Professional Intensive Course
District Heating and Cooling Systems

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

Course Reader

Six-hour professional training resource

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Project

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Authors and contributors

The Course Reader is compiled from the six approved SHaKE module guidebooks. Authors and contributing institutions are listed at the beginning of each module.

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Guide to using the SHaKE Professional Intensive Course

The SHaKE Professional Intensive Course is a six-hour training package developed for professionals who need a focused overview of current district heating and cooling (DHC) technologies, operation and refurbishment. It forms part of the SHaKE educational package and builds directly on the six English-language O1 modules.

The professional course does not reproduce or summarise every topic of the full O1 curriculum. For each module, the developing partner selected the presentation slides considered most relevant to professional practice. The theoretical sections in this Course Reader have been aligned to those selected slides. Wherever possible, the wording of the approved O1 guidebooks has been retained, so that the professional course remains consistent with the reviewed SHaKE learning materials.

The six condensed presentations are the core teaching materials for delivery of the course. This Course Reader provides the accompanying theoretical background and self-check questions. Participants who require more detailed explanations, additional topics, exercises or case studies can continue with the complete O1 materials available through the SHaKE project website.

Target groups

The course is primarily intended for professionals and continuing professional development participants working with district energy and related fields, including:

- district heating and cooling operators, engineers and technical staff;
- building services and energy engineers;
- energy consultants and designers;
- municipal and local energy planners;
- professionals involved in energy efficiency, decarbonisation and building or network refurbishment;
- trainers and educators delivering short professional courses on district energy systems.

Basic prior knowledge of energy systems, building services or district heating and cooling is recommended. The course is designed as a professional overview rather than an introductory engineering programme.

Learning outcomes

After completing the intensive course, participants should be able to:

- explain the role of modern district heating and cooling systems in the energy transition and in energy communities;
- interpret key demand-side, substation and primary-network concepts relevant to professional DHC practice;
- compare major heat-production options and explain the role of waste heat, heat pumps and renewable heat integration;
- describe the main district cooling technologies and the role of combined heat and cold production and thermal energy storage;
- recognise common operational malfunctions and distinguish between anomaly-detection and fault-detection approaches;
- identify key technical priorities when refurbishing legacy district heating systems and transitioning toward lower-temperature operation;
- relate the technical concepts presented in the course to practical DHC planning, operation and refurbishment decisions.

Suggested six-hour training schedule

The course can be delivered as a continuous six-hour programme using the following recommended sequence. Trainers may adapt the emphasis and timing to the professional background of the participants while keeping the six modules as the common content framework.

Time	Topic	Link to SHaKE module	Professional focus
0:00–0:45	Introduction to modern DHC and energy communities	Module 1	Why DHC matters for the energy transition
0:45–1:30	Heat and cold demand, substations and control	Module 2	Demand-side understanding for professionals
1:30–2:30	Heat production, waste heat, heat pumps, renewables	Module 3	Technology options and integration
2:30–3:15	District cooling and combined heat/cold systems	Module 4	Cooling technologies and sector coupling
3:15–4:15	Advanced systems, optimisation, digital tools	Module 5	Operation, control, digitalisation, fault diagnosis
4:15–5:15	Refurbishment of existing DH systems	Module 6	Legacy systems, demand-side management
5:15–6:00	Discussion, case examples, self-check	All modules	Application to professional practice

Recommended use by trainers

The presentations and Course Reader are designed to be used together. A practical delivery sequence is:

Introduce the module with the condensed presentation. Use the slides as the main visual structure and focus on the professional topics selected by the developing partner.

Use the Course Reader as supporting theory. The reader can be provided as pre-reading, a participant handout or a reference during the session. It follows the content of the condensed slides rather than the complete O1 module.

Connect the content to professional practice. Use the examples, operational implications and case-study elements included in the selected materials to invite participants to compare the content with their own systems and experience.

Check understanding. The self-check questions at the end of each module can be used immediately after the module, as a short formative check, or together during the final discussion block.

Close with cross-module discussion. The final 45 minutes are reserved for discussion, selected case examples, self-check and application of the course concepts to professional practice.

Recommended pathway for participants

- Review the condensed presentation for each module and use the corresponding Course Reader section to reinforce the technical background.
- Complete the module self-check questions to identify concepts that may require further review.
- Use the final discussion to connect the six module themes and consider how the technologies and approaches apply to the participant’s own professional context.

- Consult the complete SHaKE modules for higher education (https://www.shakeproject-dhc.eu/learning-materials/) for further detail, additional teaching materials, exercises, case studies and references.

Assessment and self-check

Each module ends with five short self-check questions and an answer key. They are intended primarily as formative checks of understanding rather than as a separate examination. Trainers may use them after each module or select questions from across the modules for the final 45-minute discussion and review block.

Where useful, the answer key can be followed by a short discussion of why the correct option is appropriate and how the issue appears in real DHC systems. This keeps the assessment closely connected to professional judgement and application.

