Impact of Domestic Hot Water Preparation Systems on District Heating Network Design and Operation

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Abstract

With more ambitious energy efficiency standards in newly constructed buildings and increased renovation rates in existing buildings, domestic hot water preparation systems are of increasing importance for the connected heat load, total heat demand, flow temperature requirements and return temperatures of residential buildings. This means, that the design and operation of district heating networks is heavily impacted by the domestic hot water preparation systems of its consumers. In this case study, three domestic hot water preparation systems are investigated regarding their impact on the district heating network design and operation. The investigated systems include instantaneous domestic hot water preparation and hot water storages, both at 60 °C, as well as preparation with buffer storages at 45 °C with heat exchangers on apartment level. Instantaneous preparation results in lower heat demand, distribution heat losses and return temperatures, while yielding similar costs as hot water storages (both at 60 °C). Domestic hot water preparation at 45 °C allows to significantly reduce the district heating network's flow temperature (from 75 to 50 °C) and also yields lower heat demand, distribution heat losses and return temperatures. However, because of high costs for the heat exchangers on apartment level, this system is not economically competitive in the evaluated case.

Keywords: domestic hot water, district heating, simulation study

1. Introduction

Studies such as the *Heat Roadmap Europe* (Persson et al., 2019) show that for the European Union to reach a cost-efficient energy system transformation, in the future a large share of district heating and cooling, especially in urban areas, will be needed. Existing and newly constructed district heating systems must be operated with low temperatures and use excess heat or renewable sources, such as solar thermal, geothermal or ambient heat, to contribute to the reduction of CO_2-equivalent emissions (Lund et al., 2014). Low temperature district heating offers new possibilities for higher energy efficiency and better utilization of renewable energy sources on a system level.

With more ambitious energy efficiency standards in newly constructed buildings and increased renovation rates in existing buildings, domestic hot water (DHW) preparation systems are of increasing importance for the connected heat load, total heat demand, flow temperature requirements and return temperatures of residential buildings. This means, that the design and operation of newly constructed district heating networks (DHN) and the transformation of existing DHN is heavily impacted by the domestic hot water preparation systems of its consumers.

A fundamental distinction of DHW systems is between instantaneous preparation and systems that use storages. There are innovations of the DHW systems' design that include reduced temperature levels e.g., with additional heat exchangers on apartment level or electric temperature boosters (direct electric or via heat pumps) (Østergaard et al., 2022).

In this study, the impact of three DHW preparation systems on the DHN design and operation is investigated regarding total heat demand, heat distribution costs and temperature levels for the case study district called "Sullivan". The Sullivan district is part of a former US-Military base that is being transformed into a residential area and consists of a mix of newly constructed and refurbished buildings as well as single family dwellings, apartment buildings and commercial buildings (Figure 1). It is planned to supply the district's 121 buildings through a subgrid, that is connected to the main district heating network of Mannheim, Germany, but is operated on lower temperatures to achieve a higher efficiency and allow to integrate local renewable energy technologies

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such as air source heat pumps or solar thermal systems.

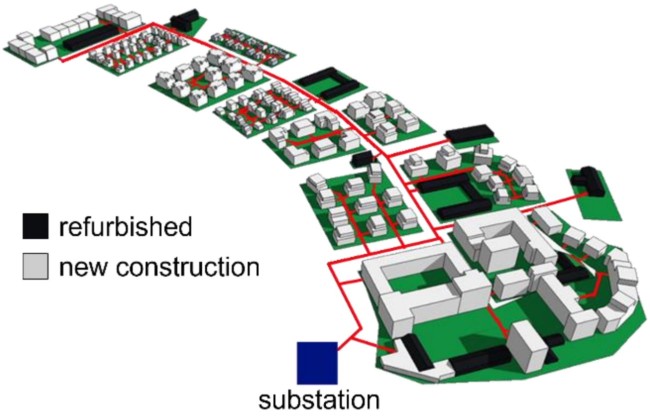

Figure 1: Scheme of the Sullivan district in Mannheim with newly constructed (white) and existing refurbished buildings (black).

