Feasibility study on energy storage in existing thermal energy distribution networks in the industrial and public sector

A methodology for calculating the storable thermal energy, estimating the effects of the storage process and the investment costs

Alexander Emde[1,2*], Bianca Haehl[3*], Alexander Sauer[1,2], Verena Lampret[1,2*]

1 Fraunhofer Institut für Produktionstechnik und Automatisierung, Nobelstr. 12, 70569 Stuttgart, Deutschland, +49 711 970 1916, alexander.emde@ipa.fraunhofer.de, https://www.ipa.fraunhofer.de

2 Universität Stuttgart, Institut für Energieeffizienz in der Produktion, Nobelstr. 12, 70569 Stuttgart

3 EnBW City, Schelmenwasenstraße 15, 70567 Stuttgart, b.haehl@netze-bw.de

Abstract: The aim of this publication is to present the topic of energy storage in existing thermal energy distribution networks, focusing on its use as a sensible heat storage system with water as a working fluid. From a techno-economic feasibility perspective, this paper examines an implementation approach. The usage of the network grid as a storage system is examined by calculating the thermal storage capacity and determining the effects storage will have on the flow velocity as well as the system operative pressure. A comparison of the resulting costs of energy storage in the network infrastructure compared to coupled storage systems showed the economic and space-saving advantages of energy storage in thermal networks.

Keywords: Thermal network storage, thermal energy storage, energy distribution networks, energy storage

1 Introduction

Heat and cold storage systems in conjunction with heat and cooling networks are becoming increasingly important within the energy transition [1, 2]. In Germany both thermal storage facilities and thermal energy distribution networks are promoted by the Federal Government through the combined heat and power act in order to increase efficiency in the field of heat generation [3]. In Power2Heat approaches, the stored thermal energy can be used at a later time, thus compensating the fluctuation of non-dispatchable renewable sources, i.e. wind and solar energy [4]. Industrial companies are increasingly interested in energy storage technologies [5]. The biggest challenges for energy storage technologies on an industrial scale are the investment costs and the high space requirements [6]. Thermal energy storage can enable an increase in overall efficiency and better reliability in the energy distribution system. Thus, potentially leading to a better operational efficiency, lower investment and operating costs and less pollution of the environment [7].

In various studies by Fraunhofer ISE and the German Aerospace Center (DLR), the storage demand for Germany and the storage capacity of heat storage facilities in connection with a European network were quantified regarding different scenarios for the emission reduction targets [8] [2].

Thermal storage can be integrated into energy systems in many ways. Thus, it is important to know how to implement them as cost-effectively as possible. A cost optimal variant is the utilization of the inherent storage capacity of heat or cooling distribution networks. These networks can therefore be used for the temporal decoupling of supply from demand for thermal energy. Basically, the inherent storage involves the alteration of the normal operation temperature of the thermal or cooling network in order to increase its thermal inertia.

2 State of the art

For thermal storage in combination with thermal energy distribution networks, a distinction must be made between coupled storage systems and inherent network storage systems.

In contrast to inherent network storage, the capacity of coupled storage systems does not exclusively rely on the distribution infrastructure of the network. The storage is implemented ad-hoc and hence additional to the network operational infrastructure. With regard to the state of the art, the use of coupled sensible storage has been widely researched and already frequently implemented [9]. In the field of short-term storage over several days, buffer storage tanks ensure the temporal decoupling of the demand for heat or cold from the generation of it. They decouple the heat/cold and power generation. When operating a combined heat and power (CHP) plant, electricity generation can be reduced if there is less demand for electricity and the heat storage unit can be used to cover the heat requirement. If there is an increased demand for electricity, excess heat is stored [10]. The minimum load can be increased and the resulting excess heat can be temporarily stored if the demand for heat is low. If there is a high demand for heat, the short-term load peaks are compensated via the buffer storage tank. As a result of lower cycle times the running times are extended and the service life is increased. A more efficient, flexible and continuous operation of the CHP plant is ensured [11–13].

Eckert and Gerhardt state that in addition to the use of buffer storage tanks in smaller plants, they are also used in conjunction with CHP technology and local or district heating networks [10]. In Germany, the incentive to expand district heating networks with storage facilities is to be increased in the future by means of subsidy measures [14]. For example, in Denmark, implementation is already growing strongly [14], whereas thermal storage facilities are generally designed to cover the peak load of the network for 8-12 hours [9].

Large-scale storages are used in four different variations: as tank storage, as pit storage, as aquifer storage and as earth probe storage [15]. These different variations of coupled storage constitute the main competing technologies for inherent network storage. They are hence relevant for this study because they allow comparisons between the two categories of thermal storage technologies, in particular in regard with their respective investment costs. In the following some studies are listed that focus on network inherent grid storage.