Adapting the course

The suggested agenda provides a common six-hour structure, but trainers may adjust examples, discussion time and the emphasis placed on individual topics to suit the participants. The condensed professional presentations define the core O2 scope. Additional material from the full O1 modules may be used as optional extension material when more time is available.

Available course materials

The O2 Professional Intensive Course package consists of:

- this integrated Course Reader, including the professional theoretical extracts and module-level self-check questions with answer keys;
- six condensed professional presentation decks, one for each SHaKE module;
- the full O1 SHaKE educational package, available online for further study and reference.

The professional presentations and the corresponding reader sections should be treated as paired materials: the presentations define the scope of the intensive course, while the reader provides the approved theoretical background needed to support them.

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Module 1: Introduction to District Heating Systems

Professional focus: Why DHC matters for the energy transition

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1.1 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.

1.2 Advantages of District Heating and Heat Supply Options

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.

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.

1.4 Historical Development: Generations of District Heating

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.

1.4.1 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.

1.4.2 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.

1.4.3 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.

1.4.4 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.

1.5 Renewable Energy in District Heating

1.5.1 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.

1.5.2 Waste-to-Energy in District Heating: Vienna Spittelau

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.

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.
- 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.

1.6 Waste Heat Utilization and Fifth-Generation Energy Communities

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.

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.

1.7 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.

1.8 Self-check Questions

Select the best answer. The answer key is provided below.

1. What was a primary reason for the development of first-generation steam district heating systems?

- A. To support individual electric boilers in each building
- B. To reduce boiler accidents in residential buildings
- C. To eliminate the need for distribution pipelines
- D. To operate networks at ambient temperature

2. Which characteristic is associated with third-generation district heating?

- A. Steam distribution at very high pressure

- B. Hot water above 120 °C in concrete ducts
- C. Supply temperatures below 100 °C, pre-insulated pipes and modular substations
- D. Ambient-temperature bidirectional networks only

3. What supply temperature range is typical of fourth-generation district heating?

- A. 10–25 °C
- B. 50–70 °C
- C. 120–200 °C
- D. Above 200 °C

4. Which statement best describes geothermal energy in district heating?

- A. It is independent of local geological conditions
- B. It always requires combustion at the heat source
- C. It can provide low-operating-cost, low-CO_2 heat, but feasibility depends on geological conditions
- D. It can only be used for electricity generation

5. What is a defining feature of fifth-generation district heating energy communities?

- A. One-way heat delivery from a single high-temperature plant
- B. Bidirectional heat flows with buildings acting as consumers and producers
- C. Exclusive use of steam as the heat-transfer medium
- D. Elimination of heat pumps from connected buildings

Answer key

1	2	3	4	5
B	C	B	C	B

Source note: The theoretical text is selected from the approved SHaKE Module 1 Guidebook and follows the topics included in the selected O2 presentation. Full references are provided in the original guidebook.

Module 2: Heat and Cold Energy Demands of Buildings

Professional focus: Demand-side understanding for professionals

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2.1 Substations and the Importance of Low Return Temperature

In a substation, heat exchangers are the key elements. Indeed, they allow to separate hydraulically the primary and secondary networks and to exchange to required power. One or several heat exchangers can be used in a single substation to supply space heating, domestic hot water or to improve the performance of all systems. Indeed, the efficiency of the heat exchangers is the principal parameter to take into consideration to reduce the primary return temperature and so to improve the district heating network performances. Usually, plate heat exchangers are used in counterflow configuration because they are more compact and more efficient than other types of heat exchangers.

During operation, the power and the secondary supply temperature required are not constant. Indeed, it evolves generally according to the outdoor temperature. Hence, a constant mass flow rate at the primary side will imply an augmentation of the primary supply temperature as the required power declines (for the same primary supply temperature). This effect is to be avoided to not degrade the overall performance of the DH network. Consequently, the primary mass flow rate must be monitored according to the secondary side's needs. This is made possible by driving a control valve located on the heat exchanger primary side through a controller, supply temperature setpoint curve and a sensor measuring the secondary supply temperature.

According to the difference between the measured and the setpoint secondary supply temperature, the controller orders the closing or the opening of the control valve.

2.2 Substation Architectures

Once all the components are designed, the global substation architecture must be set. As a substation commonly supply space heating and domestic hot water at least two heat exchangers are used in a single substation. Hence different substation hydronic architectures are widely used.

2.2.1 One Heat Exchanger Configuration

The one heat exchanger used two heat exchangers but only one in the interface between the primary side and the secondary side.

This configuration is not widely used and is less efficient than the other configurations presented below. Indeed, despite its simplicity this configuration is supplied with a temperature always equal or superior to 60°C to supply DHW. That's led to higher primary return temperatures

2.2.2 Parallel Configuration

A substation in parallel configuration is the most widely used architecture. Two heat exchangers operate respectively for space heating and DHW, they share the same supply line at the same temperature.