2. Consumers

In a past research project, the investor's plans for the Sullivan district have been analyzed and comprehensive thermal simulations of the heat consumers' space heating and DHW demand have been conducted. The resulting design capacities and heat load profiles, including return temperatures, were used to design DHN for three DHW preparation systems (Figure 2):

- DHW preparation in hot water storages at 60 °C
- Instantaneous DHW preparation at 60 °C
- DHW preparation with storages at 45 °C, with heat exchangers on apartment level

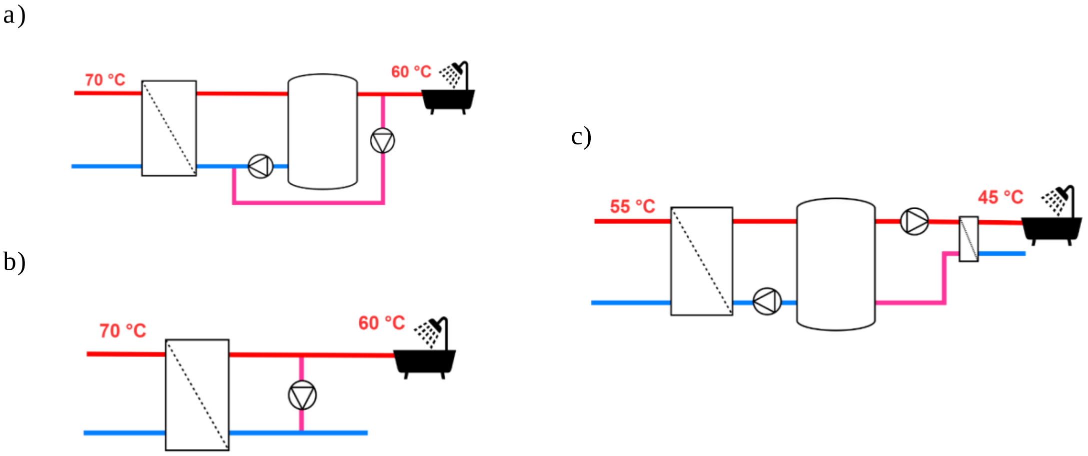

Figure 2: Simplified h*ydraulic schemes of the investigated domestic hot water preparation systems. a) Preparation in a hot water storage at 60 °C. b) Instantaneous preparation at 60 °C. c) Buffer storage at 45 °C with distribution towards heat exchangers at apartment level*

All DHW systems are installed in parallel to the space heating systems, which are using underfloor heating. For hygienic and comfort reasons, circulation systems were assumed for all building types. For DHW preparation at 60 °C a minimum return temperature of 55 °C for the circulation system was assumed. For DHW preparation at 45 °C the circulation return temperature was reduced. The minimum district heating flow temperature (at the consumers) was set to 70 °C for DHW preparation at 60 °C. DHW preparation at 45 °C allows lower minimum flow temperatures of 50 °C.

Figure 3 shows the simulation results aggregated for the whole district as daily mean values. For all DHW preparation systems the return temperatures follow a sine curve, which is proportional to the course of the potable water temperature. The space heating return temperature is highly dependent on the buildings' energy efficiency standards (newly constructed and refurbished) and their usage schedules (residential and commercial). DHW preparation in storages at 60 °C results in higher return temperatures than instantaneous DHW preparation at 60 °C. By reducing the flow temperature and using buffer storages as well as heat exchangers on apartment level, the return temperature is also reduced, because of the reduced circulation temperatures in the buildings.

