superior insulation and upgrading secondary heating elements—such as installing larger radiators or underfloor heating—to maximize the heat transfer surface. When the building's thermal "leaks" are plugged, the requirement for high-intensity heat disappears, allowing the entire system to operate at a more sustainable, lower energy state.

Finally, managing such a sophisticated and sensitive thermal balance requires a move away from the "set and forget" control logic of the past. Modern LTDH systems rely on smart controls and real-time monitoring to constantly adjust heat delivery based on actual demand and weather forecasts. By using digital twins and advanced sensors at both the plant and the apartment level, operators can ensure that every kilowatt of heat is delivered exactly where and when it is needed. This level of precision prevents the oversupply and high return temperatures that plagued older systems, ensuring that the transition to low-temperature operation delivers on its promise of a more resilient, cost-effective, and environmentally friendly urban future.

1.3.3 Technical Considerations in the Transition

1.3.3.1 Supply System and Network Modifications

The shift toward low-temperature operations is most effectively managed through a progressive lowering of network temperatures. Instead of a system-wide drop, operators often establish pilot zones or secondary loops where new technologies can be tested without risking the stability of the entire grid. This phased approach allows for the gradual integration of 4th or 5th generation district heating (DH) concepts. While 4th generation systems focus on low-temperature water (around 55−70°C), 5th generation systems (often called Ambient Loops) operate near ground temperature, using decentralized heat pumps at each building to provide the final temperature boost. Upgrading generation sources is central to this shift, moving away from high-combustion boilers toward low-temperature-compatible heat pumps and waste heat recovery units that thrive in these lower thermal regimes.

1.3.3.2 Building-Level Adaptations and the DHW Challenge

For a building to remain functional under a low-temperature regime, the internal heating infrastructure must be reconsidered. Traditionally, radiators were sized for 90°C water; at 50°C, their heat output drops significantly. To compensate, refurbishment must focus on improving thermal envelopes—upgrading windows, walls, and roofs—to reduce the overall heat load. When the building loses less heat, existing radiators or underfloor heating systems can work efficiently even with lower inlet temperatures. Furthermore, the substation heat exchangers must be specifically selected to operate well at a lower ΔT, ensuring maximum energy transfer even when the temperature difference between the primary and secondary circuits is minimal.

One of the most critical technical hurdles is Domestic Hot Water (DHW) preparation. Since LTDH supply temperatures may drop below the 55−60°C required to instantly kill bacteria, managing Legionella risk is paramount. This is often solved through decentralized strategies, such as using booster heaters (electric or small-scale heat pumps) to provide a final thermal lift for water at the point of use. Alternatively, pasteurization strategies or high-efficiency "instantaneous" heat exchangers in apartment substations can be used to ensure that water is never stored at risky, lukewarm temperatures, thus eliminating the biological hazard without requiring the entire network to run at high heat.

1.3.3.3 Control, Optimization, and Smart Grids

Because low-temperature systems operate with much lower temperature margins, there is less "room for error" in heat delivery. This necessitates more precise control strategies than those used in legacy systems. Modern networks integrate smart thermostats and weather compensation logic, which allows the system to anticipate changes in outside temperature and adjust the flow before residents even feel a chill. This evolution is further supported by real-time demand response integration, where the network can "communicate" with buildings to shave off peak loads, ensuring that the supply is always optimized against the actual consumption of the urban fabric.

1.3.3.4 Predictive Maintenance and Monitoring

In a modernized district heating network, maintenance shifts from a reactive "fix-on-failure" model to a proactive, predictive maintenance approach. Given that these systems represent massive capital investments, ensuring long-term reliability and efficiency is vital for economic viability. By integrating a dense web of sensors and data analytics, operators can monitor the health of the infrastructure in real-time.

Advanced technologies, such as acoustic sensors and thermal flow monitoring, allow for the early detection of faults—such as minor leaks or insulation degradation—long before they become catastrophic breaks. This data-driven oversight not only reduces high maintenance costs and emergency repair bills but also ensures that the network continues to operate at its peak design efficiency, preserving the environmental and economic benefits of the refurbishment for decades to come.

1.3.4 Measuring and Billing Heat Consumption

For a district heating system to operate efficiently, it must move beyond simple heat delivery to sophisticated heat consumption metering. This process requires a coordinated set of components working in tandem to calculate the energy actually extracted by a building or individual apartment. A standard modern metering assembly (seen in figure 10) consists of several high-precision elements:

- A Flow Sensor: To measure the exact volume of the heat-carrying medium passing through the system.
- Supply and Return Thermometers: To record the temperature difference (ΔT) between the water entering and leaving the consumer's circuit.
- A Processing Computer: The central "brain" that integrates the flow and temperature data to calculate the total thermal energy consumed, typically measured in kilowatt-hours (kWh) or gigajoules (GJ).

