ANNEX 84

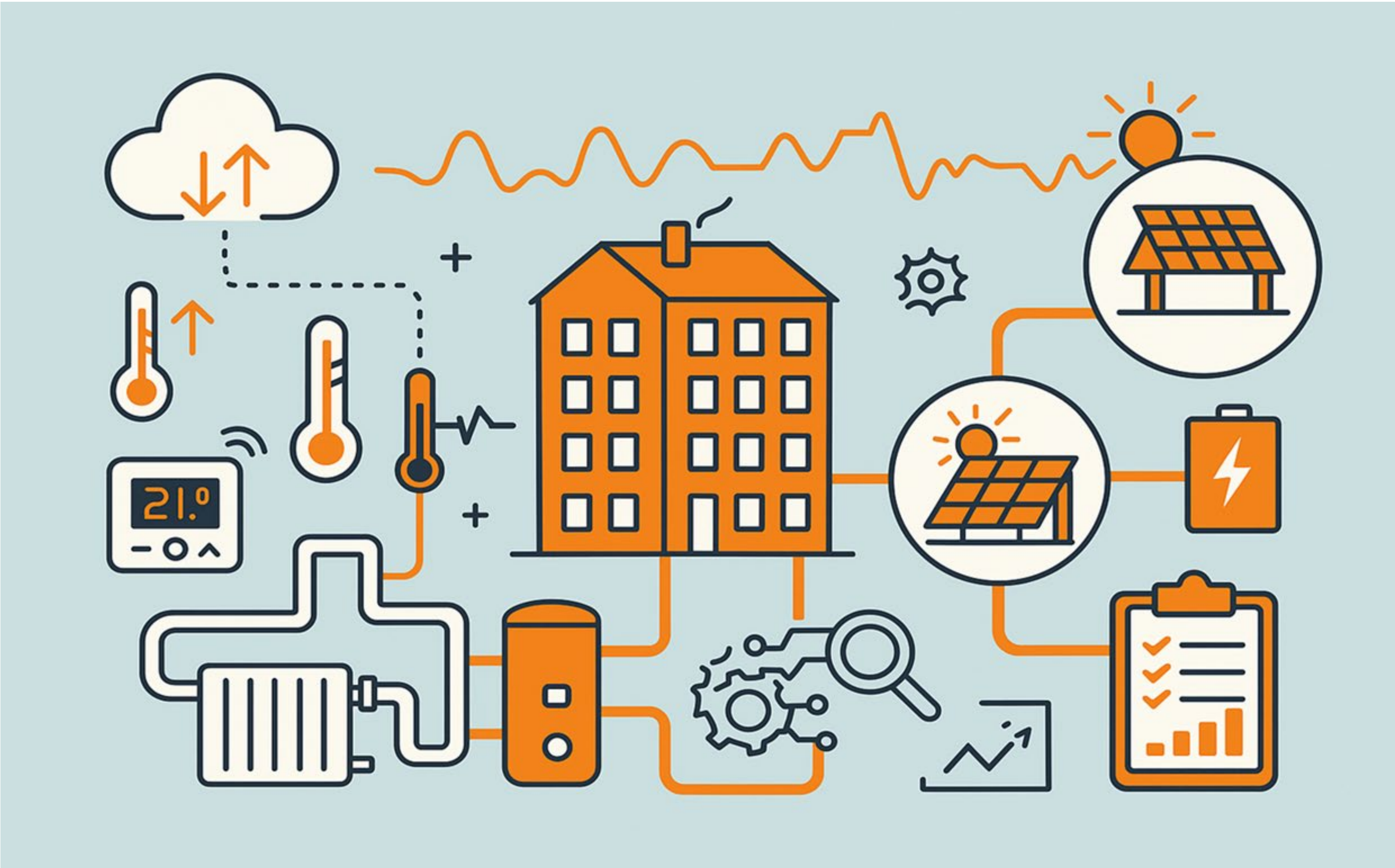
EBC
Energy in Building and
Communities Programme

International Energy Agency

Demand Management of Buildings in Thermal Networks (Annex 84) – Deliverable WI B.3: Role of DHC substations as element in demand response option on building scale

Energy in Buildings and Communities Technology Collaboration Programme

September 2024



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September 2024

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
Annex 73: Towards Net Zero Energy Resilient Public Communities
Annex 74: Competition and Living Lab Platform
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-Efficient Heating, Cooling and IAQ Control in Residential Buildings
Annex 93: Energy Resilience of the Buildings in Remote Cold Regions
Annex 94: Validation and Verification of In-situ Building Energy Performance Measurement Techniques
Annex 95: Human-centric Building Design and Operation for a Changing Climate
Annex 96: Grid Integrated Control of Buildings
Annex 97: Sustainable Cooling in Cities

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities
Working Group - Building Energy Codes

Summary

Buildings connected to district heating and cooling (DHC) networks are equipped with a heating/cooling substation, where the hot/cold district water loop interfaces with the building's heating/cooling and domestic hot water (DHW) loops. These in-house substations play a crucial role in supplying thermal energy in line with building demand. They are designed to transfer heat from the (primary) DHC system to the (secondary) building energy system, ensuring the required supply water temperature, pressure, and mass flow to meet the thermal and DHW comfort needs of end-users.

To date, the primary focus of DHC operators has been to secure supply of heat/cold at a maximum temperature difference (delta T), in order to minimize mass flow rates and hydraulic effort in the DHC system. Flexible operation of substations – considering load management and demand response – has not traditionally been a priority for either DHC or building operators. However, to unlock thermal flexibility at the building level (e.g., through thermal storage capacity or variation in supply and return temperatures) while maintaining end-user comfort, building systems must evolve. This includes enabling third-party access, implementing automated fault detection and remediation, and introducing demand management at the building level.

This report focuses on the following research questions:

- What is the typical equipment used in the most common DHC substations today?
- Are there significant differences across countries, and what are they? This includes national best practices, technical specifications, standards, guidelines, and legal framework.
- Based on the above, what are the minimum design requirements for a DHC substation, and which components are most commonly used?
- What thermal flexibility potential can be provided by these components?
- What is the flexibility readiness status of a typical DHC substation, and how can it be quantified?

In summary, this document provides an overview of current practices in DHC systems, with a special focus on the role of substations. It serves as a reference and starting point for future demand-side management initiatives, offering insights into where flexibility potential exists and identifying the technical and legal barriers that must addressed in various national contexts.

Table of content

Abbreviations

Abbreviations	Meaning
COP	Coefficient of Performance
DH	Districht Heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
DR	Demand Response
DSM	Demand Side Management
EES	Eco-Efficient Substation
HX	Heat Exchanger
NTU	Number of transfer units
SH	Space Heating
TCC	Technical Connection Conditions

1. Scope and objectives

1.1 Overview of subtask B and Work Item B.3

The objective of Subtask B is to

- Collect which technological options exist to enable demand response in buildings connected to thermal grids
- Evaluate their current market readiness resp. research status
- Evaluate their technical / economic potential
- Highlight limitations and bottlenecks
- Collect examples
- Evaluate in how far demand response by selected technical options – in combination with each other and in combination with a control strategy and system – improves the performance of a DHC system

Subtask B is organized in five Work Items:

- B.1 – Classification of building types connected to DHC systems
- B.2 – Supply, storage and distribution of heat, cold, domestic hot water, and electricity on building level for demand response and flexibility option
- B.3 – Role of DHC substations as element in demand response option on building scale
- B.4 – Role of monitoring, sensoring and control technology
- B.5 – Evaluation and summary

Work Item B.3 concentrates on the current technical state of district heating and cooling (DHC) substations. It aims for giving an overview over the technical equipment and components of the variety of substation design options. Special emphasis is placed on national peculiarities, guidelines and technical rules as well as the legal framework that is given in different countries were DHC is used. A classification of district heating (DH) substation design is given and the minimum requirements for the technical equipment of DHC substations are described. With the aim of developing some kind of flexibility readiness measure for the thermal flexibility a certain substation is able to provide for the thermal grid, the flexibility options of typical substation components are investigated.

1.2 Activities

Buildings connected to DHC networks are equipped with a heating/cooling substation, where the hot/cold district water loop meets the heating/cooling and domestic hot water (DHW) loops.Building substations are designed to transfer heat from the (primary) DHC system to the (secondary) building energy system thus maintaining a requested supply water temperature of the secondary systems to meet the thermal and DHW comfort demands of end-users.So far the main interest of DHC operators is secure supply of heat/cold at a maximum Delta T to limit mass flow rate and hydraulic effort in the DHC system. Flexible operation of substations accounting for load management and demand response was not in the focus of neither the DHC operator side nor from the building operator's point of view.

The work within Work Item B.3 aims at getting an overview of the current status of DHC substations and the thermal flexibility they can provide in context of DHC. This report consists of the following parts:

Activity 1: Development of a DH substations classification

- concentrates on district heating substations and suggests a classification. Furthermore, general information on the DH substation is given regarding technical specification of the single components, functional schemes and related information. Some insight on potential flexibility is already given.

Activity 2: Special features of DC substations in contrast to DH substations

- focuses on the specifics of district cooling substations that are different from district heating substations. Some additional information on national peculiarities in Singapore are also given.

Activity 3: National pecularities (technical and legal)

- gives an overview on national peculiarities of the DH substation regarding standards, guidelines, technical specifications and differences in ownership for different countries where district heating is used.

Activity 4: Identification of thermal flexibility potential a DHC substation can provide

- concentrates on the identification of flexibility potential of DH substations with regard to the different components that are able to provide thermal flexibility.

2. Current status of district heating sub-stations

2.1 Overview and classification

The objective of Activity 1 is to develope a classification scheme for DH substations in buildings connected to a thermal network. Substations in DH networks can be categorized based on various criteria. To maintain a certain clarity, the classification proposed in Figure 1 focuses solely on the technical aspects of DH sub-stations. From a broad perspective to more detailed technical aspects, the categories are as follows:

1. The **location** of the substation within the thermal grid.
2. The **hydraulic separation** between the building installation and the DH network.
3. The types and number of consumers, as well as the **system configuration** on the secondary (building) side
4. The **control strategies** used for space heating (SH) and/or domestic hot water (DHW) heating.

The criteria and their characteristics are further explained below.

Beyond technical criteria, there are also non-technical aspects to consider, such as the ownership of certain parts of the substation and possible legal requirements (e.g., monitoring, billing, security issues). These factors vary depending on the national regulations and are discussed on a country-by-country basis in the following sections.

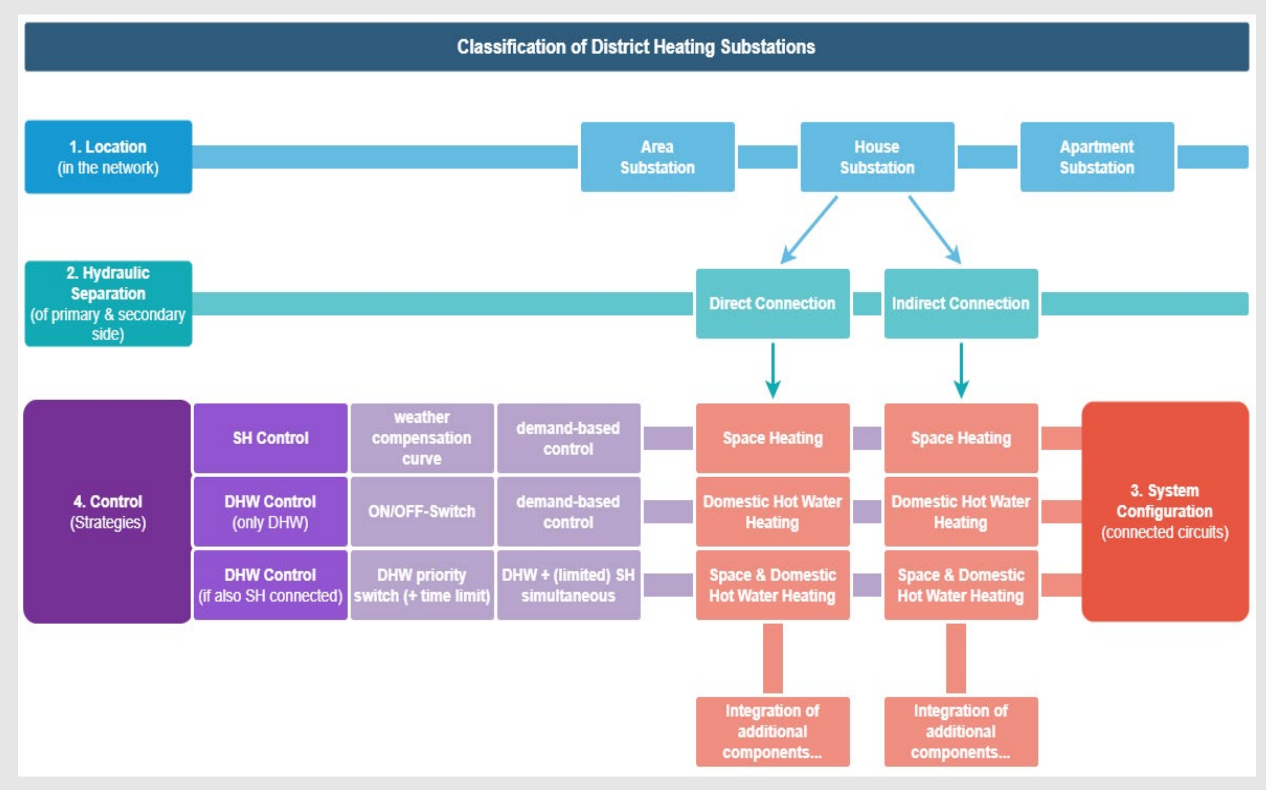

Figure 1: Classification of DH substations

2.2 Location

As shown in Figure 2, district heating substations are located in different parts of the thermal grid. The **area substation** serves local distribution network and regulate temperature and pressure to match local requirements. In contrast, both the **house substation** and the **apartment substation** are located inside buildings. As the names suggest, a **house substation** supplies the entire building and is typically located in the house connection room (see also Figure 3). An **apartment substation** serves only one individual apartment within a multi-family building.

Substations are designed based on thermal load, the type and number of supplied hydraulic circuits, and supply company specifications.

While *apartment substations* allow for distributed adaptation of supply water temperatures, local DHW production, and individual heat metering (which is essential for billing in some coutries), they are more expensive than house substations. Each of these apartment substations serve only one single apartment of the building.

Since house substations are far more widespread than the other two types, this study will focus primarily on DH house substation [1].

