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sweet swiss energy research for the energy transition

Summary

The Swiss energy sector faces a major challenge: how can existing district heating systems decrease temperature to increase energy and exergy efficiency, while enabling integration of low-grade renewable energy sources? In this work, various temperature-reduction measures are systematically analysed with the overarching goal of providing a guideline for temperature reduction in district heating systems to advance Switzerland's energy transition.

District heating (DH) systems supply heat using various energy sources by means of thermally insulated pipes to buildings with individual usages. Traditional DH operates at high temperatures (often above 90 °C) but depending on the heat source it can be more efficient to shift to lower temperatures (<70 °C). Reducing network temperatures not only minimizes heat losses, but also enables the use of renewable, low-temperature heat sources in combination with electric heat pumps.

The core of this work provides a focused analysis of temperature reduction strategies, which are categorized into four levels: production, distribution, substations, and final users. Each level includes specific actions to lower network temperatures. Structured guidelines showcase each action's technical implications and potential benefits, supported by a matrix that outlines the actions for easy application and evaluation by professionals and planners. A cost-benefit analysis has been conducted to facilitate decision taking among the numerous possible options for temperature reduction. In particular, it is shown that optimizing thermal bypass valves can lead to significant heat savings and cost reductions, with an attainable ROI of 6-8 years. This action has the potential to be replicated in almost 800 existing DH systems in Switzerland.

A Modelica-based simulation framework is applied to investigate the dynamic thermo-hydraulic behaviour of a DH grid system in Losone, which has been taken as a reference to quantify the impact of temperature reduction actions. Simulations of bypass flow reduction during summer operation indicate substantial improvements in system efficiency and reduction in heat losses. The optimized bypass control leads to a temperature reduction 0.5 K for the Losone case study. Applying optimized bypass control to all relevant Swiss DH grids could allow annual savings of round 3 GWh.

This work aims at providing a concise and practical guideline for reducing temperatures in district heating systems, combining actionable temperature reduction principles with economic and technical analyses. The actions are key for enhancing efficiency of district heating networks and accelerating the integration of renewable energy sources. Future research should focus on further integrating renewable energy and exploring 5th generation district heating and cooling systems, especially in view of the increasing demand for cooling in buildings.

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1 Introduction

Thermal networks are essential for the Swiss energy transition and decarbonization of the building stock. The integration of renewable energies into thermal networks requires a rethinking of conventional concepts. Often, existing networks can benefit from a temperature reduction, allowing a transitioning from the third generation DH (~90 °C) to the fourth generation (<70 °C). In this work, we describe the design concepts required to reduce temperature levels in existing networks.

A major challenge toward enabling a larger penetration of renewable energy sources in DH systems is associated to the need to reduce the temperature of existing high-temperature thermal networks. By allowing efficient operation of heat pumps, such temperature reduction measures facilitate the integration of low-grade renewable energy sources and waste heat. Based on a systematic literature review and an in-depth simulation study, this work investigates how this transition can be realized for existing high-temperature networks in Switzerland, primarily from a technical point of view.

In a first step, a comprehensive literature review is conducted with the aim of identifying and cataloguing existing district heating classes. Then, based on the scientific and technical literature, a matrix is created to catalogue the actions aimed at lowering the grid temperature. For each action, a qualitative score was defined concerning the technical and economic feasibility of possible actions. Actions deemed most promising were further explored quantitatively, showing calculated and simulated results applied to a real case study in Losone.

2 State of the Art

2.1 District Heating and Cooling Temperature Classification

District heating consists of supplying heat to different buildings and users through pipelines. From the early 1900s to the present, heat generation technologies and temperature levels have changed greatly and are still evolving. In order to distinguish and classify district heating, the scientific community has debated widely about it since the early 2000s, going so far as to introduce the concept of "generations". These generations provide a standardized classification of DH systems that has been widely discussed in various studies and articles. In general, higher DH generations facilitate the integration of renewable energy, reduce energy and exergy losses, decrease the carbon footprint and allow to provide both cooling and heating with the same thermal network.

Following these reasons, one study [1] proposes to adopt the DTS (District Thermal Systems) concept instead of DH (District Heating), to indicate a larger concept of thermal networks able to satisfy or integrate thermal uses in buildings (space heating, domestic hot water, space cooling) by means of networks of pipes connected one side to final users/prosumers and other side to available heat sources. Otherwise, in some cases, the concept of DH should evolve into a broader DHC (District Heating and Cooling). For the same reason, the “Swiss District Heating Association” since 2023 has also changed its name to “Thermal Networks Switzerland”, with the aim of expanding to all companies active in distributing heating and/or cooling at local, district and neighborhood scale.

In Figure 1 the classification proposed by [2] has been described, to provide clear, unambiguous, and user-friendly descriptions for the application of 'generations' terminology. This classification is widely used and recognized internationally, both by academics and professionals in the field.

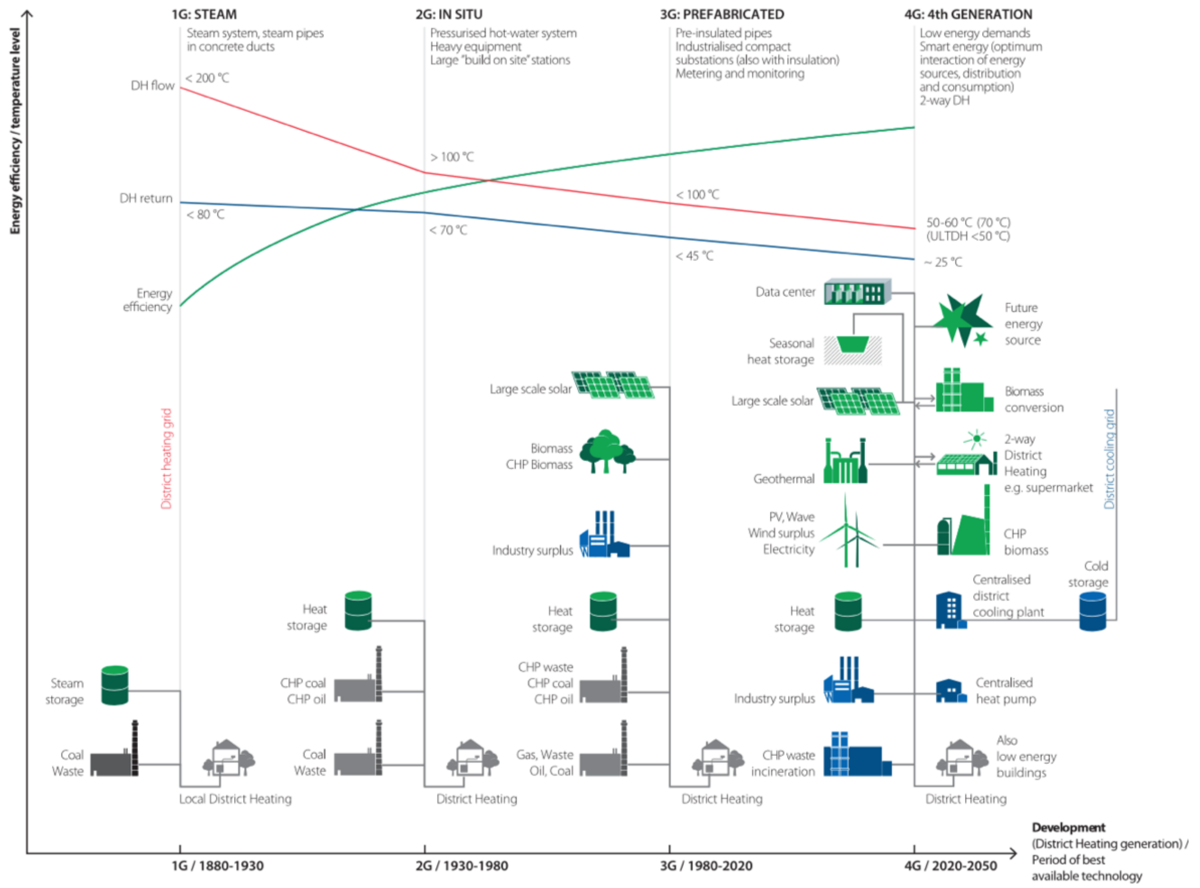

Figure 1 : District heating and cooling generational evolution proposed by [2]

The distinction between fourth and fifth generation (the latter not shown above), although not proposed by Lund, is considered a consequence of the Danish classification by various scientific studies on the subject, as well as fundamental to the integration and use of renewable and low-temperature sources in district heating and cooling networks. In Appendix A, the different five classifications are briefly described and commented about.

Swiss classification and comparison with the Danish one

In addition to the classification based on five generations, another approach has been developed, more focused on the levels of operating temperature and components users' side. This approach is adopted as method of classification in Switzerland according to [3], but is available also in other contributions such as [4].

This typological classification cannot be framed directly by the previous approach, which is mainly based on level of supply temperature and on the age of the DTS, and it is connected to the energy efficiency of the served built environment. According to [3] DTS are classified in:

- High temperature (HT): systems operating at temperatures above 60°C, which most often use waste to energy plants or wood boilers as heat sources. In this category there is one case (1C);
- Low temperature (LT): systems operating below 60°C, which are spreading rapidly implying new supply concepts and storage technologies. In this category there are three sub-classes (2C, 3C, 4C).

In case of HT (here named 1C-HT), heat can be supplied directly through heat exchangers for space heating and production of DHW. LT cases are particularly suitable for new or recently renovated buildings that have higher energy performance and lower energy requirements than older buildings and can be heated with lower temperatures systems coupled by radiant emitting components. Since temperature levels influence the technologies to be used in buildings, three sub-classes among LT DTS have been defined:

- 2C-LT (Supply temperature from 30°C to 60°C): Heat can be supplied directly for space heating. For DHW, the temperature must usually be increased, for example, using a HP. In order to cool the building a cooling system is required and excess heat is not reused. Heat losses along the network are in the range 3–7 % of heat supplied. Energy requested for pumping is around 1–2 % of heat supplied.
- 3C-LT (Supply temperature from 20°C to 30°C): Heat cannot be supplied directly for space heating and DHW; a HP is required. In order to cool the building, a cooling system is required, but the heat produced is directly injected into the network and can be reused. Heat losses along the network are lower than 3 % of heat supplied. Energy requested for pumping is around 1–2 % of heat supplied.
- 4C-LT (Supply temperature lower than 20°C): Heat cannot be supplied directly for space heating and DHW; a HP is required. The network temperatures could be also appropriate for direct cooling of the building by means of a heat exchanger (i.e. without a cooling machine). Excess heat is injected and reused. Heat losses along the network are negligible. Energy requested for pumping is around 2–3 % of heat supplied.

Figure 2 [1] proposes a comparison between the Danish classification and the Swiss classification, considering the DH supply temperature, and the relative possible use or integration of renewable energies.

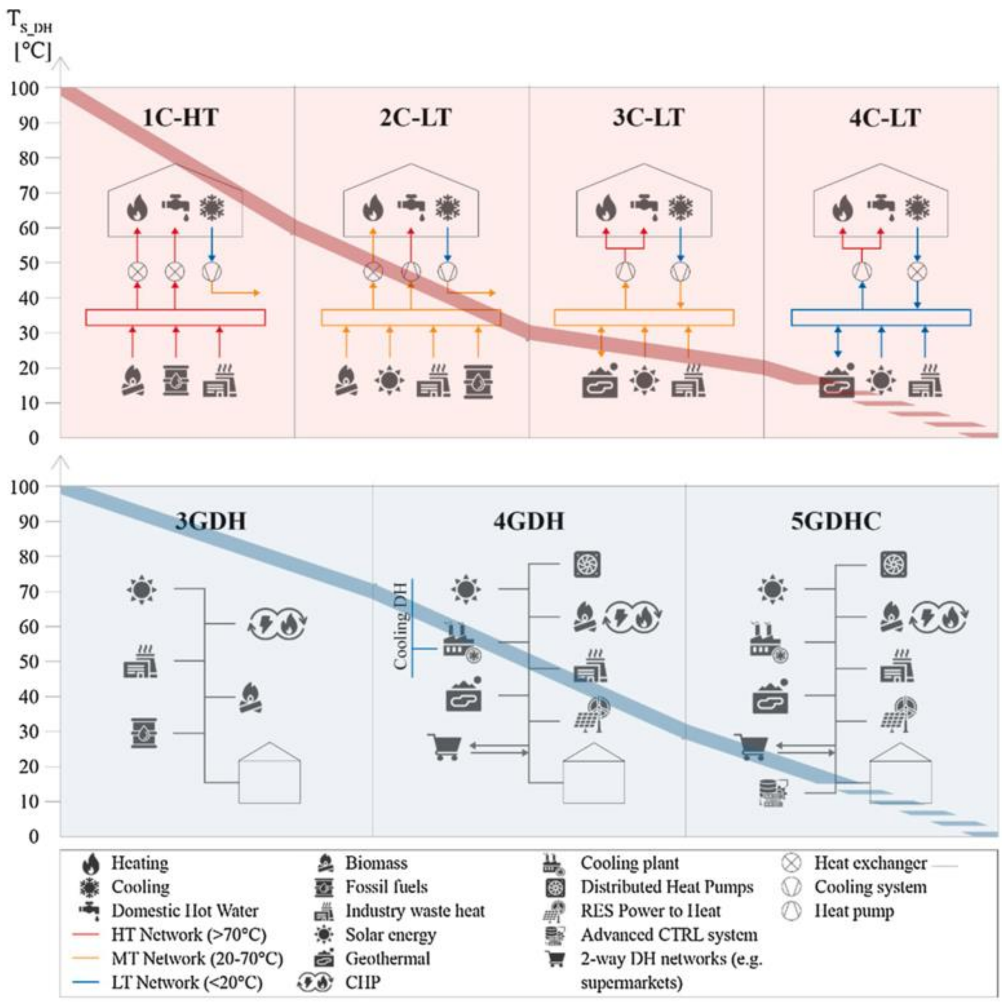

Figure 2 : Comparison of the two classification methods in terms of technological configuration (boxes behind the graph area) and network operative temperatures (ordinate axis on the left). Red shaded objects refer to the classification based on supply temperature and operation scheme, while blue shaded objects refer to the classification based on generation scheme (arrows in red, orange and blue means heat provided to or extracted from the buildings). Source (Caputo et al., 2021).

<u>Temperature levels</u>

Current 3GDH systems operate with typical supply temperatures of around 80-90°C. This allows to connect any type of local distribution systems both for space heating and DHW.

Important considerations about the network temperatures and their implications for the heat distribution to the users are summarized hereafter.

Often, a network that was designed for 80-90°C may be operated at a slightly lower supply temperature (70-80°C). This is due to the oversizing of the systems, and to the existence of residential buildings (or in general space heating demand) that do not actually need such high temperatures.

The observation also indicates that old radiators, in existing buildings, may work with supply temperatures as low as 65°C, which means, that the network supply temperature may be set at 70°C or slightly lower. This requires substations which are standard in structure, but with a larger heat exchanger. With boilers, DHW is mostly stored in tanks, but these are often too small to effectively cover the normal usage. In fact, the boiler is required to heat up DHW, thus obtaining a quasi-instantaneous production. With a 70°C DH network, the DHW storage tank must be large enough to cover DHW usage by the users and must also be equipped with a large surface heat exchanger in order to reach legionella-safe storage temperature (Swiss standards: 58°C).

Networks operated at 50°C will allow to connect buildings with medium temperature radiators. In this case, DHW has to be produced instantaneously.

Supply temperatures between 35°C and 50°C allow to connect buildings with modern underfloor heating through heat exchangers while other users need local temperature boosters, in terms of heat pumps for heating. All users do need, however, a micro heat pump and/or electrical heaters for DHW. Networks with supply temperatures lower than 35°C include local heat pumps both for heating and DHW production.

An important point is that, when lowering the temperature on a DH grid, the spread (e.g. the difference between supply and return temperatures) decreases, thus leading to an increase of mass flowrate and pressure drop. Consequently, the piping may be required to have a higher-pressure limit. For example, the network design pressure in the Lystrup project in Denmark is chosen at 10 bar instead of the conventionally used 6 bar system [5]. The piping selection and size must thus be verified following grid temperature reduction. On the other hand, when lowering the supply temperature below a certain level, more users require the use of booster heat pumps. With booster heat pumps, the network must deliver less energy (as a result of the additional electrical input), thereby limiting the effect of increased mass flowrate.

Figure 3 below shows a concept to classify the network temperatures levels, linked with the DH classifications (Danish and Swiss) where within each level the substation technology is homogeneous.

The reduction of network temperature levels should aim at minimizing heat production, distribution and utilization costs, maximizing low-temperature waste heat or renewable heat sources exploitation as well as the fulfilment of consumer needs in terms of hygiene and comfort [6]. Also, lower temperatures allow the usage of alternative materials and techniques for the network piping, resulting in easier installation and lower investment costs. One further effect of lower temperature networks with booster local heat pumps is given by the fact that the initial common investment is lower, resulting in a lower financial risk (a higher investment is made only when a user connects himself to the grid).

Lower supply temperatures enable higher CHP plant performance, higher central heat pump COP, higher waste and renewable energy utilization and lower distribution heat losses.