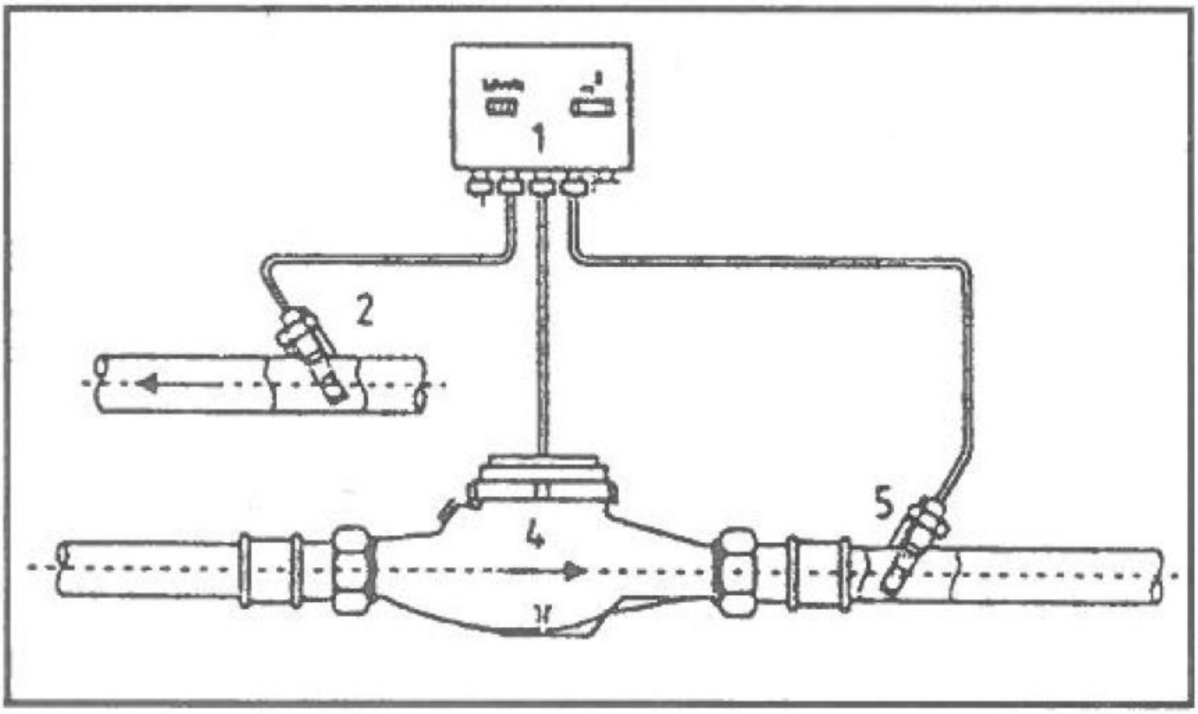


Figure 10. Heat consumption meter [10]

1.3.4.1 Hierarchical Metering Structures

Modern refurbishment projects allow for the measurement of heat consumption at various levels of the urban fabric. While central heat consumption measurement for an entire building remains the standard for bulk billing, more granular structuring is required for fair cost distribution. Depending on the building's architecture and the management requirements, metering can be organized by:

- Entire building (main connection point)
- Specific building parts (e.g., separate wings or commercial ground-floor units)
- Individual flats (providing direct accountability for residents)
- Per consumption site (individual radiators or specific zones)

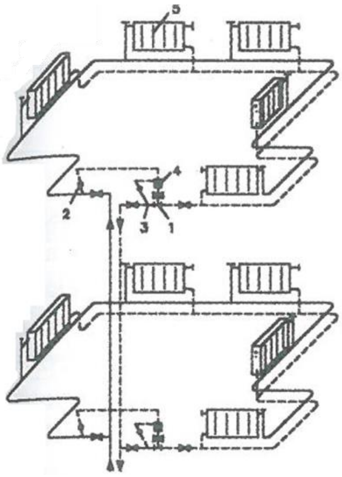


Figure 11. Apartment measuring example [10]

1.3.4.2 The Challenge of Single-Pipe vs. Double-Pipe Systems

The ease of implementing individual metering is heavily dictated by the building’s internal pipework. In double-pipe systems, where each apartment has a clear, single entry and exit point for its heating circuit, individual metering is easily realized. This allows for the installation of a single apartment-level meter that provides highly accurate billing data.

In contrast, traditional single-pipe systems present a significant technical hurdle. Because a single vertical pipe (string) often serves one room in several different apartments, it is physically impossible to install a single meter that captures a specific flat's total consumption. In these legacy housing estates, refurbishment often necessitates the use of heat cost allocators mounted on individual radiators or, more ideally, the complete conversion of the internal network to a horizontal, apartment-based distribution system to allow for modern billing standards.

1.4 Business Models and Economic Aspects of District Heating

The financial and structural framework of a district heating (DH) system is as critical as its technical design. Because these systems require massive upfront capital, their success depends on long-term planning, stable financing, and a business model that aligns the interests of the operator with the goals of the community.

1.4.1 Common Business Models

The way a DH system is owned and operated significantly influences its strategic priorities, from carbon neutrality to consumer pricing.

Public Utility Model: Predominant in Nordic countries like Denmark and Sweden, these systems are owned by municipalities. The primary focus is on affordability, energy security, and meeting local climate goals. Any profits are typically reinvested into the infrastructure or used to lower tariffs for residents.

Private Utility Model: Common in liberalized energy markets, these are operated by private firms focused on profitability and operational efficiency. While they bring private capital to the table, they may require government incentives or strict regulations to ensure long-term investments in decarbonization rather than short-term gains.

Public-Private Partnership (PPP): This model seeks to balance public interest with private sector efficiency. By sharing ownership and risks, the public sector can achieve social and environmental goals while leveraging private investment and management expertise through performance-based contracts.

Cooperative Model: In this community-centric approach, the end-users themselves own the system. Profits are either shared or reinvested to improve the service. This model is particularly effective in smaller municipalities and "eco-villages," as it fosters high local acceptance and transparency.

1.4.2 Revenue Streams and Cost Structures

While heat sales to buildings remain the primary source of income, modern DH systems are diversifying their revenue. Operators are increasingly exploring ancillary services, such as providing flexibility to the electricity grid by using large-scale heat pumps or thermal storage. Additionally, government subsidies, feed-in tariffs for green heat, and carbon credits within Emission Trading Schemes (ETS) provide vital financial support for the transition away from fossil fuels.

On the expenditure side, OPEX includes the cost of fuels (if any), electricity for pumping, and ongoing maintenance. In a refurbished, low-temperature network, these costs are significantly lower than in legacy systems, as heat losses are minimized and the reliance on expensive fossil fuels is reduced.

1.4.3 Heat Pricing and Motivational Tariffs

Pricing models are designed to be "cost-reflective" while ensuring that heat remains affordable. Most structures consist of a Fixed Charge to cover infrastructure and maintenance, and a Variable Charge based on actual energy consumption (measured in MWh or GJ).