Each heat exchanger is coupled with its own control system operating with different supply setpoint secondary temperatures

This configuration is simple to control, to install and is not expensive.

2.2.3 Series Configuration

A substation in series configuration is composed of two heat exchangers respectively for space heating and DHW. This configuration enables to use the primary return temperature of one heat exchanger to supply completely or partially the needs of the other heat exchanger.

Depending on the temperature needed for space heating, the DHW heat exchanger supplies or is supplied by the space heating heat exchanger. Indeed, the DHW supply temperature is around 60-55°C. So, if the required temperature of the space heating emitters is inferior to the DHW supply temperature, the primary return temperature of the DHW heat exchanger is able to supply the space heating one. On the contrary, if the required temperature of the space heating emitters is higher than the DHW one, the space heating heat exchanger return temperature can supply the DHW one.

The series configuration is more complex to install because of the complexity of the control system.

2.2.4 Two-Stage Configuration

A substation in two-stage configuration is composed of three heat exchangers, two in parallel respectively for space heating and DHW and a third one connected to the return line of the two other heat exchangers used to preheat the DHW. This configuration enables to lower the overall primary return temperature and so to improve the efficiency of the DH network.

The two-stage configuration benefits the advantages of the parallel configuration and the series configuration. Indeed, this configuration is easy to install and control and reduces the primary return temperature. However, the parallel configuration is generally preferred, as the efficiency gain does not justify the additional cost associated with using a third heat exchanger.

2.2.5 Comparison of Substation Configurations

Configuration	Performance	Price	Complexity
1 HEX	--	+	0
Parallel	+	+	+
Series	-	-	--
Cascading / 2-stage	++	--	-

2.3 Primary Network Architectures

Once the secondary network and the substation are designed, the primary network must be sized. This section aims to give information about the different possibilities to build the primary network and how to design the pipes.

The basic function of primary pipes carries the hot water from the heat production plant to the substations and carries cold water in the other way. Nevertheless, according to the strategies the conception of the primary network can be more complicated by using several pipes with different temperature levels.

2.3.1 Two-Pipe Network

Usually, the basic strategy with only two pipes is used to provide DHW and space heating. These pipes are set in parallel, one for the hot supply and one for the warm return. This is the cheapest and simplest structure. The supply temperature is set to reach the highest temperature needed in a substation. If the DHC networks are also connected to substations with a need of a lower temperature, the substation will always be correctly provided but the performance of the network will not take profit of low return temperatures.

2.3.2 Three-Pipe Network

To improve the DHC network performance, a third pipe set in parallel can be added to the previous scheme to supply heat at a different temperatures. For example, one pipe to supply space heating or DHW and another separate pipe to supply substation only connected to building with low temperature emitters. This configuration is most expensive in terms of installation but allows the heat losses through the pipes to be reduced.

2.3.3 Three-Pipe Cascading Network

The return pipe from a high-temperature substation is used to supply a substation with lower temperature needs. This arrangement reduces heat losses and reduces the return temperature.

2.3.4 Four-Pipe Network

For DHC networks capable of supplying space heating, DHW and space cooling a configuration with four pipes in parallel is used. Here, two pipes are used for heating demand (one pipe for hot supply and one for the warm return) and the two other pipes are used to supply cooling demand, one pipe for cold supply and one for warm return). All the demand can be reached simultaneously.

2.4 Self-check Questions

Select the best answer. The answer key is provided below.

1. Why is a low primary return temperature desirable in a district heating network?

- A. It allows the network to operate only with steam
- B. It helps improve overall district heating network performance
- C. It eliminates the need for heat exchangers
- D. It requires higher secondary supply temperatures

2. Which substation architecture is described in the guidebook as the most widely used?

- A. One heat exchanger configuration
- B. Parallel configuration
- C. Series configuration
- D. Two-stage configuration

3. What is a principal advantage of the two-stage substation configuration?

- A. It eliminates DHW production
- B. It raises the overall primary return temperature
- C. It lowers the overall primary return temperature by preheating DHW
- D. It uses only one heat exchanger

4. What is the main characteristic of the basic two-pipe primary network?

- A. One hot supply pipe and one warm return pipe
- B. Two hot supply pipes at different temperatures
- C. Two pipes for heating and two pipes for cooling
- D. The return pipe is always used as a second supply pipe

5. Which primary network configuration can supply heating and cooling simultaneously?

- A. Two-pipe network
- B. Three-pipe network

- C. Four-pipe network
- D. One-pipe network

Answer key

1	2	3	4	5
B	B	C	A	C

Source note: The theoretical text is selected from the approved SHaKE Module 2 Guidebook and follows the topics included in the selected O2 presentation. Full references are provided in the original guidebook.

Module 3: Heat Production

Professional focus: Technology options and integration

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3.1 Waste Heat Recovery and Classification

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

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

Industrial Waste Heat:

- a) Steel, cement, and glass manufacturing.
- b) Chemical and petroleum refining.
- c) Food processing and paper production.