Lower return temperatures lead to benefits such as lower pumping cost, lower network heat loss and higher plant efficiency if biomass combustion with flue gas condensation or heat pumps are used. There is no constraint for minimum return temperature on the primary circuit. Operational errors are more critical for low temperature networks, due to more rigorous operational conditions. Analysis and operational monitoring of users and avoidance of bypasses may be necessary in order to avoid errors.

Furthermore, 4GDH does not exclude higher supply temperatures during cold winter periods but does prioritize low supply temperatures for higher heating demands. Networks designed at higher spread still allows the network to operate with a low supply temperature for a significant amount of time.

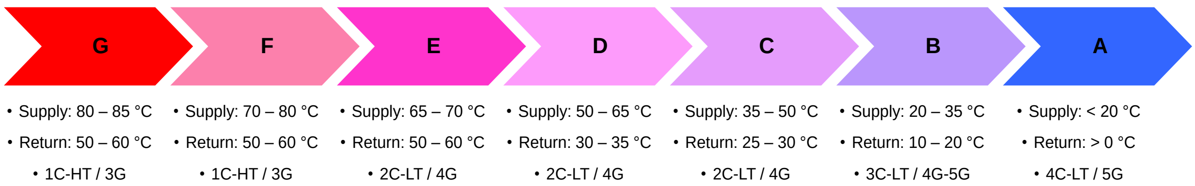

Figure 3 : Concept of network efficiency, based on network temperature reduction.

The present study could not deepen in detail the effects of environmental aspects. As pointed out in [7–9], this could be made with the internalization of environmental impacts, computed on the entire life cycle. Within the frame of a so-called thermo-economic analysis, an objective function corresponding to a cost which includes environmental impact costs may then be optimized (e.g. minimized), thus obtaining optimum design and operation solutions, which often include low-temperature grids, depending on the users-temperature needs.

2.2 Temperature Reduction Strategies

Over the past ten years, numerous studies have been published on the Low-Temperature District Heating (LTDH) approach within the 4GDH concept and related technology options. These include several research projects undertaken in the framework of the IEA-DHC technology collaboration program. Among them, the LTDH for Future Energy Systems project provided an overview of pioneering LTDH implementations [10].

In Europe, the DHC+ platform presented a strategic research agenda in 2012 that outlined visions for 2020 and 2050. This agenda outlined EU targets on near-zero-carbon energy solutions by 2050, which were shared by DHC+. The 4GDH/LTDH concept was seen as a solution based on lower and more flexible distribution temperatures, assembly-oriented components, and flexible materials. This low temperature concept was later confirmed in the new strategic research and innovation agenda by RHC-ETIP (Renewable Heating and Cooling - the European Technology and Innovation Platform).

A few research projects within the European Research Framework and other programs have been carried out, focusing on the development of low-temperature heat distribution. These include projects such as Sunstore2 and Sunstore4, which developed solar district heating systems in Denmark. Other LTDH-oriented projects funded by the Horizon 2020 program include Storm, Flexynets, SDHp2m, Reuseheat, Cool DH, TEMPO, Related and Rewardheat. Regional Interreg programs have funded LTDH projects, such as Heatnet NWE, D2Grids and Lowtemp. Other European research projects include Life4HeatRecovery and Heatstore. The total turnover of these European research projects exceeds 100 million EUR. The “DHC+ Platform” resume EU-funded projects that drive innovation in DHC (direct involvement of Euroheat & Power's and beyond Euroheat & Power's portfolio).

Also, major national initiatives were undertaken in Denmark, Germany, Austria, France, and the Netherlands. In Denmark, the 4GDH research center was active between 2012 and 2018, with a total turnover of almost 10 million EUR. In Germany, the 'Wärmenetzsysteme 4.0' initiative provided 100 million EUR between 2017 and 2020 to fund feasibility studies and pilot projects related to 4GDH/LTDH. In Austria, the flagship project ThermaFlex used more than 8 million EUR between 2019 and 2022 to explore greater flexibility in new and extended district heating systems. In France, the national heat fund can support the introduction of cold district heating systems. These national initiatives demonstrate the growing importance and interest in low-temperature heating and the 4GDH concept throughout Europe.

There are also other mentionable key projects, primarily funded by the IEA and the European Community, that focus on the transition towards low-temperature district heating networks.

A significant project is CASCADE “A comprehensive toolbox for integrating low-temperature sub-networks in existing district heating networks”, which explores the possibility of integrating LTDH into the return line of an existing large urban DH network. This approach leads to a reduction in the return temperature of the DH, improving system efficiency and allowing congestion problems of the mass flow to be overcome.

Another project related to the transformation of existing heating networks into low-temperature systems is “Leave 2nd generation behind: cost-effective solutions for small-to-large scale DH networks”. The aim of the project is to develop cost-effective routes for the transition of existing networks into low-temperature systems, considering the barriers, especially those related to the network and substation side.

The project LowTEMP “Low Temperature District Heating for the Baltic Sea Region” is a project funded by the European Union (European Regional Development Fund & European Neighborhood Instrument) within the framework of the Interreg Baltic Sea Region Program 2014–2020. The goal is to promote the adoption of low-temperature heating, considering all new installations, network expansion, renovation of existing networks even in cases where buildings have not been retrofitted.

The project STEP “Stepwise transition strategy and impact assessment for future district heating systems” deals with the transition towards low-temperature heating. The experimental analysis conducted on 10 real buildings revealed that there is already potential in the existing equipment to reduce the operating temperature of the heating system.

In the project "Transformation roadmap from high to low-temperature DH", the strategies proposed for the transition towards the 4th generation DH mainly consist of identifying temperature errors in distribution networks, substations, and heating systems in buildings; increasing the thermal lengths in substation heat exchangers; and reducing the temperature demand in buildings through the reduction of heat demand or increase of the heat transfer surfaces.

The project "OPTi-TRANS" aims to enhance discussions with DH companies to assist the transition towards low-temperature heating, considering potential actions at a technical level (e.g., at the building level, new sources, management) and at an economic level, including business models and pricing, considering the uncertainty related to the transition.

Finally, the project "Towards 4th Generation DH: Experiences with and Potential of Low Temperature DH" aims to provide a roadmap for the transition to sustainable energy and the total phase-out of fossil fuels. This includes estimating the benefits of using low-temperature heating schemes.

Results and considerations at international level

The results of the relevant research carried out so far converge on the following considerations:

A first result drawn is that the decarbonization of energy systems will eliminate heat recovery from fossil cogeneration plants that currently dominate the supply of heat to district heating systems. The proportion of low-temperature heat supply will therefore increase in future systems, as the combustibility levels of available biomass and waste combustion will not be sufficient to replace the current use of fossil fuels.

The literature also agrees that the presence of high temperatures in existing district heating systems is an initial barrier to the implementation of many low-temperature heat sources.

Furthermore, the introduction of low-temperature heat distribution with supply temperatures below 70°C will increase the profitability of implementing geothermal heat, heat pumps, excess industrial heat, solar collectors, flue gas condensation and heat storage in district heating systems.

Finally, the distribution of low-temperature heat will be a significant economic driver for the expected use of higher carbon prices to achieve decarbonization within the EU, due to the stronger 2030 carbon dioxide emission reduction target.

Multiple measures to lower DH network temperatures have been considered in the literature, often inherent to a single category of action.

The Transformation roadmap by [11], for example, while dwelling more on the benefits that a reduction in DH network temperatures would bring across the board, takes an analysis of DH network users in several European nations and makes suggestions for lowering their temperatures, with action on the type of heating bodies, flow rate regulation and DHW production.

The literature, however, lacks a comprehensive map of feasible measures that also presents an estimate of costs and benefits for each. Hence, a hierarchy of sequential actions that can be taken has not yet been drawn up, starting with those that have greater immediate benefits for less cost, and progressively schedule more effective investments.

A work that comes very close to this idea was carried out by [12], who introduced a proper action flow with the aim of reducing the supply temperature of DH networks, dividing the measures into three levels: network, substation, heating devices. It does not aim to be a complete guide, nor to be the most effective in terms of cost-benefit analysis, but rather, it identifies the key interventions, leaving room for further analysis. Therefore, four possible themes are identified to consider for a more careful choice of the set of actions to apply, without however these criteria being applied to the single suggested action. These are:

- Various limitations on buildings and substations.
- Substations and pipes can be in different areas of the city.
- Large and heterogeneous systems, often require a considerable amount of data processed.
- Different device models, which consider multiple phenomena, must be included.

In conclusion, while there are various strategies to reduce the temperatures of the DH network, a more systematic and comprehensive approach is needed to evaluate and implement these measures. Furthermore, it will be important to consider the various factors identified when choosing the set of actions to apply.

2.3 Status in Switzerland

In Switzerland, heating of living spaces accounts for 71 % of final energy consumption in buildings, of which 42 % comes from oil, 26 % from natural gas, and only 3 % from district heating [13]. Decarbonization of heating systems is thus a key element in achieving the goals of the Energy Strategy 2050, according to which district heating should reach at about 15 % of thermal consumption [14], considering the reduction in demand due to building renovation. This trend will also involve cooling systems, given their vast untapped potential [13]. Of course, estimates and targets need to be adapted to local spatial conditions.

District heating plants in Switzerland with type of sources

Starting in 2019, data on district heating networks in Switzerland were made available by the federal government (https://opendata.swiss/de/dataset/thermische-netze-nahwarme-fernwarme-fernkalte) based on information provided by plant operators to document their status over time. According to these geodata, there were 1044 district heating plants in operation in Switzerland as of December 2020. Demonstrating recent interest in this technology, the number of facilities has more than doubled in the past decade, with peaks in the appearance of new facilities between 2012 and 2014.

In Switzerland, district heating networks are small; in fact, half of them have thermal capacities of less than 1 MW [1]. This is a special situation characterized by small plants densely distributed over a sparsely populated territory.

To date, waste-to-energy represents the main primary source from end-use heat (52 %), followed by biomass (29 %), geothermal (8 %), natural gas (7 %) and other marginal sources. In neighborhoods and small towns, an increase in biomass supply has recently been observed. In parallel, technological developments have led to an increase in heat pumps connected to the energy grid.

According to data provided by SFOE and Swisstopo (2021), most Swiss district heating networks operate at temperatures above 60°C, classifying themselves as 3GDH or 1C-HT. A study by [1] estimated that out of a total of more than 1’000 networks, about 25 were operating in 2014 at low temperatures. That study shows that these networks are mostly powered by low-temperature renewable sources such as waste heat and ambient heat, resulting from geothermal systems, sewage treatment plants, groundwater, and lakes. Moreover, most of the 25 networks considered at the time could be defined as 5GDHC or 4C-LT type, while only three networks would be 4GDH, 2C-LT and 3C-LT type.

Although these are promising technologies, the presence of low-temperature district heating networks in the country remains small.

Temperature levels in of district heating networks in Switzerland and connected buildings

Caputo et al. analyzed the operating temperatures of the main DH networks in Switzerland [1]. They showed that the largest are still 2nd or 3rd generation networks, with high distribution temperatures. One result of that study is that a benchmark of the supply and return temperatures of the main DH networks in Switzerland depends on the amount of heat supplied. The largest networks in terms of the amount of heat delivered are those with the highest supply temperatures (90-110°C), and that even networks with relatively low supply temperatures (60-70°C) do not necessarily have low return temperatures. The large Swiss thermal networks have significant potential to lower their operating temperatures while remaining within an achievable target for third-generation networks with the current state of the art.

Regarding heat demand, the required temperature levels follow the building requirements for space heating (SH) and domestic hot water (DHW). In Geneva, a study measured the supply and return temperatures for space heating [15], and DHW supply and return temperatures are shown as well. For an outdoor temperature of -5 °C, typical SH supply and return temperatures are as follows:

- For systems with radiators (sample of 110 SH circuits), supply temperatures are typically 55-60°C and return temperatures between 46-53 °C;
- For systems with underfloor heating (sample of 18 SH circuits), supply temperatures are typically 33-44°C and return temperatures are 28-36 °C.

However, "[...] return temperature differences are often too small, indicating excessively high flow rates that may be caused by the lack of thermostatic valves, oversized or improperly regulated circulation pumps, or improper balancing of hydraulic circuits." [11].

Thus, domestic hot water production becomes a critical point in the substation in terms of temperature levels, which is explained, among other things, by constraints aimed at preventing the development of legionella. Moreover, the relative share of domestic hot water increases as SH demand decreases (renovations, new construction, etc.) is a fact.

<u>Two real case studies examining temperature reduction in substations</u>

As part of the SWEET DeCarbCH research project, Callegari, Hollmuller et al. [15] presented two case studies monitoring temperature reduction in substations of two existing DHs:

1. a second-generation DH system (2GDH) from the 1960s, providing 359 GWh/year at 110°C/70°C (supply/return);
2. a fourth-generation DHW system (4GDH) from 2007, which provides 5.8 GWh/year at 80°C/40°C.

After a comparative overview of both case studies, the individual substations were classified in terms of their influence on DHW return temperature. For the 2GDH system, monitoring of selected SSTs, combined with NTU analysis, further addresses the problem of high domestic hot water return temperatures and identifies whether the problem lies in the secondary side (building and/or distribution system) or the domestic hot water heat exchanger. For the 4GDH system, a specific monitoring campaign allows characterization of the benefits of cascading domestic hot water preparation and space heating. It is complemented by a numerical sensitivity analysis under different operating conditions.

3 Temperature Reduction Guideline

This chapter presents a comprehensive list of possible actions to reduce network temperature, going into detail by describing the effects and seeking to qualitatively evaluate the technical criticalities and impacts of each.

The results presented in this chapter are based on an in-depth analysis of the technical and scientific literature described in chapter 2. The research indicates that few studies address the challenge of district heating temperature reduction in its entirety, considering all the aspects and criticalities related to heat production, distribution, substations, and users. The objective of this work is to summarize and organize the findings, create a list of concrete actions, and describe them in a way that can be addressed and evaluated by professionals and planners in the DH sector.

3.1 Actions to reduce network temperature

Based on the state of the art and literature research presented in Section 2.2, a list of actions that contribute to reducing network temperature was elaborated.

The actions are divided into “levels,” corresponding to thermal production, distribution, substations and final users. Each level is then divided into "classes of actions" and finally into "actions”. Regarding the "final users" and "substation" levels, the actions were divided into "new buildings" and "existing buildings”.

Figure 4 summarizes and describes the actions found:

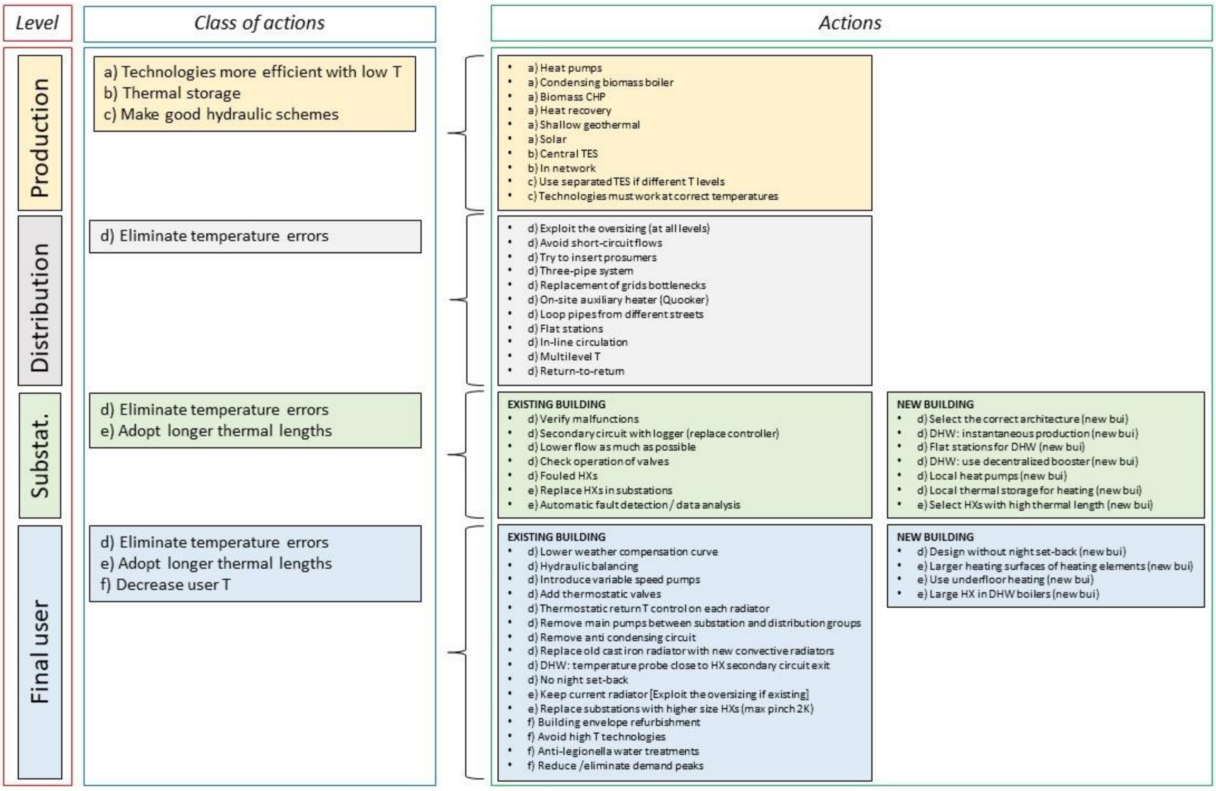

Figure 4 : Scheme with actions aim to reduce the temperature of the DH networks. Divided into levels (production, distribution, substations and final user), classes of actions and actions.