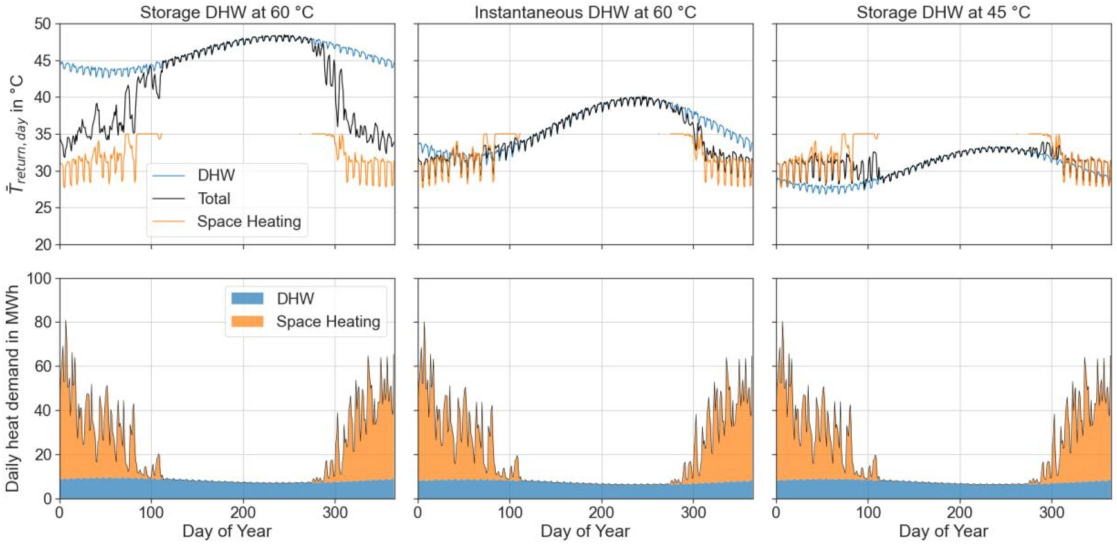

Figure 3: Daily mean values of return temperatures for DHW, space heating and total as well as for the heat demand aggregated for the whole Sullivan district.

The total yearly heat demands as well as the total yearly mass flow weighted average return temperature for all three systems are displayed in Table 1. The space heating demand at 4,554 MWh/a is equal for all systems. Thus, DHW has a share in the total energy consumption of about 40 %. The simulation results show, that instantaneous DHW preparation yields lower total heat demand, because storage heat losses are avoided. By reducing the temperatures in the buffer storage and the DHW distribution pipes, the heat losses are also reduced, which also results in a reduced total heat demand compared to DHW preparation in storages at 60 °C.

Table 1: Simulation results aggregated for all consumers in the Sullivan district

	Total heat demand (space heating and DHW) in MWh/a	Yearly mass flow weighted average return temperature (space heating and DHW) in °C
Storage at 60 °C	7,576	38.7
Instantaneous at 60 °C	7,311	33.0
Storage at 45 °C	7,353	31.1

Additionally, the connected heat loads the consumers were evaluated. The total connected heat loads of the district heating network for the three DHW preparation systems are displayed in Table 2. For instantaneous DHW preparation the individual buildings have much higher connected heat loads, as the maximum DHW demand must be considered. However, the simultaneity is much lower compared to storage systems, which have reduced connected heat loads. This results in a slightly increased total connected heat load (+ 11 %) of instantaneous DHW preparation, when simultaneity is considered.

Table 2: Connected heat loads with and without simultaneity

	Total connected heat load, simultaneity not considered in MW	Total connected heat load, simultaneity considered in MW
Storage at 60 °C	8.1	7.0
Instantaneous at 60 °C	18.4	7.8
Storage at 45 °C	8.1	7.0

3. District Heating Network

A district heating network route is designed to connect all the consumers (see Figure 1). The total route length amounts to 5.1 km. The pipes are dimensioned individually for the three different DHW preparation systems. For all systems the pipes are dimensioned for a maximum specific pressure loss of 300 Pa/m. Simultaneity factors are considered individually for each pipe segment, dependent on the number of consumers supplied through the segment. The design temperatures are set to 75 °C / 40 °C flow and return temperature, respectively, for DHW preparation at 60 °C. For DHW preparation at 45 °C the design temperatures are reduced to 60 °C / 30 °C.