A critical tool in modern DH management is the Motivational Tariff. This structure penalizes consumers who return water to the network at excessively high temperatures. By creating a financial incentive for residents and building managers to optimize their internal secondary systems, the operator can lower the entire network's return temperature, which is the fundamental requirement for system-wide efficiency.

1.4.4 Transitioning to "Heat-as-a-Service"

The future of DH economics is shifting toward Performance-Based Contracts and service-oriented models. In the Heat-as-a-Service model, customers do not pay for units of energy, but for a guaranteed level of comfort (e.g., a constant indoor temperature of 21°C). This shifts the incentive: the supplier now makes more profit by making the building more efficient and using less energy. Combined with Digital and Smart DH integration, these models enable dynamic pricing and demand response, turning the heating grid into a highly optimized, consumer-friendly service.

1.5 DH development: Involving downtown areas

1.5.1 Bunhill Heat and Power Network, London [11]

The Bunhill Heat and Power Network in the London Borough of Islington serves as a global landmark for urban energy innovation, see figure 12. It is the first project in the world to successfully harvest waste heat from an underground train network—the London Underground—to provide affordable, low-carbon heating for local residents and public buildings.

1.5.1.1 Phases

Phase 1: Establishing the Foundation

Launched as a decentralized energy solution, Phase 1 centred on a gas-fired Combined Heat and Power (CHP) plant located on Central Street. In this configuration, waste heat generated as a byproduct of electricity production was captured and repurposed for district heating rather than being dissipated into the atmosphere. This initial phase established the network infrastructure, serving approximately 800 homes and several local public buildings.

Phase 2: Pioneering Waste Heat Recovery

The Phase 2 extension represents a significant technological leap toward the 4th generation district heating principles discussed earlier. The heart of this expansion is a new energy centre built at the site of a London Underground ventilation shaft on the corner of Moreland Street and Central Street.

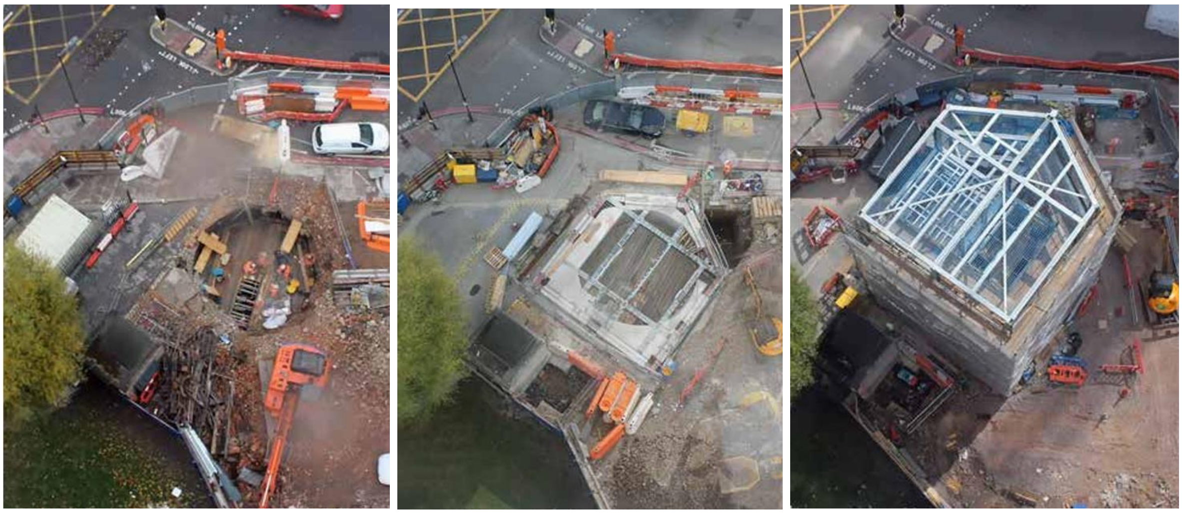


Figure 12. Phases of construction of Bunhill Heat and Power Network in London [11]

This facility utilizes a large-scale heat pump (figure 13) to extract low-grade waste heat directly from the Tube’s ventilation system. By "upgrading" this warm air from the tunnels into usable thermal energy for the water-based heating grid, the project demonstrates how cities can turn a nuisance (tunnel heat) into a valuable resource.

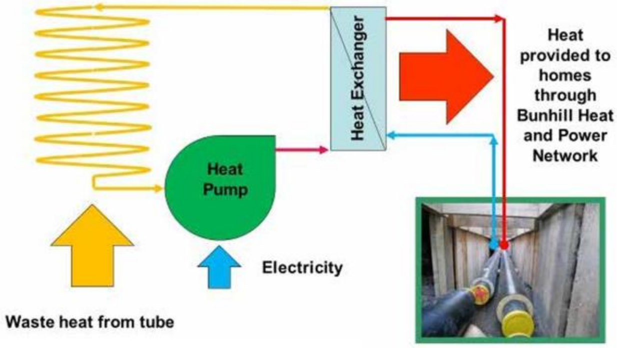


Figure 13. Schematic diagram of heat pump district heating [11]

Figure 14. Buildings supplied by two heating centres [11]

Figure 15. Ventilation shaft fan (left) and thermal energy storage (right) [11]

1.5.1.2 System Resilience and Environmental Impact

A key technical advantage of the Bunhill refurbishment and expansion is the interconnectivity between the two energy centres (figure 14). The design ensures high system resilience; if one facility requires maintenance or fails, the other can take over the load, ensuring a continuous heat supply for the community.

The impact of this expansion is substantial:

- Expanded Reach: The Phase 2 extension connects an additional 550 properties, including the King Square Estate and Moreland School, bringing the total service reach to over 1,350 homes.
- Carbon Reduction: By shifting toward heat pump technology and waste heat recovery, the extension is estimated to reduce carbon emissions by approximately 500 tonnes of CO_2 per year.
- Urban Integration: The project shows how district heating can be successfully retrofitted into a dense, historic downtown area by repurposing existing infrastructure like ventilation shafts.