3.2 Structurization and description of actions into matrixes format

Each action was analyzed and briefly described, with special emphasis on the technical implications and on the effects on temperature reduction.

For this regard, matrices were created and presented on the following pages. Colors of the tables are the same of the levels shown in Figure 4.

Action FINAL USER	Meaning	How - principle	How - action	Purpose / benefit	Type of intervention	Risks / drawbacks / limits	Countermeasures to limit risks and drawbacks
Lower climatic compensation curve	If old buildings have been even partially insulated, therefore lower secondary Temperatures are sufficient	Lowering the controller parameters which regulate the secondary circuit temperatures	Try lower values and verify the effect	The needed heat rate can be provided with lower primary side temperatures	Programming the controller	It could take time to check which are the best setpoints (with different weather conditions)	A strategy must be found specifically to the site, for example analyze the data in winter, mid-season and summer
Hydraulic balancing	Adjusting the secondary flowrate to the user demand	Secondary flow must be split in each radiator and circuit at the expected flowrate	Compare theoretical flowrate with actual one, check/install graduated valves, try to reduce flowrate in single circuits	If each radiator receives the correct flow rate, the total flow rate is minimal. This results in a lower return temperature	Analyze single flowrates, and eventually install calibration valves (to adjust valves)	Data are not always available or easily usable	Each strategy must be found specifically to the site
Introduce variable speed pumps	Variable speed pumps can adapt the flowrate to real needs	The pump is regulated through DP, e.g. when radiators valves open, the DP lowers and the pump increases speed	Replace the pumps and install related sensors and controllers	Flowrate is minimized as well as the electricity consumption	Replacement of single piece of equipment	Keep the working point in the range of maximum efficiency. The supply must be suspended	
Add thermostatic valves	Thermostatic valves controls the flow rate entering into a radiator based on ambient setpoint	The valves have an ambient temperature sensor which acts to the valve opening	Introduce the valves at radiator level.	Flowrate is adjusted to keep the ambient temperature setpoint, reducing return temp	Replacement of several pieces of equipment	The change must be made at each flat level, not always easy	Information must be provided at flat level
Thermostatic return T control on each radiator	Thermostatic return valves (RTL) which control the mass flow rate (on return from a radiator) based on water return T	The valve uses a temperature sensor located inside, and closes when a set value is exceeded.	Introduce the valves at radiator, UFH circuit without mixing valve or DHW heating level	Flowrate is adjusted in order to keep the return temperature setpoint	Replacement of several pieces of equipment	The change must be made at each flat level, not always easy	Information must be provided at flat level

Action FINAL USER	Meaning	How - principle	How - action	Purpose / benefit	Type of intervention	Risks / drawbacks / limits	Countermeasures to limit risks and drawbacks
Remove main pumps between substation and distribution groups	Main pumps require a bypass of groups departures. When demand is low, the return T to substation increases	Each departure group must have its own pump bringing water from main circuit	Remove main pump	Water flow will adapt to demand and bypassed flow will be avoided	Remove main pump, adjust electrical drawing and reset control parameters		
Remove anti condensing circuit	Boiler anti-condensing circuit is unnecessary and dangerous since it forces a higher supply temp.	When converting a user to district heating, the circuit must be removed	Remove the circuit, provide a new connection scheme	The temperature of the primary side supply may be equal to the temperature effectively entering the substation.	Remove the circuit, adjust electrical drawing and reset control parameters		
Replace old cast iron radiator with new convective radiators	Old cast iron radiators require a higher supply temperature for the same effect	New convective radiators have a HX efficiency much higher than old cast iron ones	Replace the elements	The needed heat rate can be provided with lower primary side temperatures	Replace the elements	There could be some space problems	
DHW: temperature probe close to HX secondary circuit exit	Temp. sensors for the regulation of supply temperatures for both DHW and SH should be located close to the exit of the secondary side supply pipe in the heat exchangers	This is to avoid that the sensor is blocked by the DHW tank temperature (heat conduction through pipes)	Install sensor next to heat exchanger.	Control valve regulation is improved. In improper positions, the temp. sensor may not respond properly to increased flow on the primary side, causing a short circuit (typical in summer with heating off, but flow on the primary side not)	Move/change position of the probe	The supply must be suspended for some hours	The intervention must be done in summer, and when the DHW tank is thermally charged
No night reduction	The night set-back involves a peak request in the morning			The morning peak is tamed		The night reduction makes no sense with floor heating	

Action **FINAL USER**	**Meaning**	**How - principle**	**How - action**	**Purpose / benefit**	**Type of intervention**	**Risks / drawbacks / limits**	**Countermeasures to limit risks and drawbacks**
Keep current radiator [Exploit the oversizing if existing] ***Existing buildings***	When refurbishing a building keep the existing radiator, which will be oversized	An oversized radiator will allow a lower DTlogmean	Keep current radiator	A lower DTlogmean will allow a lower supply (and return) temperature on primary side for the same temperature on secondary side	Keep the radiator and evaluate the possible supply temp reduction	Current radiator may need to be replaced anyway	Find new radiator with suited characteristics
Replace substations with higher size HXs (max pinch 2K) ***Existing buildings***			Replace substations or replace HXs in substations			The intervention must be made on the great part of users' demand	Users should be prioritized
Larger heating surfaces of heating elements ***NEW buildings***	This allows transferring the same amount of heat by lower water temperatures	The DTlogmean decreases, but the surface increases	Select bigger heating surfaces	The user will need secondary water at lower Temp.	Selection process	DHW could require higher Temp.	
Use underfloor heating ***NEW buildings***	This allows transferring the same amount of heat by lower water temperatures	The DTlogmean decreases, but the surface increases		The user will need secondary water at lower Temp.		DHW could require higher Temp.	
Large HX in DHW boilers ***NEW buildings***	This allows transferring the same amount of heat by lower water temperatures	The DTlogmean decreases, but the surface increases	Select bigger heating surfaces	The user will need secondary water at lower Temp.	Selection process		

Action FINAL USER	Meaning	How - principle	How - action	Purpose / benefit	Type of intervention	Risks / drawbacks / limits	Countermeasures to limit risks and drawbacks
Building envelope refurbishment	This will lower the demand for SH	If the heating demand decreases, lower delta Tlogmean is required from the heat exchangers, so the flow and return temp. may lower	Setpoint change on the controller	The lower return temperature will contribute to a lower return T. The supply T will not change if this is made at one clients' though	Building renovation is expensive, so it is not a goal hear. However, when this is done, it is possible to change part of the system and setpoints at secondary circuit	Building renovation is an expensive operation, so it is not a goal. However, when this is done, it is possible to change part of the system and setpoints	
Avoid high T technologies	High T technologies need high T	Replace with electrically driven chillers	Avoid absorption systems, thermal convectors, processes				
Anti-legionella water treatments	Anti legionella may be realized with water treatments instead of high T Storage					Systems are normally expensive	
Reduce /eliminate demand peaks	Smoothing of morning peaks. No night-time reduction. Using the capacity of building storage	Morning peaks, if superposed, require high installed power with low energy	Beginning with the largest customers, shifting or reducing peaks, possibly eliminating night-time reduction. Differentiating tariffs to regulate daily load profiles				

Action SUBSTATION	**Meaning**	**How - principle**	**How - action**	**Purpose / benefit**	**Type of intervention**	**Risks / drawbacks / limits**	**Countermeasures to limit risks and drawbacks**
Verify malfunctions	Temp. sensors, actuators, control units, valves may be broken or stuck		Verify and replace faulty equipment				
Secondary circuit with logger (replace controller)	Logger may help in analyzing parameters dynamics.						
Lower flow as much as possible	Primary side two-way valve should be controlled to lower flow						
Check operation of valves	Avoid Temp. fluctuation on secondary circuit due to bad valve control or to valve oversize			Temperatures in HXs more stable			
Fouled HXs	Fouled HXs may cause a decrease in heat exchange coefficient thus resulting in a shorter thermal length		Clean HXs				
Select the correct SS architecture	For example, cascade solutions						
DHW: instantaneous production	Instantaneous production goal is to heat up DWH at final user Temp. to avoid DHW storages at high Temp. due to Legionella		The primary or secondary circuit is directly connected to the DHW line with a heat exchanger	The use Temp. can be 45°C, meaning that the input temp. could be 50°C (therefore lower than standard supply Temp.)		The direct production may have to face higher peaks. Storage on primary side may be expensive	Storage may be on secondary side
Flat stations for DHW	This will avoid having all the distribution at 50°C if not needed for space heating		Secondary line is distributed to every flat for local DHW production purpose.	The heat is delivered when and where it is needed.		The system is more expensive (space). Instantaneous DHW requires higher secondary Temp.	Secondary lines must be well insulated
DHW: use decentralized booster	Decentralize booster allow to quasi-decouple the network Temp. from the DHW Temp.		Use of HPs or electrical resistance with grid preheating	This decouples the network Temp. from the DHW Temp., thus allowing a (very) low network Temp.		The limit is related to find a proper HP that suites the needed application	

Action **SUBSTATION**	**Meaning**	**How - principle**	**How - action**	**Purpose / benefit**	**Type of intervention**	**Risks / drawbacks / limits**	**Countermeasures to limit risks and drawbacks**
Local heat pumps	HPs evaporator on primary side (supply or return)			Supply and return Temp. are decoupled from the secondary, allowing a (very) low network Temp. The network Temp. is lower because it must supply the evaporators. HPs can also produce DHW. If the supply Temp. is low enough, HPs can provide cooling.		Major drawback is installation cost	
Local thermal storage for heating				Avoiding water congestion and shaving demand peaks		Costs, space	
Replace HXs in substations	Longer thermal lengths will reduce DTlogmean		Do first Fouling detection check				
Automatic fault detection / data analysis	An automatic system would send early alerts for malfunctioning situations						
Select HXs with high thermal length							

Action DISTRIBUTION	Meaning	How - principle	How - action	Purpose / benefit	Type of intervention	Risks / drawbacks / limits	Countermeasures to limit risks and drawbacks
Exploit the oversizing (at all levels)	Pipes are often oversized, thus a certain margin should exist for higher mass flow rates		Analysis is needed				
Avoid short-circuit flows	Short-circuit is used to maintain T when request is low		Install thermostatic valves, so that short-circuit is limited to the strict minimum.				
Try to insert prosumers	Prosumers deliver heat to the system thus facilitating the central plant. Therefore, grid mass flow rate may be contained		Technologies for the prosumer inclusion (proper bidirectional substation) - a lower T grid may facilitate the prosumers to connect				
Three-pipe system	Different possibilities: one pipe for SH, one for DHW, common return. In summer, hot water is recirculated in the second supply pipe						
Replacement of grids bottlenecks	Lowering T may result in higher mass flow rate. This could lead to flow problems in part of the grid, called bottlenecks		Increase pipes diameter	Eliminate the bottleneck	May be too expensive, depending on the entity of the problem		Analysis of the benefit
On-site auxiliary heater (Quooker)	A small storage keeps water locally warm		See Quooker				
Loop pipes from different streets	Connecting in loop supply lines will keep supply warm and return cold						
Flat stations	Flat stations between primary and secondary side, also for heating						
In-line circulation	Circulation line is embedded in supply DHW pipe, thus reducing losses						
Multilevel T	New 4GDH in existing 3GDH systems						
Return-to-return	Feed suitable buildings using the return line only			Flow rate reduction		Works for lower temp users	

Action PRODUCTION	**Meaning**	**How - principle**	**How - action**	**Purpose / benefit**	**Type of intervention**	**Risks / drawbacks / limits**	**Countermeasures to limit risks and drawbacks**
Heat pumps	HPs are more effective when working at low temperature on users side, both at supply and at return					Low temperature heat source not always available	Geothermal sources, lakes and Sewage treatment plants are good sources near many cities in Switzerland
Condensing biomass boiler	Efficiency increases with lower return temperatures						
Biomass CHP	Heat efficiency increases with lower supply and return temperatures						
Heat recovery	The lower the grid temperatures, the wider the possibilities of using low temperature wase heat						
Shallow geothermal	Shallow geothermal sources provide low temperature heat, therefore the use of heat pumps (central or individual) is needed						
Solar	Solar system efficiency increases with low temperature circuits						
Central TES	type: Sensitive, Latent duration: hourly, daily, Seasonal						
Use separated TES if different T levels	This will favour technologies with efficiency strongly depending on temperature						
Technologies must work at correct temperatures	This will favour technologies with efficiency strongly depending on temperature						

4 Cost-Benefit Analysis

Actions should be considered starting from user level up to production level. However, within one level it is not always clear which action is more effective and more efficient in terms of impact (e.g. temperature reduction) vs. costs. We propose a cost-benefit analysis for two actions at user level: (1) the introduction of thermostatic radiator valves and (2) the replacement of old high temperature radiators with new low temperature radiators.

4.1 Thermostatic Valves Integration

Thermostatic Radiator Valves (TRV) are used to close the water flow to the radiator as soon as the room-temperature setpoint is reached. This results in an overall reduction of user water flow compared to the situation where no valves are installed, thus allowing too much flow through the radiator, resulting in a higher return temperature from the radiator. The installation of TRV will reduce thermal losses and increase the central plant efficiency, especially if this is equipped with highly temperature sensitive items, like heat pumps or condensing boilers.

Of course, the more users have TRVs, the lower the overall flow and thus the return temperature. But, as pointed out in [11], it must be ensured, that they are working properly.

In Switzerland, the distribution of flats by number of rooms is given in the following table, as well as the surface distribution of each flat category. Values of heat demand (for heating) per flat and per flat category is calculated. Assuming 20 W/m^3 as an average maximum heating demand average. Therefore, the total maximum heating demand per flat category can be estimated and, assuming a 50 CHF as unitary cost per installed valve, a cost per kW for each flat category is deduced.

		# of Room/s (source: Federal Bureau of Statistics)					
		1	2	3	4	5	6
Number of flats	#	1’137’900	225’376	74’456	74’456	86’780	86’780
Volume of flat	m^3	93	150	208	277	361	464
Tot max heat rate	kW	2’112’398	677’390	310’124	412’337	625’892	805’943
Unitary cost of TRV	CHF/kW	27	33	36	36	35	32

The average cost of TRVs weighted on the number of flats is therefore equal to 29 CHF/kW.

Using manufacturer data, it can be estimated, that with a secondary supply temperature of 70°C, a TRV that would reduce the room temperature from 22°C to 20°C will lower the return temperature from the radiator by 4°C. Therefore, the cost of installing valves in a given grid may be compared with the benefit of reducing temperature at central level or at grid level due to lower thermal losses. The following graph shows such a cost/benefit ratio for different rates of TRV installed in the system.

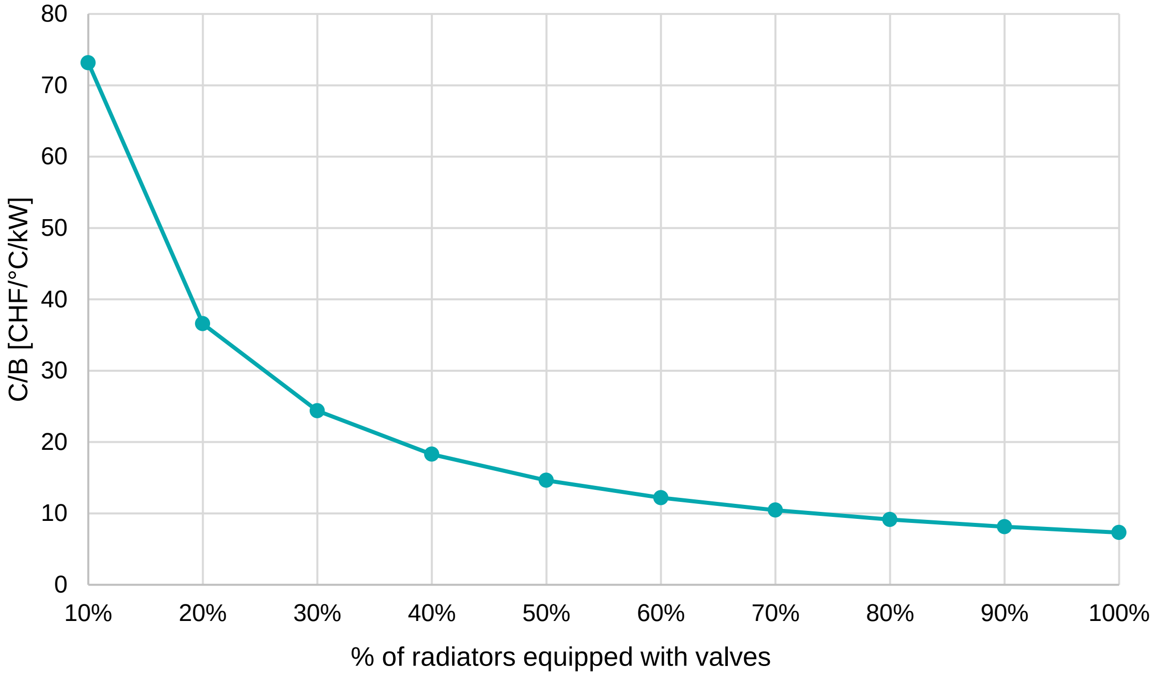

Figure 5 : Cost/Benefit indicator for the installation of a TRV (thermostatic vales at each radiator) in each room, in terms of cost in CHF per °C of decremental at central plant level.