Power Generation Waste Heat:

- a) Thermal power plants (coal, natural gas, biomass).
- b)Internal combustion engines and gas turbines.

Commercial and Residential waste heat:

- HVAC systems, refrigeration, and water heating.

Transportation Waste Heat:

- Engine exhaust gases and friction losses in vehicles.

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

Temperature level	Examples
Low-Temperature Waste Heat (<100°C)	Examples: Exhaust from cooling towers and HVAC systems; Waste heat from industrial wastewater; Heat from refrigeration and air conditioning systems; Low-temperature flue gases (e.g., food processing, breweries).
Medium-Temperature Waste Heat (100°C – 300/400°C)	Examples: Exhaust gases from internal combustion engines and turbines; Waste heat from boilers, kilns, and drying processes; Chemical processing and refining operations; Steel and metal casting processes.
High-Temperature Waste Heat (>300/400°C)	Examples: Exhaust gases from steel, cement, and glass industries; Heat from metal smelting and refining; Flue gases from power plants and incinerators; High-temperature furnaces and reactors.

3.2 Waste Heat Revalorization

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

3.2.1 Reuse

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

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

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

Examples of reusing waste heat are:

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

3.2.2 Active Technologies

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

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

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

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

3.3 Vapor Compression Heat Pumps

Vapor Compression Heat Pumps (VCHPs) recover and upgrade low-grade waste heat to high temperatures. They are key for decarbonization through heat electrification and are widely applicable, including in district heating. COP = condenser load / compressor power (typically 2–6). Using waste heat boosts COP by reducing temperature lift.

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

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

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

Qin + W = Qout

Qin = Heat absorbed from the low-temperature source (evaporator)

W = Work input (compressor energy)

Qout = Heat released at the high-temperature sink (condenser)

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

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

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

3.3.1 Main Components

1. Evaporator

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

2. Compressor

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

3. Condenser

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

4. Expander

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

3.4 Configurations and Connections for Waste Heat Sources

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

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

- Distilleries
- Industrial laundries
- Waste heat district heating
- Supermarkets
- Data centres

3.4.1 Direct Connection to a Primary Circuit

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

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

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

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

3.4.2 Intermediate Heat Exchanger (Indirect System)

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

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

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

Disadvantages: It introduces thermal resistance and necessitates extra maintenance.

3.4.3 Closed-Loop System with Secondary Heat Fluids

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

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

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

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

3.4.4 Storage Systems (Thermal Storage Tanks)

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

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

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

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

3.4.5 Integration with Air or Gas Flows

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

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

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

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

3.5 Self-check Questions

Select the best answer. The answer key is provided below.

1. Which statement best describes waste heat recovery?

- A. It is the deliberate release of unused heat to the environment.
- B. It captures waste heat so that it can be reused or transformed into useful heat, mechanical energy or electricity.
- C. It is limited to high-temperature industrial waste heat.

- D. It requires a heat pump in every application.

2. Which technology is listed as an example of passive waste heat reuse?

- A. Thermoelectric generator
- B. Organic Rankine cycle
- C. Heat recovery steam generator (HRSG)
- D. Vapor compression heat pump

3. What is the main function of a vapor compression heat pump in waste heat recovery?

- A. To lower useful heat to ambient temperature
- B. To upgrade low-grade waste heat to a higher useful temperature level
- C. To convert all waste heat directly into electricity
- D. To eliminate the need for heat exchangers

4. Which main components form a vapor compression heat pump cycle?

- A. Evaporator, compressor, condenser and expansion device
- B. Boiler, turbine, generator and cooling tower
- C. Pump, storage tank, radiator and fan
- D. Economizer, HRSG, absorber and turbine

5. When is an intermediate heat exchanger configuration particularly useful?

- A. When the waste heat fluid is corrosive, contaminated or outside the heat pump equipment limits
- B. When no temperature difference exists
- C. Only when the heat source is outdoor air
- D. Only when the waste heat source is perfectly compatible with the heat pump

Answer key

1	2	3	4	5
B	C	B	A	A

Source note: The theoretical text is selected from the approved SHaKE Module 3 Guidebook. Full references are provided in the original guidebook.

Module 4: District Cooling

Professional focus: Cooling technologies and sector coupling

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4.1 Chillers

A chiller removes heat from a process, machinery, or building to maintain a controlled temperature. This is done by circulating a cooled fluid (often water or a water-glycol mixture) that absorbs heat from the target area and transfers it to the environment.

They are commonly used in industrial, commercial, and HVAC (heating, ventilation, and air conditioning) systems to cool equipment, processes, or buildings. Therefore, from hundreds to thousands of kW of cooling. Chillers are widely used in industries such as manufacturing, medical facilities, data centres, and food processing to maintain optimal temperatures.

4.1.1 Operation and Types of Chillers

As observed in the guidebook, the role of the evaporator is to produce chilled water. The device releases the water at about 6°C and pushes it throughout the facility with the help of a pump. The water returns to the evaporator where the refrigerant at about 12°C absorbs the unwanted heat.