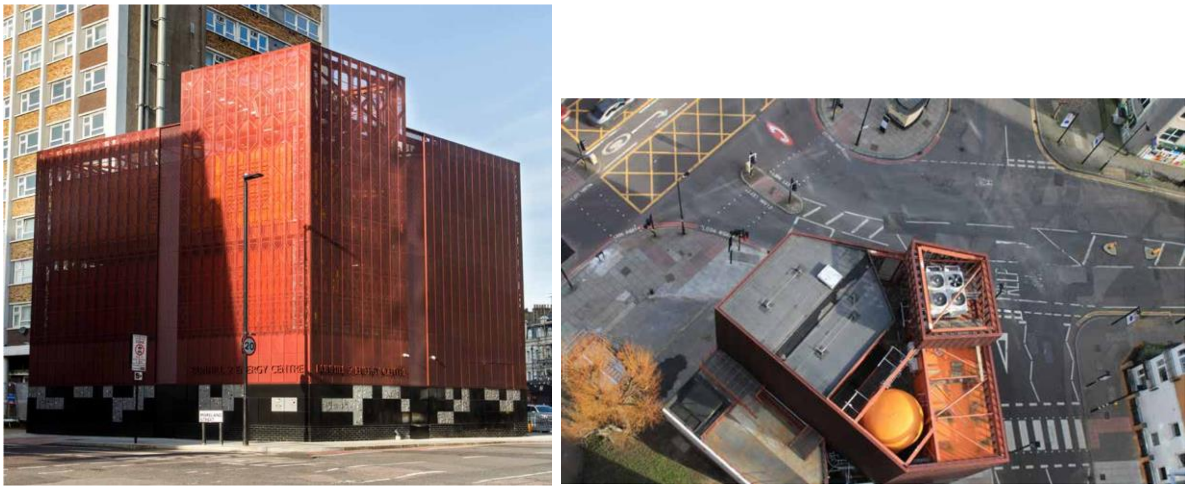


Figure 16. The heating center after renovation [11]

1.5.2 Citigen Project, London [12]

The Citigen Project, located in the heart of London’s financial district, represents a sophisticated evolution of urban energy systems. While many traditional networks rely on a single energy source, Citigen acts as a multi-vector energy hub, integrating heating, cooling, and power generation into a unified, high-efficiency grid.

1.5.2.1 Harvesting the London Aquifer

A cornerstone of the Citigen modernization is the installation of a 4 MW heat pump system that taps into a hidden urban resource: the London Aquifer, see figure 17. By utilizing three boreholes drilled 200 meters below the surface, the system draws natural warmth from the ground, which remains at a stable average of 14°C. This geothermal energy is then "upgraded" by the heat pumps to provide space heating and hot water.

Beyond geothermal extraction, the system is designed to be highly circular. It actively recycles waste heat from local power and chill generation—energy that would otherwise be wasted and vented into the atmosphere. This dual-source approach provides enough heating capacity to meet the demand of approximately 2,300 homes or businesses while simultaneously adding 2.8 MW of new cooling capacity for the surrounding business district.

1.5.2.2 Flexibility and Grid Balancing

One of the most advanced technical features of the Citigen project is its focus on operational flexibility. The energy center houses a massive 320,000-liter thermal storage tank. This "thermal battery" serves several critical functions:

Peak Shaving: By storing hot water during periods of low demand, the system can meet high-demand peaks without overstretching the heat generation plants.

Grid Integration: The storage capacity allows Citigen to act as a balancing tool for the wider electrical grid. When there is an excess of renewable energy available on the national grid (e.g., on very windy or sunny days), the project can use that surplus electricity to run its heat pumps and store the resulting heat for later use.

This synergy between the thermal and electrical grids transforms the district heating network from a passive utility into an active participant in the broader energy transition, maximizing the use of renewable resources while ensuring reliability for the City of London.