Figure 4 shows the distribution of pipe diameters (DN) for the three DHN as well as an average DN. Because of the higher peak loads for instantaneous systems, the average of the pipe dimensions is larger, especially for lead in pipes. Down the line, in transport pipes, the effect is reduced because of lower simultaneity. For storage systems at 45 °C the design temperature difference between flow and return is lower, which leads to larger pipe dimensions compared to storage systems with DHW preparation at 60 °C.

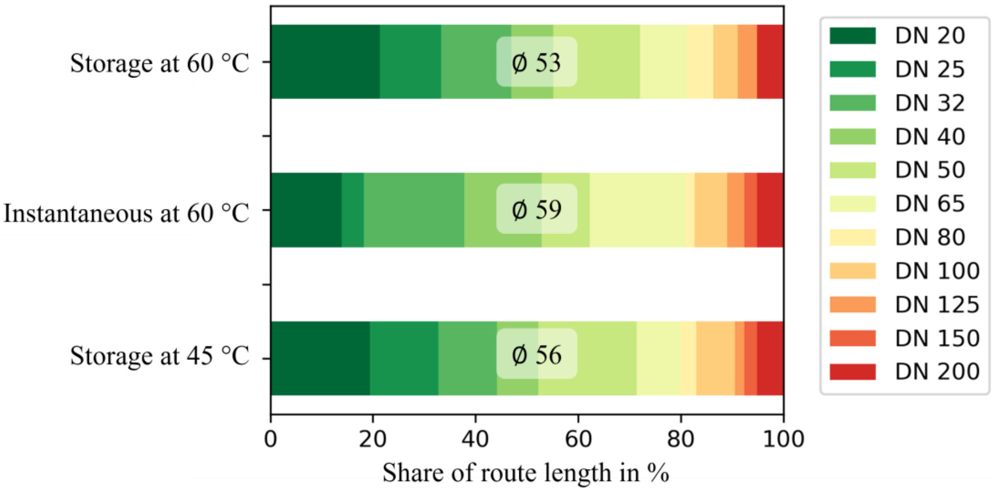

Figure 4: Distribution of pipe diameters for DHN with three different DHW preparation systems. Ø-Numbers indicate the average DN. Total route length: 5.1 km

The thermo-hydraulic DHN model is described by Zipplies et al. (2022). The pipes considered are steel pipes with plastic casing, which are constructed as twin-pipes with the highest insulation standard. Annual simulations are performed, using the previously described load and return temperature profiles as input. For the instantaneous DHW preparation, the simulations yield that the pipes are cooling down during periods without load. To ensure that the consumers' temperature demand can be satisfied all the time, bypasses are considered for the DHN with instantaneous DHW preparation for some of the consumers (marked in Figure 5). The bypasses are controlled so that the flow temperature is always kept above 58 °C. For storage systems this is not necessary because periods without demand occur less frequently and with shorter duration. However, the simulation results show, that the influence of the bypasses on the distribution heat losses (+ 0.8 %) and average return temperatures (+ 0.1 K) is very small.