There is another loop connected to the condenser, which is between the cooling tower and the condenser. After entering the condenser at about 27°C or ambient temperature, the water leaves at approximately 5 degrees higher. Alternatively, the refrigerant can dissipate heat directly through an outdoor fan-coil.

Chillers are classified based on how they dissipate heat:

- Air-Cooled Chillers: Use fans to blow air over a condenser coil to release heat. Ideal for small to medium-sized systems or where water access is limited. Common in commercial HVAC systems.
- Water-Cooled Chillers (Centrifugal): Use water and cooling towers to dissipate heat more efficiently. Suitable for large-scale industrial applications where greater efficiency is required.

Water-cooled chillers have a cooling tower, so the efficiency is higher than air-cooled chillers because they condense depending on the ambient wet bulb temperature, which is lower than the ambient dry bulb temperature. The lower a chiller condenses, the more efficient it is.

The selected professional presentation indicates typical capacity ranges of approximately 15–1,500 kW for air-cooled chillers and 50–10,000 kW for water-cooled chillers.

4.1.2 Key Metrics and Efficiency

- Cooling Capacity (Qo): Measured in tons of refrigeration or kilowatts (kW), indicating the amount of heat removed.
- Power Consumption (Wc): Compressors consume (kW) the most electricity in the system, making their design critical for efficiency. Water pumps and fans must be considered as they can represent 10% of the consumption.
- Energy efficiency ratio (EER): A measure of efficiency calculated as the ratio of cooling provided to energy consumed (kW cooling / kW electricity).
- Seasonal energy efficiency ratio (SEER): Like the EER, but over an entire season, by calculating the cooling output divided by total electric energy input (kWh cooling / kWh electricity).

SEER uses a set indoor temperature, along with different outdoor temperatures and load capacities to simulate real life. The EN 14825 standard defines the test methodology. Energy efficiency class depends on SEER and type of equipment, between A+++ and G, with A+++ being the most efficient classification.

Source / capacity	100%	74%	47%	21%
Air source	35°C	30°C	25°C	20°C
Water source	30°C	26°C	22°C	18°C

System performance depends on good design and professional installation of the entire system; regular maintenance; the size of the building being conditioned and its energy efficiency; the size of the system and its air handling capacity; the amount of time the system is used daily; the indoor temperature; and the outdoor air temperature.

In district cooling networks, high-capacity water-cooled chillers are commonly selected, and thermal energy storage can be used to match cooling production with district demand at different times.

4.2 Absorption Refrigeration Machines

Vapor absorption chillers have no compressor in the unit. Instead, they use a heat source, e.g., solar energy or waste heat, to drive the coolant through the system. No electricity is required for the main compression function. Moreover, they are more silent and resistant to leakages as no vibrant elements exist. The gases used are based on natural refrigerants only.

Absorption refrigeration systems use a heat source to drive the refrigeration cycle instead of mechanical energy like compressors. These systems typically use a refrigerant and an absorbent fluid.

4.2.1 Main Components

- Evaporator: Where the refrigerant absorbs heat and evaporates.
- Absorber: Where the refrigerant vapor is absorbed by the absorbent fluid.
- Generator: Where the refrigerant is separated from the absorbent using heat, regenerating the refrigerant.
- Condenser: Where the refrigerant releases heat and condenses back into a liquid.

4.2.2 Relevant Parameters

- Cooling Capacity (Qo): The amount of heat removed by the evaporator from the space or process being cooled, typically measured in kW.
- Heat Input (Qg): The heat required to drive the absorption cycle, typically provided by a heat source like natural gas, waste heat, or solar energy. It is often measured in kW.
- Coefficient of Performance (COP): The cooling capacity (Qo) ratio to the heat input (Qg).

COP is a key performance indicator of energy efficiency. A higher COP indicates a more efficient system. In absorption refrigeration, typical COP values range from 0.5 to 1.5, significantly lower compared to vapor compression systems.

4.2.3 Comparison with Vapor Compression Systems

Compression systems	Absorption systems
Work operated	Heat operated
High COP	Low COP (currently maximum ≈ 1.4)

Compression systems	Absorption systems
Performance (COP and capacity) very sensitive to evaporator temperatures	Performance not very sensitive to evaporator temperatures
System COP reduces considerably at part loads	COP does not reduce significantly with load
Liquid at the exit of evaporator may damage compressor	Presence of liquid at evaporator exit is not a serious problem
Performance is sensitive to evaporator superheat	Evaporator superheat is not very important
Many moving parts	Very few moving parts
Regular maintenance required	Very low maintenance required
Higher noise and vibration	Less noise and vibration
Small systems are compact and large systems are bulky	Small systems are bulky and large systems are compact
Economical when electricity is available	Economical where low-cost fuels or waste heat is available

4.3 Thermal Energy Storage (TES)

Thermal energy storage (TES) stores heat or cooling for later use, separating generation from consumption. The concept is similar to electrical batteries, but instead of storing electricity, heating or “cooling” is stored, increasing a fluid’s temperature, or using phase change (generally solid to liquid and vice versa). This means that heating or cooling can be generated when an extra surplus or renewable electricity, or waste heat, is available and then consumed when needed. This is especially interesting in DCNs, where central or waste cooling is independent of individual or industrial consumers.