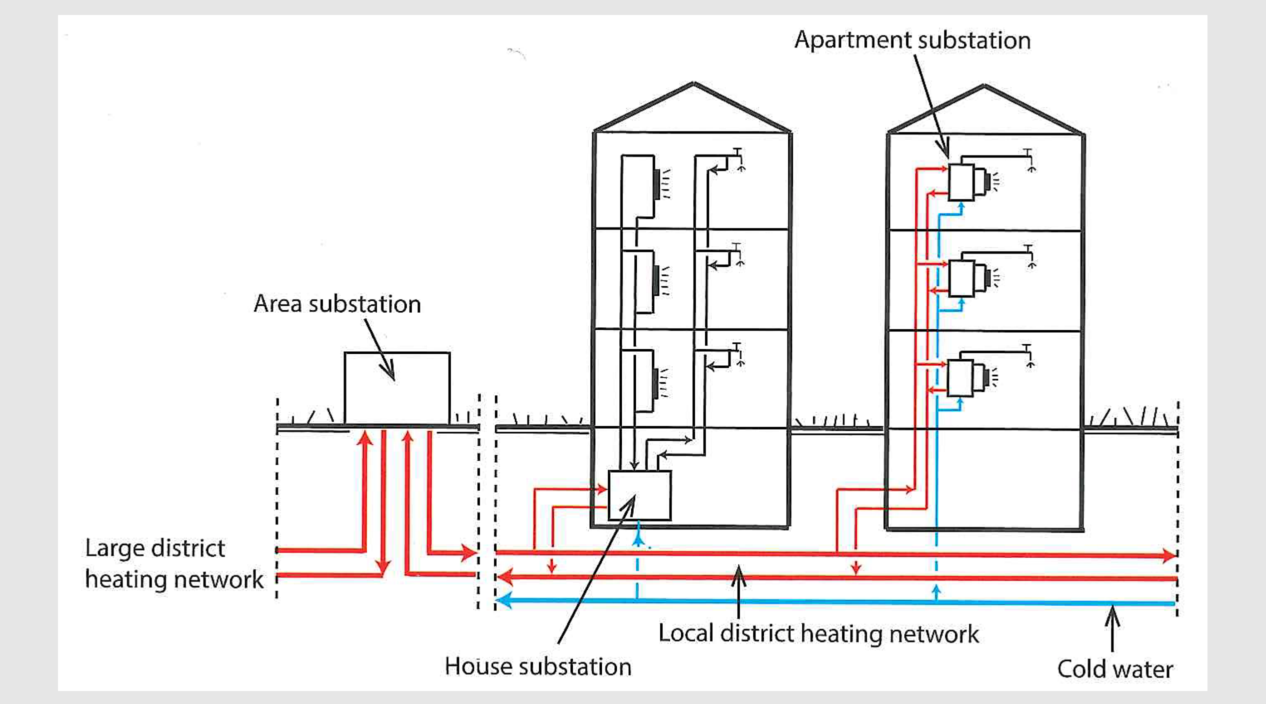

Figure 2: Differences between area, house and apartment substations [Frederiksen, & Werner, (2013)] [1]

2.3 Hydraulic separation of DH substations

2.3.1 Overview of connection types and components of DH house substations

Various components are required to facilitate heat transfer from the district heating network to the building installation; Figure 3 illustrates the general structure of this process and provides insight into the terminology used.The house substation consists of the transfer station and the house control center, both are located in the house connection room.

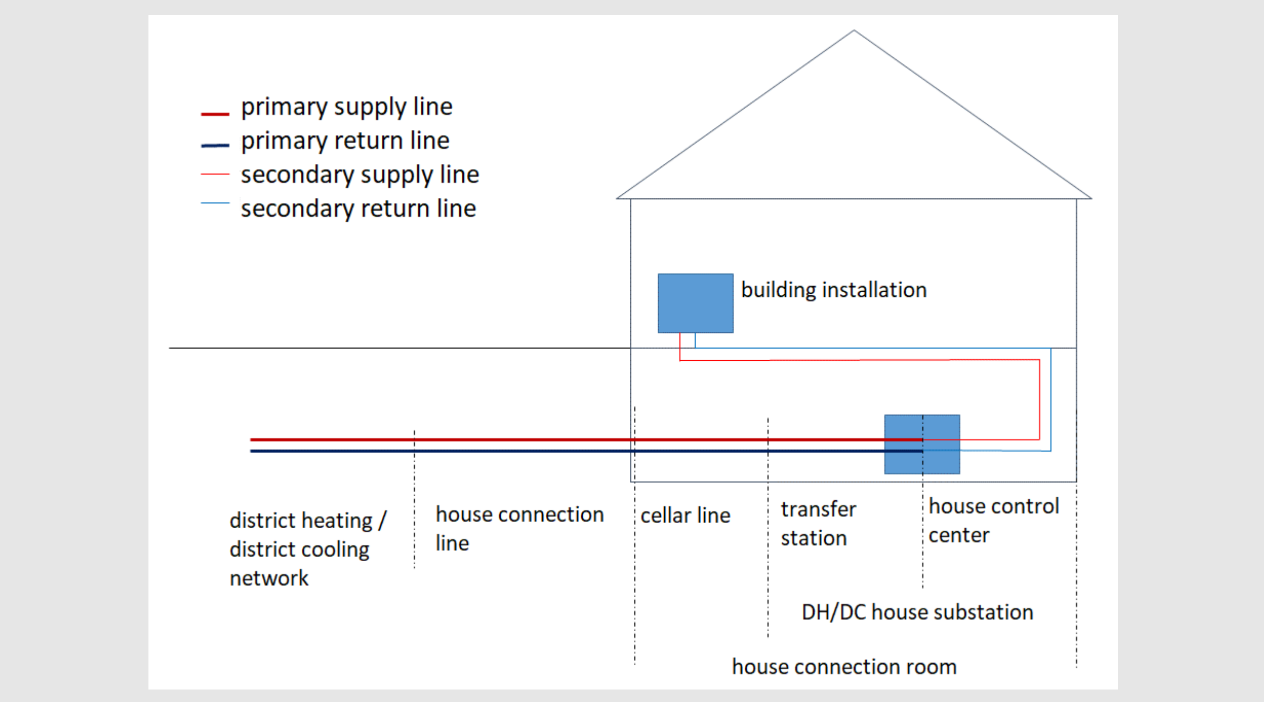

Figure 3: Heat transfer from the district heating/cooling network to the building using house substations

The connection of the house substation to the district heating grid can be either direct or indirect. With **direct connection**, the heat transfer medium from the DHC network flows directly through the building installation, as shown in Figure 4. This type of connection is only possible if the static pressure and the return pressure of the thermal grid are lower than the maximum permissible pressure of the building installation. Water quality plays a crucial role in drect connections. It affects the choice of material for the equipment in the house control center and the building installation. From a network operator's point of view, a direct connection also harbors certain risks, e.g., increased operating costs to ensure water quality or uncertain legal security in the event of damage (liability problems, etc.). For instance, if buildings with old building installations are connected.

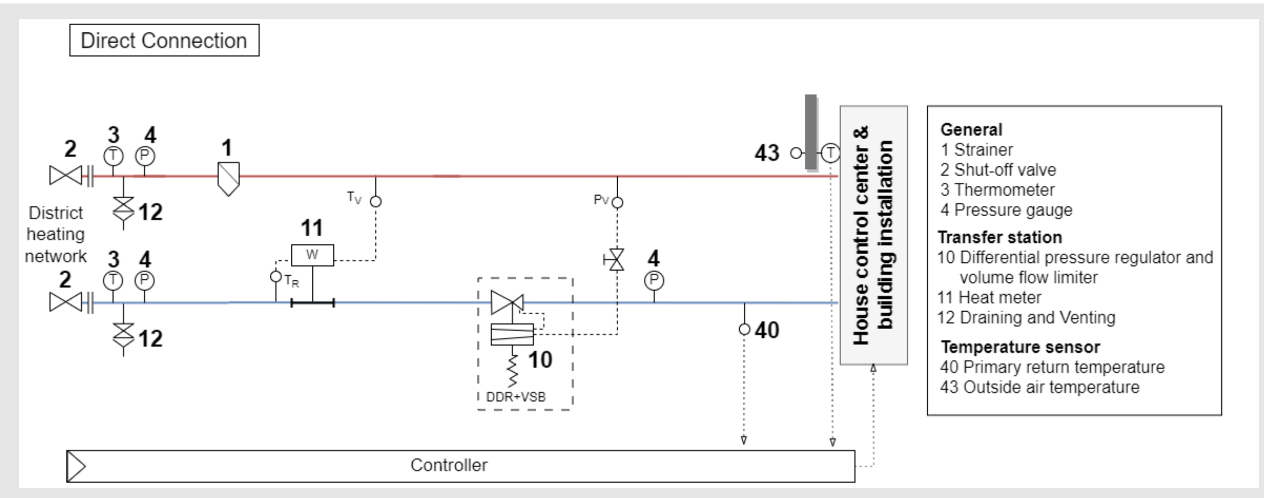

Figure 4: Direct connection between building installation and thermal grid

With an **indirect connection**, the heat transfer medium from the DHC network is hydraulically separated from the building installation by a heat exchanger. This results in two separate hydraulic circuits: the primary (DHC network) and the secondary circuit (building energy system). Figure 5 Illustrates an example of the setup. An indirect connection is required when the parameters in the thermal grid such as pressure, temperature and/or water quality are unsuitable for the connected building installation. This is often the case in old buildings. With indirect connection the pressure level can be determined freely and therefore, the building installation can be carried out with a lower pressure level and thus possibly less expensive. This justifies the more complex house substation in many cases. For the supplier there is no risk connecting old systems in which the pressure level or aging conditions appear questionable.

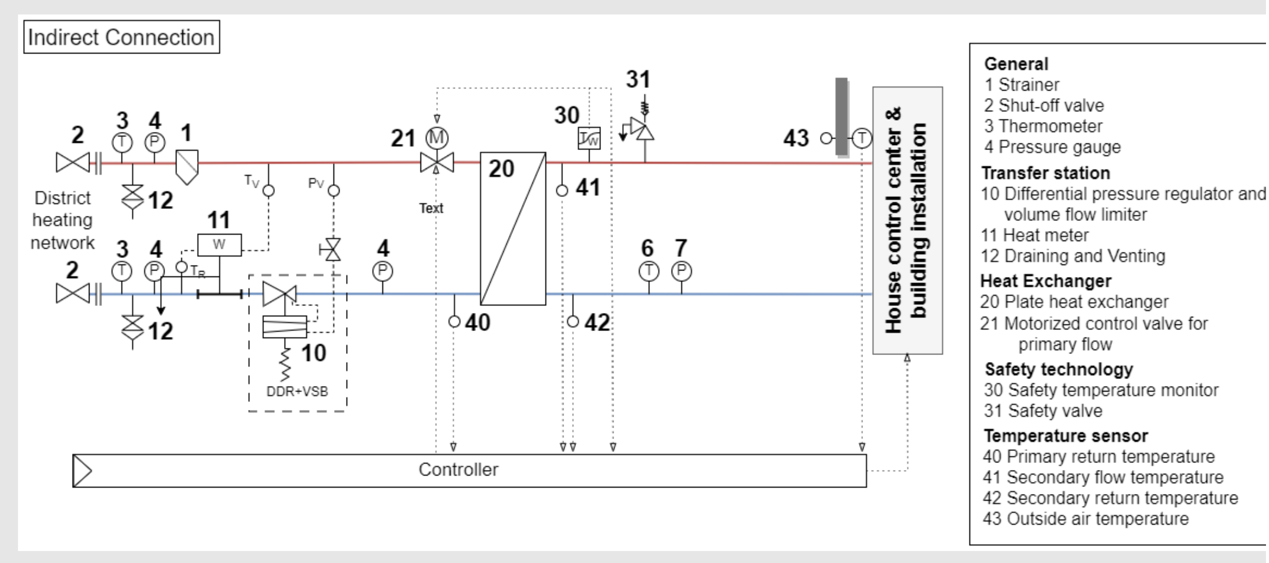

Figure 5: Indirect connection between building installation and thermal grid

When connecting the DHC substation to the thermal grid, it is essential to comply with the technical connection conditions (TCC) set by the network operator. For example, in many German supply areas, only indirect connections are permitted in primary networks Due to the predominantly old building stock and the associated risks (as outlined above).

Figure 6 compares the differences between direct and indirect connections. The essential components required for substation control are labeled (A–E) for both setups.

- (A) Controller
- (B) Temperature sensors
- (C) Actuator and control valve
- (D) Differential pressure controller
- (E) Non-return valve.

More detailed information on substation control equipment and control strategies will be provided later in this report.

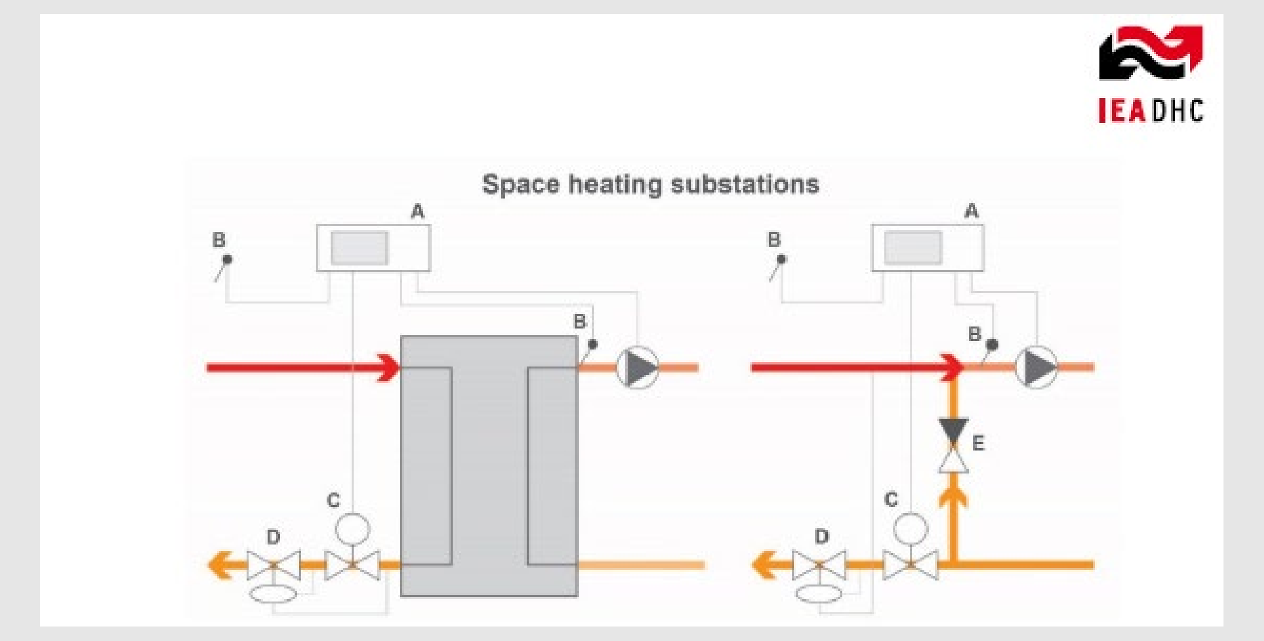

Figure 6: Example of the basic layout for an indirect (left) and a direct (right) space heating substation

2.3.2 Regarding indirect connection – characteristics of the heat exchanger

Since the heat exchanger is the key component that differentiates indirect from direct connections to the district heating grid and has a major impact on the flexibility of the house substation, it will be examined in more detail in this section.