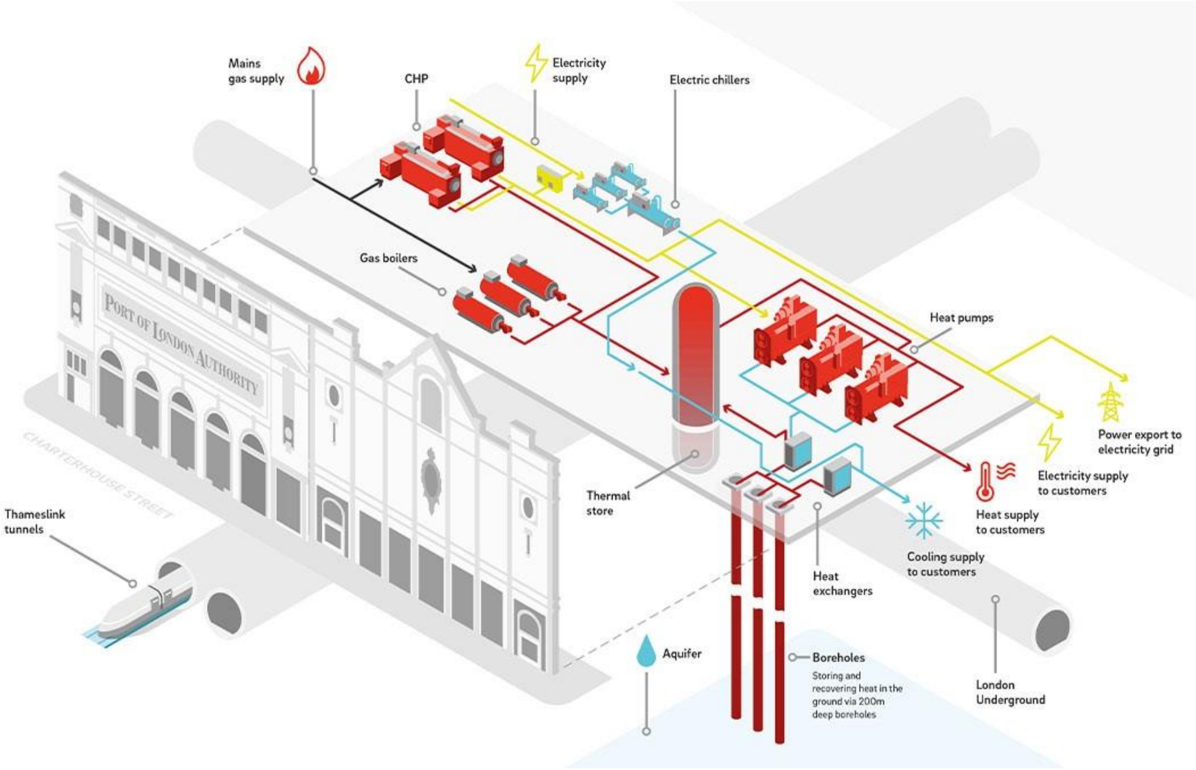


Figure 17. Functions implemented in Citigen [12]

1.5.3 Somers Town Decentralised Energy Network, London [13]

The Somers Town Decentralised Energy Network provides a strategic blueprint for how local authorities can manage the uncertainties of refurbishment through incremental implementation. This network provides heat and hot water to five housing estates, a new community centre, and the Edith Neville School, while simultaneously providing electricity to the Francis Crick Institute via a private wire.

1.5.3.1 A Phased, Data-Driven Approach

Recognizing the challenge of limited historical operational data, the Council opted for a phased solution to ensure system efficiency. By connecting the first estates before finalized plant sizing, engineers could study real-world demand patterns and performance. This allowed for the selection of a Combined Heat and Power (CHP) engine size that was accurately matched to the network's actual needs, rather than relying on theoretical estimates.

First Phase: This initial stage involved the installation of the core district heating network connecting four housing estates. A key innovation during this phase was the retrofit energy centre, which was creatively integrated into the basement of an under-used car park from the 1960s, demonstrating the potential for repurposing existing urban voids.

Second Phase: Following the analysis of operational data from Phase 1, the second phase saw the installation of the optimized CHP engine and thermal stores. This phase also expanded the network's reach to include an additional housing block, the community centre, and the school.

1.5.3.2 Lessons from London’s Downtown Refurbishments

The Somers Town project, alongside Bunhill and Citigen, highlights several vital takeaways for urban district heating development:

- Creative Infrastructure Reuse: Whether utilizing London Underground ventilation shafts (Bunhill), deep aquifers (Citigen), or under-used basement car parks (Somers Town), refurbishment thrives on the clever adaptation of existing urban features.
- Risk Mitigation Through Phasing: Especially in residential areas with unpredictable legacy systems, a phased rollout allows for data-driven optimization that prevents over-sizing and inefficient operation.
- Cross-Sector Integration: Linking residential heat demand with the electricity needs of large institutional partners like the Francis Crick Institute creates a more robust economic and technical ecosystem.

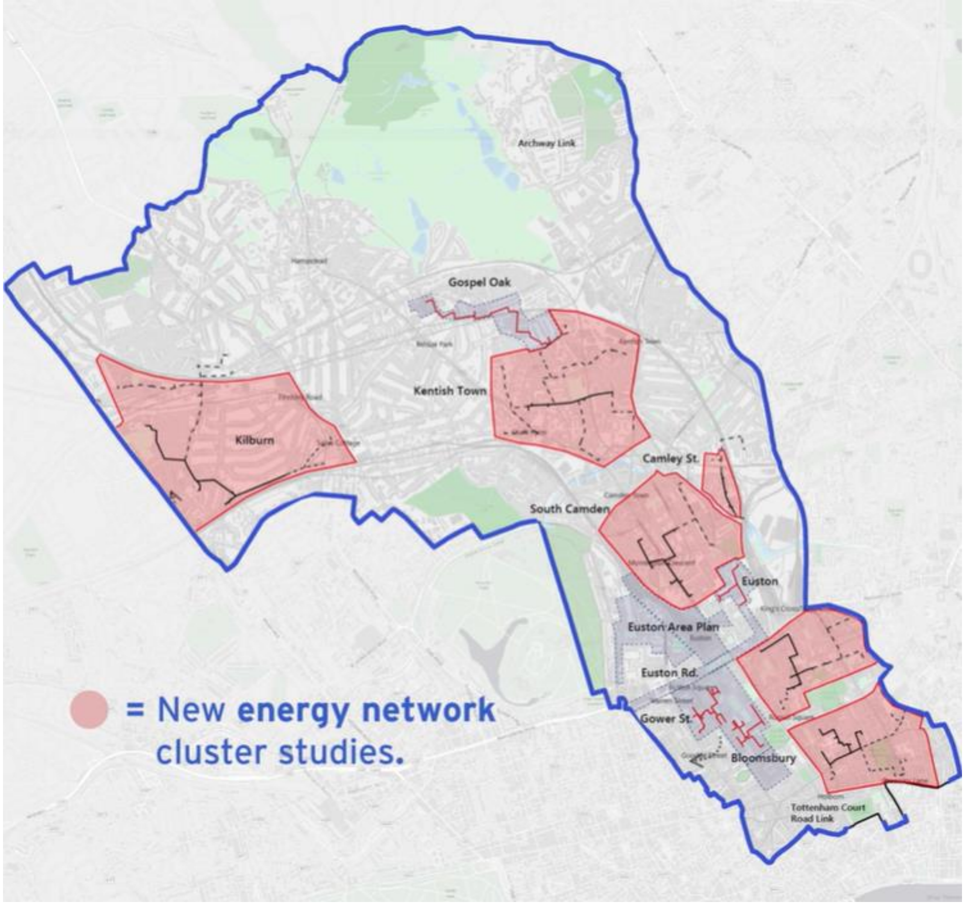


Figure 18. Somers Town Decentralised Energy Network [13]