4.3.1 Main Benefit of TES in District Cooling

In DCNs, TES typically involves storing cool energy in an insulated water tank. The tank is cooled or frozen during off-peak periods (nights or weekends) and melted or warmed during on-peak periods (weekdays).

This reduces the need for large chillers during peak demand by discharging TES to meet some or all of the load. Extra chiller capacity charges TES during off-peak times while meeting off-peak cooling loads. Lower-capacity chillers reduce investment and operational costs and reduce electrical stress from the grid.

4.3.2 Types of TES

Generally, TES technologies for cooling storage include latent heat storage systems, such as ice TES or phase change materials (PCM); sensible heat storage systems, based on chilled water and low-temperature fluids; and thermochemical heat storage systems, based on chemical reactions. Borehole thermal energy storage and aquifer thermal energy storage can be used for long-term storage.

	Ice storage tank	Chilled water storage tank	Low-temperature liquid storage tank
Type of storage	Latent heat	Sensible heat	Latent heat
Discharge temperature	1°C to 7°C	4°C to 6°C	-1°C to 2°C
Recharge temperature	-8°C to -2°C	4°C to 6°C	-1°C to 2°C
Recharge chiller plant and power	0.8 to 1.1 kW/ton (0.23 to 0.31)	0.6 to 0.7 kW/ton (0.23 to 0.31)	0.7 to 0.8 kW/ton (0.23 to 0.31)

General benefits of integrating TES into a district cooling network include reducing the installed refrigeration capacity, avoiding peak consumption during high electrical tariff periods, reducing CO_2 emissions through improved operating efficiency, and allowing a smaller refrigeration plant because part of the required cooling energy is already accumulated in the storage tank.

4.4 Self-check Questions

Select the best answer. The answer key is provided below.

1. Which chiller type uses water and cooling towers to dissipate heat more efficiently?

- A. Air-cooled chiller
- B. Water-cooled chiller
- C. Absorption chiller only
- D. Thermoelectric chiller

2. What does the Energy Efficiency Ratio (EER) express?

- A. Cooling provided divided by electrical energy consumed
- B. Heat input divided by cooling capacity
- C. Annual cooling demand divided by floor area
- D. Water flow divided by compressor power

3. What is the main driving input of an absorption refrigeration machine?

- A. Mechanical compressor work
- B. A heat source such as waste heat, solar energy or natural gas
- C. Only ambient air
- D. Only chilled water

4. What is the typical COP range stated for absorption refrigeration systems?

- A. 0.1–0.3
- B. 0.5–1.5
- C. 2–6
- D. 8–15

5. What is a principal benefit of TES in district cooling?

- A. It increases peak chiller capacity requirements
- B. It shifts cooling production to off-peak periods and reduces peak plant requirements
- C. It eliminates the need for chilled water
- D. It can only be used with air-cooled chillers

Answer key

1	2	3	4	5
B	A	B	B	B

Source note: The theoretical text is selected from the approved SHaKE Module 4 Guidebook; the capacity ranges and short DCN-integration note reflect the selected O2 presentation. Full references are available in the original materials.

Module 5: Advanced Systems in District Heating and Cooling

Professional focus: Operation, control, digitalisation and fault diagnosis

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5.1 Why Malfunction Detection Matters

In order to meet the European objective relative to the District Heating and Cooling (DHC) networks, the performance of existing networks must be improved. For heating networks, improving performance primarily means increasing the share of renewable energy in the energy mix. In practice, this generally involves lowering the overall return temperature of the network, which makes it possible to increase the use of low temperature renewable energy sources such as geothermal energy and waste heat while also reducing the heat losses in the pipes and energy consumption in primary pumps.

However, because heat supply in DHC networks relies on numerous control, mechanical, and hydraulic components, malfunctions may occur. Inappropriate or faulty equipment anywhere in the network can negatively impact the overall return temperature. So before considering control optimization, it is essential to ensure that the network is operating properly. However, according to [1], in a study carried out on 2 Swedish networks, only 26% of substations were operating correctly. The malfunctions in the substations do not necessarily disrupt the heat supply, but they can significantly affect the overall performance of the DHC network.

5.1.1 Overview of Faults in DHC Networks

Due to the complexity of the DHC network's operation, causes of malfunctions can be very diverse. The malfunctions are divided into 5 categories depending on the localization or the type of malfunction: leakage, faults in the secondary systems (customer installation), faults due to the substation control valve and actuator, faults in control systems and controllers and faults in the heat exchanger. It appears that the two main sources of malfunction are leaks and problems with customers' hydraulic systems.