Figure 7 presents a schematic representation of a heat exchanger with countercurrent flow between the district heating circuit (DH) and the building circuit (B). The sybols T_{inDH} and T_{outDH} represent the inlet and outlet temperatures of the flow (G_{DH}) of the heat exchanger on the DH side. Analogously, the symbols T_{inB} and T_{outB} denote the flow temperatures going in and out of the heat exchanger on the building's side (G_B).

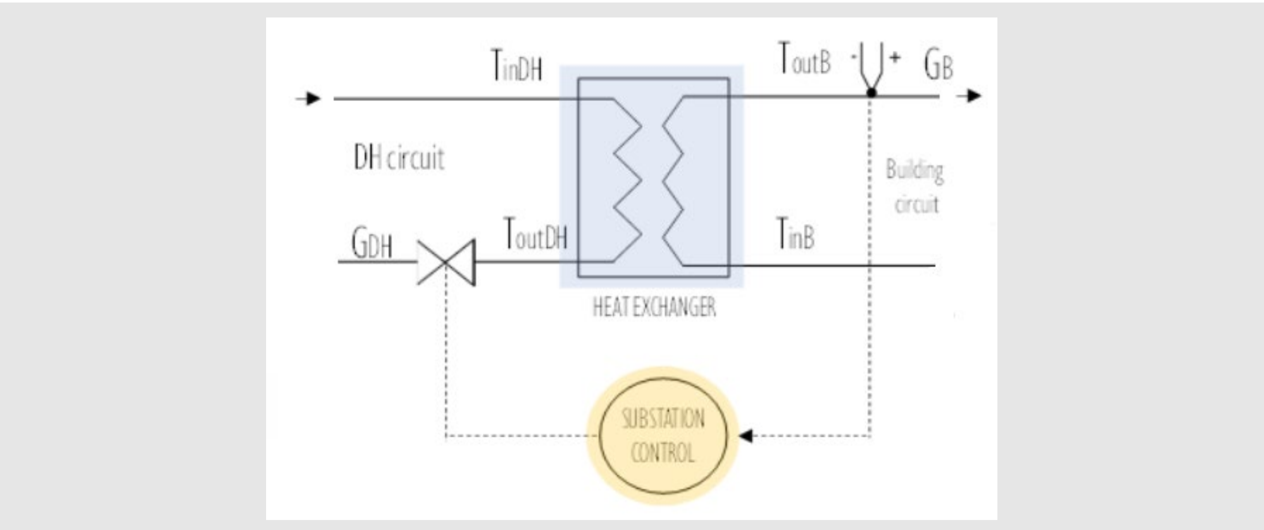

Figure 7: Heat exchanger and notation for key variables

Heat exchanger effectiveness

The effectiveness of a heat exchanger (Equation 1, refers to Figure 7 for the meaning of the quantities) is defined as the ratio of the actual thermal power transferred (Φ) to the maximum possible thermal flux (Φ_{max}) under ideal countercurrent configuration. This metric assesses the heat exchanger's performance under specific operating conditions, considering both its design and real-world operation.

$$\varepsilon = \frac{\Phi}{\Phi_{max}} = \frac{\Phi}{G_{DH}(T_{inDH} - T_{inB})} \quad (1)$$

A related parameter is the number of transfer units (NTU), which summarizes the heat exchanger's design and operational parameters into a dimensionless form (Equation 2):

$$NTU = \frac{UA}{G_{DH}c} \quad (2)$$

where U is the global heat transfer coefficient, A is the heat exchanger area and c the specific heat capacity and G_{DH} the mass flow rate in the DH circuit. Relations between ε and NTU can be found in the literature depending on: a) the heat exchanger configuration (e.g., parallel flows, countercurrent, cross flow) or b) the ratio between minimum and maximum global thermal capacity of the two fluids (i.e. how much a stream limits the heat exchanged with respect to the other).

NTU is a crucial parameter for the heat exchanger design, as a higher NTU value indicates better heat exchanger performance. It also plays an important role in off-design conditions. In particular, if the heat exchanger is oversized for its design conditions, it can still deliver the required heat flux even under suboptimal operating conditions (e.g., lower inlet temperatures or reduced mass flow rates in the primary circuit).

Heat exchanger UA

As shown in the previous section, both effectiveness (ε) and NTU can be used to assess the thermal flux capacity of the substation heat exchanger. Both parameters are strongly dependend on the product UA (Where U is the heat transfer coefficient and A is the heat exchanger area). Given two inlet temperatures (T_{inDH} and T_{inB}) and two mass flow rates (G_{DH} and G_B), higher UA values allow for greater thermal flux. A high UA enables the system to operate flexibly, spanning from 0 kW to a higher maximum heat transfer rate. This becomes especially important in case of a high thermal demand needs to be supplied with lower mass flow rates or lower supply temperature.

During operation, UA varies with mass flow rates [Guelpa, & Verda, (2019)] [2]. Figure 8 illustrates how UA evolves, showing an approximate linear relationship with mass flow rate. This means that heat exchanger flexibility depends on a) the UA in typical operations and b) the variability of U with G that can be quantified as the UA value at maximum mass flow rate. The heat exchanger configuration also plays a crucial role. Most substation heat exchangers are plate heat exchangers [Frederiksen, & Werner, (2013)] [1], which are well approximated using a countercurrent flow model.

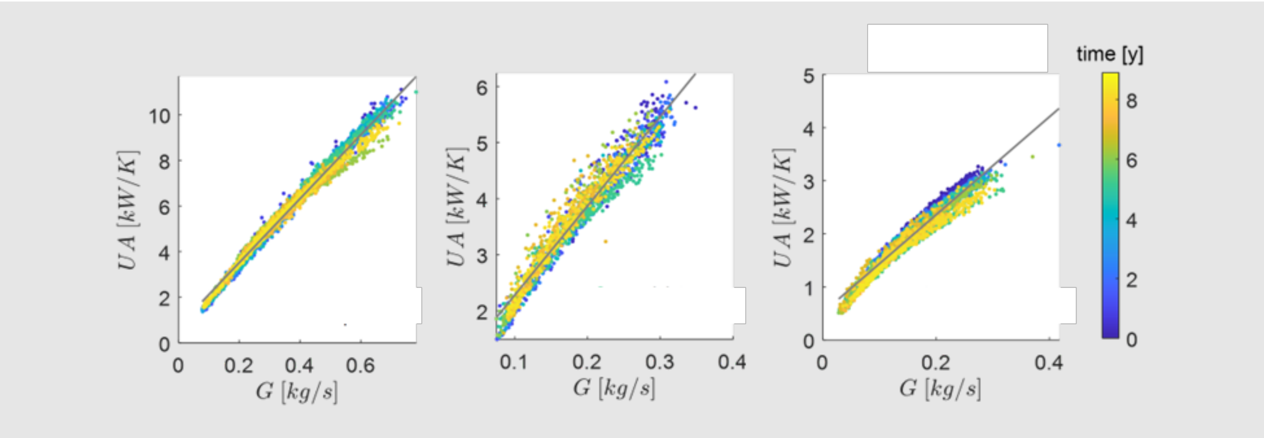

Figure 8: Examples of variation of UA depending on mass flow rate [2]

Fouling and its impact on heat exchanger performance

Fouling occurs when unwanted material deposits accumulate on the heat exchanger surfaces, leading to several negative effects: The first is the modification of the global heat transfer coefficient of the heat exchanger, following Equation 3. As a consequence, it affects the heat exchanged, as shown in Equation 4.

$$UA = \frac{1}{\left(\frac{1}{A_i h_i}\right)+\left(\frac{Rf_i}{A_i}\right)+\left(\frac{s}{Ak}\right)+\left(\frac{Rf_O}{A_O}\right)+\left(\frac{1}{A_O h_O}\right)} \qquad (3)$$

$$\Phi = UA\Delta T_{mlog} \qquad (4)$$

where ΔT_{mlog} is the mean logarithmic temperature difference, s is the wall thickness, k the conductive coefficient, h the convective coefficient. The fouling factor Rf indicates thermal resistance due to the fouling (this is zero for clean heat exchanger). Since higher fouling levels reduce UA, it is possible to monitor fouling by tracking UA values [Guelpa, & Verda, (2019)] [2]. Fouling directly affects system flexibility, since heat transfer is lower at a given supply temperature and mass flow rate. This means that fouling acts as a reducer of the NTU (indeed, if UA reduces the NTU reduces).

2.4 System configuration and secondary side

Apart from being directly or indirectly connected, the question arises as to what the subsequent consumer circuit looks like. DH can be used for space heating only, for both space heating and domestic hot water heating, or exclusively for domestic hot water preparation. The connected circuits can be either directly or indirectly connected, but it is possible to have a combination of both – where one circuit is directly connected, and another is indirectly connected. Furthermore, several principles of DHW heating can applied individually or in combination. It is also possible that space heating for one building is divided into multiple heating circuits, each requiring a different flow temperature, depending on the heat transfer system (e.g., radiators, underfloor heating, etc.).

Figure 9 illustrates various configuration options, ranging from basic setups with only one heating circuit to more complex ones incorporating additional space heating and DHW heating circuits. Someconfigurations also include support from solar thermal energy or buffer storage systems.

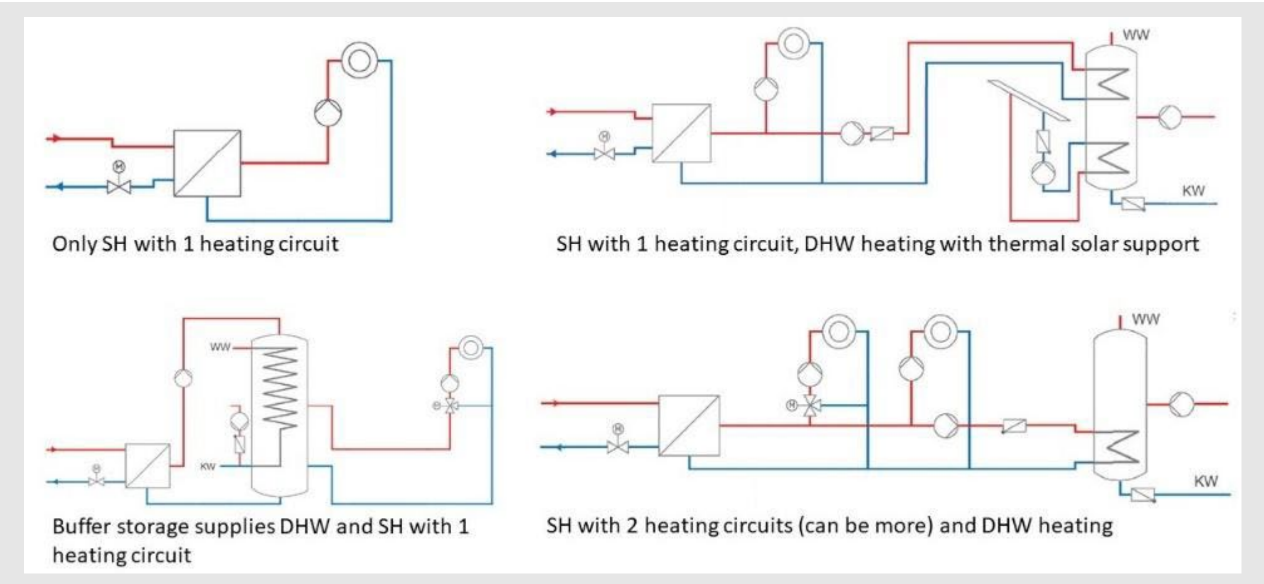

Figure 9: Example of different system configurations connected to the thermal grid

2.4.1 Scope of Work Item B.3

Work Item B.3 focuses on the substation and its regulated components. Therefore, the type of connected heating circles is not part of B.3, but rather B.2, where building-level technologies are analyzed. However, since DHW storage tanks can be regulated by the substation controller, they fall within the scope of B.3.

2.4.2 Domestic hot water heating principles

In general, there are three primary types of DHW heating systems. Figure 10 illustrates the fundamental principles behind each system:

5. Flow-through system (also known as an instantaneous water heater or fresh water station): cold drinking water flows through a heat exchanger, where it is heated instantly to the desired DHW temperature.
6. Storage system: DHW is heated inside a storage tank via an internal heat exchanger.
7. Storage charging system: this system uses an external heat exchanger and a charging pump to fill a DHW storage tank.

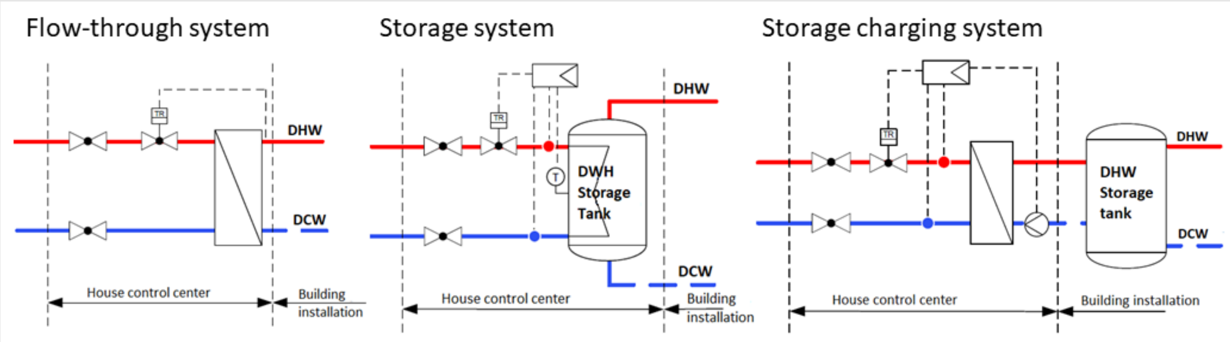

Figure 10: Types of domestic hot water heating systems

2.4.3 Operational Differences and Control Strategies

DHW heating circuits with a hot water storage tank can be utilized for demand-side management, whereas the flow-through system operates only when hot water is needed. Figure 11compares the control equipment layout for a domestic hot water heat exchanger (flow through principle) and a domestic hot water storage tank (with an internal heat exchanger). The essential components for both systems include: (A) Controller, (B) Temperature sensor, (C) Actuator and control valve, (D) Differential pressure controller, and (E) Bypass valve (which may be located internally within the unit).

To develoeload management strategies for thermal grids and to estimate their impact on load flexibility, it is crucial to have a general understanding of disbtribution and size of hot water storage tanks supplied by DH substations.