4.2 New radiators vs. old cast iron radiators.

Typical water temperatures in old cast iron radiators have average values 60°C higher than room temperature.

This means, that with an ambient temperature of 20°C the secondary supply temperature is around 80°C, while the secondary return temperature is 60°C.

With modern radiators, however, the same heating capacity can be reached with lower water temperatures (~50 °C). As a price reference, a new radiator 1.4 m wide and 1.1 m high was estimated with 1100 CHF.

		# of Room/s (source: Federal Bureau of Statistics)					
		1	2	3	4	5	6
Number of flats	#	1’137’900	225’376	74’456	74’456	86’780	86’780
Volume of flat	m3	93	150	208	277	361	464
Tot max heat rate	kW	2’112’398	677’390	310’124	412’337	625’892	805’943
Unitary cost of radiators	CHF/kW	593	732	792	795	763	711

The average cost of radiators weighted on the number of flats is therefore equal to 644 CHF/kW.

Using manufacturer data, we can see, that these radiators allow the supply secondary temperature to decrease from 80°C to 50°C. This is a very significant decrement. The following graph shows such a cost/benefit ratio for different rates of new radiators installed in the system instead of the existing old cast iron high temperature radiators. The cost/benefit ratio may be compared to the economical benefit of reducing the supply temperature at central level or at distribution grid level, due to lower thermal losses.

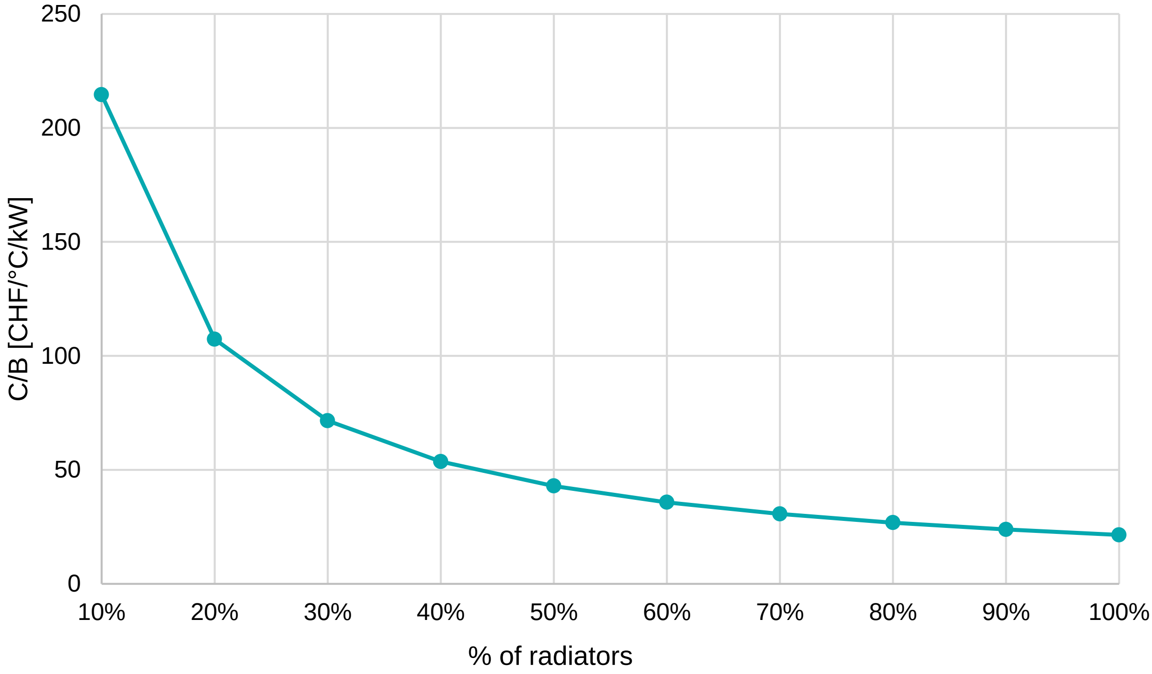

Figure 6 : Cost/Benefit indicator for the installation of low temperature radiators in each room, in terms of cost in CHF per °C of decremental at central plant level.

5 Temperature Reduction Simulation Framework

State of the art temperature reduction research and industry know-how still lacks tangible data on impact of specific actions. For example, influence of temperature reduction on heat generation efficiency (e.g. boilers or heat pumps) is quantified [6], but only indications are given on grid optimization actions' costs and benefits. Research did order actions [16] but costs and benefits are only discussed and qualitatively indicated. More data, quantifying benefits of actions, needs to be provided to facilitate stakeholders' decision making.

Implementing and testing actions during operation of district heating systems is typically difficult to perform as security of heat supply cannot be compromised. To circumvent this limitation, a Modelica-based simulation framework has been developed here to allow virtual (numerical) testing of such temperature-reduction measures [17–19]. The simulation framework uses physical model components from the open-source Modelica Buildings Library [20,21] which has been adapted to the needs of this work in close collaboration with the Lawrence Berkeley National Laboratory, which is also an active research partner in DeCarbCH.

Here, the simulation framework has been adapted and applied to investigate bypass flow reduction during summer operation of district heating grids, which is a potential low-cost and high-benefit action. The extended Modelica simulation framework provides a solid basis to address other questions related to the improvement of energy and exergy efficiency of 5^{th} generation district heating and cooling in the second phase of DeCarbCH.

5.1 Bypass Flow Reduction

Bypass flow reduction was identified as a promising action, but with no clear tangible data on benefit and cost from the existing literature. The impact of this measure on single grids is expected to have low implementation cost and offer a positive impact on return temperature, distribution heat losses and heat generation unit efficiencies. Large energy saving potential lies within the high replication aspect: this action addresses almost every district heating grid currently in operation.

The bypass flow reduction action is situated inside the temperature reduction guideline as follows (see Figure 4):

Level: Distribution

Class of Action: Eliminate Temperature Errors

Action: Avoid Short-Circuit Flows

<u>Introduction</u>

District heating grids need to maintain a minimum pre-specified temperature level at customer substations. This is called a minimum supply temperature control as shown in Figure 7. As stagnating water flow leads to dropping supply temperatures, a circulation flow needs to be forced through supply pipes. Bypass valves are used for this task and are implemented in terminal grid sections located at the end of grid branches. Those valves are installed either between distribution pipes in maintenance holes or inside buildings at consumer substations. Bypass flow is usually not metered, as it does not count as sold heat.

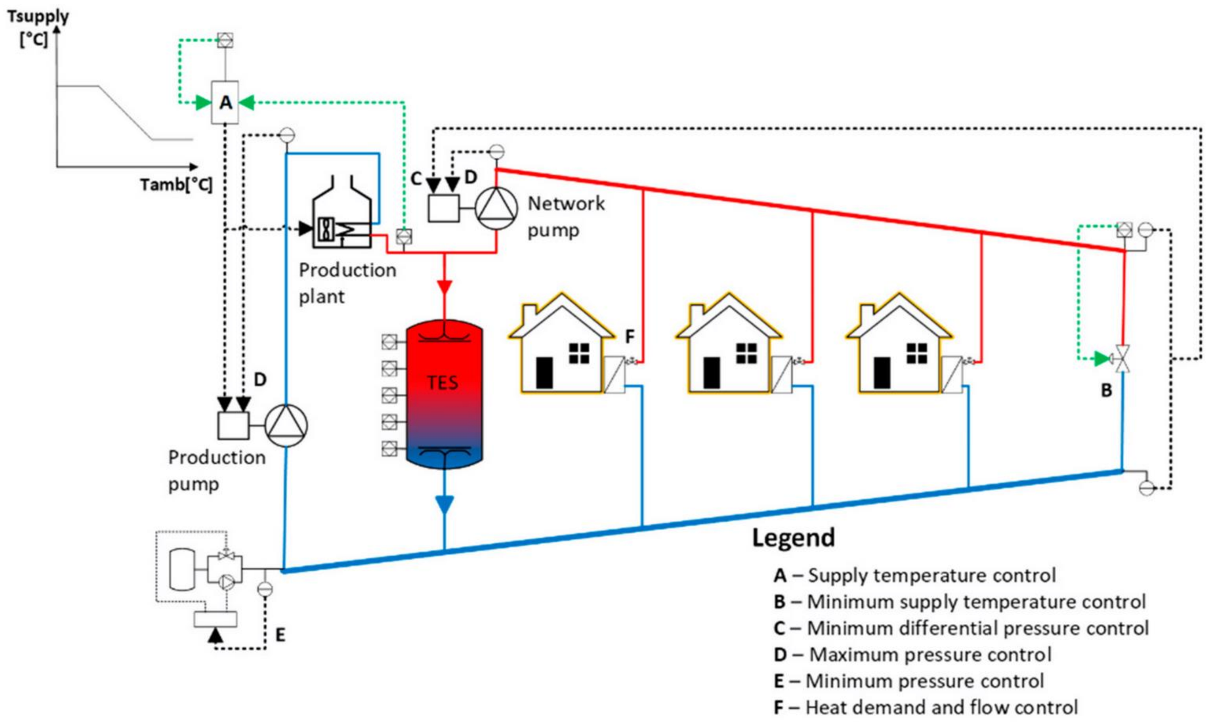

Figure 7 District Heating Grid Control. Bypass Control represented by B: Minimum Supply Temperature Control [22]

Bypass flow is especially important for remote grid branches with low heat demand. The bypass flow required increases with longer pipes and lower consumer heat demand. A need for significant bypass flow usually only occurs during summer when almost no space heating is required. The focus of this study is therefore set on summer operation of district heating grids.

The same principles would apply for 5GHDC grids for cooling. During summer operation, cooling operation with e.g. a lake source needs to maintain a given (maximum) cooling temperature to maintain enough cooling power. Circulation flow using bypass valves could ensure this temperature requirement is met.

<u>Problem Description</u>

Thermal bypass valves are currently state of the art in district heating grids, maintaining a required temperature at customer substations using thermostatic controllers. However, a robust control strategy for bypass flow needs to be developed. Appropriate temperature setpoints and correct placement of temperature sensors are required. Current bypass control leads to unnecessary bypass flow, which increases return temperatures and heat losses. Furthermore, constant or fixed bypass valves are still found in district heating systems. These valves are effectively uncontrolled and lead to significant return temperature lift throughout the year. Constant bypass valves need to be exchanged to thermal bypass valves. Other control strategies such as model predictive control could be applied but are currently not yet deployed.

<u>State of the Art</u>

The principle of bypass valves is well known in academia:

> “Identification of unintentional circulation flows: For certain operational purposes, circulation flows are necessary. These are managed by either hot water circulation systems on the customer side or by a valve in a bypass.” [6].

Despite a good understanding of the principle, important control and design issues remain unresolved:

> "It is particularly important that bypasses are temperature-controlled in the manner shown, and that they are not just simple, hand-operated valves (which can be in particular found in some old grids)." [23]

Recent research of [24], quantifies possible benefits of optimal bypass control. A theoretical low temperature district heating case study with 60 °C supply temperature was set-up. Then a perfect-forecasting model predictive control for minimum temperature control was implemented. Results indicated an overall system efficiency increase from 49 to 57 %. This theoretically shows that bypass flow optimization can significantly improve efficiency:

> "This theoretical benchmark ensures a just-in-time delivery of warm water by taking into account time delays in the network. In a simulation case study of a small neighborhood in Genk, Belgium, the benchmark shows that substantial improvement regarding bypass control is possible." [25]

Comparing research of [24] to current research in Switzerland, two aspects were found which led to this in-depth bypass flow study. Firstly, own research showed much higher district heating supply temperatures of 80 °C during summer operation of several district heating grids in Switzerland. This levers efficiency increase potential, as minimized bypass flow at high temperature levels reduces e.g. heat losses even more. Secondly, perfect-forecasting model predictive control cannot be realized leaving a gap for feasible implementation strategies using available technology.

Aim

We develop a method to optimize bypass valve control in existing district heating grids in terms of energy- and mass-flow.

A case study analysis, using a thermo-hydraulic model of an existing district heating grid shall show how bypass valve control can maximize grid efficiency while ensuring adequate supply temperatures.

A cost/benefit estimation of the applied action and its implementation impact on the whole Swiss district heating sector shall identify national total energy saving potential.

Method

In this work, the following methodology has been applied:

1. Analysis of current bypass control for a representative Swiss grid in a concrete case study
2. Development of a dynamic simulation model capable of predicting temperatures and mass flows from plant to substation.
3. Parametrization of the model using realistic design and measurement data from the representative grid chosen in step 1.
4. Simulation of the impact and the dynamic effects of different bypass control strategies on efficiency-related key performance indicators. Identification of optimized bypass control through systematic variation of relevant control parameters.
5. Estimation of the costs and benefits of optimized bypass control on the investigated case study.
6. Estimation of the extrapolated impact of optimized bypass control on all applicable Swiss district heating systems similar to the case study.

Representative Grid - Case Study

The selected type of wood district heating grid allows replicability thanks to similar design guidelines of 3GDH grids with wood as main energy source. This type of grid commonly uses “QM Holzheizwerke”, a quality management program for wood district heating, which is highly established in Switzerland [26].

An existing 3GDH wood grid in Losone, Ticino, Switzerland, was defined as case study. The grid was analyzed using design grid data and 5-minute measured operational data. System specifications are shown in Figure 8. This district heating grid type can be deemed representative of the nearly 800 wood 3GDH grids out of a total of round 1'200 thermal grids in Switzerland [27].

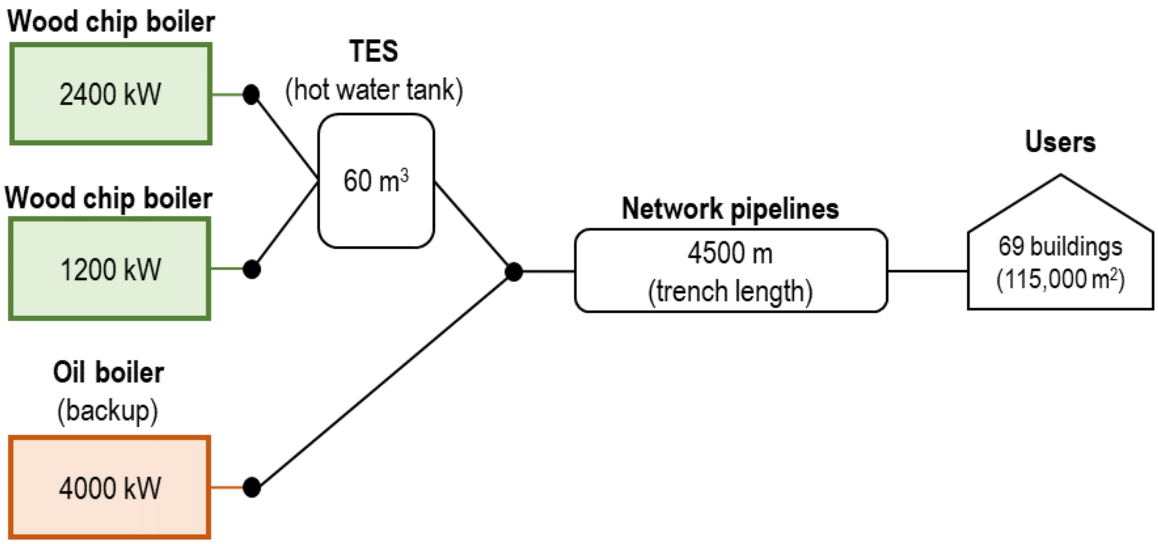

Figure 8 Schematic of the Wood District Heating Case Study [28]

The 2021 customer heat demand (sold energy) of the whole district heating grid was 10.0 GWh. The boilers generated 11.8 GWh of heat. Annual systems losses were therefore 15 %, annual system energy efficiency was 85 %. Electrical energy consumption of circulation pumps has been neglected. The summer period (no space heating demand) was defined from 1st of May until 30th of September. As shown in Figure 9, during this period the ambient temperature remains mainly above 18 °C. These temperatures are above the limit where space heating is required. See also Figure 10, for referencing ambient temperature to heat output of the plant. The heat production during this period was 1.9 GWh – i.e. roughly 16 % of the total annual production.

To investigate and verify the system performance against design data, measurement data was rigorously analyzed. Figure 9 shows temperature levels and heat load of the DH system. Main points can be summarized as follows:

- Grid supply temperature measured at the plant is varied between 85 °C during the winter period and 78 °C during summer period. Summer temperature reduction is possible due to the decreased heat demand.
- Return temperature measured at the plant during the winter period is 55 °C and 65 °C during summer period. This highlights that bypass flow as well as non-optimized substations raise return temperature levels significantly.