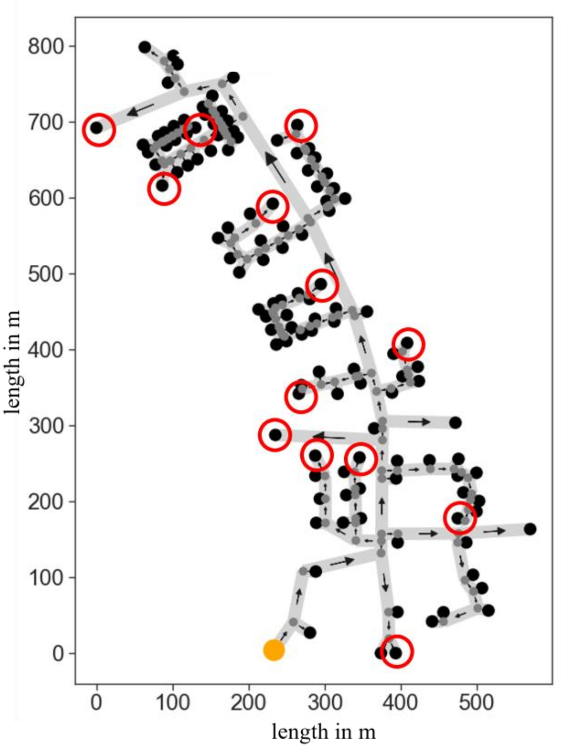

Figure 5: Graphical representation of the district heating network. Red circles indicate substations, where bypasses were considered for instantaneous DHW preparation at 60 °C

The aggregated simulation results are given in Table 3. For all variants, the relative distribution heat losses are very low (around 4 to 5 %). This results from several factors, such as relatively low flow and return temperature levels, a relatively high linear heat density (1.5 MWh/m/a), the usage of the highest insulation standard (DS3), and the usage of twin-pipes. The return temperatures at the heat supply show only little differences to the return temperatures at the consumers (see Table 1). Another interesting indicator is the yearly mass flow weighted average mean temperature (flow and return). This can be used to calculate cost reduction gradients (CRG) which are described in the following chapter. Instantaneous DHW preparation at 60 °C yields slightly (2.9 K) lower mean temperatures (compared to storages at 60 °C), whereas DHW preparation at 45 °C significantly reduces the mean temperatures (-11.4 K). This is of course largely a consequence of the flow temperature reduction.

Table 3: Results of annual simulations

	Storages at 60 °C	Instantaneous at 60 °C	Storages at 45 °C
Heat sold in MWh/a	7,576	7,311	7,353
Distribution heat losses in MWh/a	416	396	309
Distribution heat losses in % related to totally supplied heat	5.2	5.1	4.0
Hydraulic work in MWh/a	25	21	34
Yearly mass flow weighted average return temperature in °C	38.7	32.9	30.9
Yearly average return temperature (over time) in °C	41.9	35.0	31.0
Yearly mass flow weighted average mean temperature (flow and return) in °C	56.9	54.0	45.5

4. Economic evaluation

An economic evaluation is conducted over a period of 30 years, where a discounting interest rate of 3 % is considered. The considered costs include initial and replacement investments, costs for operation and maintenance as well as heat supply costs. The heat supply costs are varied in a range from 30 to 100 €/MWh. All cost assumptions are given in Table 4. For the piping the parameter for ground condition ($f_{condition}$) is assumed as - 25 % (corresponding to “green areas”) and the parameter for piping (f_{piping}) is assumed as 0 % (corresponding to “plastic casing”).

Table 4: Cost assumptions for economic evaluation

Position	Cost function / Value	Reference
District Heating Network (Piping)		
Investment costs in €/kW	$c(DN) = (270 + 2{,}2 \cdot DN) \cdot (1 + f_{condition}) \cdot (1 + f_{piping})$	Große et al., 2017
Operation and maintenance costs in %/a of initial invest	0,5	Verein Deutscher Ingenieure, 2012
Economic life time in years	30	Große et al., 2017
Network Pump		
Investment costs in €	9.900	wilo, 2017
Operation and maintenance costs in %/a of initial invest	3	Verein Deutscher Ingenieure, 2012
Economic life time in years	10	Verein Deutscher Ingenieure, 2012
Electricity costs in €/MWh	240	
Substations		
Investment costs in €/kW	$c(\dot{Q}) = 0{,}026 \cdot (\dot{Q})^{-0{,}46}$	Große et al., 2017
Operation and maintenance costs in %/a of initial invest	3	Verein Deutscher Ingenieure, 2012
Economic life time in years	30	Große et al., 2017
Storages		
Investment costs in €/l	2,39	Forschungsgesellschaft für Energiewirtschaft mbH, 2017
Operation and maintenance costs in %/a of initial invest	3	Verein Deutscher Ingenieure, 2012
Economic life time in years	30	Verein Deutscher Ingenieure, 2012
Apartment substations		
Investment costs in €/kW	75	Meesenburg et al., 2020
Operation and maintenance costs in %/a of initial invest	3	Verein Deutscher Ingenieure, 2012
Economic life time in years	30	Verein Deutscher Ingenieure, 2012