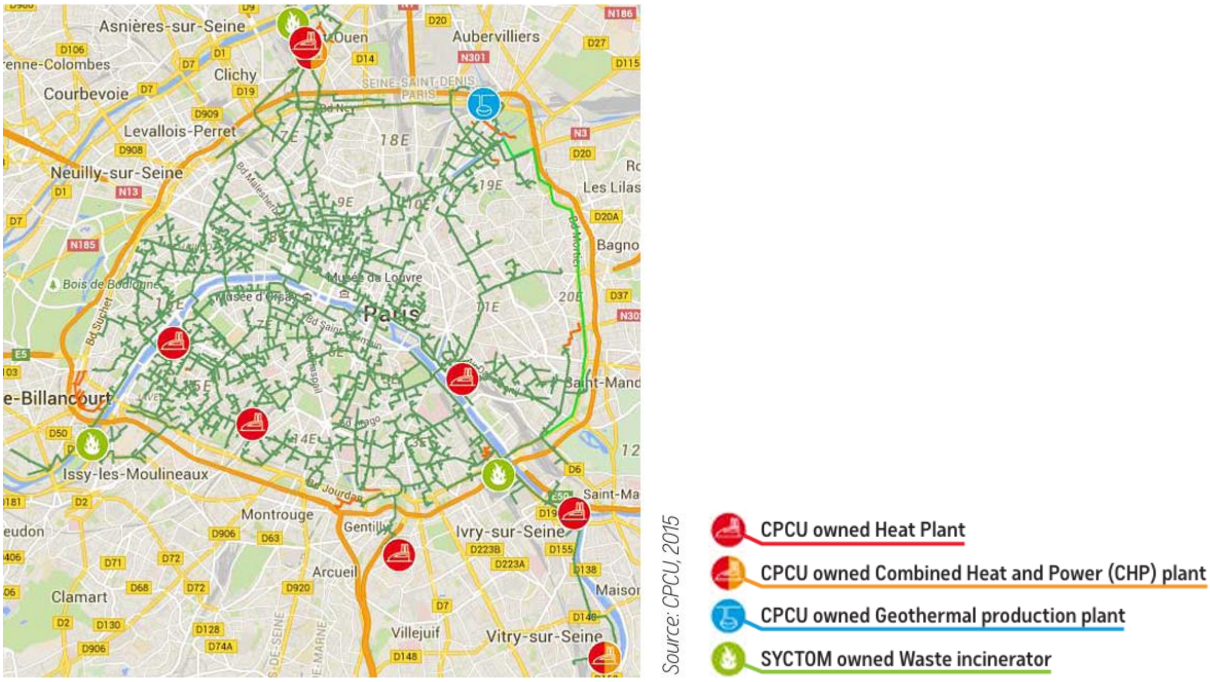
1.5.4 Paris District Heating and Cooling Development [14]

The energy landscape of Paris (seen in figure 19) is defined by two major interconnected networks: the CPCU (Compagnie Parisienne de Chauffage Urbain) for heating and Fraicheur de Paris for cooling. These networks demonstrate how high-density metropolitan areas can achieve massive economies of scale while diversifying their energy portfolio to include renewable and recovered sources.

1.5.4.1 The CPCU Heating Network

The CPCU network is a massive infrastructure project spanning approximately 475 km and producing roughly 5,500 GWh/year of heat. Its social and institutional impact is profound, as it serves the equivalent of 500,000 households, including: 100% of the city's hospitals, ensuring critical healthcare infrastructure has a reliable and efficient heat supply. Approximately 50% of social housing units. Approximately 50% of publicly-owned buildings.

The network relies on a diverse mix of energy production facilities distributed across the metropolitan area. This includes waste incinerators owned by SYCTOM, as well as geothermal production plants, a biomass plant, Combined Heat and Power (CHP) plants, and dedicated heat plants owned by CPCU. This diversification allows the city to shift its base load toward greener sources like waste-to-energy and geothermal as it modernizes. However, the network faces new challenges since it is old and steam-powered, distribution needs also to be refurbished.



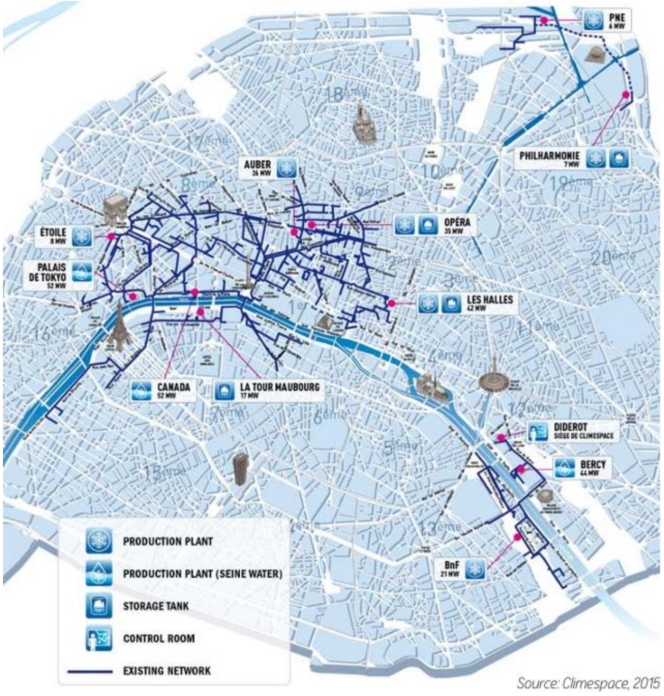
Source: CPCU, 2015

Figure 19. Map of district heating in Paris [14]

1.5.4.2 Fraicheur de Paris District Cooling

Complementing the heating grid is Fraicheur de Paris, one of the largest district cooling networks in the world, see figure 20. With a cooling capacity of 330 MW and an annual output of approximately 412 GWh/year, this 71 km network provides an essential service to the city’s commercial and cultural centers.