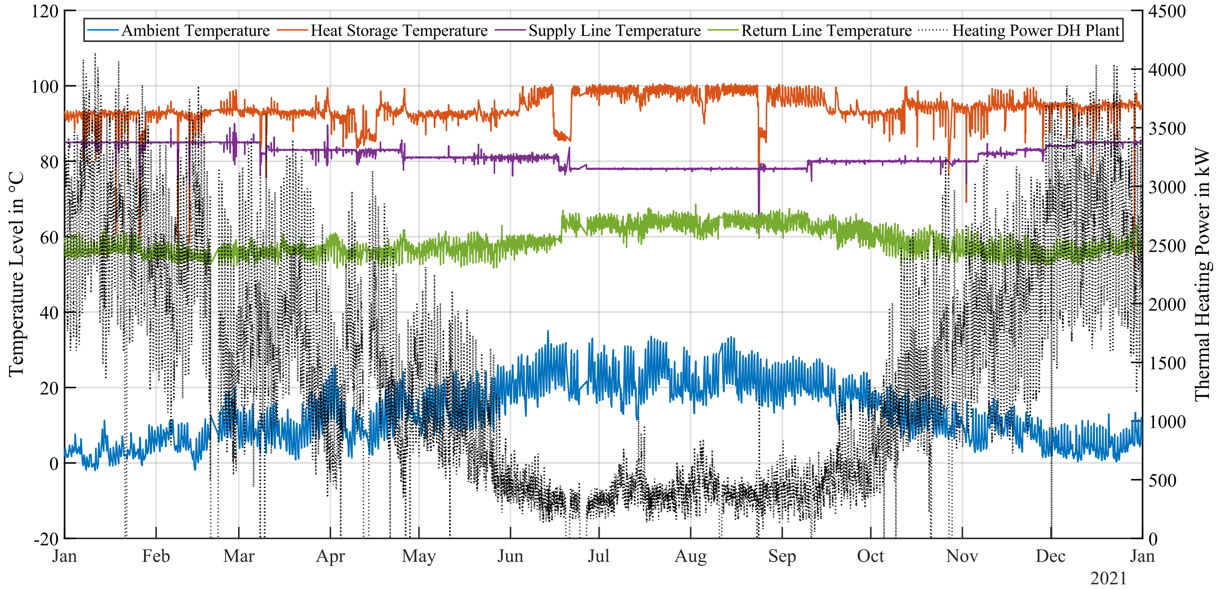

Figure 9 Temperature Levels and Heat Output Data of the Losone District Heating Plant. Averaged 1h Values, Data Gaps Linearly Interpolated.

Figure 10 shows the correlation between heat output and ambient air temperature. During summer operation with ambient temperatures > 18 °C, the heat output stagnates at round 400 – 500 kW. This marks the band load, consisting mainly of domestic hot water demand.

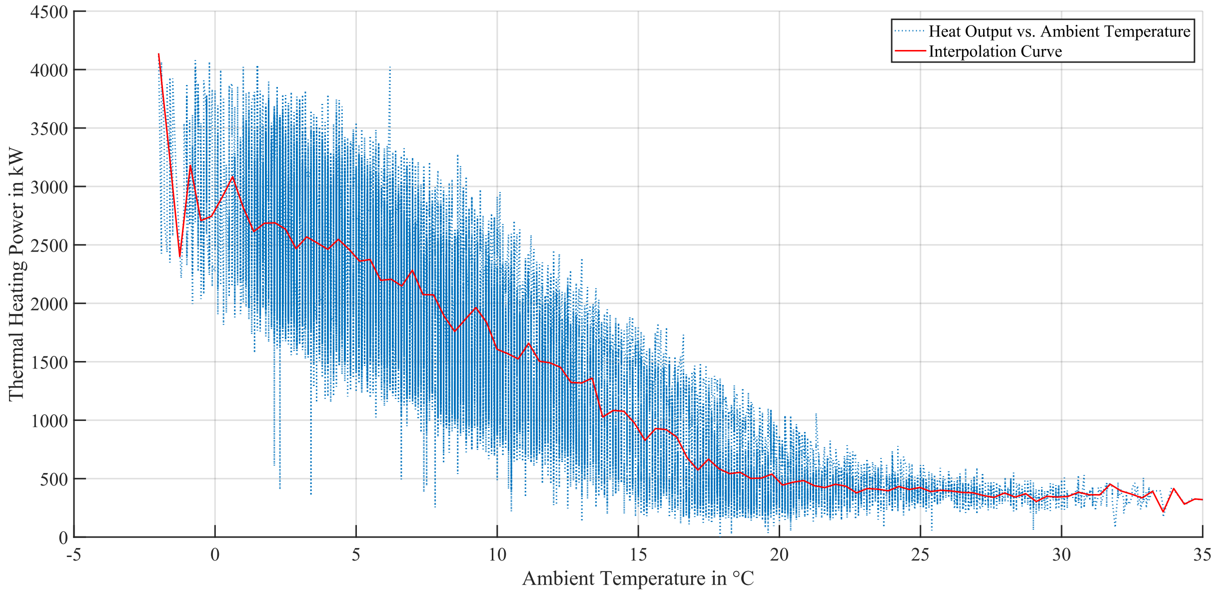

Figure 10 Heat Output vs. Ambient Air Temperature of the Losone District Heating Plant. Averaged 1h Values, Data Gaps Linearly Interpolated.

The case study considered a total of seven thermal bypass valves located at terminal substations. In operation, the valves were set to 60 °C, according to the grid operator. Measurement data shows high return temperature levels of up to 65 °C during summer operation, indicating excess bypass flow as well as low temperature gradients at non-optimized substations. System efficiency can be increased by optimizing operation of the grid. Lower return temperature can lead to lower heat losses, lower pumping energy (decreased flow rate), more efficient flue gas condensation and higher storage capacity.

A thermo-hydraulic model for the relevant parts of the district heating systems including ground-coupled distribution pipes and bypass valves was developed in Modelica and calibrated using the case-study measurement data. The developed model allowed simulation of mass flows, temperatures and heat losses, using real grid data as boundary conditions.

District Heating Model Set-Up

The district heating simulation can predict mass flows, heat flows and temperature profiles at each pipe segment and substation of a designated grid section. Modelling the heat generation plant and building heat distribution was not required and therefore excluded from the model and represented by boundary conditions instead. A simulation timestep of 5 min was chosen to suit measurement data resolution and to consider the dynamic behavior of the system e.g. sudden changes in consumer heat demand.

The following data was available from the district heating grid:

- Distribution grid CAD plan including diameter and insulation level of each distribution pipe;
- Nominal mass flow and heat demand of customer substations;
- Schematic principle and control system overview of the plant;
- 5-min measurement data for 2021 of all relevant temperature levels, mass flows, energy flows and cumulated energy from heat meters at the plant and at consumer substations.

The simplified schematic in Figure 11 shows the main model components, namely:

- Plant: supplies heat at a prescribed temperature level. For the summer bypass study, a feed temperature of 79.5 °C was set, which is the average supply temperature during the summer period.;
- Distribution: represents the actual layout of the grid section e.g. length and simplified geographical position. The pipe model includes pipe diameter, insulation level and length. Pipe specifications including insulation level and heat conductivity were obtained from manufacturer data sheets;
- Consumer: implements substation heat demand with a heat exchanger unit. Demand data is prescribed using heat meter measurements (mass flow and temperature gradient) from each consumer substation.

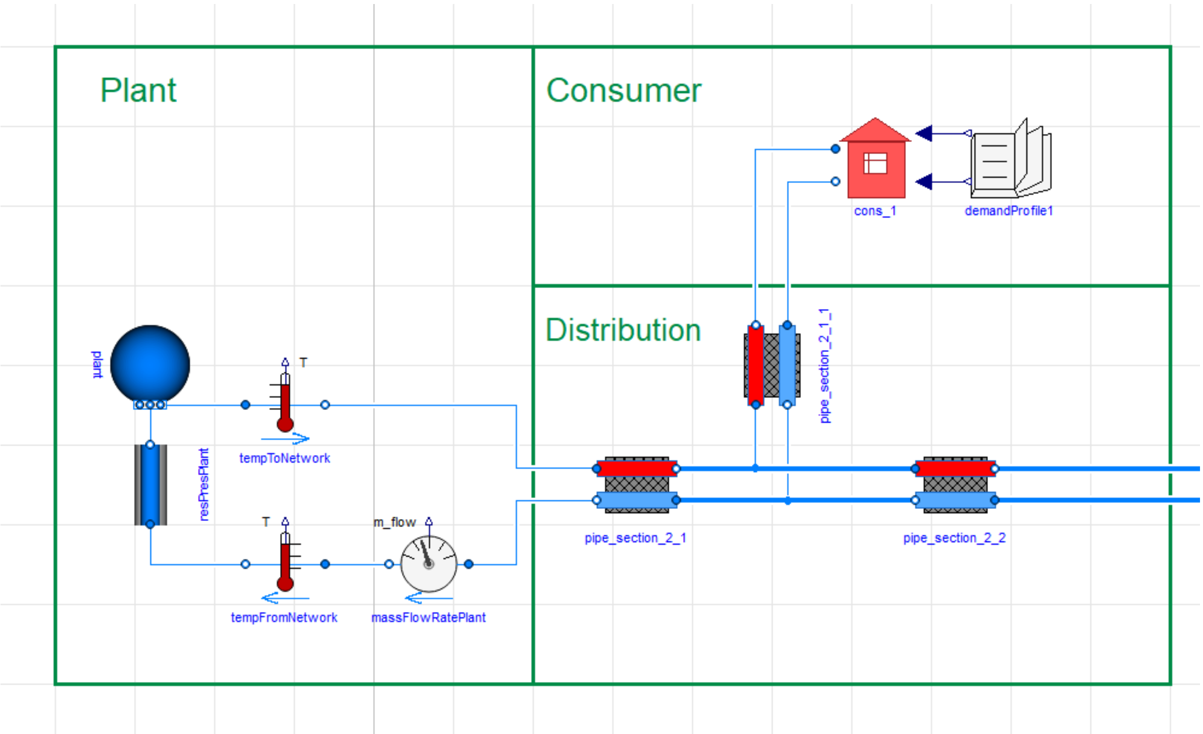

Figure 11 District Heating Model Schematic Overview in Dymola/Modelica

Pipe-Model Evaluation

The simulation required a buried pipe model thermally coupled with the surrounding ground. One important function of the model is to predict the temperature profile according to mass flow through the pipe together with heat losses.

As initial step, available pipe models in the Modelica Buildings Library as well as the Open Modelica Library were evaluated. Substation measurement data of a grid sub sector with two consumers was used to calibrate the pipe model. A validated discretized pipe from the Modelica buildings library was identified as most suitable and implemented in the model.

Limitations of the model calibration approach are given by the different methods of temperature measurement. Temperature sensors in district heating substations do not represent the temperature inside a buried pipe, but of a semi-submerged sensor (see Figure 15) inside a pipe located in a technical room. This phenomenon is well described in [29]. Recognizing this aspect, the model is calibrated using only periods with mass flow over the substation. This method allows the usage of standard measurement equipment installed in 3GDH systems.

The model was calibrated for the summer operation mode where bypass flow is relevant. Figure 12 shows the good agreement between simulated and measured supply temperature at the substation where the bypass valve is located. A representative period of 0.5 days during summer operation was selected, the 8^{th} of June 00:00 to 12:00. This is a period with continuous mass flow at the consumer substation. Average deviation for this period is 0.1 K, maximum deviation is 0.8 K.

Temperature measurement from the district heating plant was acquired from heat meters at substations. Heat meters are regulated by the standard EN 1434:2022 (Thermal energy meters), referring to EN 60751:2022 (Industrial platinum resistance thermometers and platinum temperature sensors) for temperature sensors. The fault limit for absolute temperature is 0.3 K (class B sensor, without measurement unit error). Putting this fault limit into relation with the deviation simulation-measurement uncertainties, the accuracy of the model calibration proved to be satisfactory for the simulation study.

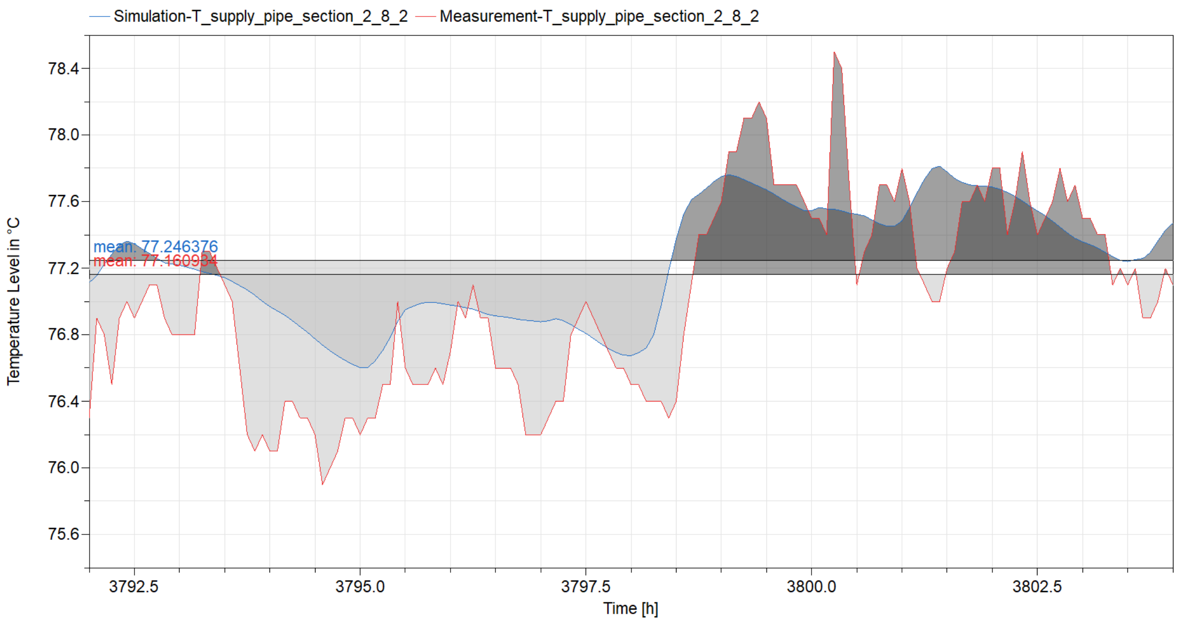

Figure 12 Simulated vs. Measured Supply Temperature at Substation 2.8.2 (8^{th} of June, 00:00 to 12:00)

Grid Simplification

The district heating grid, shown in Figure 13, was investigated by focusing on seven different grid branches, whereof each branch of the grid uses its own bypass valve. The branch or section “east” as highlighted in Figure 13 and shown by a schematic in Figure 14 was selected for the in-depth bypass flow optimization study

This section east comprises 18 consumers with mixed usage including residential, office and commercial. The total installed substation heat capacity is 3.1 MW. The section delivered 4.8 GWh of heat to consumers (measured heat, excluding losses), which represents 53 % of the total district heating grid demand. The maximum distribution grid distance from plant to last consumer in this branch is 1000 m.

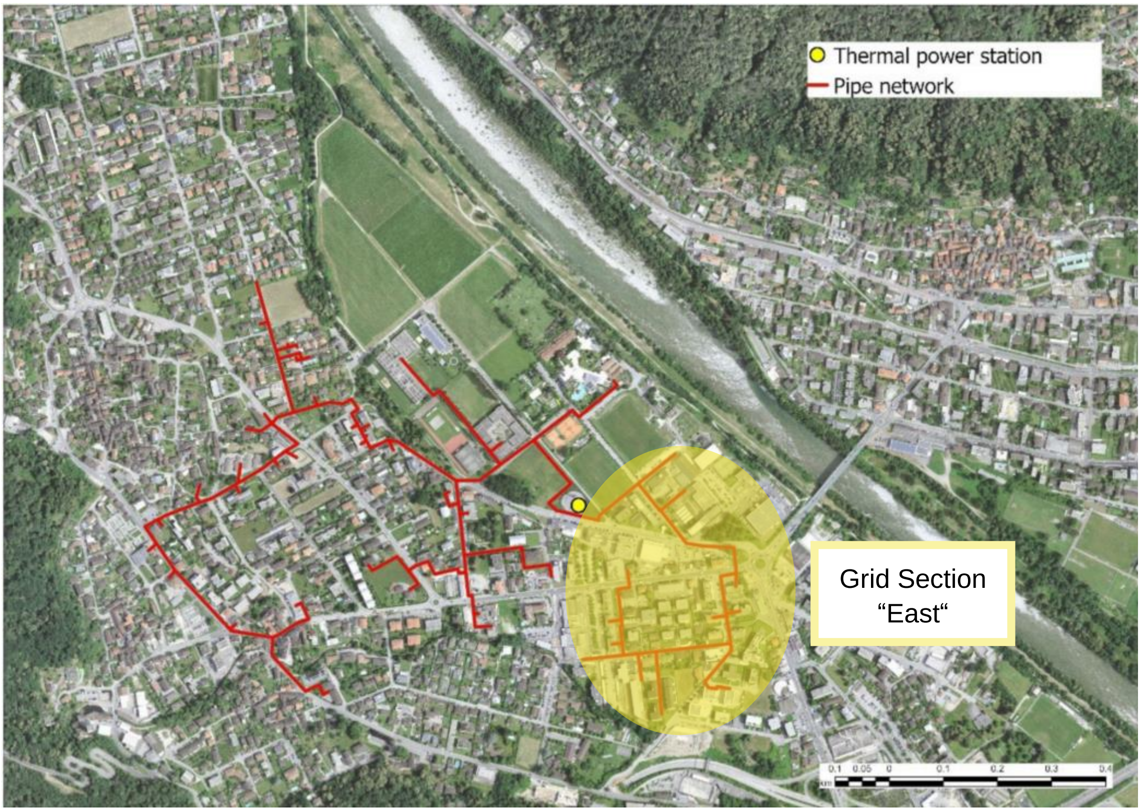

Figure 13 Wood District Heating Plant Losone. Grid Section “East” highlighted. [28], modified.