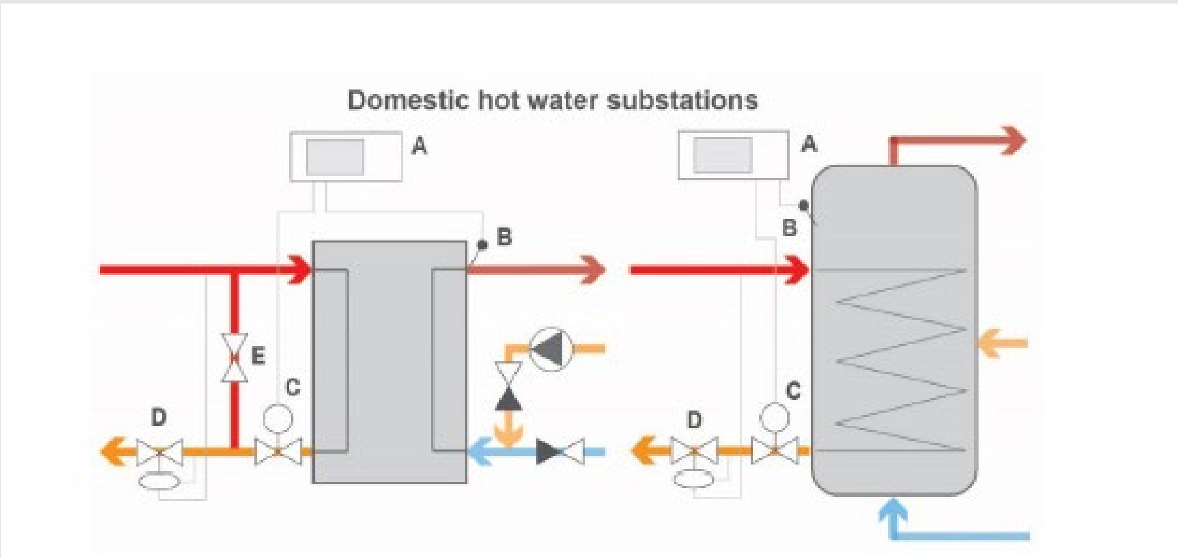

Figure 11: Example layout of a domestic hot water heat exchanger (left) and a domestic hot water storage tank (right)

Table 1 provides an overview of the three DHW heating principles, comparing advantages and disadvantages as well as expected return temperatures.

Table 1: Comparison of different DHW heating princples

	Flow-through system	Storage system	Storage charging system
Description	• direct heating of hot water, when required • provide an on/off sensor	• water tank with built-in heating surfaces in which drinking water is heated and stored • peak loads are covered by the storage	• combination of flow-through and storage system • charging via an external heat exchanger and a charging pump • variable charging quantities for volumes greater than 500 l • peak loads are covered by the storage tank • provide on/off sensor
Advantages	• low costs • low return temperature • low space requirements • reduced risk of legionella *Note: It is the only system compatible with 4GDH, because having storage tanks will result in higher return temperature, and requires higher supply in the network.*	• low demands on the control system • peak load smoothing possible • high tap quantity possible • less sensitive to pollution	• low return temperatures • high tap quantity possible • small constant charging capacity • high degree of utilization oft he heat exchanger
Dis-Advantages	• high connected load (hot water peak demand must be covered) • requires good regulation • sensible to high levels of lime and contamination in drinking water • low compensation of load peaks *Note: In Sweden, storage tanks have not been installed for more than 20 years. Peaks are mitigated by diversity factors, so in reality it is not an issue.*	• rising return temperature during charging • heat losses of storage tank • risk of legionella	• high investment costs • required complex control • heat losses of storage tank • risk of legionella
Connection	primary side connection preferred	primary side connection possible depending on the pressure level of the district heating network	primary side connection possible depending on the pressure level of the district heating network
Possible return temperatur	< 30 °C	~ 45 °C	< 35 °C

2.5 Control equipment and strategies

2.5.1 Substation control strategies

Various substation regulation aspects can affect the substation flexibility. Some of these are discussed below.

- *Climatic curve regulation/weather compensation control.* The climatic curve is a widely used control approach in DH thermal substations. It is based on a proportional-integral logic that adjusts the supply temperature on the secondary side depending on the expected thermal demand. The control logic is presented in Equasions 5–6, where *e* represents the regulation error and *kp* and *ki*, are the proportional and integral regulation constants, respectively. The valve opening level, which controls the mass flow rate at the primary side, G_{DH}, depends on the error value, i.e., the difference between the secondary-side supply temperature, T_{out_b}, and its set-point T_{SP}. The set point temperature is determined by a default function, known as the climatic curve, which is typically a linear function that depends on the external temperature or the expected building thermal demand. The curve is selected based on the building's load profile.

$$\sqrt{G(t)} = \sqrt{G(t-1)} + k_p e(i-1) + k_i \int e(t)\, dt \quad (5)$$

$$e = (T_{outB} - T_{SP}) \quad (6)$$

$$T_{SP} = T_{SP}(setting, T_{ext}) \quad (7)$$

  If climatic curve control is used, mass flow rates can increase significantly when the building circuit water is cold – such as after a shutdown or attenuation period due to thermal losses. In such cases, the error e in Equasion 5 becomes large, causing a higher mass flow rate. For networks that experience frequent switching off or significant attenuation (common in milder climates), this approach can be enhanced with a mass flow limiter, as described in the following sections.

- *Differential of Return Temperatures logic*: This control strategy follows the same principle as the climatic curve regulation but modifies the error calculation method. Specially, when the building circuit temperature is significantly lower than the DH circuit temperature, the system limits the error value, thereby restrichting valve opening. This is defined by Equasion 8:

$$e = \begin{cases} (T_{outB} - T_{SP}) & if\ (T_{outB} - T_{SP}) < 0\ and\ (T_{outDH} - T_{inB}) < \gamma \\ (T_{outDH} - T_{inB}) - \gamma & if\ (T_{outB} - T_{SP}) < 0\ (T_{outDH} - T_{inB}) > \gamma \\ 0 & if\ (T_{outB} - T_{SP}) > 0 \end{cases} \quad (8)$$

  When the difference between T_{outDH} and T_{inB} is high, the error is limited, causing the valve to open more slowly. The parameter γ represents a regulation variable, whichdetermines how quickly the mass flow changes – a higher γ results in slower indoor temperature increases.

- *Limitations on the mass flow increase*: This control strategy regulates the rate of mass flow change over time. If the mass flow derivative exceeds a predefined value, the system restricts the flow increase. This approach prevents excessive peaks and allows for greater flexibility during peak demand periods.

- *Limitations on the maximum mass flow rates*: In some cases, the substation control system enforces a maximum allowable mass flow rate. If the estimated mass flow rate (from Equasion 1) exceeds this threshold, it is capped at the predefined limit. This is often done a) to prevent exceeding the mass flow limit b) to reduce thermal peaks. The relaxation of the value leads to larger substation flexibility.

2.5.2 Control of building circuit mass flow

The building circuit mass flow rate depends on a) the opening degree of the thermostatic valves (if available), b) the regulation of the pumps (if a variable speed pump), c) the manual valves in the radiators. If a) and b) are unavailable, the mass flow remains nearly constant throughout the heating season. When variable-speed pump is used, it can be adjusted to modify the circuit mass flow based on the operating conditions. This provides a significant degree of flexibility since it allows modifying the efficacy of the system and, in some cases, enables operations that otherwise would not be possible (e.g., supply at lower temperature).

2.5.3 Maximum mass flow rate processed by the thermal substation

The thermal substation’s mass flow rate is constrained by the maximum allowable velocity and pressure drop. The constraint reduce system flexibility by limiting heat exchange capacity at a given supply temperature.

2.5.4 Objectives and prerequisites of DH control equipment

The primary objective of DH control devices is to maximize the cooling of DH water, ensuring optimal utilization of the supplied DH water volume flow. Actuators adjust their position based on the outdoor temperature (or another suitable reference variable such as demand-based signals) and on time-based control settings. The control device is also responsible for switching on and off the circulators in the heating system.

Modern substations feature weather-compensated control, which adjusts controls the flow temperature of the secondary side based on the average outdoor temperature and DHW heating mode. Generally, house substations are designed to prioritize DHW heating over space heating. If both space heating and DHW demand occur simultaneously, space heating is reduced or temporarily interrupted to ensure DHW priority. The domestic hot water temperature and the flow temperature of the heating medium are regulated to a constant value.

Prerequisites for a proper functioning of the control device are a hydraulically stable system and the avoidance of sudden changes in demand (e.g. switching consumer groups on and off). To reduce peak loads, limiting functions, such as flow temperature rise limitation and low night reduction are implemented. Changes in demand should not be compensated immediately by the control equipment with maximum power and maximum volume flow. A limitation of the DH water volume flow and the offer of an outdoor temperature driven supply temperature are provided by the heat supplier.

2.5.5 Basic and specific requirements on DH controllers

Basic DH control equipment requirements are categorized as:

1. Software requirements
2. Hardware requirements
3. Requirements on control elements and display standard

Software requirements: DH controllers basically include the software for a standard system variant. It can be freely configurable (all connected field devices can be functionally linked), a combination of functional blocks (e.g. charging function of thermal storage) or a selection from several fixed system variants (providing the possibility of parametrization only). The parametrization is divided into different operating levels, where the accessibility of individual levels is allowed via corresponding access codes or hardware. It has to be possible to integrate meter signals if required for power and volume flow limitation on the primary side and to realize different limitation values for DHW as well as for summer/winter operation of space heating.

Hardware requirments: There has to be a direct connectivity of all field devices to be processed by the software for a control process (sensors, actuators, heating medium pumps, etc.) and an interface to the heat meter. Several input signal types, such as ohmic signals, switching on/off signals, active signals (0 - 10 V, 4 - 20 mA) as well as mechanical and electronic counter inputs, have to be accepted.

Requirements on control elements and display standard: The standard controller contains an annual clock with adjustable or automatic summer/winter changeover, enabling the input of at least two switching cycles per heating circuit and day, as well as the input of an absence period. The current date and time must be kept up to date for at least 48 h in the event of a power outage.

Coming from basic to the **specific requirements** of DH control equipment, the standard features are:

- weather-compensated flow temperature control
- return temperature limitation
- control of DHW heating
- time programs for setback operation
- automatic summer and winter changeover
- anti-blocking function for heating pumps and actuators
- frost protecting circuit
- storage tank charging before start of heating
- control of the circulation pump by the controller when used in DHW systems
- thermal desinfection

Some features can be optional:

- memory for recording limit value curves and error messages
- duplication of input values for similar system types
- adjustable minimum valve lift (minimum flow control)
- room connection
- integration of solar thermal energy
- weather-compensated control of buffer storage tanks
- floor drying

The connectivity of a remote control for at least the set-point change of the flow temperature (directly or indirectly via the room temperature) and the switch of operating modes. Other functions to be aimed for in remote control are:

- switching the system on and off
- operating time extension
- display temperatures
- feedback of operating states and malfunctions

2.5.6 Setting parameters and measured values for heating control circuits

Usually, the **outdoor temperature** serves as the reference variable for the flow temperature. Short-term outdoor temperature fluctuations are compensated by the controller via adjustable damping.

The set-point of the **heating medium's flow temperature** is a function of the outdoor temperature (heating characteristic). The basic relationship is as follows: If the outside temperature drops, the flow temperature must be increased to keep the room temperature constant. Figure 12 and Figure 13 illustrate two ways in which the relationship between outside temperature and flow temperature can be implemented in the controller.

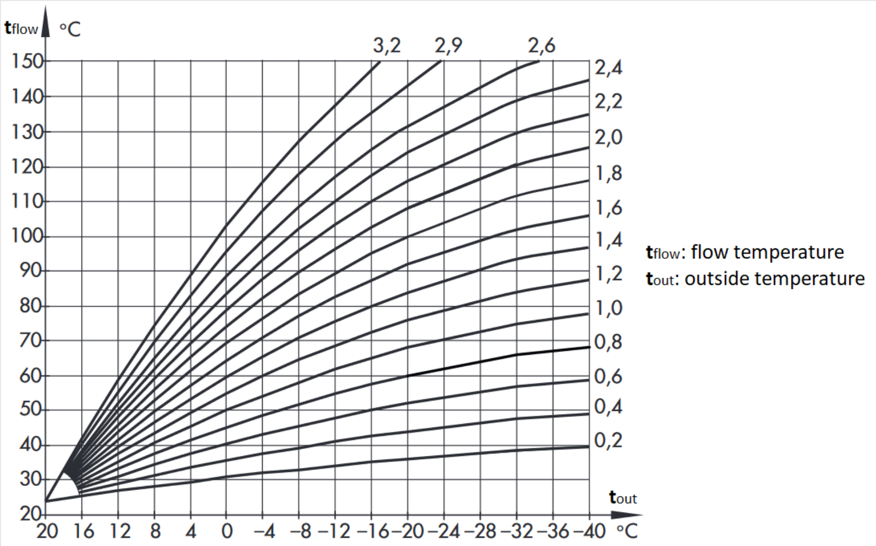

Figure 12: Heating characteristics using the example of TROVIS 5573 [Samson, (2023)] [3]

In weather-compensated control, as shown in Figure 12, the heating characteristic in the controller defines the setpoint for the flow temperature as a function of the outdoor temperature. The outdoor temperature required for control can either be measured by an outdoor sensor or received via a 0 to 10 V input. The slope of the heating characteristic can be adjusted in the controller. The Handbook of the controller TROVIS 5573 [Samson, (2023)] provides recommendations for different heating characteristics depending on the distribution technologies and design temperatures, as shown in Table 2.

Table 2: Comparison of different DHW heating principles

Building	Distribution	Design Temperatures	Slope (approx.)
Old	Radiator	90 °C/ 70 °C	1.8
New	Radiator	70 °C/ 55 °C	1.4
New	Radiator	55 °C/ 45 °C	1.0
/	Underfloor heating	depending on installation	< 0.5

Outside usage periods, reduced set points can be used for control: The reduced flow set point is determined by the difference between the 'Day set point' (rated room temperature) and 'Night set point' (reduced room temperature). The 'maximum flow temperature' and 'minimum flow temperature' parameters limit the flow temperature upwards and downwards. For the **limitation of the return temperature**, a separate gradient characteristic can be applied, adjusting the return temperature based on the outside temperature.

With the help of the 4-point characteristic, shown in Figure 13, a customized heating characteristic can be set. As the name indicates, the 4-point characteristic is defined by four key values: outdoor temperature, flow temperature, reduced flow temperature and return temperature. The ‘maximum flow temperature’ and ‘minimum flow temperature’ parameters also apply here to restrict temperature levels as needed [3].