A key technical innovation in the Paris cooling system is the use of Seine River water for "free cooling" at specific production plants. By utilizing the natural thermal capacity of the river, the system significantly reduces the electricity required for chillers during cooler months. The network also utilizes large thermal storage tanks to manage peak demand, similar to the strategies seen in the London Citigen project, ensuring the grid remains balanced and efficient during heatwaves.



Source: Climespace, 2015

Figure 20. Map of district cooling in Paris [14]

1.5.5 Drinking Water Network as Heat Source, Copenhagen [15]

In the search for sustainable, low-exergy heat sources, the city of Copenhagen has investigated a novel concept: using the drinking water distribution network (DWDN) as a thermal reservoir for district heating. This approach treats the city's water supply pipes as a low-temperature heat source, where thermal energy is extracted via large-scale heat pumps to support the heating grid, as seen in figure 21.

1.5.5.1 Technical Performance and System Coupling

The potential for heat extraction from Copenhagen's drinking water infrastructure is estimated at approximately 21 MW. By integrating heat pumps into the water supply line, the system can harvest ambient thermal energy stored in the water, see figure 22. However, the project highlights the critical distinction between component efficiency and overall system efficiency:

Heat Pump COP: The individual heat pumps achieve a respectable Coefficient of Performance (COP) between 2.8 and 3.2.

System COP: When accounting for distribution losses, network pressures, and the potential need for reheating, the system-wide COP drops to approximately 1.7.

This disparity suggests that while the technology is viable, utilizing a drinking water network as a primary heat source is not always thermodynamically advantageous compared to other waste heat sources. The high energy cost of maintaining the thermal balance of the potable water often outweighs the gains of the extracted heat.

1.5.5.2 Seasonal Advantages and Thermal Management

Despite the efficiency challenges, the system offers unique secondary benefits for municipal management. During the summer months, extracting heat from the drinking water network serves a dual purpose. By pulling energy out of the water to provide domestic hot water through the district heating grid, the temperature of the drinking water supply is lowered. This helps maintain the quality and freshness of the potable water in the pipes, reducing the risk of microbial growth that can occur when underground pipes are warmed by the surrounding urban soil.

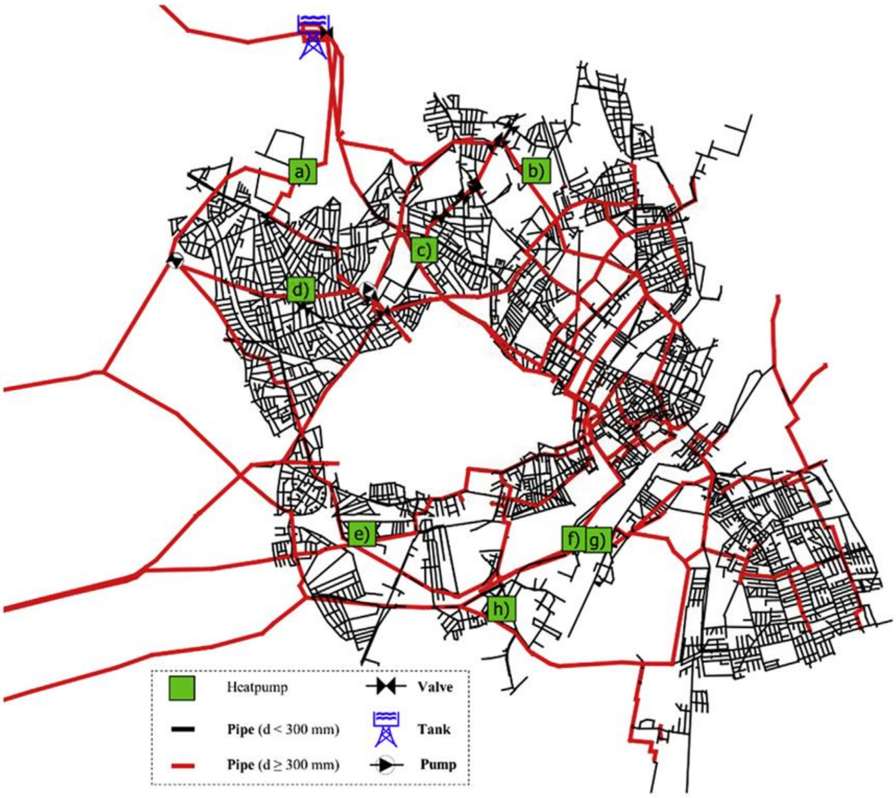


Figure 21. Map of heat pumps installed in the Copenhagen district heating system [15]

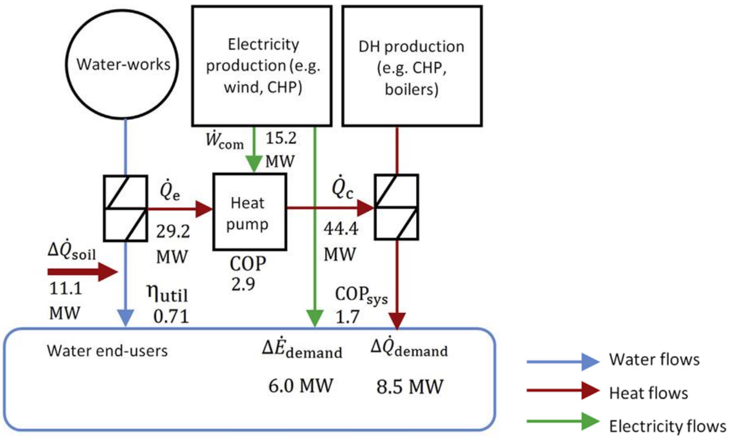


Figure 22. Energy system model with drinking water heat pumps [15]

1.5.6 Dynamically Distributed District Heating, Helsinki [16]

Helsinki is pioneering a hybrid strategy to gradually transition its extensive 3rd generation district heating (DH) system toward 4th generation, low-temperature operations. Rather than attempting a massive, high-risk conversion of the entire network at once, the city utilizes a dynamically distributed approach. This method focuses on "islanding" specific sub-areas, allowing them to operate independently while still maintaining a strategic connection to the central grid.