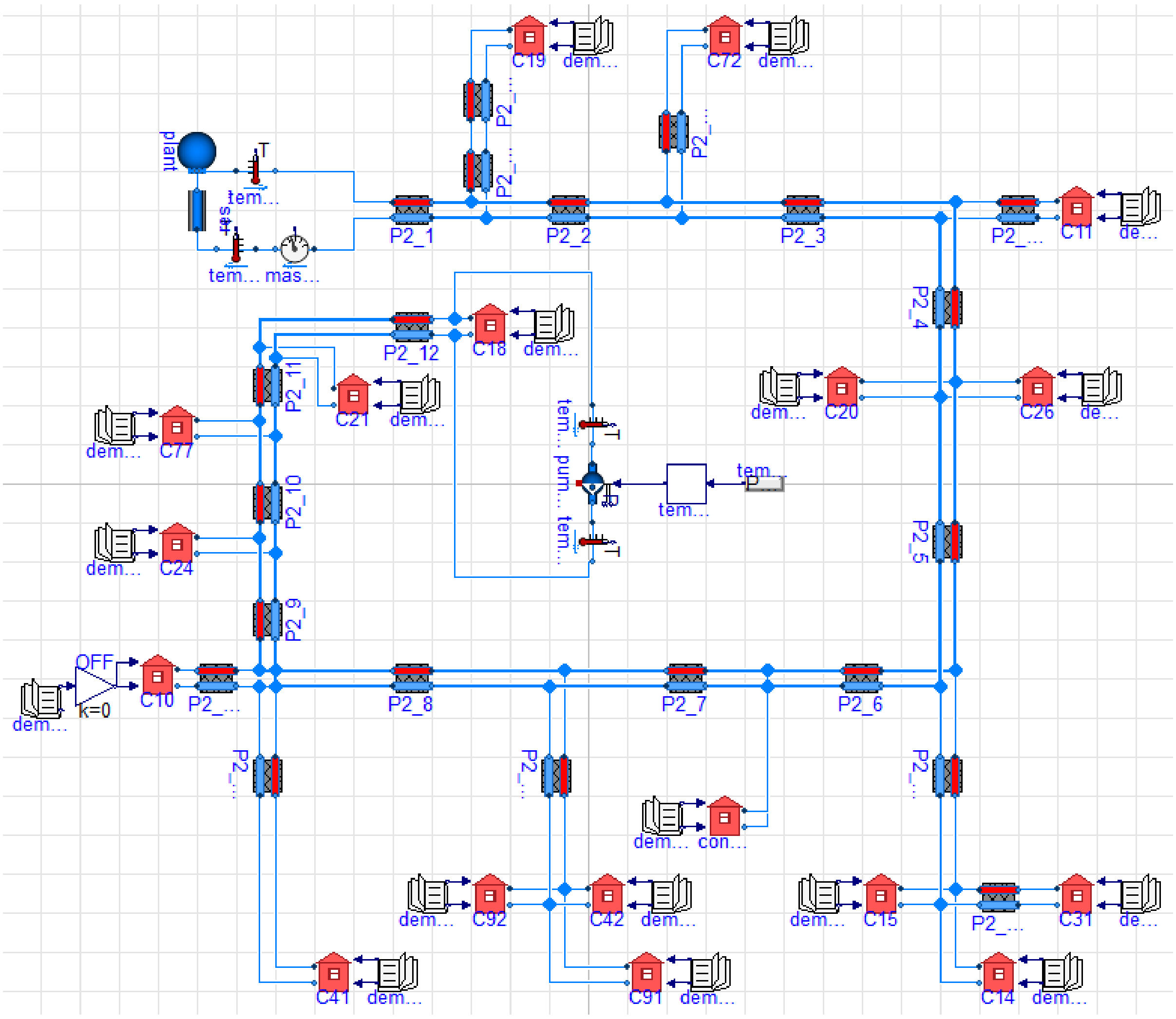

Figure 14 Wood District Heating Model Grid Section "East" in Dymola/Modelica. Compare with Figure 15.

The simulated period is two weeks, from June 1st to June 14th. This period represents a relevant summer operation mode with significant bypass flow. As no significant changes in system behavior are expected during this period, a result extrapolation from the simulated 2-weeks towards the full summer period was made.

The extrapolation of simulation results is a limitation of the study results. Due to the chosen approach, it was not possible to study how a constant or standard thermal bypass valve would affect the grid during the heating season (October to April). As heat demand and mass flow are significantly higher in the heating season than during summer operation, the effect of bypass valves is limited in winter. Therefore, the benefits were only applied during summer operation, possibly underestimating the benefits over the whole year, especially for a constant bypass which operates all year round.

Bypass Implementation

The bypass was modelled with a pipe parallel to the terminal consumer substation. A pump is used to define a specific flow, operated by a controller. In the model, the bypass is either controlled with a temperature hysteresis (thermal or controlled bypass) or a constant mass flow is set (constant or uncontrolled bypass). Figure 15 shows the thermal bypass model implementation versus an actual valve design.

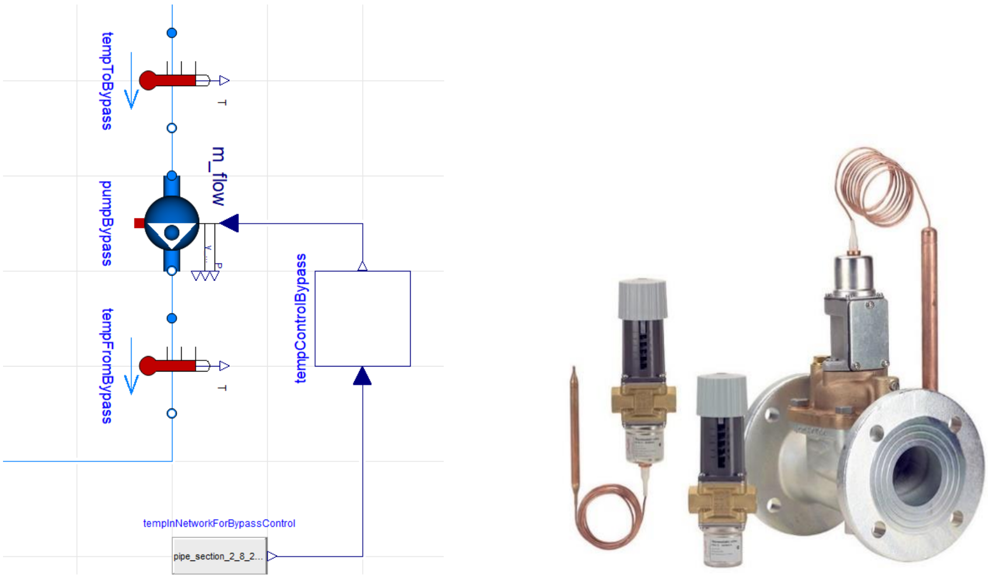

Figure 15 Thermal Bypass Valve. Left: Model Implementation with a Pump Prescribing Mass Flow Over the Bypass Controlled by a Thermal Hysteresis. Right: Thermal Bypass Valves in Different Nominal Diameters with Capillary Tube Temperature Sensor © Danfoss. Compare with Grid Model Overview Figure 14.

The bypass valve control was divided into three setups:

1. Constant Bypass (worst-case scenario): a certain amount of the nominal mass flow of the substation is flowing through the bypass valve. This constant bypass was initially installed in the real case study grid and later changed to thermal bypass valves.
2. Standard Thermal Bypass (as-is scenario): the thermal valve setpoint is set to 65 °C, as data analysis showed that current set points seem to be higher than the operator stated (60 °C).
3. Optimized Thermal Bypass (goal scenario): the thermal valve setpoint is set to a temperature that is as low as possible while still ensuring a certain temperature in a certain time at the customer substation.

The bypass nominal mass flow was stated with 5 % of the nominal substation mass flow in design data of the case study grid. Considering the different sizes of substations, a 20 % bypass flow was chosen to be analyzed within this work. The investigated substation has only a nominal capacity of 20 kW, while the whole grid section east has a substation capacity of 3.1 MW. The nominal mass flow of the bypass valve therefore emulates a consumption of 4 kW.

<u>Temperature Requirement</u>

Minimum supply temperature control is defined by customer requirements. For heating applications, a distinction can be made between space heating, process heating and domestic hot water. The most common applications are space heating and domestic hot water. Analyzing the building types in the given case study, residential and commercial buildings are predominant. As only summer operation is relevant to this investigation, the temperature defining heating application is that required for production of domestic hot water.

In Switzerland, domestic hot water temperature requirements are defined by the standard SIA 385/1. Taking into consideration that larger residential buildings use domestic hot water circulation units, the governing temperature is 55 °C for the temperature coming from the circulation line back into the domestic hot water tank. Thus, temperature leaving the hot water tank must be higher and is recommended at 58 °C. Considering (i) a small temperature gradient over the substation heat exchanger which is dimensioned for peak winter operation and (ii) a small temperature decrease due to thermal loss over insulated distribution pipes, we define a required minimum supply temperature at the primary (district heating) side of 60 °C. In other words, this is the required temperature of the district heating supply line coming into the consumer building during summer operation.

The customer expectation and district heating grid operator responsibility are to guarantee this minimum supply temperature is always met. Studying measured load profiles, domestic hot water use is neither constant, nor directly related to consumer usage of e.g. shower or kitchen sink usage. Instead, it is typically governed by the loading cycle control of the domestic hot water system. Case study measured data in Figure 16 shows that for the predominant multi-dwelling buildings the interval between domestic hot water loading cycles is between 3 and 6 h and lasts for 0.5 to 1 h (see Figure 18). For cycle loading a hot water tank which is predominant at residential or commercial buildings without sensitive hot water applications, it is not necessary to instantly provide the required temperature. The cycle loading can start with lower temperatures, reaching the desired temperature at the end of the cycle. In this work, we have taken 33 % of the minimum heat demand duration which in this case is 0.15 h (9 min) as acceptable delay time until the minimum required temperature is attained at the substation.

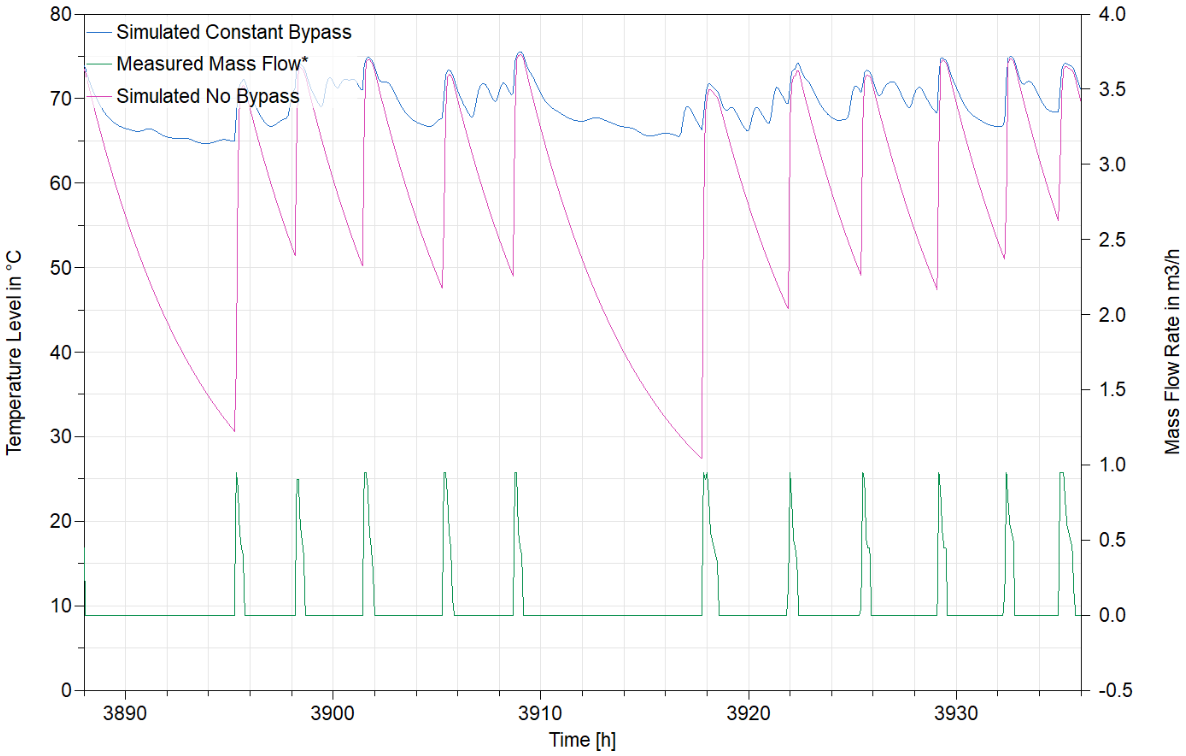

Figure 16 Measured Mass Flow Rate (secondary axis, green) vs. Simulated Supply Temperature (primary axis, blue, pink) With Constant and Thermal Bypass Control (Setpoint 65 °C) at the Terminal Substation during Summer Operation (4th-5th of June)

<u>Optimized Bypass</u>

The optimized thermal bypass is controlled in such a way that the minimum supply temperature of 60 °C is reached within a maximum delay time of 0.15 h. This way, a lower heat loss and return temperature level shall be achieved.

A longer delay time seems possible, finding an optimum between energy efficiency and hygienic requirements (e.g. legionella avoidance). Specific data on time requirements of domestic hot water boiler loading cycles is not available. A more in-depth analysis of the domestic hot water systems would be beneficial. This exceeds the scope of this work but can be addressed by future research.

Simulation Results

The results of the bypass simulation study are structured as follows:

1. Simulation Overview
    a. Distribution Grid Level
    b. Substation Level
2. Bypass Simulation Results
3. Key Performance Indicators

The conducted thermo-hydraulic simulations show the effect of dropping temperatures along the distribution grid as a result of heat losses. Figure 17 depicts temperatures along the supply grid sections for a single day (2nd of June, as an example). This temperature profile is dependent on water flow, pipe length and diameter as well as insulation levels. During heat demand, the temperature drops significantly from 79.5 °C at the plant to 71.2 °C at the last pipe section. The temperature drops even further if there is no heat demand from the substation. The lowest supply temperature at pipe section 2.12 is 65 °C, which is the setpoint of the thermal bypass valve in this simulation run.

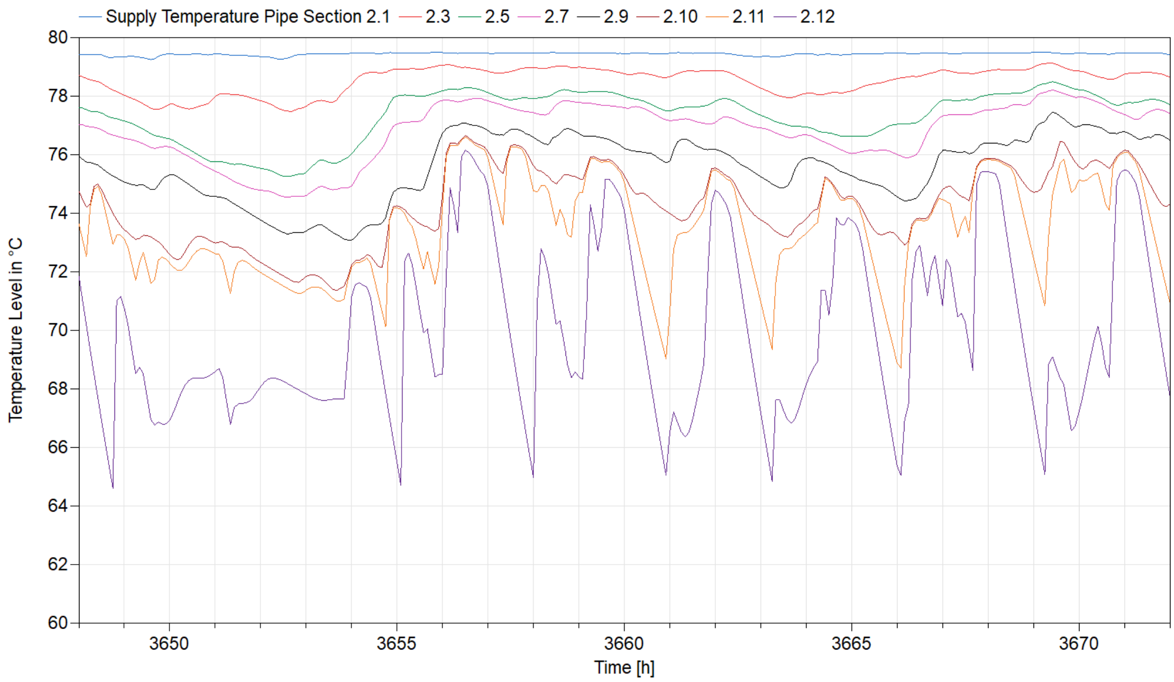

Figure 17 Simulated Distribution Grid: Temperature Levels of Supply Pipe Sections at Plant (Section 2.1) to Last Consumer (Section 2.12) During Summer operation (2nd of June). Compare with Pipe Section Naming in Figure 14.