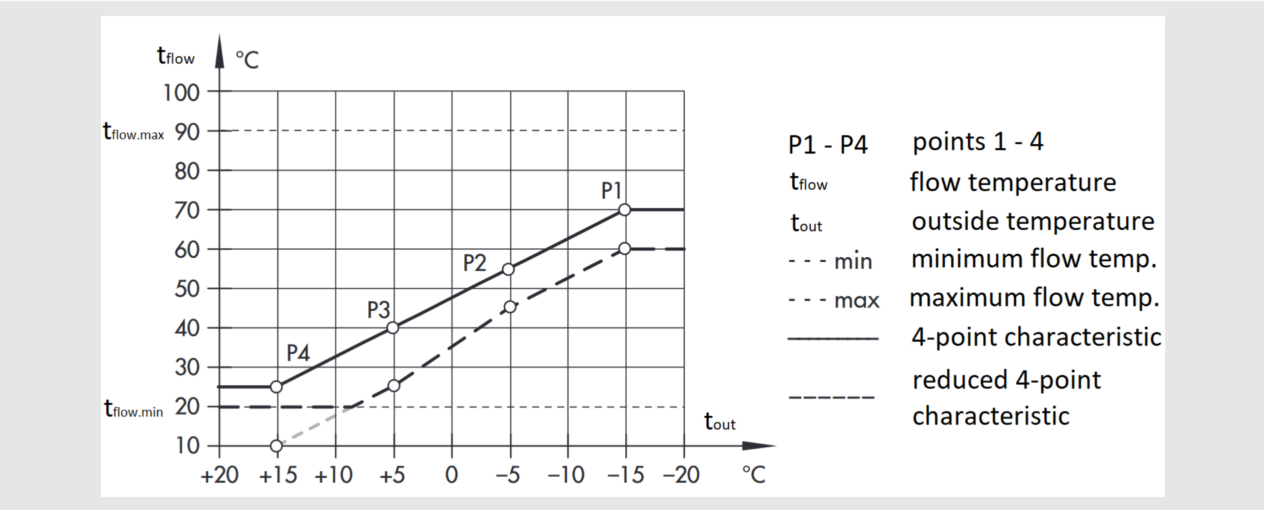

Figure 13: 4-point characteristic usingTROVIS 5573 [Samson, (2023)] [3]

The **control quality** can be adjusted in cases when:

- There is a deviation between the actual and setpoint values in static range (e.g., ±3 K from the set point)
- Proportional band X_P: 10–100 K or gain K_P: 0.1–10
- Integral time T_n: 60–600 s

2.5.7 Remote control

If the substation supports remote control, physical access is no longer required to modify the settings. This significantly increases flexibility, as control updates can be made using optimized or advanced control strategies. In particular, the following settings can be available adjusted remotely:

- Modification of climatic curve settings, i.e., adjusting the parameters of the climatic curve.
- Modification of on/off or setback times, i.e., changing the schedule for when the building heating system is switched on/off or in setback mode.
- Modification of mass flow upper limits (e.g. on the mass flow), i.e., the limitation described in Section 2.5.1

The larger the number of settings that are remotely controlled, the higher the substation flexibility.

3. Current status of district cooling substations

3.1 General information

Supply temperatures for district cooling systems can be:

- Conventional chilled water (4–7°C)
- Ice water (+1°C)
- Ice slurry systems (–1°C)
- Secondary heat transfer fluid for charging ice thermal storage (–5 to –10°C)

Most district cooling systems today with 7°C chilled water due to the higher Coefficient of Performance (COP) in central chiller plants and minimal thermal losses. This temperature is also optimal for dehumidification in buildings. Chilled water supply temperatures are adjusted based on ambient temperature to minimize energy losses and improve plant efficiency. In northern climates (e.g., Canada, northern US, Scandinavia), the temperature difference between chilled water in the pipes and the temperature of surrounding soil is minimal. As a result, insulation is only required in warmer climate zones where higher ground temperatures increase thermal losses. The primary application of distributed chilled water is space cooling, but in some cases, it is also used for process cooling.

The control of temperature differences (ΔT) is crucial in district cooling systems, as they operate with significantly lower ΔTs than district heating systems:

- The minimum supply temperature is approximately 1°C (ice-based systems) or 4°C (chilled-water based systems).
- The typical return temperature is around 12°C in older systems. In the Middle East, newer systems report in temperatures of approximately 17°C, achieved due to climate conditions.
- This results in a typical maximum $\Delta T = 12\ K$ (ice-based systems) or $\Delta T = 5 \text{ to } 8\ K$ (chilled-water based systems), compared to district heating systems, where typically $\Delta T \geq 40\ K$ is designed.
- The system design ΔT is controlled at customers substations, typically by adusting the chilled water flow rate into each building.

A district cooling substation:

- Interfaces between the district cooling system and the building cooling system
- Can be direct or indirect connected to the building installation
  - Direct connection: district cooling water circulates directly within the building to thermal equipment (e.g., air handling units, fan coil units, induction units)
  - Indirect connection: one or more heat exchangers separate the district cooling system from the building system
- Consists of control valves, controllers, measurement instruments, an energy meter, and a crossover bridge (hydraulic decoupler and/or heat exchangers)
- To maintain high return temperatures, thermal equipment (AHU coils, fan coil units, etc.) should be designed for high ΔT and variable flow operation and chilled water supply temperature at building installation should be reset based on outside air temperature.

Regardless of the building's cooling system, the design elements of a district cooling substation remain the same. All equipment is selected based on the contracted cooling load of the building.

3.2 DC substation for indirect connection

A district cooling substation with an indirect connection is like a district heating substation. Typical equipment for an indirectly connected DC substation includes:

- heat exchangers
- control valves
- energy meters (dynamic and static flow meters)
- pressure gauges
- thermometers
- shut-off valves
- strainers

Figure 14 (taken from [Skagestadt & Mildenstein 2002]) illustrates a basic district cooling substation with an indirect connection [4].

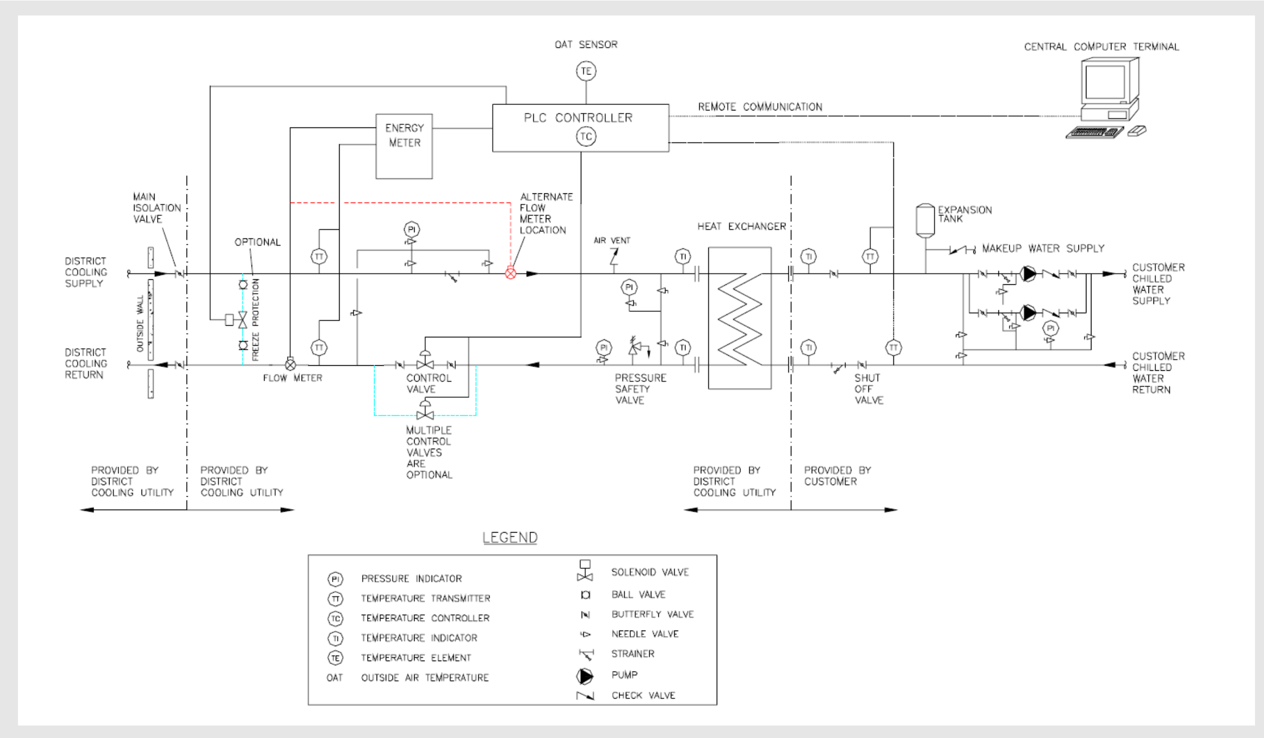

Figure 14: Indirect connection of building installation to district cooling system [Skagestad & Mildenstein 2002] [4]

3.3 DC substation for direct connection

A directly connected DC substation is more cost-effective than a indirect one in certain cases. In North America, most DC systems use direct connections or a combination of both direct and indirect connections.

Figure 15 (taken from [Skagestadt & Mildenstein 2002]) illustrates a basic district cooling substation with direct connection [4]. The chilled water is pumped from the primary system (district cooling) to the secondary system via a bypass bridge or decoupler. Some advantages and disadvantages of direct connection are as follows:

Advantages of direct connection:

- Cost savings by eliminating heat exchangers and associated water treatment equipment, as water treatment is handled cnetrally

- Reduced space requirements for the DC substation
- Lower investment costs and reduced pumping requirements for the distribution system through potential increased system ΔT
- Increased supply temperature from central chillers, which can enhance the COP of cold generation by eliminating heat exchanger approach temperature losses. Eventually, it can also result in fewer thermal losses during distribution
- Less maintenance and fewer shutdowns for cleaning of heat exchangers

Disadvantages of direct connection:

- Higher costs for the secondary system, as building design pressure must match the district cooling system (~1000 kPa)
- Greater risk of damage and contamination, potentially affecting both primary and secondary systems
- Building-specific water treatment needs may not be met, as water treatment is only provided at the central plant
- Increased risk of outage when a failure occurs in one or more buildings

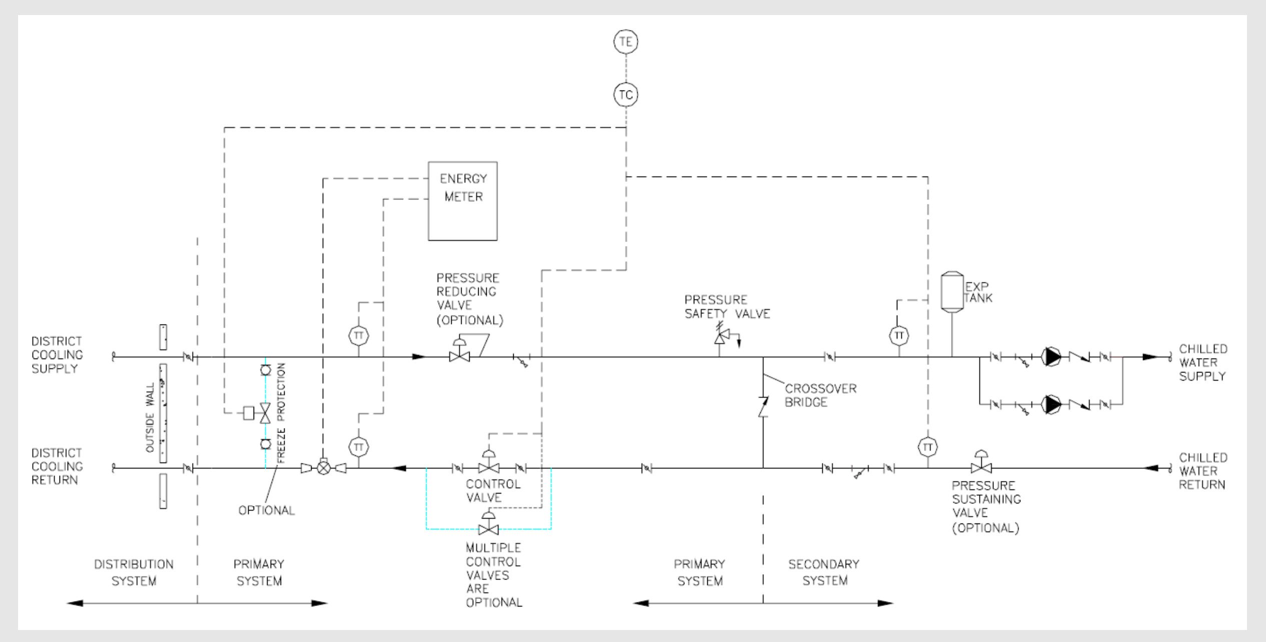

Figure 15: Direct connection of building installation to district cooling system [Skagestad & Mildenstein 2002] [4]

3.4 How to decide if direct or indirect connection is required

There are some general guidelines for selecting a connection type:

- Buildings with chilled water systems designed for a minimum of 1000 kPa pressure and up to 60 m in height can be directly connected
- Buildings with chilled water systems, designed for lower pressure requirements must be indirectly connected using heat exchanger
- Buildings with chilled water systems, designed for pressures other than 1000 kPa, with penthouse chiller locations at a height of more than 60 m, or with basement chiller locations with operating pressures exceeding 1000 kPa (without the possibility of hydraulically separate the upper floors) must use indirect connection.
- Hybrid connections are possible for buildings with chilled water systems for a minimum of 1000 kPa and with a height exceeding 60 m elevation (above grade): up to 60 m it can be directly connected and indirectly above this elevation
- Oder buildings with significant rust or chromates contamination may require a heat exchanger

3.5 Regulations for district cooling systems in Singapore

To prevent “Low Delta-T Syndrome” and optimize chiller performance, Singapore’s district cooling systems enforce strict guidelines on supply and return temperatures of chilled water in the substation network, requiring customers to install and properly maintain a self-regulatory chilled water control system installed on the heat exchanger in the substations:

- The cold supplier must ensure that chilled water supply temperatures at the inlet of heat exchanger (indirect system) do not exceed an agreed threshold.
- CustomerS must ensure that the return temperature of chilled water at the outlet of heat exchanger does not fall below a threshold.
- TCustomres must maintain a demand load of at least 50% of declared peak power and not exceed 100%.
- If a secondary chilled water system is used within a building, customers must ensure proper water treatment to prevent fouling and corrosion of the heat exchanger system.

4. National legal framework related to DHC substations

4.1 Overview

When discussing demand management possibilities in buildings, the legal framework, national standards, and technical specifications must be considered. This section compiles recommendations and national practices in the form of guidelines, standards, accepted technological rules, laws, and regulations. The purpose of this collection is to identify minimum requirements on substations, manufacturing, commissioning, testing/qualification, as well as measurement and billing across different countries. In general, some contries (e.g. Germany) have numerous rules and standards, while others (e.g., Italy) have significantly fewer.

4.2 Germany

4.2.1 Minimum requirements for DH substations

Figure 16 illustrates requirements for a DH substation, using an indirect connection as an example. The highlighted equipment is essential for safe, secure and energy-efficient operation and represents the current industry standard.