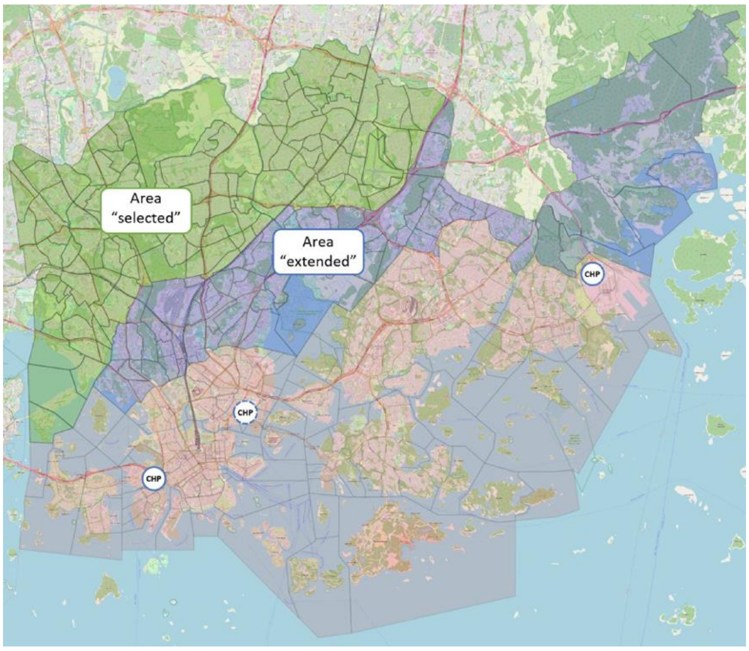


Figure 23. Areas included in the assessment of dynamically distributed district heating concept ("selected" and "extended") with major DH supply sites marked as small circles [16]

1.5.6.1 The Strategy of Modular "Islanding"

The core enablers of this transition are storage and islanding, which provide the flexibility and resilience needed in a complex urban setting. Under this model, sub-areas can be disconnected from the main network during the peak heating season to operate as localized "islands." These islands rely on their own distributed heat supply and local storage, though they can still draw from the central network if local demand exceeds capacity.

Key technical components of this strategy include:

- Large Seasonal Heat Storage: These systems are integral to the viability of islanded sub-areas. They are charged during the summer months when heat is abundant and cheap, then discharged to supply heat during the colder winter months.
- Reduced Central Stress: Because islanded areas can operate independently, they significantly relieve stress on the central network during high-load situations, enhancing the overall stability of the city's energy infrastructure.
- Context-Sensitive Performance: The success of this approach is highly dependent on local conditions, such as the availability of excess summer heat and the cost-efficiency of the specific storage and distributed generation technologies used in that area.

1.5.6.2 Future Heat Supply: Small Modular Reactors (SMRs)

As part of its long-term decarbonization plan, Helsinki is exploring the integration of Small Modular Reactors (SMRs) into its heat supply mix. As shown in the projected supply graph below, SMRs could eventually provide a stable, carbon-free base load for the city's district heating system.

This future vision combines the high-density energy production of SMRs with the flexibility of heat pumps (HPs), biomass boilers, and existing thermal storage to ensure a reliable and sustainable year-round heat supply.

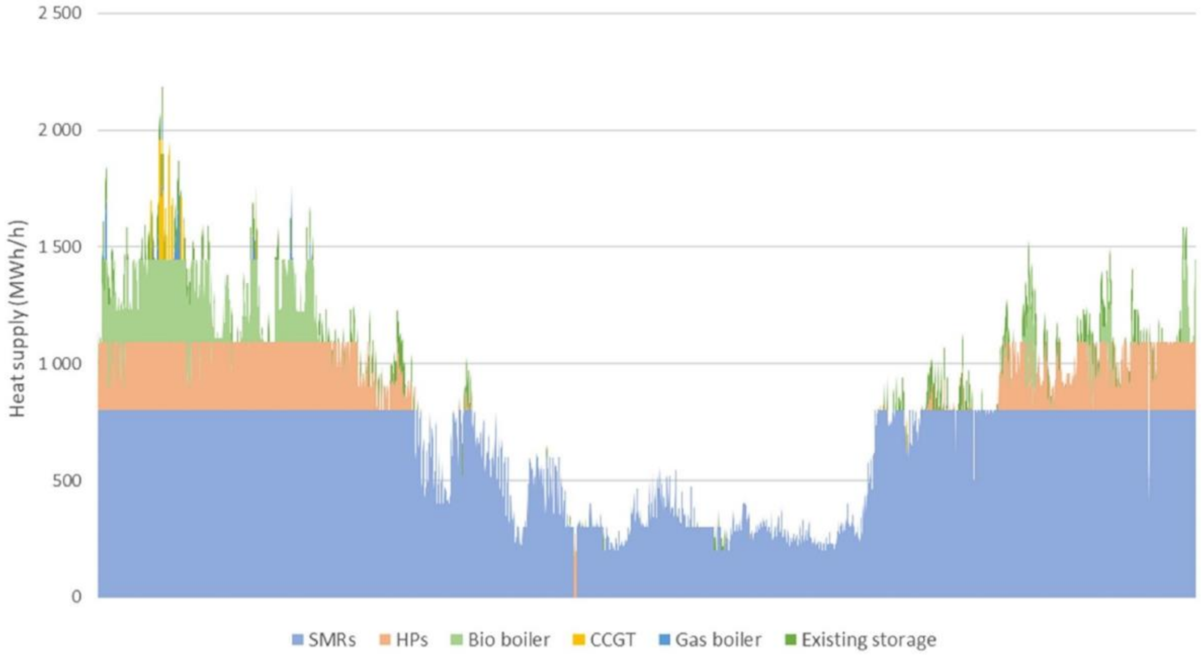


Figure 24. Heat supply of the existing system with three SMR units as baseload corresponding to a reference scenario with no area specific heat storages included [16]

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