An in-depth result analysis of the terminal substation at the multi-dwelling residential building is depicted in Figure 18. The plot shows measured mass flow (the demand profile) and simulated temperatures for the different bypass controls. The defined mass flow is plotted against simulated supply temperatures at the terminal substation. Specific heat demand patterns occur. For 0.5 to 1 h of heat demand, a break with no heat demand follows, with a duration of usually 2.5 h to a maximum of 7 h. This marks the previously discussed domestic hot water cycle loading operation.

Further, different bypass control settings are simulated and plotted against mass flow. If there is no mass flow or heat demand, respectively, the temperature in the supply pipe drops. With no bypass installed, the temperature would reach 31 °C. With constant as well as standard thermal bypass, 65 °C is maintained. The optimized bypass has a lowered setpoint of 40 °C (Hysteresis is 39-41 °C).

The substation demand pattern is of special interest for bypass control. If there are long periods without any heat demand, the bypass control is in operation, as water stagnates and cools down. If there is continuous heat demand (as in winter operation) bypass flow is not necessary. In this simulation period on 4th of June, after heat demand stops, bypass control with a setpoint of 65 °C starts operating after 1 h. Whereas the bypass control with a setpoint of 40 °C starts operating after 4 h, allowing the heating fluid in the distribution pipes to cool down, decreasing heat losses.

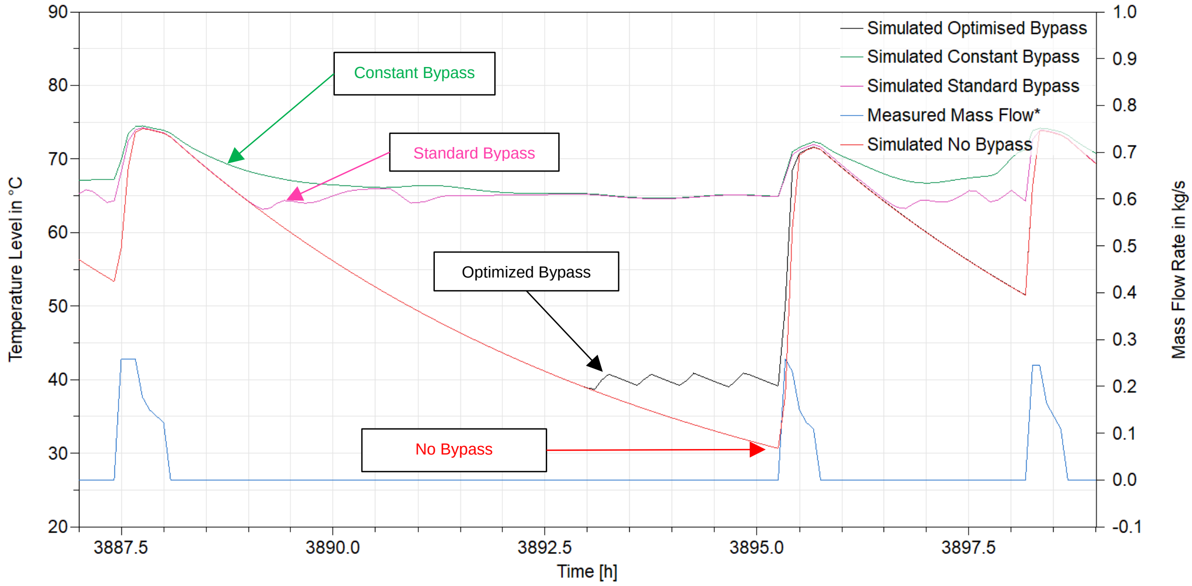

Figure 18 Simulation of Terminal Substation – Demand Pattern: Measured Mass Flow (secondary axis) vs. Simulated Supply Temperatures (primary axis) during Summer Operation (4th of June) with Different Bypass Control (No Bypass, Constant Bypass, Temperature Bypass Standard, Thermal Bypass Optimized)

Looking at a shorter period of 3 h on the same day, Figure 19 shows the amount of time it takes to reach the minimum supply temperature for different bypass controls. Heat demand occurs after a zero-demand period of 7 h (supply pipe cools down, as shown in Figure 18). The pre-defined maximum waiting time of 9 min is reached by the constant and standard thermal bypass control (0 min) and the optimized thermal bypass control (8.4 min). With no bypass installed it takes only 1.8 min longer (10.2 min). Nevertheless, it is a coincidence, that the operation could work without a bypass. Long periods without heat demand would compromise supply temperature requirements.

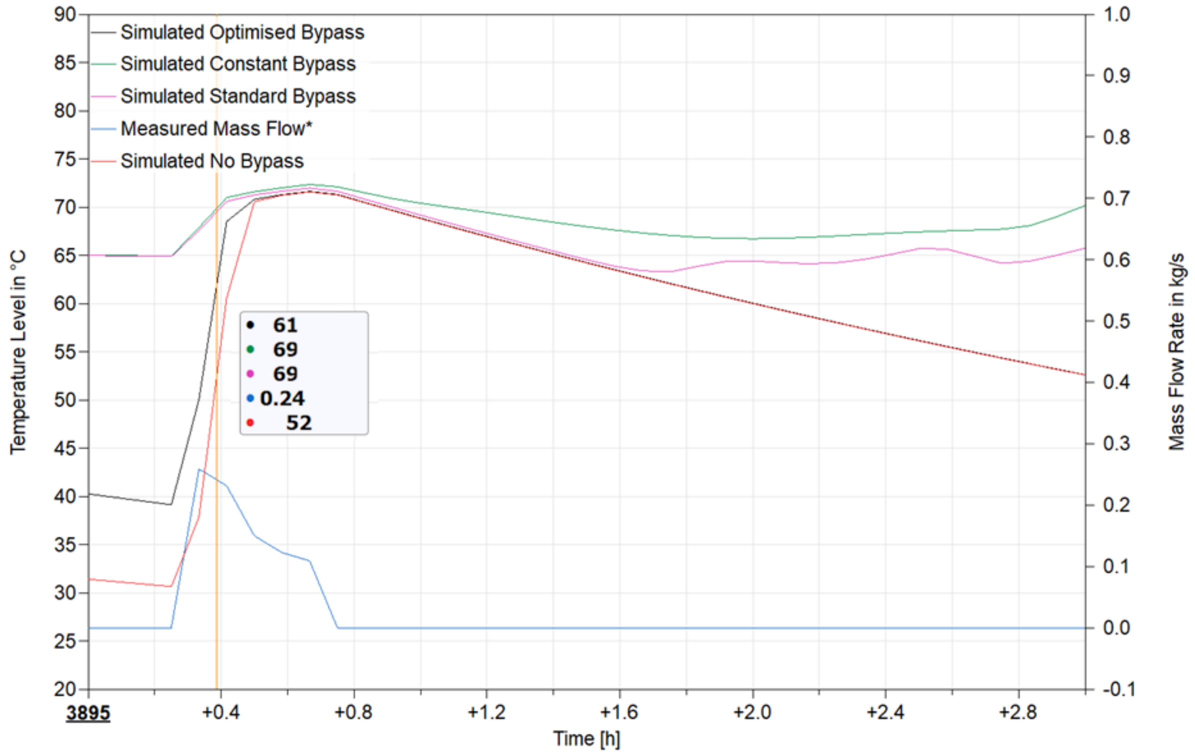

Figure 19 Simulation of Terminal Substation - Time to Minimum Supply Temperature: Measured Mass Flow vs. Simulated Supply Temperature with Different Bypass Control (Thermal Optimized Bypass, Constant Bypass, Thermal Standard Bypass, No Bypass)

The different bypass control strategies are simulated for the pre-defined 2-week simulation period of June 1st to June 14th. Based on these results, an extrapolation for the whole summer period was done.

The following key performance indicators (KPI's) are introduced, quantifying the impact of different bypass control on the performance of the district heating system:

$$Distribution\ Grid\ Efficiency\ in\ \% = \frac{Total\ Consumer\ Heat\ Demand}{\text{Heat from Plant}} = 1 - \frac{Heat\ Losses\ Supply + Heat\ Losses\ Return}{\text{Heat from Plant}}$$

$$Temperature\ Reduction\ Return\ in\ K = \text{Return Temperature at Plant (constant bypass)} - Return\ Temperature\ at\ Plant\ (current\ bypass)$$

An overview of the most important simulation results and KPI's are shown in Table 1. Four different simulation runs have been done, comparing the different bypass control strategies. The boundary conditions of the different simulation runs remain unaltered and are informative, such as the supply temperature and the consumer heat demand.

Table 1 Result Overview Simulation Bypass Study

		KPI's			Simulation Results 2-Week Period							Extrapolation Summer Period				
Bypass Control	**Supply Temperature at Plant**	**Distribution Grid Efficiency**	**Return Temperature Reduction**	**Time to Required Temperature**	**Heat Losses Supply Line**	**Heat Losses Return Line**	**Total Heat Losses**	**Heat from Plant**	**Total Consumer Heat Demand**	**Return Temperature at Plant**	**Theoretical Pump Power**	**Heat from Plant**	**Total Consumer Heat Demand**	**Heat Losses**	**Theoretical Pump Power**	
	°C	**%**	**K**	**min**	**MWh**	**MWh**	**%**	**MWh**	**MWh**	**°C**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**	**%**
Constant Bypass	79.5	74.4	0.0	0	6.7	4.5	25.6	41.9	31.2	55.5	2.4	455.3	338.6	122.4	25.5	5.6
Thermal Bypass Standard 65 °C	79.5	74.5	-0.3	0	6.7	4.5	25.5	41.8	31.2	55.1	2.3	454.2	338.6	121.4	25.3	5.6
Thermal Bypass Optimised 40°C	79.5	74.7	-0.5	8	6.7	4.4	25.3	41.7	31.2	55.0	2.3	453.2	338.6	120.4	25.2	5.6
No Bypass	79.5	74.7	-0.5	10	6.7	4.4	25.3	41.7	31.2	55.0	2.3	453.1	338.6	120.4	25.2	5.6

With a constant bypass control (reference scenario) the return temperature at the plant is 55.5 °C, distribution grid efficiency is 74.4 % and total heat losses over the summer period are 122.4 MWh or 25.6 %. Relative summer heat losses are significantly higher (+10.6 %) than the measured annual relative heat losses of 15 % (which also include plant losses). This is a result of the lower consumer heat demand during summer operation.

A standard thermal bypass (65 °C setpoint) lowers return temperature at the plant to 55.1 °C (–0.4 K), raises distribution grid efficiency to 74.5 % (+0.1 %) and reduces total heat losses over the summer period to 121.4 MWh (–1 MWh).

An optimized thermal bypass (40 °C setpoint) lowers return temperature at the plant to 55.0 °C (–0.5 K), raises distribution grid efficiency to 74.7 % (+0.3 %) and reduces total heat losses over the summer period to 120.4 GWh (–2 MWh).

Using no bypass lowers return temperature at the plant to 55.0 °C (–0.5 K), raises distribution grid efficiency to 74.7 % (+0.3 %) and reduces total heat losses to 120.4 MWh (–2 MWh). The minimum feed temperature is not reached in the given time.

In summary, these results show that implementation of an optimized thermal bypass valve control have a positive effect on decreasing return temperature and lowering heat losses. Impact on the grid highly depends on the nominal bypass flow, temperature set point, grid location and consumer demand.

<u>Benefit Quantification</u>

The simulation study quantified benefits for a single branch of an existing 3GDH wood district heating grid in detail. The benefit shall now be quantified for the whole grid. Simulating the whole grid is feasible but requires either modeling the whole distribution grid and all its 69 consumers or an aggregation of certain grid clusters. Furthermore, analysis and cleaning of all measured data is necessary. Reviewing these aspects, the benefit of setting up a full grid model is outweighed by its too time intensive setup. A simplified extrapolation is therefore made: all seven installed bypass valves on the respective branches are deemed to have the same characteristics as the investigated branch. This way, the gained KPI's can be applied to all seven branches at the case study Losone. Results are shown in Table 2.

Table 2 Extrapolation of Simulation Bypass Study Results

	Case Study Losone KPI's				
	Return Temperature Reduction	Annual Heat Loss Reduction	Annual Heat Loss Cost Reduction	Annual Boiler Cost Reduction	Annual Heat Pump Cost Reduction
Action	**K**	**MWh**	**CHF**	**CHF**	**CHF**
Switching from constant to optimised thermal bypass	-0.5	13.5	677	105	618
Switching from standard to optimised thermal bypass	-0.2	6.6	332	37	220

When switching from constant to optimized thermal bypass, these results indicate that a total heat loss reduction of 13.5 MWh could be achieved during summer operation (1st of May – 30th of September). When switching from standard to optimized thermal bypass, a total heat loss reduction of 6.6 MWh could be achieved. The annual heat loss reduction was calculated by multiplying the heat loss reduction in MWh by the seven branches. The reduced cost for heat was calculated with a wood chips price of 50 CHF/MWh [30]. The annual cost reduction is thus round CHF 700 or CHF 300, respectively. Finally, cost reductions for more efficient heat generation were calculated using cost reduction gradients based on [6]. The existing wood boiler with flue gas condensation has a cost reduction gradient of 0.11 CHF/(MWh·K). A scenario for a future upgrade of the district heating system is the integration of a heat pump which supplies base load including summer heat demand. The heat pump has a significantly higher cost reduction gradient of 0.65 CHF/(MWh·K). Taking these numbers, a further annual cost reduction of round CHF 40 – 100 could be attained for the existing biomass boiler and round CHF 200 – 600 for a heat pump, respectively. This highlights that temperature reduction will become much more relevant with the integration of temperature sensitive heat generation technologies like heat pumps, which have a higher performance at lower temperatures.

Cost Quantification

The rough cost of implementing an optimized bypass valve control was estimated using two scenarios: (i) switching from constant to thermal bypass valves (two workers involved) and (ii) optimizing thermal bypass valve set points (one worker only). The cost estimation was calculated per valve, duration of work, a surplus for preparation and other work, material and labor cost. It was normalized to the installed wood boiler heating capacity of the thermal grid which is 3.6 MW.

1. Constant bypass valve installed: change to thermal bypass valve

7 bypass valves * (4 h/valve * 1.5 surplus * 210 CHF/h + CHF 400/valve)= CHF 11’600

11’600 CHF / 3.6 MW heating capacity = 3’200 CHF/MW

2. Thermal bypass already installed: set point change

7 bypass valves * (1 h/valve * 1.5 surplus * 120 CHF/h)= CHF 1’300

1’300 CHF / 3.6 MW heating capacity = 360 CHF/MW

Impact on the Swiss District Heating Market

Wood chip fired district heating systems are highly established in Switzerland. Out of 1’447 grids registered by SFOE in June 2024, 912 grids are wood chip fired [27]. Figure 20 shows a map of Switzerland with thermal grid locations. The green symbols represent wood fired grids.