The association Energieeffizienzverband für Wärme, Kälte und KWK e.V. (AGFW) shows in its publication "Das Fernwärmenetz als thermischer Speicher" the economic aspects, technical solutions, loads and life cycle of thermal energy storage in supply, return and in the combination of supply and return lines [11].

Lorenzen examines in his master thesis about heat distribution networks and smart grid the dynamic storage behaviour of a heat network through change of boundary conditions using a simulation model in Matlab/Simulink. At a general level, the analysis shows the viability to use the heat networks as energy storage. It concludes that long storage periods are accompanied with increasing heat losses, resulting in a loss of efficiency. According to the operative objectives, network storage is particularly suitable for compensating consumption deviations and short-term supply deviations. [16]

The VDI-Gesellschaft Energietechnik investigates the storage capacity of heat networks with a connected load of 290 MJ/s using the simulation tool "BoFIT". The study concludes that the storage of energy in the network feed flow is accompanied by a reduction in the mass flow by the consumer, a lower power consumption of the pump and higher heat losses. When stored in the network return the mass flow of the network and the power consumption of the pump increase. The heat losses in the network return flow also increase. The energy storage in the feed and return flow shows the highest energy storage capacity with constant storage performance and constant network mass flow. [17]

Groß analyses in his dissertation "Untersuchung der Speicherfähigkeit von Fernwärmenetzen und deren Auswirkungen auf die Einsatzplanung von Wärmeerzeugern" the processes during storage in district heating networks using the simulation tool TRNSYS-TUD. The study shows the complexity of network storage processes and the significant savings potential of network storage with small or no storage tanks. The dissertation concludes that network storage should be implemented when the storage tank is fully loaded. Using network storage can double the running time of cogeneration units. District heating networks require load-dependent feed temperature limits. Lower feed temperatures lead to a smaller temperature spread and an increased total mass flow, which can lead to high-pressure losses. [18]

Basciotti et al model the heat distribution network in Altenmarkt im Pongau (Austria) as a case study with the simulation environment Modelica/Dymola. The aim is to find a control strategy for using the volume of the pipe network as a sensible storage system and estimating its effects on the operation of the distribution network. For the automatic control algorithm the flow temperature and the pressure loss between the supply and return flow of the heating network are used as variables. The study concludes that daily peak loads can be reduced by up to 15 % and that heat losses increase by 0.3 % compared to the business as usual operation. Moreover, fuel costs can be reduced by 2 % and CO_2 emissions by 20 %. [19]

Li et al. designs a physical model with an iterative solution method that considers the dynamic temperature changes of a distribution network. The aim is to investigate whether the heat network can be used as an energy storage system and whether this storage can improve the dispatch ability of wind power plants. Case studies were carried out and revealed that the methodology used enables an improvement of the overall economic performance of the system, its flexibility and the utilization of wind energy [20].

Currently the city of Hennigsdorf (Brandenburg, Germany) aims to increase the share of climate-neutral heat sources in their existing heating network by 80 % within the next years. To accomplish this, the city plans to combine the waste heat from the local steelworks, solar thermal collectors and a multifunctional large heat storage tank (22,000 m³) thus achieving daily, monthly and seasonal flexibility. In addition, the existing distribution network itself is to be used for the storage of short-term peak demand and for controlling the loads on the heat storage unit coupled to the distribution network. The described pilot project serves as an example for the creation and retrofit of similar thermal distribution networks [21].

The "8. Fachtagung Optimierung in der Energiewirtschaft" dealt with thermal unsteady storage in the supply flow of district heating networks. The objective was to increase the operating hours of CHP plants and to reduce the use of peak load boilers. It concluded that network storage within the supply flow is associated with energy savings for the pump and an increase in the operating hours of the CHP plant. However, depending on the power plant characteristics, its efficiency may deteriorate [22]. From an economic point of view, in this case, the increased heat loss had a stronger influence than the improved pump system performance.

Gu et al. proposed an operation model for an integrated energy storage system combining a district heating network and buildings to compensate between wind energy and thermal demand. The use of a mixed integer non-linear programming model exhibited benefits in terms of operational economics and wind power utilization [23].

Contrary to the above listed studies, this work does not investigate network storage in district heating distribution systems, but in distribution systems of industrial or process-specific nature. Both heating and cooling networks are considered. Especially cooling networks, which have been neglected in the consulted studies. In addition, not only the mathematical and physical backgrounds of network storage are addressed, but their feasibility is also examined from a techno-economic perspective. The analysis includes various methodology steps, including system analysis, which are described in the following section.

3 Methodology

In order to examine network inherent thermal storage and its feasibility, a methodical approach is needed. This approach pursues the objectives of calculating the additional storable energy capacity in distribution networks and determining the effects and investment costs of network storage. The methodology consists of the four steps shown in Figure 1.