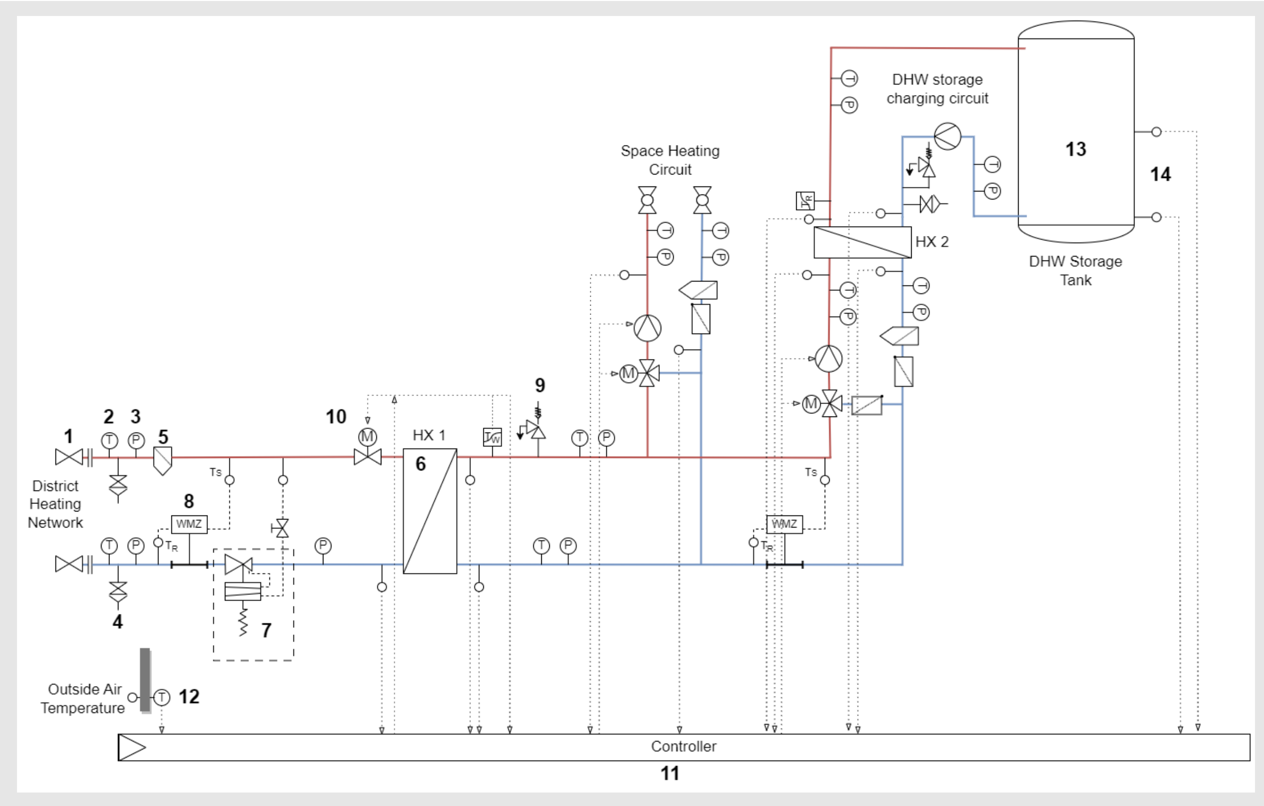

Figure 16: Minimum equipment for the safe, secure and energy-efficient operation of a DH substation

The following components are required as a minimum for a district heating substation:

- Shut-off valves (1) in the supply and return lines
- Visual display of temperature (thermometer (2)) in the flow and return lines
- Visual display of pressure (manometer (3)) in the flow and return lines
- Venting in the flow (top) and draining in the return (bottom) (4)
- Strainer in the flow before heat exchanger inlet (5)
- Heat exchanger (6): In Germany (as almost everywhere in northern Europe) plate heat exchangers are used. The advantages are that they are compact, cheap, and reliable. Their compactness helped to develop ever larger prefabricated substations.
- The differential pressure regulator with flow limitation (7) is installed in the return line of the primary side. It regulates the differential pressure between two defined pressure values. The first pressure value is located in the primary flow line, the second is in the regulator itself downstream of the orifice plate. By integrating the orifice plate it is possible to adjust the flow rate due to the contractually agreed connected load. The functions of differential pressure control and volume flow limitation do not necessarily have to be combined in one component. Alternatively, they can also be achieved with other components. The diagram shown serves as an example of the functions required for safe and efficient operation of the house station.
- Calibrated heat meters (8) ensure the correct measurement and billing of the purchased heat. For this purpose, a flow rate measurement and a temperature difference measurement between primary flow and return are required. The heat supplier is responsible for ensuring the consistency of the measurement. As a rule, heat meters are recalibrated or replaced every 6 years.
- Safety valve (spring-loaded) (9)
- Modulation valves for control (10) are either *self-operated valves* (mechanical valves), or *motorized valves*, driven by electrical power. *Self-operated valves* usually provide *proportional (P-)control* and therefore, some static deviation of a few Kelvin from the set point can't be avoided (control error). They are often used in the smaller size range of DHW temperature control. *Motorized valves* typically provide *PID-type control* (proportional with added integration and derivation), or of another elaborated, similar type that is able to avoid static errors. They are often used for outside air temperature-compensated control of supply temperatures and larger controllers for DHW temperature control that require greater force to move the spindle.
- Control unit (11) for the flow temperature of the secondary side, this includes: temperature sensors in flow secondary side, return primary side, outdoor temperature (if weather-compensated) and a connection to the modulation valve, more information already given in 2.1.5.
- Outdoor temperature sensor (12)

If DHW heating is connected, the following additional components are required:

- Hot water tank (13)
- Switch-on and switch-off temperature sensors (14)

4.2.2 Ownership

Traditionally, ownership boundaries between the heat supplier and consumer are defined within the house substation. Within the substation, the transfer station is owned by the utility, while the house control center is owned by the building owner. Historically, these components were separate, with each owner responsible for procurement, installation, operation, and maintenance. This remains the standard for lare-scale plants. However, in smaller and medium-sized plants (up to approx 400 kW_{th},), compact stations are now the norm. In these cases, the transfer station and the house control center are combined into a single structural unit. As a result, and due to different business models, the boundaries of ownership and responsibility within a substation are blurred.

4.2.3 National standards and guidelines in Germany

In Germany a lot of standardization guidelines and accepted rules of technology are available. The most important ones in the field of district heating substations are coming from:

- the German energy efficiency association for heating, cooling and CHP (AGFW - Der Energieeffizienzverband für Wärme, Kälte und KWK e.V. [5])
- the German Institute for Standardization (DIN - Deutsches Institut für Normung [6])
- the association of German engineers (VDI - Verein Deutscher Ingenieure [7])

Since the information given in section 2 is mainly based on the standards mentioned below, the individual guidelines are only mentioned with a brief summary in order to avoid repetition.

Standards from the German Institute for Standardization (DIN):

DIN 4747:2022-08 District Heating System - Safety equipment of network substations, house substations and consumer's installations connected to hot-water district heating networks

- Document applies to the safety equipment of substations, house stations and house systems for direct or indirect connections to heating water district heating networks. The safety equipment mainly consists of devices for detecting pressure and temperature and devices for limiting them.

DIN 18012:2018-04 Service connections for buildings - General planning criteria:

- This standard applies to the planning of connection facilities for the supply sectors electricity (low voltage network level), gas, domestic hot water, district heating and communication for residential and non-residential buildings. It contains specifications on the constructional and technical requirements for their installation.

DIN EN 12098-1:2021-09 Energy performance of buildings - Controls for heating systems - Part 1: Control equipment for hot water heating systems

- This draft standard applies to electronic control devices for heating systems with water as heat transfer medium and a flow temperature of up to 120 °C. These control devices are used to control heat distribution and/or generation as a function of the outdoor temperature, time and other reference variables. It also deals with control devices with integrated switch-on optimization function or switch-on/switch-off optimizations function. Safety-related requirements for heating systems are not affected by this standard. The dynamic behavior of valves and actuators is not covered in this draft standard. A system with multiple distribution circuits and/or generators requires a coordinated solution to avoid undesirable interactions and is not covered by this standard.

DIN 1988-200:2012-05 Codes of practice for drinking water installations - Part 200: Installation Type A (closed system) - Planning, components, apparatus, materials; DVGW code of practice

- German supplementary standards to European standards. It applies in conjunction with DIN EN 806-2 to the planning of drinking water installations, installation type A (closed system) in buildings and on land. It contains additional specifications for the consideration of national laws, ordinances and the existing German technical regulations and specifies the planning bases and the components, apparatus and materials suitable for the installation of the systems. In particular, the relevant information from the DIN 1988-2, DIN 1988-5 and DIN 1988-7 standards is used, which is required to maintain the high technical standard of drinking water installations recognized in Germany.

Additional Standards for drinking water installation are covered in the series of DIN EN 806-1: Specifications for installations inside buildings conveying water for human consumption:

- Part 1: General (2001-12)
- Part 2: Design (2005-06)
- Part 3: Pipe sizing - Simplified method (2006-07)

Association of German engineers (VDI):

VDI 2036:2022-07 Building installations for district heating

- This guideline serves planners, engineers and executing companies as a planning and design guide for house central heating control and building installations according to DIN 4747. which are supplied with direct or indirect connection from a heating water district heating network. Historically, the procedures and regulations for the construction and operation of oil and gas heating systems have been familiar to planners, engineers and contractors. Due to increased requirements and changes in technology, district heating is now an alternative for supplying areas with low heat density. Due to the requirement of the Energy Saving Ordinance (EnEV) not to exceed a prescribed annual primary energy requirement, modern district heating supply with the use of combined heat and power (CHP) is gaining importance, depending on the primary energy factor.

The German energy efficiency association for heating, cooling and CHP (AGFW) gives technical rules and guidelines that serve as a preparatory, supplementary or also concretizing set of regulations to the national and European body of standards. The editions relevant for substations are:

FW 207 Requirements for heat meters for substations- technical specifications and warranty conditions

- This worksheet applies to all heat meters for use in district heating substations for recording the quantity of heat supplied. It contains the necessary technical specifications for proper operation and the necessary warranty conditions.

FW 309/4 Energy performance of district heating – heating water district heating stations and substations

- This information sheet specifies the parameters for the energy calculation of district heating substations. Within the scope of energy balancing according to the methodology EN 15316 and EN 15603 or DIN V 18599, the performance data of district heating substations are also required. This data can be determined in accordance with the mentioned standards according to this document.

FW 508 Requirements for outside temperature compensators (OTC)

- Depending on the application, the operation of district heating substations and the downstream heat consumers is controlled either as a function of the outside temperature and time or according to demand. According to the requirements of the market, control devices in various performance grades are required. These range from standard control equipment for individual buildings to remote operability via telephone, internet or building services bus systems to networking with higher-level control systems for service providers in the field of building management. These tasks are largely performed by digital control devices. Analog control devices are usually only found in existing systems and are replaced by digital control devices in the event of a defect or system modernization. This worksheet defines both the basic requirements and the essential key data to ensure a comparable performance standard for the control equipment.

FW 509 Requirements for district heating-house substations in heating water systems

- The worksheet applies to prefabricated house substations for connections to heating water district heating networks. The worksheet does not apply to apartment substations covered in AGFW FW 520.
- Standardized, prefabricated house substations have achieved cost reductions compared to on-site construction. These are generally referred to as compact stations, regardless of their size and function. The principle of these compact stations is that all system components - both of the transfer stations and the house central station - are combined completely ready for operation, i.e. also including electrical installation, and are mounted "compactly" on a frame. Compact stations are delivered ready for the month, installed on site and only have to be connected to the supply lines of the district heating and the building installation.
- Compact stations are created individually according to the requirements of the individual district heating supply companies. This concerns the design parameters and selection of the individual components, right down to their arrangement.

FW 510 Requirements for circulation water in industrial and district heating systems and recommendations for their operation

- This worksheet specifies the requirements for the quality of the circuit water in district heating systems. It also provides information on planning, design and operation. The aim of the worksheet is to minimize the risk of damage caused by water-chemical disturbances, such as lime scaling and corrosion, and to ensure the operational safety and availability of the plants.

FW 515 Technical connection conditions heating water

- Pursuant to §17 AVBFernwärmeV, district heating supply companies issue technical connection conditions (TCC), which represent a summary of the technical rules applicable to the specific supply case. These are part of the contract and thus binding for the companies commissioned with the planning and construction.
- TCCs serve to define technical and qualitative minimum standards in the respective supply area and are thus a prerequisite for an economical, safe and secure supply of heat. Minimum specifications recognized by experts for the entire industry in Germany are an indispensable basis for the economic efficiency of the supplying industry and thus for a cost-effective heat supply.
- Due to the large number of details to be taken into account, it is hardly possible for individual - especially smaller - district heating supply companies to draw up TCCs that are free of contradictions, or this would involve a great deal of effort. A template, which can be easily adapted to the existing company-specific parameters, leads to a significant relief of the AGFW member companies.

Additional information concerning the periphery of district heating substations are given in (selection):

- FW 501 Definitions for regulators for heating water and steam
- FW 521 CE-conformity assessment of district heating substations
- FW 523 Comparison of drinking water heating systems
- FW 525 Inspection and maintenance of district heating substations
- FW 526 Implementation of DVGW standard W 551 in district heating supplied plants
- FW 527 Safety requirements for domestic substations, stations and domestic systems to be connected indirect district heating networks
- FW 528 District heating substations - implementation of the ordinance on industrial safety and health
- FW 530 Operations to achieve low return temperatures

4.3 Sweden

District Heating Substations – Design and Installation

ENERGI Företagen – Technical Regulations F:101 – Feb 2016 [8]

- Substations must be CE-marked unless they fall under Article 3 of the Pressure Equipment Directive (PED) 97/23/EC, i.e., they must include a declaration of conformity.
- Substations can be connected to higher-level supervisory and control systems so long as it complies with the heat supplier’s requirements and meets the heating needs of the building.
- Both space heating and domestic hot water circuits must be fitted with temperature sensors.
- Domestic Hot Water control system: consists of a control valve, a valve actuator, sensors and a controller. although self-acting thermo-mechanical valves may also be used in detached house substations.
- Heat meters are the property of the district heating supplier.
- The heat supplier must be able to connect the metering equipment to a communication system for remote meter reading.

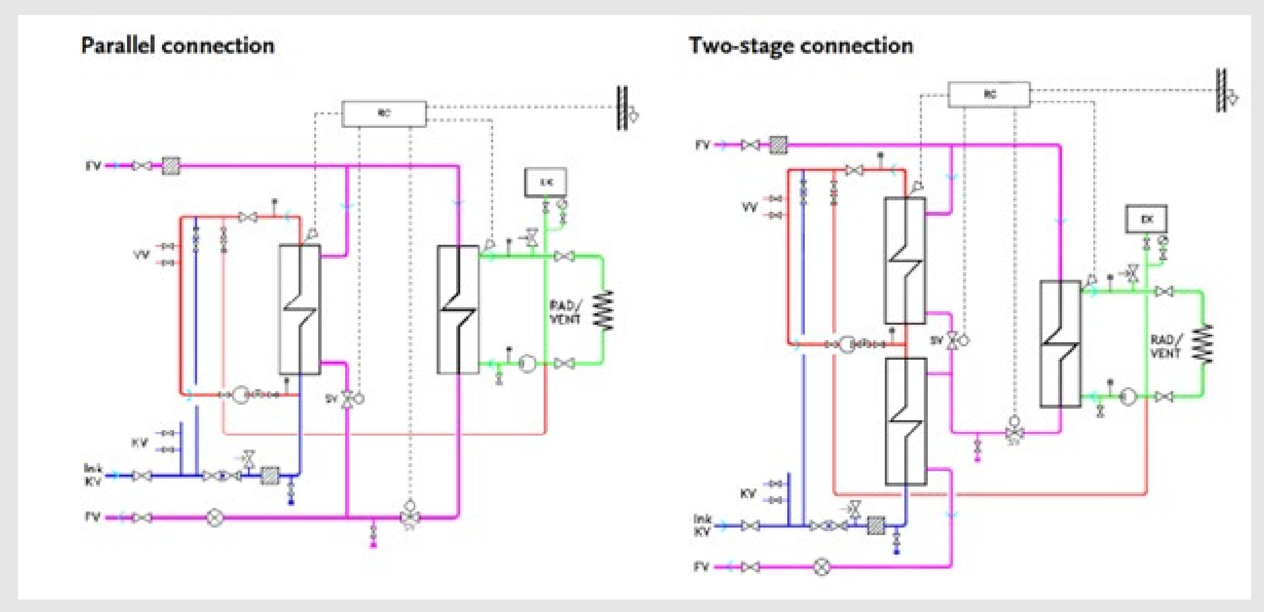

Figure 17: Parallel and two-staged connection

Figure 17 illustrates the difference between parallel and two-stage connection.