Figure 6 shows annual full costs corresponding to the three different DHN designs shown in Figure 4, when heat supply costs of 50 €/MWh are assumed. The levelized cost of heat (LCOH, in relation to the heat sold) range from 75 €/MWh (storage at 60 °C) to 100 €/MWh (storage at 45 °C). Instantaneous DHW preparation at 60 °C yields LCOH of 79 €/MWh. From the illustration of the cost distribution, it can be concluded that the differences in costs for heat supply, heat losses, pump energy, piping and substations are rather small. However, the heat exchangers on apartment level add significant costs for the DHW preparation at 45 °C. Because the Sullivan district consists mainly of multi-family houses, more than 1,000 apartments would have to be equipped with heat exchangers. At the assumed rated thermal power of 24 kW per apartment, these would come at a cost of 1,800 € per apartment.

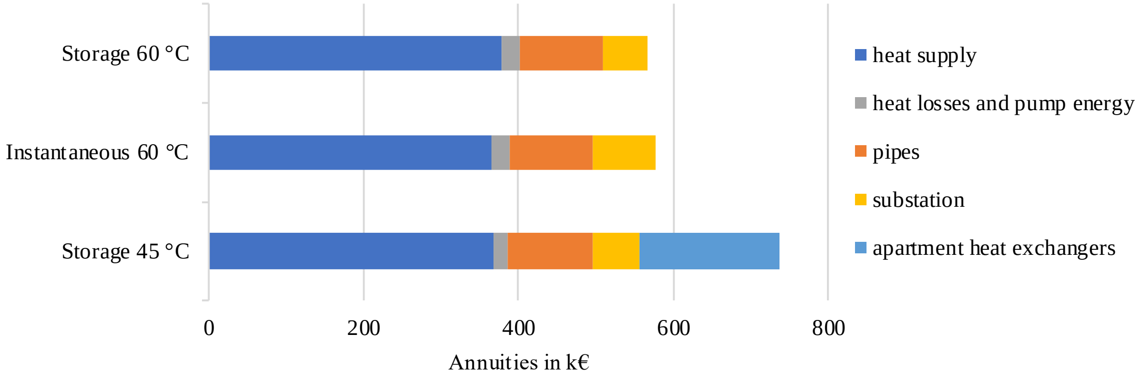

Figure 6: Annual full costs for all three variants for heat supply costs of 50 €/MWh

As mentioned before the heat supply costs are varied in a range from 30 to 100 €/MWh. Because of the reduced heat demand for DHW preparation and heat losses, instantaneous DHW preparation and DHW preparation in storages at 60 °C reach a cost equilibrium at heat supply costs of 90 €/MWh.

The study described so far evaluates the DHN temperature's impact on the heat distribution and consumption. However, the effect on the heat supply is not yet been taken into account. To do this, cost reduction gradients (CRG) are calculated. Geyer et al. (2021) define CRG as the benefit in LCOH of a case with lower temperatures compared to a reference case with higher temperatures, in relation to the temperature reduction (eq. 1).

$$CRG = \frac{LCOH_{Benefit}}{Temperature\ reduction}\ \left[\frac{€}{MWh \cdot K}\right] \qquad \text{(eq. 1)}$$

For instantaneous DHW preparation at 60 °C and DHW preparation at 45 °C the necessary CRG for reaching a cost equilibrium are calculated, using DHW preparation with storages at 60 °C as the reference case. The values for the CRG are calculated using the yearly mass flow weighted average mean temperature (flow and return, see Table 3). The results are plotted in Figure 7 over the heat supply costs.