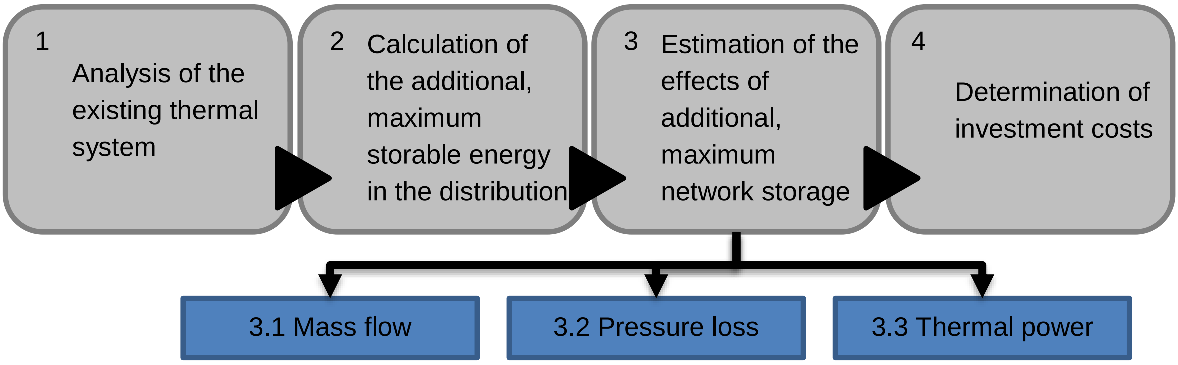

Figure 1: Methodical approach.

1. Before thermal storage can be integrated into a system, the system must be analyzed and characterized with regard to its three components - generation, distribution and consumption of thermal energy.

Producers can provide thermal energy in form of heat and cold. According to this, there are different types of thermal energy generators, which can operate with specific maximum or minimum supply or return temperatures. The supply temperature is given by the load characteristics; the return temperature is mostly limited due to efficiency losses or technical restrictions of the generators [24]. Within the scope of this work, changes in efficiencies are not considered.

The pipe or insulation material and their dimensions characterize the distribution networks. The networks are also characterized by the network parameters temperature (supply *S* and return *R*), pressure *p* and mass flow of the working fluid $\dot{m}_A$ by the consumer or mass flow of the distribution network $\dot{m}_{net}$. The mass flow can be converted into the volume flow and the flow velocity. To simplify the analysis, it is assumed that the respective flow temperature from the producer $\vartheta_{S,A}$ to the consumer and the respective return temperature from the consumer $\vartheta_{R,A}$ back to the producer are constant in the pipeline. In the analysis the assumption for a net that a constant pressure p_{net}, network mass flow $\dot{m}_{net}$, mean volume flow $\dot{V}_{m,net}$ and a mean flow velocity $u_{m,net}$ prevail at a constant temperature level for the supply and return flow, helps to simplify the analysis and it is valid. As a basis for this, the mean water density ρ_m, which depends on the mean temperature ϑ_m between the supply and return and the assumed constant at a specific network pressure p_{net}. Allowing the following equations to become applicable:

$$\vartheta_{m,1} = \frac{\vartheta_{S,1} + \vartheta_{R,1}}{2} \qquad [°C] \qquad (1.1)$$

$$\rho_{m,1}(\vartheta_{m,1}, p_{net}) \qquad [\frac{kg}{m^3}] \qquad (1.2)$$

$$\dot{V}_{m,net,1} = \frac{\dot{m}_{net,1}}{\rho_{m,1}} \qquad [\frac{m^3}{s}] \qquad (1.3)$$

$$u_{m,net,1} = \frac{\dot{V}_{m,net,1}}{A_m} = \frac{\dot{V}_{m,net,1} * 4}{{d_{m,i}}^2 * \pi} \qquad [\frac{m}{s}] \qquad (1.4)$$

Where A_m: mean circle area within the pipelines $[m^2]$
$d_{m,i}$: mean inner diameter of pipelines $[m]$ ((1.3) and (1.4) following [25]).
Together with the pipe length of the supply (l_S) and return flow (l_R), the volume of the existing network V_{net} is calculated from the volume of the supply pipeline (V_S) and the volume of the return pipeline (V_R). If the supply and return pipelines have different inner diameters, the following applies:

$$V_{net} = \sum_{m=1}^{j} V_{S,j} + \sum_{n=1}^{k} V_{R,k} = \sum_{m=1}^{j} l_{S,j} * \pi * \left(\frac{d_{i,S,j}}{2}\right)^2 + \sum_{n=1}^{k} l_{R,k} * \pi * \left(\frac{d_{i,R,k}}{2}\right)^2 \qquad [m^3] \qquad (1.5)$$

Afterwards, the loads are analyzed as the last component of the thermal system. These can be connected both directly and indirectly to the piping system and specify certain maximum (heating systems) or minimum (cooling systems) temperature limits. The limits depend individually on the type of load, the pressure, the temperature and the mass flow control components or the control options within the house stations.