- Parallel connection: The most common setup, whereheat exchangers (HXs) are connected in parallel across the supply's incoming and return connections. One HX for the radiator circuit and one for the DHW circuit.
- Two-stage connection: The return water from the radiator circuit is used to preheat the DHW. This results in a lower return temperature compared to parallel connection, provided a DHW demand esists in the substation.
- The primary-side return temperature must not exceed the secondary-side return temperature by more than 3°C.

The Swedish District Heating Association recommends that there should be no storage of water below the domestic hot water design temperature, in order to achieve the best possible environmental requirements applicable to the water. A temperature of 60 °C must be reached and maintained in hot water storage or buffer tanks for a sufficient time to ensure that any Legionnaires' disease bacteria are eliminated before the water is distributed to taps.

4.4 Austria

There is limited literature on requirements specific to Austria. In general, the regulation and technical specifications for DH substations align with the German standards and requirements.
The calibrated heat meter must be securely anchored to the substation.

4.5 Italy

Italian Legislation related to DH substations includes:

- Main rules related to the design / use of pressure equipment, applicable to safety for pressurized substations
  - Raccolta R 2009 – Italian higher institute for prevention and work safety [9]: provisions, issued (as technical specifications *Titolo II del D.M. 1.12.75 ai sensi art. 26 del decreto medesimo*) for central

heating systems using hot water under pressure with a temperature not exceeding 110 ° C, and pressure larger than 35kW. The provisions do not apply to heat generators that are CE / PED certified.
  - PED: *DIRECTIVE 2014/68/EU European Parliament and council 15th may 2014* on the harmonization related to the market of pressure equipment (recast). It applies to the design, manufacture and conformity assessment of equipment operating under pressure and of assemblies subjected to a maximum allowable pressure PS higher than 0.5 bar. The Directive aims to ensure a high level of protection of public interests, such as the health and safety of people, the protection of pets and property, as well as fair competition on the Union market.
- Rules on building energy efficiency (*e.g. from transposition European directive 2002/91/CE, European directive 2010/31/UE*). In this framework D. Lgs. 102/2014 e s.m.i. which provided for the adoption of thermostatic valves in heating devices. This requires proper pumping systems, to operate with variable flow rate and appropriate checks to allow the correct functioning of the heat exchanger substation.
- Rules on plant/system management: *Decree of the President of the Republic 16 aprile 2013, n.74* defines the general criteria for the operation, management, control, maintenance and inspection of heating systems for the winter and summer air conditioning of buildings and for the preparation of water for hygienic-sanitary use. *Decree of the President of the Republic 16 aprile 2013, n.75*. Concerns the regulation of the accreditation criteria to ensure the qualification and independence of the experts and bodies to whom the energy certification of buildings is entrusted. *Ministerial Decree 10 febbraio 2014*: Defines the new booklet for air conditioning in rooms and the energy efficiency control report.

Other guidelines/good practices are provided in 1) *Linee guida per l'applicazione di piccole e medie reti di teleriscaldamento nei comuni in zone E ed F*, by ENEA the National Agency for New Technologies, Energy and Sustainable Economic Development, a public body aimed at research, technological innovation and the provision of advanced services in the sectors of energy environment and sustainable development. The document represents a guideline for the application of small and medium-size district heating networks in municipalities in cold climatic zones. 2) *Termoregolazione e contabilizzazione individuale in impianti allacciati a reti di riscaldamento, guidelines on provided by* Ordine degli Ingegneri of Turin (Association of engineers) and the company Iren energy. This provides the description of the equipment required for district heating, plant diagrams for the thermal substations for different kind of installation as well as, the preliminary activities required for the installation.

4.6 Denmark

4.6.1 Standards

- **DS 418** (SH demand): Rules for the calculation of heat loss from buildings. The rules provide a simple and practical method for assessing heat losses, suitable for the design of requisite heating plants. For building components, they further provide a method for the calculation of design heat transmission coefficients, suitable for the assessment of apparent thermal insulation properties. The simplification involved in the rules depends on the assumption of steady-state. Space heating installations in Denmark are designed according to a design heat loss scenario where an indoor temperature of 20 °C and a design outdoor temperature of -12 °C is considered. According to the standard, the heating installations should be able to cover the design heat loss of the building with heating system supply and return temperatures of 60 °C/40 °C. The design heat loss is calculated by adding the transmission heat loss through constructions and the ventilation heat loss.
- **DS 439** (DHW demand): This Code of Practice applies to water supply installations connected to public or private water supply systems or to smaller private systems. According to these standards, DHW should be available at the kitchen tap and shower within a waiting time of 10 seconds, with minimum temperatures of 45 °C and 40 °C, respectively, for comfort reasons. In order to avoid the risk of Legionella, DHW should be supplied from the DHW tanks or the DHW heat exchanger at temperatures above 55 °C, while DHW circulation should return at a minimum of 50 °C. However, specific national policies must be used

to design and fulfill the requirements to avoid any risk of Legionella for DHW preparation. To meet these requirements and ensure proper DH temperatures, it is essential to ensure that sufficient heat can be transferred to the DHW circuit while low temperatures can still be ensured in the DH system. For the DHW tank, it should also be ensured that the tank volume relates to the thermal power of the heat exchanger in a way that ensures enough available hot water to satisfy the hot water consumption during maximum hot water tapping. The requirements depend on the type of building serviced and the type of DHW installation. In this text, we will focus on two types of customers and two types of typical installations, according to the investigated case buildings.

The typical customer types are:
1. Single-family houses
2. Apartment buildings

Typical DHW installations are (comparative scheme is shown in Figure 11):
1. DHW tanks (storage system)
2. Instantaneous heat exchangers for the preparation of DHW (flow-through system)

The instantaneous heat exchanger should be dimensioned for a total effective power of 32.3 kW and a necessary power of 42 kW if lime deposits and heat losses from the heat exchanger are taken into account. Installations on the primary side of the heat exchanger should be designed for a maximum flow of 0.26 l/s (or 940 l/h) when design primary side temperatures of 60 °C/30 °C are considered.

For the DHW tank, the total effective power of the heat exchanger relates to the volume of the tank. For example, a tank with a volume of 140 L requires a heat exchanger with a necessary thermal power of 2.7 kW. In apartment buildings with DHW tanks the small simultaneity factor for consumption of DHW in several apartments can be considered. For instance, approximately 75 apartments can be expected to hold a hot water tank with a volume of 2625 L and a heating capacity of 98 kW.

- **DS 469**: This standard specifies requirements for heating and cooling systems. The requirements are intended to give a technically correct quality level, with the required thermal indoor climate maintained with the lowest possible energy consumption. The standard applies to all types of heating- and cooling systems, which have the purpose to supply rooms and buildings and connected systems with heating or cooling. The heating media respectively the cooling media in the system can be either e.g. water, air or electricity.

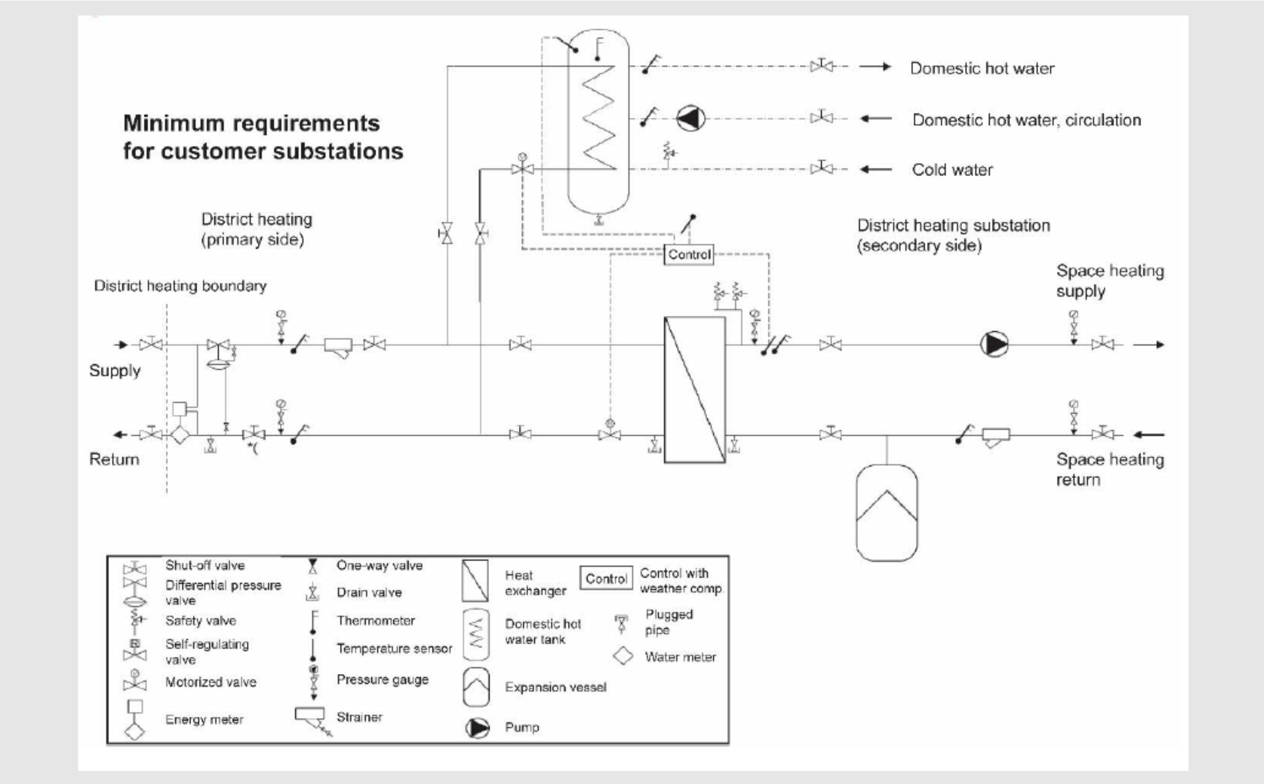

Figure 18: Minimum requirements for customer substations

- **DS 16975:** The target is to describe what is an eco-efficient substation (EES), how this eco-efficient substation is considered, tested and certified. The EES concept includes as much substation efficient design as possible, without trying to cover an exhaustive point of view. The scope of the EES is to focus on a reachable future, realistic compliance with the existing system and ways of handling substation issues in a harmonized manner across Europe. The proposed standard is compilable with the expected development in Europe in the future such as: • New buildings with less demand for energy and more demands for lower temperatures. • The connection systems should be standardized in order to make the substation replacement as easy as possible. The aim is to consider the whole life of the system, including all seasons and not only the peak load operation. The most important period to consider, is the long duration time with both heating and domestic hot water demands. EES should be certified, and marked according to certification that is given according to testing results and environmental ranking. Only EES with capacity up to 500 kW per heat exchanger for heating and domestic hot water respectively, can be certified. Small substations intended for single-family houses or flats, shall not be certified. A certificate can include one specific substation or a series of substations. This document contains 3 main parts:
  - Technical: Describes the main and optional components of the EES
  - Environmental: Describes the various parameters and components that give the efficiency to the substation, how these are ranked and the marking procedure
  - Testing and certification: The testing and certification procedures.

- **DS 1148:** This standard applies to series produced water to water heat exchangers, for district heating appliances and its purpose is to establish uniform methods to test and ascertain the following: – product identification – performance characteristics – pressure drop.

- **Varme Ståbi:** is the heating industry's solid and reliable reference book containing basic theoretical concepts in heating technology as well as instructions on the dimensioning and execution of heating installations in practice. The key statements are shown in Table 3.

Table 3: Instructions on space and domestic hot water heating related to Varme Ståbi

Space heating	Domestic hot water
General - Must be provided through an indirect connection (heat exchanger) - The heat exchanger should be designed to deliver the design heat demand of the house with supply and return temperatures of 60 °C/30 °C at design outdoor temperature of -12 °C **Floor heating** - Floor heating systems must be designed to deliver the design heat demand in a room with supply and return temperatures of 45 °C/30 °C at design outdoor temperature of -12 °C	- DHW installations should be designed to cover the design heat demand for DHW with supply and return temperatures of 50 °C/30 °C - The design DH flow required to meet the standard peak heat DHW demand in single-family houses of 32.3 kW cannot exceed 900 l/h - The installation should include a heat storage if the peak heat demand for DHW is above 55 kW

- The weather compensation control is typically installed in all apartment buildings. The supply temperature is gradually decreased and optimized according to the variation of the outdoor temperature based on the building heat losses. Proper control of supply temperatures reduces the distribution heat losses in the pipelines and can lead to lower return temperatures. In real operations, the heat demand accounts for both the building heat losses and the heat gains. As the SH elements are typically oversized due to the stringent design requirements, the weather compensation curve can be further optimized while still ensuring the same thermal comfort with lower supply temperatures.

4.6.2 Ownership and rental unit

Typically, the substations are owned by the building's owners (private, cooperative, etc). In order to ensure low temperatures, it is essential that the customer substations work properly and that they are compatible with low-temperature operation. However, old substations may not be replaced before they break down entirely and not all customers have the money to pay for a replacement. A solution to this issue could be to give the customers the opportunity to rent their substation through the DH company and thereby the opportunity to pay for the cost of a new substation through the normal heating bill. Thereby the customers do not need to pay the initial cost of a substation and often, if the existing substation is old and inefficient, the additional cost on the heating bill will be covered by the savings obtained when installing the new substation.

One of the DH companies offering this type of service is Viborg District Heating. Their customers are typically small single-family houses, and hence the substations are small units. The current cost of renting the substation is approximately EUR 22 per month, which covers the installation, the substation itself, and a service agreement for the substation. Thereby, the customer does not have to worry about the maintenance and cost of replacing malfunctioning components during the 20-year period that the rental agreement covers. If relevant, the customer can buy the substation after the first six-month period, which can be relevant especially in relation to customers selling their house at some point during the contract lifetime. The typical procedure of the installation consists of five steps. The first step is customer interest and then contacting a DH. Second, the DH company provides any necessary extra information and answers customer questions. Third, a craftsman visits the house to identify how the new substation can be installed and which extra costs might be included. Fourth, if the customer accepts the offer and signs the contract, the craftsman installs the new unit and lets the DH company know that the new substation is now in operation. Last, the DH company establishes and documents the new substation and rental agreement in their system. The procedure is illustrated in Figure 19 below.