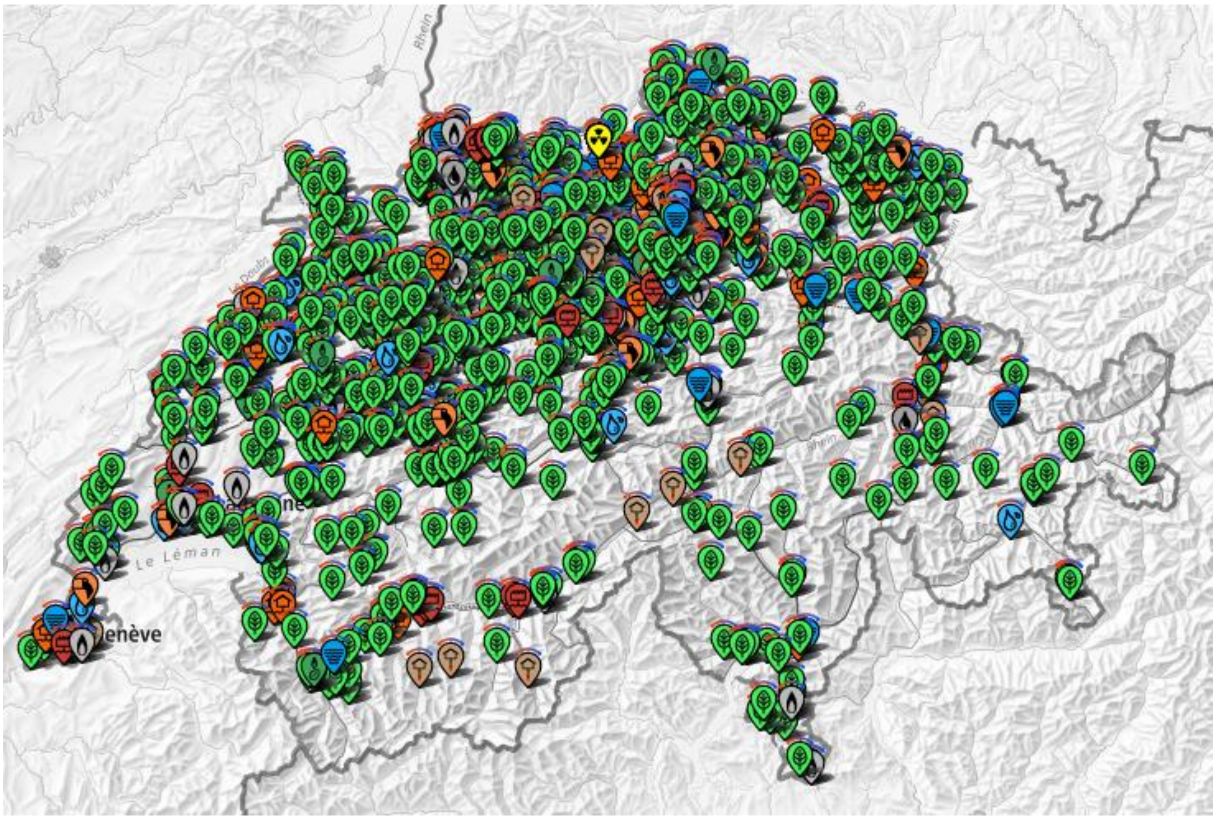

Figure 20 Installed Thermal Grids in Switzerland, accessible on: https://opendata.swiss/de/dataset/thermische-netze-nahwarme-fernwarme-fernkalte

The impact of implementing optimized bypass valve control in every grid are shown in Table 3 by extrapolating the results of this work. The following assumptions have been made:

- The current installed bypass control of district heating grids is mainly thermal bypass valves. The ratio between currently installed thermal and constant bypass control is 4:1.
- The SFOE dataset provides heating power data for only 781 grids. Grids without heating power dataset were excluded from this analysis.
- Total installed heating capacity with energy source wood chips is 1.76 GW (SFOE Dataset).
- The scaling between the case study size and the average dataset grid is done using an average between heating power (case study: 3.6 MW, average dataset: 2.25 MW) and energy produced (case study: 11. 8 GWh, average dataset: 5.63 GWh): a scaling factor of 430 (instead of 781 grids) was defined. This factor represents how many grids in Switzerland would exist if they had the same heating capacity and energy demand as the Losone case study. In other words, this means that the case study is slightly bigger than the average heating capacity and energy demand and is only multiplied by the scaling factor, instead of the number of grids.
- The number of bypass valves is based on the case study and scaled using the same factor as above. This implies that the case study represents an average grid layout.

Table 3 Impact of implementing optimized thermal bypass valves in Swiss wood chip fired district heating grids

Annual Heat Loss Reduction	**3**	**GWh**
Annual Heat Loss Cost Reduction	**173**	**kCHF**
Annual Boiler Loss Cost Reduction	**22**	**kCHF**
Annual Heat Pump Cost Reduction	**129**	**kCHF**
Annual Total Cost Reduction Boiler	**194**	**kCHF**
Annual Total Cost Reduction Heat Pump	**302**	**kCHF**
Investment Cost Optimized Thermal Bypass	**1631**	**kCHF**

Discussion

The results in Table 3 show that implementing an action with low temperature reduction measure, reducing 0.2 - 0.5 K return temperature and 0.1 – 0.3 % of heat losses of an existing district heating grid have a tangible influence on the efficiency and economic performance of Swiss thermal grids fired by wood chips. These results indicate that annual heat savings of 3 GWh and cost savings of round CHF 200’000 could be achieved if applying it to current technology of flue gas condensing wood chip boiler. If centralised band load heat pumps would be integrated in the system, the annual heat savings would rise to CHF 300’000. The associated cost for switching all grids from a mix of constant and non-optimized thermal bypass valves to optimized thermal bypass valves is CHF 1’630’000. A return of investment can be achieved in 6 - 8 years while product lifetime of 20 years can be expected.

6 Conclusion

In this work, strategies for reducing temperature have been explored and detailed by examining the latest advancements in the field. A method has been presented to combine the results of a concrete simulation study with practical principles for planning and operating district heating networks.

An extensive matrix of possible temperature reduction actions was created, summarizing currently known temperature reduction actions. The most crucial issue, hindering current widespread implementation of actions, was identified: costs and benefits need to be quantified to give district heating operators a clear decision basis on which temperature reduction actions shall be implemented in which order. A so-called cost/benefit ratio was introduced and calculated for three different actions where currently no data was available on their ability to reduce temperature as compared to their implementation cost.

A Modelica simulation framework was further advanced and applied to quantify benefits for a concrete case study in Losone. Here, we investigated the action of avoiding bypass flow on the heat distribution level. A method for optimized minimum supply or bypass temperature control was introduced. The Modelica framework allows dynamic thermo-hydraulic simulation of a representative case study for district heating. The numerical study revealed how a low-cost optimization action could lead to a temperature reduction of 0.5 K for the case study which has the potential to be applied in more than 800 wood-fired district heating grids in Switzerland. Applying optimized bypass control to all relevant Swiss DH grids could allow annual heat savings of 3 GWh and annual cost savings of CHF 200’000 – CHF 300’000 based on current energy prices. A return on investment could potentially be achieved in 6-8 years with a product lifetime of 20 years.

7 Outlook

The transition towards lower temperatures in district heating systems is crucial for enhancing the efficiency and sustainability of Switzerland's energy infrastructure. This report has outlined a set of temperature reduction actions to achieve this goal.

Future research including P+D projects will continue to explore innovative solutions to further integrate renewable energy sources in combination with heat pumps into new and existing district heating systems. These systems are highly dependent on decreased temperature levels. Future research shall contribute towards completing the cost/benefit ratio quantification presented in this work. A completed action matrix will allow to accelerate implementation of transformation pathways from high to low temperature district heating systems.

The bypass control optimization could be further enhanced by applying model predictive control and combining it with other temperature reductions actions. Along this way, the use of dynamic simulation frameworks, like the one used here, enhances understanding of district heating and cooling systems. This approach facilitates the holistic optimization of energy system designs and allows for the development and virtual testing of various optimization strategies, thus reducing operational risks and eliminating the need for costly field experiments.

8 References

[1] Caputo P, Ferla G, Belliardi M, Cereghetti N. District thermal systems: State of the art and promising evolutive scenarios. A focus on Italy and Switzerland. Sustain Cities Soc 2021;65:102579. https://doi.org/10.1016/J.SCS.2020.102579.

[2] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/J.ENERGY.2014.02.089.

[3] Hangartner D, Ködel J, Mennel S, Sulzer M. Grundlagen und Erläuterungen zu Thermischen Netzen. 2018.

[4] Sommer T, Sulzer M, Wetter M, Sotnikov A, Mennel S, Stettler C. The reservoir network: A new network topology for district heating and cooling. Energy 2020;199:117418. https://doi.org/10.1016/j.energy.2020.117418.

[5] Dalla Rosa A, Li H;, Svendsen S;, Werner S;, Persson U;, Ruehling K;, et al. General rights IEA DHC Annex X report:Toward 4th Generation District Heating Experience and Potential of Low-Temperature District Heating. APA; 2014.

[6] Averfalk H, Benakopoulos T, Best I, Dammel F, Engel C. Low-Temperature District Heating Implementation Guidebook: Final Report of IEA DHC Annex TS2. Implementation of Low-Temperature District Heating 2021.

[7] Molyneaux A, Leyland G, Favrat D. Environomic multi-objective optimisation of a district heating network considering centralized and decentralized heat pumps. Energy 2010;35:751–8. https://doi.org/10.1016/j.energy.2009.09.028.

[8] Curti V, von Spakovsky MR, Favrat D. An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part I: Methodology. International Journal of Thermal Sciences 2000;39:721–30. https://doi.org/10.1016/S1290-0729(00)00226-X.

[9] Curti V, Favrat D, von Spakovsky MR. An environomic approach for the modeling and optimization of a district heating network based on centralized and decentralized heat pumps, cogeneration and/or gas furnace. Part II: Application. International Journal of Thermal Sciences 2000;39:731–41. https://doi.org/10.1016/S1290-0729(00)00225-8.

[10] Schmidt D. Low Temperature District Heating for Future Energy Systems. Energy Procedia 2018;149:595 – 604. https://doi.org/https://doi.org/10.1016/j.egypro.2018.08.224.

[11] Averfalk H, Werner S, Felsmann C, Rühling K, Wiltshire R, Svendsen S. Transformation roadmap from high to low temperature district heating systems. 2017.

[12] Guelpa E, Capone M, Sciacovelli A, Vasset N, Baviere R, Verda V. Reduction of supply temperature in existing district heating: A review of strategies and implementations. Energy 2023;262. https://doi.org/10.1016/j.energy.2022.125363.

[13] Pampuri L, Belliardi M, Bettini A, Cereghetti N, Curto I, Caputo P. A method for mapping areas potentially suitable for district heating systems. An application to Canton Ticino (Switzerland). Energy 2019;189. https://doi.org/10.1016/j.energy.2019.116297.

[14] Kemmler A, Kirchner A, Kreidelmeye S, et al. Energieperspektiven 2050+ – Technischer Bericht – Gesamtdokumentation der Arbeiten. 2021.

[15] Callegari S, Augustin ;, Novoa-Herzog R;, Schneider S;, Brischoux P;, Duret A;, et al. Strategies and potentials of temperature reduction on existing district heating substations: two case studies SWEET DeCarbCH Deliverable D7.1.2. 2023.

[16] Guelpa E, Capone M, Sciacovelli A, Vasset N, Baviere R, Verda V. Reduction of supply temperature in existing district heating: A review of strategies and implementations. Energy 2023;262:125363. https://doi.org/10.1016/J.ENERGY.2022.125363.

[17] Sotnikov A, Sandmeier E, Sulzer M, Sergi T, Mennel S, Sommer T. Thermal stability and heat transfer in the reservoir low-temperature network. J Phys Conf Ser, 2019.

[18] Sommer T, Sotnikov A, Sulzer M, Scholz V, Mischler S, Rismanchi B, et al. Hydrothermal challenges in low-temperature networks with distributed heat pumps. Energy 2022;257:124527. https://doi.org/10.1016/J.ENERGY.2022.124527.

[19] Maccarini A, Sotnikov A, Sommer T, Wetter M, Sulzer M, Afshari A. Influence of building heat distribution temperatures on the energy performance and sizing of 5th generation district heating and cooling networks. Energy 2023;275. https://doi.org/10.1016/j.energy.2023.127457.

[20] Wetter M. Modelica Buildings Library 2024. https://simulationresearch.lbl.gov/modelica/index.html (accessed June 3, 2024).

[21] Wetter M, Zuo W, Nouidui TS, Pang X. Modelica Buildings library. J Build Perform Simul 2014;7:253–70. https://doi.org/10.1080/19401493.2013.765506.

[22] Buffa S, Fouladfar MH, Franchini G, Gabarre IL, Chicote MA. Advanced Control and Fault Detection Strategies for District Heating and Cooling Systems—A Review. Applied Sciences 2021, Vol 11, Page 455 2021;11:455. https://doi.org/10.3390/APP11010455.

[23] Frederiksen S, Werner S. District heating and cooling. Studentlitteratur Lund; 2013.

[24] Vandermeulen A, van der Heijde B, Patteeuw D, Vanhoudt D, Helsen L. A theoretical benchmark for bypass controllers in a residential district heating network. Energy 2018;151:45–53. https://doi.org/10.1016/J.ENERGY.2018.02.156.

[25] Vandermeulen A, van der Heijde B, Patteeuw D, Vanhoudt D, Helsen L. A theoretical benchmark for bypass controllers in a residential district heating network. Energy 2018;151:45–53. https://doi.org/10.1016/J.ENERGY.2018.02.156.

[26] Keel A, Binggeli D, Good J, Thalmann S, Jenni A, Küttel P. QM Holzheizwerke 2018. https://www.qmholzheizwerke.ch/home.html (accessed June 4, 2024).

[27] Swiss Federal Office of Energy SFOE. Thermal networks (local heating, district heating, district cooling) 2024. https://opendata.swiss/en/dataset/thermische-netze-nahwarme-fernwarme-fernkalte.

[28] Toffanin R, Caputo P, Belliardi M, Curti V. Low and Ultra-Low Temperature District Heating Equipped by Heat Pumps—An Analysis of the Best Operative Conditions for a Swiss Case Study. Energies (Basel) 2022;15. https://doi.org/10.3390/EN15093344.

[29] van der Heijde B, Fuchs M, Ribas Tugores C, Schweiger G, Sartor K, Basciotti D, et al. Dynamic equation-based thermo-hydraulic pipe model for district heating and cooling systems. Energy Convers Manag 2017;151:158–69. https://doi.org/10.1016/j.enconman.2017.08.072.

[30] Holzenergie Schweiz. Preisindex Schnitzel und Holzpellets - Fachthemen - Holzenergie. 2024 2024. https://www.holzenergie.ch/fachthemen/preisindex-schnitzel-und-holzpellets (accessed June 20, 2024).

[31] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88:568–76. https://doi.org/10.1016/j.apenergy.2010.09.020.

[32] Boesten S, Ivens W, Dekker SC, Eijdems H. 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. Advances in Geosciences 2019;49:129–36. https://doi.org/10.5194/adgeo-49-129-2019.

[33] Revesz A, Jones P, Dunham C, Davies G, Marques C, Matabuena R, et al. Developing novel 5th generation district energy networks. Energy 2020;201:117389. https://doi.org/10.1016/j.energy.2020.117389.

9 Appendix

A: Generation Definition of District Heating

First Generation of District Heating Technology (1GDH)

The first commercial district heating systems were implemented in the United States in 1880, based on the steam distribution results obtained in 1876-1877 by Birdsill Holly in his pioneering Lockport experiments. This steam distribution technology, although considered outdated to this day, is still used in two major district heating systems: the Manhattan system in New York and the Paris system. Both urban areas are extremely dense and offer very favorable conditions for low heat distribution costs. In fact, Paris has the best conditions for efficient heat distribution in the entire European Union [31]. Therefore, both systems can afford to use the first generation of outdated district heating technologies in their current operations.

Second-generation district heating technology (2GDH).

The first commercial European district heating systems were introduced in Germany in the 1920s, initially with steam distribution. However, several German engineers disputed the choice of steam as the heat carrier and argued for the need to use water as the heat carrier to increase the efficiency of the system. These engineers became early adopters of second-generation technology when they implemented their new ideas in new district heating systems. However, rather high supply temperatures (above 100 °C) were applied, with a large temperature difference between flow and return, so that smaller diameter pipes could be used. This second-generation technology was recognized as the best technology available between 1930 and 1980. Second-generation technology was also applied in the USSR during the introduction and expansion of district heating in the 1930s and 1950s. Russian experiences and methods were later transferred and used in China when district heating was first introduced in the 1950s and 1960s.

Third-generation district heating technology (3GDH).

The two international oil crises of the 1970s sparked increased interest in Europe in using district heating systems as a general means of reducing dependence on fuel oil imports. This was especially the case in the three Nordic countries: Denmark, Sweden, and Finland. Engineers in these three countries advocated lower supply temperatures (below 100 °C) to improve system efficiency. At the same time, other productivity gains were achieved by using prefabricated and pre-insulated pipes together with prefabricated substations. This third-generation technology has been recognized as the best technology available since about 1980 and it is currently being used in the expansion of all European district heating systems. This technology is also used in Russia and China for expansion of existing systems.

Fourth Generation District Heating Technology (4GDH)

The awareness of global warming that emerged in the 1990s with the creation of the UNFCCC in 1992 and the Kyoto Protocol in 1997 created a renewed interest in district heating systems as a means of replacing fossil fuels using renewables and various low-temperature heat sources.

Early adopters of low-temperature district heating were engineers who designed several pilot solar district heating systems in Sweden, Denmark, and Germany. These experiences flowed into the Marstal system in Denmark, where seasonal heat storage was introduced for the first time in a European district heating system. The development of the Marstal system was supported by Sunstore projects, funded by European research programs.

The conditions and corresponding five expected capacities of 4GDH were defined by [2]. This definition paper was written by a group of researchers affiliated with the 4GDH research center in Aalborg (Denmark), with core funding from Innovation Fund Denmark. The five skills identified are:

- the ability to provide low-temperature district heating for space heating and domestic hot water;
- the ability to distribute heat with low network losses;
- the ability to recycle heat from low-temperature sources;

- the ability to integrate thermal networks into a smart energy system;
- the ability to ensure adequate facilities for planning, cost, and motivation.

The purpose of developing 4GDH systems is to find a technology that can be harmonized for European conditions and support the expansion of district heating in European countries with low district heating penetration. It is expected that this new district heating technology will play the same role that 3GDH has played in the expansion of district heating in the Nordic countries.

Fifth Generation District Heating and Cooling Technology (5GDHC)

(Boesten et al., 2019) provide a definition for 5GDHC and show how this concept differs from the concept of 4GDH, since 5GDHC are decentralized, bidirectional, close to ground temperature networks that use direct exchange of warm and cold return flows and thermal storage to balance thermal demand as much as possible. Also [33] underline the novelty of 5GDHC and the different possible topology, comprising decentralized heat pumps rather than a single large energy center, giving opportunities for sharing (prosuming) heating and cooling across a very low temperature loop.

The concept of 5GDHC runs alongside the increasingly popular and interesting technology of heat pumps, which can very efficiently provide heating and cooling to buildings.