Fault category	**Approx. share reported**
Leakage	41.54%
Secondary systems	31%
Control valve & actuator	22.09%
Control systems and controller	5%
Heat exchangers	0.37%

Problems identified by DHC network operators are a mix of malfunctions and unsuitable systems on the customers' hydronic systems. Practically all the malfunctions impact either the customer's thermal comfort and/or the primary return temperature. It is therefore essential to correct these issues.

5.1.2 Available Data and Malfunction Detection Challenges

Detecting the cause of malfunctions in a heating network is a major challenge for the operators and managers of these infrastructures. Heating networks, as complex and extensive thermal systems, are subject to numerous uncertainties linked to operating conditions, the variability of thermal loads, the condition of equipment and the interaction between substations and the main network. The scientific literature emphasizes that these systems are characterized by strong hydraulic and thermal coupling, which makes it difficult to analyze each component independently.

The observed disturbances, such as temperature drops, pressure losses or excessive energy consumption, can result from a multitude of causes - leaks, valve sticking, poor hydraulic balancing, faulty sensors or even control errors. However, these symptoms can be similar regardless of the actual cause, making precise identification of the source of the malfunction particularly complex. In addition, the absence or low resolution of real-time data in some older networks still limits automated diagnostic capabilities.

Indeed, only few data are legally mandatory and usually available at substation level:

- Primary supply and return temperatures
- Secondary supply temperature
- Exchanged power at the substation
- Primary flow rate

However, to better understand the substation behavior other data are highly needed such as the secondary return temperature and the secondary mass flow rate. In addition, the return temperature at each emitter could be very useful.

5.2 Anomaly Detection and Fault Detection

Whether it is the tools used by operators or the tools proposed in the literature, two major trends emerge: anomaly detection and fault detection. Anomaly detection aims to find patterns in data that do not conform to a previously defined notion of expected and "normal behavior". This kind of detection allows to find outliers and deviations in measured data and also atypical behavior and abnormal patterns. However, it is not possible to directly determine the origin of the anomaly and so to correct the system. Moreover, to perform the anomaly detection, a normal behavior must be defined which can be complex.

The second trend concerns effective fault detection which aims to identify the changes occurring in the system so that it can no longer operate properly. This kind of detection enables to find the malfunction cause and so to correct it. However, it is harder to perform.

The malfunction detection of either an anomaly or a fault is carried out through 5 methods [8]:

- Visualization & manual analysis
- Thresholds
- Regression
- Classification
- Clustering

Each method can be used separately or in combination.

5.2.1 Normal Behaviour and Anomaly Detection

Visualization and manual analysis are the simplest and oldest methods to detect anomaly. Manual analysis involves human experts reviewing substation measurements or derived indicators, often supported by visualization tools. This approach offers high flexibility due to expert judgment, but it is inherently subjective. In practice, manual analysis can be used to detect anomalies and faults, or to conduct a more in-depth investigation of issues that have already been identified by other methods.

For example, one method seeks to compare the behavior of a reference substation, considered to operate without major issue, to other ones. The hourly average heat load is supposed to be linear according to the outdoor temperature (thermo-sensibility of the space heating) and stay constant from the outdoor temperature as soon as the outdoor temperature is high enough that space heating is no longer required. The hourly average water flow is supposed to be stable and higher in cold seasons. In a faulty substation, the hourly average heat load is less linear as expected and the water flow is unstable, underlying a problem.

All these approaches therefore depend on a reference describing normal operation, a suitable detection threshold and sufficient data quality.

5.2.2 Classification and Machine-Learning-Based Fault Detection

Classification is a machine learning task that involves assigning an instance to one of several predefined categories. Although various techniques may serve this purpose, this category specifically refers to methods that use classification algorithms to directly identify whether a fault has occurred and, if so, which type. Unlike regression models that produce continuous numerical outputs, classifiers assign inputs to discrete classes, typically represented by integer labels. In contrast to clustering, which operates on unlabeled data, classification relies on labeled examples of known faults for training. Common classification algorithms include neural networks, decision trees, and support vector machines.

It is therefore becoming necessary to use hybrid approaches combining physical modelling, data analysis and machine learning techniques to improve the location and the understanding of anomalies. However, even these innovative approaches remain dependent on the quality of the data available and detailed knowledge of the network under study.

5.3 Fault Detection Example: Fouling of the Heat Exchanger

Fabre & al [4] proposed an indicator to detect fouled heat exchanger. To build an indicator of fouling, one assumes first that most of the HEX employed on DHN are plate heat exchangers in counter flow. The specific signature of the fouling is the increase of the HEX global thermal resistance.

According to the Dittus-Boetler correlation, the convective heat transfer coefficient can be expressed in function of the mass flow rate. Assuming the conductive resistance of the plates is negligible, the thermal resistance without fouling evolves linearly with the mass-flow-rate-related variable used by the indicator. However, when fouling appears the global thermal resistance is no longer linear.