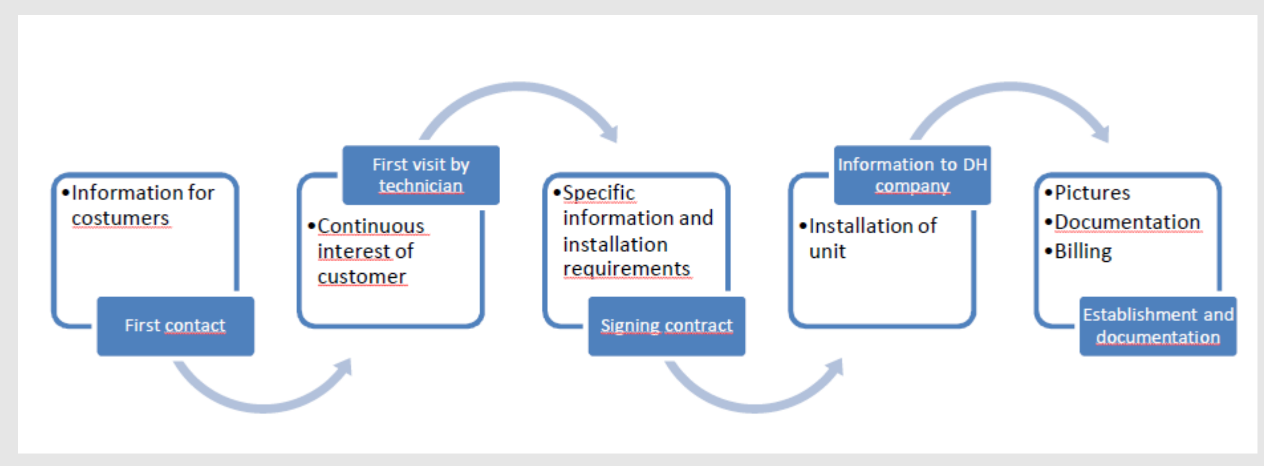

Figure 19: Typical substation installation procedure

A benefit of this solution is that return temperatures often drop to 30 °C for customers who install a new substation. This means lower return temperatures and more hydraulic capacity in the network. Furthermore, Viborg District Heating found that the customers so far generally experience an average energy consumption savings of approximately 10% plus the electricity savings of a new pump and the benefits from the motivation tariff. Additionally, the substation can be equipped with wireless access to data for fault detection purposes, and prepared for a lower supply temperature. Since the replacement of the substation may be done earlier when the customers do not need to find the money for the initial investment, this will enable low temperature operation in the DH network within a shorter time-frame.

5. Definition of flexibility readiness status

5.1 Substation flexibility: What is it and affects it?

What is substation flexibility? Flexibility refers to the ability of the system to function under different operating conditions, adjusting its outputs (i.e., the thermal flux exchanged and the temperature of the water supplied to the building). This capability depends not only on the characteristics of the thermal substation itself but also on the various elements connected to it. A schematic of a typical substation is shown in Figure 20, where the sources of flexibility discussed in this section are highlighted in different colors. Since there are many types of thermal substations, with different connections and components, a compromise was made to consider a design as complete as possible and widely used [Frederiksen, & Werner, (20139] [1]. This ensures a broad overview of flexibility sources while maintaining applicability to various DH systems.

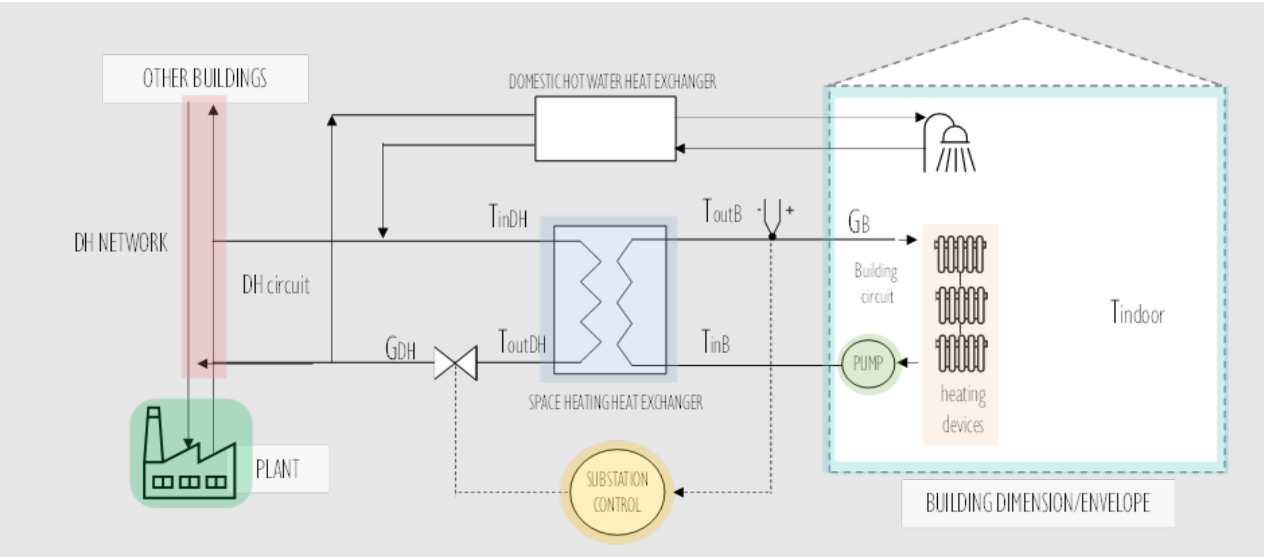

Figure 20: Elements affecting the substation flexibilty

The flexibility of a substation under steady-state conditions depends thus on the product UA, the heat exchanger configuration/design, the mass flow in the DH circuit, and the mass flow in the building circuit. Regarding the mass flow in the DH circuit, this is influenced by the temperature in the building circuit. However, since substation operations are not alsways in steady state, on the control strategy of the substation, and the regulation of the building circuit (and therefore the control of the pump and the building terminals). A limiting aspect is the maximum mass flow rate that can be processed in the thermal substation. The product UA can be significantly affected by fouling; this should be considered as a limiting factor. Another factor influencing the flexibility is related to the building heating circuit and the building heating devices; indeed, these influence the return temperature, and consequently, the temperature exiting the heat exchanger and therefore the mass flow in the DH circuit. Also, the possibility of the thermal substation to make attenuations, load shifting, control modifications, without affecting the indoor comfort conditions, depends on the characteristics of the building envelope. Further aspects concern the possibility of having a remote control of the substation, and the substation configuration, considering eventual other devices (e.g. hot water tank). Another important aspect is related to the temperature the substation is supplied with. This depends on the DH generation and the DH temperature regulation, and for what concerns the thermal losses and the thermal transient, the network dimension/thermal mass.

All these aspects, introduced here, are discussed one by one in this report. In particular:

- Flexibility aspects related to the heat exchanger were discussed in section 2.3.2

- Section 2.5.1 covered the substation itself and its control strategy
- Section 2.5.2 focused on the building circuit
- Sections 5.2 and 5.3 examine heating devices and the flexibility from over-dimensioned radiators and DHW storage tanks
- Section 2.4.4 explores how the network and production plant affect the substation flexibility

5.2 Over-dimensioning of the radiators

Most residential buildings connected to DH use radiators as heating devices. Over-dimensioning of the radiators is a crucial factor in substation flexibility. Being over-dimensioned, means having a product UA that guarantees a sufficient heat exchange also for lower values of supply temperature/mass flow rates. This depends on: a) the number of radiators and b) the heat exchanger area of the radiators. The radiator dimensioning is done considering the most severe outdoor temperature conditions. For this reason, during normal operations, these devices result in being over-dimensioned. The topic has been significantly investigated in [Østergaard (2018)], where it is shown that as much as 80% of heating systems are currently significantly over-dimensioned [10]. In [Benakopoulos et al., 2021] it is shown that only a fraction of the available radiators are used in dwellings. The degree of over-dimensioning becomes more significant if considering that during the life of a building (if not newly built) this is continuously subjected to retrofitting measures [11]. In Figure 21 a load curve is reported for a radiator, dimensioned to exchange 50 W at the design temperature (-8 °C). Different load curves are reported for different values of reduction of the building load, due to retrofitting interventions. In case of typical winter operations of the system (about 5 °C), the thermal demand of the device ranges between 30-50% with respect to the design value (depending on the retrofitting degree). This means there is large potential related to exploiting the oversizing and outnumber of heating devices. This provides a large degree of flexibility, since G_B and T_{outB} could be modified in a wider range, to achieve optimal substation operations.

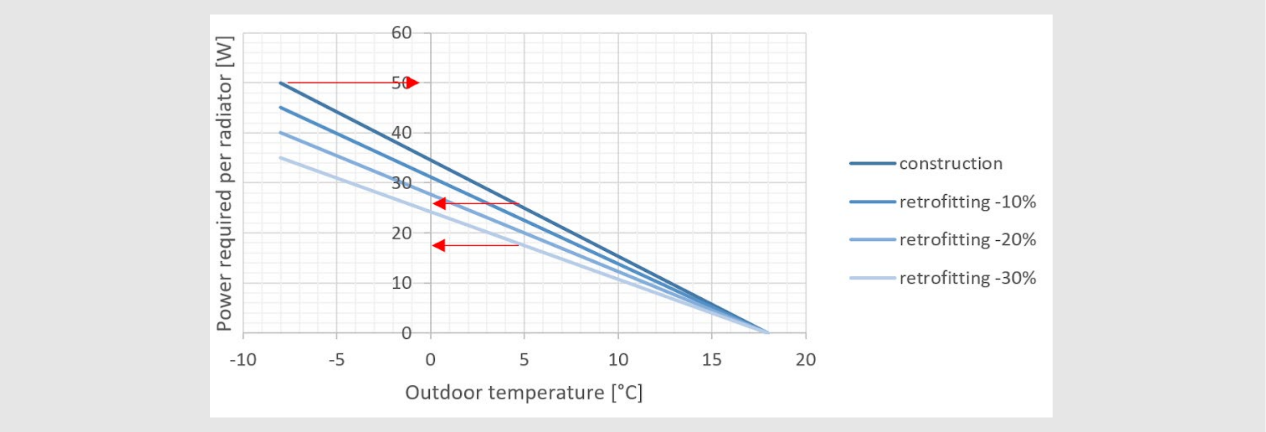

Figure 21: Load curve reduction for different retrofitting interventions

5.3 Domestic hot water heating

If a DHW system with a storage tank is used, there are some flexibility options possible:

- Variation of the storage tank charging tank temperature: There is a lower temperature limit depending on hygiene requirement and an upper temperature limit depending on lime deposit/stone formation. Both limits depend on national regulations and water quality (estimated charging temperature variance appr. $\pm 5K$).

- Shifting the “night” load: DHW tap profiles can be estimated according to typical days (e.g. typical summer work day in a residential building). Between the last withdrawal in the evening and the first withdrawal the next morning, the charging of the DHW storage tank can be shifted in time.

5.4 Network

5.4.1 Supply temperature (network generation)

Flexibility is significantly affected by the network. It depends on the supply temperature, or, more specifically on the potential temperature range that can be adopted. The first networks, built in the late 19th century [7] (first generation) used steam as heat carrier; then in the 30th - 70th, pressurized overheated water was adopted (second generation). After the 70th, hot water below 100 °C (third generation) was mainly used. In 2014, fourth generation was for the first time mentioned, [12] [Lund et al., (2014)] to describe the trend towards supply temperature reduction. The continuous decrease of the supply temperature: a) allows exploiting lower temperature heat (increasing the performance of the CHP) and enabling the possibility of integrating renewable heat and waste heat into DH and b) reduces the thermal losses during heat distribution.

Actually, as concerns the flexibility, if a wide range of supply temperature can be exploited, the system can assume a larger range of supply temperature and mass flow rates at the thermal substation. This means that:

1. Mass flow rates can be reduced/increased according to the supply temperature available and
2. Large thermal power can be exchanged when largely available if higher supply temperatures are achievable.

Therefore, the increasing adoption of low exergy heat (e.g. renewable, waste heat) plays a twofold role in the reduction of the substation flexibility. The first, is to limit the flexibility due to the lower temperature gap between supply and return. This means that the increasing reduction of the supply temperature plays a negative role in the system flexibility, especially when the return temperature reduction achieved is low. The second is that the time when larger or lower supply temperature occurs is difficult to predict.

At the same time, there are networks that also in the next future will adopt large temperature gaps. Examples are large 2nd generation district heating systems, characterized by significant energy infrastructure that cannot be refurbished in a short time or DH systems fed by renewable sources available at sufficiently high temperature (e.g., geothermal high enthalpy source). In these cases, the flexibility is higher and there is larger room for maneuver, for implementing demand response logic.

5.4.2 Network regulation

Depending on the regulation strategy of the network it is possible to distinguish three kinds of DH:

- *DH with mass flow rates regulation:* In this case the mass flow rates change depending on the regulation of the valves installed in the thermal substations.
- *DH with supply temperature regulation:* In this case the mass flow rate circulating in the system is constant during time, but lower supply temperatures are used when the demand is lower.
- *DH with both regulated mass flow rate and supply temperature:* in this case both the regulations are adopted contemporary.

In the last case there is more flexibility in the thermal substation, since a further degree of freedom exists in the regulation. In fact, in the first two cases, both the supply temperature and the mass flow rate, are defined, at a certain thermal demand of the building. In the third case, it is possible to vary the mass flow rate supplied to the substation at a defined external temperature (and therefore thermal need), by varying the supply temperature. However, it is important to take into account two main limitations on this aspect of flexibility. The first is that the supply temperature must be the same for all buildings; therefore, the supply temperature must comply with the requirements of all buildings, unless local booster devices are available. The second is that it is necessary to take into account the significant thermal transients that exist in DH, especially if large. For this reason, it is not possible to precisely regulate the daily variation of the demand in the buildings, as done when mass flows are modified, using only a temperature regulation.

5.4.3 Network thermal mass

The network thermal mass represents a significant characteristic of the network in the management of DH operations. This is due to different reasons:

8. The water exiting the thermal plants travels long distances within the pipelines before reaching the buildings. It takes time, ranging from some minutes to 1-2 hours, depending on the network dimension and the flow velocity (that usually ranges from 0.1 to 3 m/s).
9. The infrastructures (i.e. the substations, the building hydraulic circuit, the pipelines themselves) have a thermal mass and influence the transient behavior of the network. Since these are subjected to temperature increase or decrease, they absorb and release heat depending on the water temperature evolution.

Therefore, depending on the network dimension (i.e. amount of water flowing, length of the pipelines, number of buildings connected), the thermal mass has a different effect [13] [Guelpa, (2021)]. The thermal mass of the system, from a flexibility viewpoint, can be considered as a constraint or an opportunity.

This is a constraint in the sense that it makes the control of the supply temperature much more difficult at the thermal substation, that can be largely affected by a) the distance of the building respect to the thermal source and b) the temperature of the water in the previous time period (this is particularly important in case of night setback/off).

This is an opportunity since a proper advanced control could be used to exploit the thermal mass as a storage.

6. References

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