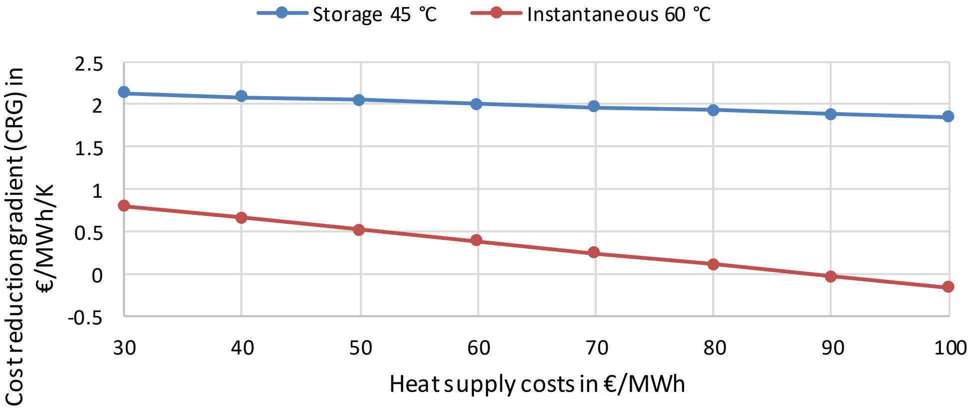

Figure 7: Necessary CRG to reach cost equilibrium with DHW preparation in hot water storages at 60 °C

The results show that for instantaneous DHW preparation at 60 °C the CRG is below 0.8 €/MWh/K and reaches negative values for heat supply costs above 90 €/MWh. For DHW preparation at 45 °C the CRG is between 1.8 and 2.1 €/MWh/K. Geyer et al. (2021) calculated CRG for different heat supply systems. The highest values were calculated for flat plat solar thermal collectors, geothermal heat supply (both: 0.67 €/MWh/K) and heat pumps (0.60 €/MWh/K). However, for geothermal heat supply only return temperature reductions and for heat pumps only flow temperature reductions were considered.

5. Summary

This case study shows that domestic hot water preparation systems have a significant impact on the total heat demand, connected heat load and temperature levels of a district heating network.

Compared to DHW preparation in storages at 60 °C, instantaneous DHW preparation at 60 °C leads to significantly higher connected heat loads for individual buildings, however because of lower simultaneity the total heat load at the heat supply is only about 11 % (7.0 to 7.8 MW) increased. Because storage heat losses are reduced, also the total heat demand is reduced for instantaneous DHW preparation (- 3 %). Another effect are reduced return temperatures, which in turn result in reduced heat losses. On the other hand, instantaneous DHW preparation makes the use of bypasses necessary. These however have low impact on the total DHN efficiency and temperature levels. At low heat supply costs (below 90 €/MWh), the economic evaluation shows slightly higher costs for instantaneous DHW preparation, mainly because of higher costs for substations. Depending on the heat supply system, the cost difference could be compensated for through cost benefits for the heat supply, that are resulting from the return temperature reduction.

DHW preparation with buffer storages and heat exchangers on apartment level also leads to heat demand reductions (- 3 % compared to DHW preparation in storages at 60 °C), because of lower temperature levels and thus heat losses in buildings. A main benefit of this variant is that the DHN supply temperature can be reduced, while the return temperatures are also reduced. However, the economic evaluations show that because of high costs for the heat exchangers on apartment level, DHW preparation at 45 °C is not competitive in this case. This is true even when the cost benefits of the temperature reduction for the heat supply are taken into account.

6. Acknowledgment

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