Moreover, it is needed to identify a threshold to have a limit from which the impact of the fouling significantly degrades the substation performance. According to the study the return temperature drops over 5°C when the ratio between the thermal resistance with and without fouling is over 1.4. It is considered that a drop of 5°C is important enough to notably downgrade the performance.

The thermal resistance without fouling can be calculated through the measured data - the temperatures on both sides and the exchanged power - just after a complete cleaning of the HEX. Thanks to the same data, the thermal resistance during operation can also be calculated. Therefore, by measuring the temperatures and flow rates on both sides, the evolution of the thermal resistance can be plotted as well as the threshold not to be exceeded. When a thermal resistance data is over the threshold, the effect of fouling is important enough to require cleaning.

This indicator can detect a specific fault; it is easy to use and has been validated through in-situ data. However, it needs data from the secondary side.

5.3.1 Operational Perspective

In conclusion, improving DHC network performance first requires identifying the most suitable hydronic systems to use on the building side as well as accurately and rapidly detecting malfunctions.

Once the secondary side is using the right equipment, the next step is to focus on detecting malfunctions for a proper operation of the DHC.

The professional presentation summarises the operational sequence as: improve and fix the hydronic elements of the secondary side; improve and fix the hydronic elements of the primary side; and optimise DHC operation.

5.4 Self-check Questions

Select the best answer. The answer key is provided below.

1. In the Swedish study cited in the module, approximately what share of substations were operating correctly?

- A. 26%
- B. 50%
- C. 74%
- D. 90%

2. Which statement best describes anomaly detection?

- A. It always identifies the root cause of a fault
- B. It finds patterns that deviate from expected normal behavior
- C. It only detects water leakages
- D. It does not require reference data

3. Which data are highlighted as highly needed for better understanding substation behavior?

- A. Only outdoor temperature and electricity price
- B. Secondary return temperature and secondary mass flow rate
- C. Only primary supply temperature
- D. Building floor area and occupancy

4. Which of the following is NOT one of the five malfunction-detection methods listed in the module?

- A. Regression
- B. Classification
- C. Clustering
- D. Combustion analysis

5. What is the specific signature used in the presented heat-exchanger fouling indicator?

- A. A decrease in network pressure only
- B. An increase in the heat exchanger global thermal resistance
- C. Constant electricity consumption
- D. A decrease in outdoor temperature

Answer key

1	2	3	4	5
A	B	B	D	B

Source note: The theoretical text is selected from the approved SHaKE Module 5 Guidebook and follows the topics included in the selected O2 presentation on detection of malfunctions. The short operational summary at the end of Section 3 reflects the conclusion slide of the selected presentation. Full references are available in the Module 5 Guidebook and the accompanying presentation.

Module 6: Refurbishment of District Heating Systems

Professional focus: Legacy systems and demand-side management

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6.1 The Role of District Heating and the Need for Refurbishment

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.

6.1.1 Historical Context and 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.

6.2 Building-Side Refurbishment

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:

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.

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.

6.2.1 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

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.

6.2.2 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.

6.3 Transition to Low-Temperature District Heating

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.

6.3.1 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.

6.4 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).

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)

6.5 Urban District Heating Refurbishment: Selected Case Studies

6.5.1 Bunhill Heat and Power Network, London

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.

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.

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.

6.5.2 Citigen Project, London

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.

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.

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.

6.5.3 Paris District Heating and Cooling Development

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.

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.

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.

6.6 Self-check Questions

Select the best answer. The answer key is provided below.

1. Which characteristic is associated with many legacy high-temperature district heating systems described in the module?

- A. Supply temperatures typically around 100–130 °C
- B. Exclusive use of ambient loops
- C. Individual apartment heat pumps in every building
- D. No transmission heat losses

2. What is the main purpose of a bypass in a single-pipe heating system?

- A. To stop the whole heating string
- B. To allow a portion of the water to skip the radiator
- C. To increase the district heating supply temperature
- D. To replace the heat meter

3. Which component is listed as a typical element of a modern compact, modular substation?

- A. Flat-plate heat exchanger
- B. Coal bunker
- C. Steam turbine
- D. Open cooling tower

4. Why is domestic hot water preparation a technical challenge in low-temperature district heating?

- A. LTDH always uses steam
- B. Supply temperatures may fall below the level needed for direct Legionella control
- C. Heat meters cannot operate below 90 °C
- D. Low-temperature systems cannot use heat exchangers

5. Which case study uses waste heat from the London Underground ventilation system via a heat pump?

- A. Citigen
- B. Bunhill Heat and Power Network
- C. CPCU Paris
- D. Fraicheur de Paris

Answer key

1	2	3	4	5
A	B	A	B	B

Source note: The theoretical text is selected from the approved SHaKE Module 6 Guidebook and follows the topics included in the selected O2 presentation. The wording of the source guidebook has been retained wherever possible; only presentation-specific selection and minor editorial linking have been applied.