2. The calculation of the maximum and additional storable energy within the existing heating or cooling network is based on the analysis of the thermal system in the first step.

The network storage can be illustrated by a coupled sensible thermal storage in the network supply and return (see Figure 2). The needed thermal power of the consumer is modelled through a variable mass flow $\dot{m}_A$ depending of the difference between supply ($\vartheta_{S,1}$) and return temperature ($\vartheta_{R,1}$). Since a heating network consists of several consumers, the sum of the consumer mass flows is equal to the network mass flow ($\dot{m}_{net}$).

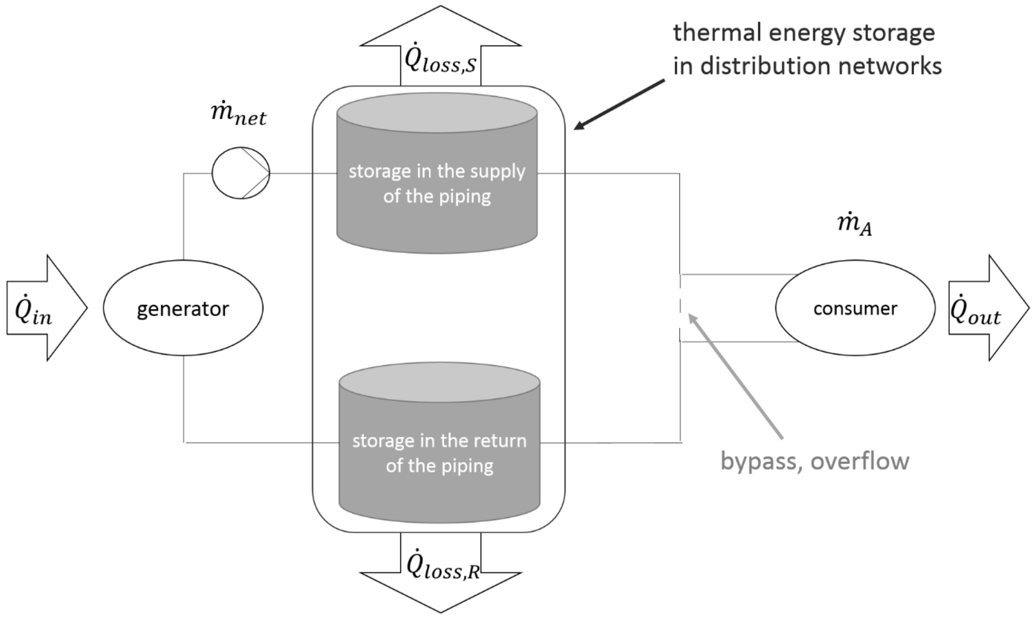

Figure 2: Heat network storage. (illustrative) (based on Groß 2012)

Because thermal systems are usually dynamic systems, a different storage capacity is available at any time. In the methodology of this work, a simplifying, time-independent calculation is made for the storable energy quantity. It is assumed that the power consumption ($\dot{Q}_{out}$) is constant and the heat losses and gains ($\dot{Q}_{loss}$) do not influence the investment and installation costs. Since the storage can be implemented both in the supply and return flow or combined in the supply and return flow, the storable energy capacity is calculated analogously but separately from each other (Q_S and Q_R) as follows:

$$Q = V * \rho * c_p * |\vartheta_2 - \vartheta_{S1}| \quad [J] \quad (1.6)$$

$$Q_{Nst} = Q_S + Q_R \quad [J] \quad (1.7)$$

((1.6) - (1.7) based on [26])

The additional energy (Q_{Nst}) that can be stored in the network depends on the calculated volume within the pipeline, the determined minimum or maximum supply ($\vartheta_{S,2}$) and return temperature ($\vartheta_{R,2}$) and the supply ($\vartheta_{S,1}$) or return temperature ($\vartheta_{R,1}$) in the initial state (see step 1). Because the entire thermal system is designed for a certain state of aggregation the aggregation of the flowing medium should not change.

3. The implementation of network storage is accompanied by different effects due to the temperature change.

3.1 The first effect is the change of the circulating mass flow by the consumer $\dot{m}_A$ and the change in the total mass flow of the network $\dot{m}_{net}$. Assuming that the temperature in the supply or return flow remains constant in the pipeline, the following applies for the change factor μ:

$$\mu = \frac{\dot{m}_{A,2}}{\dot{m}_{A,1}} = \frac{\vartheta_{S,1} - \vartheta_{R,1}}{\vartheta_{S,2} - \vartheta_{R,2}} \qquad [-] \qquad (1.8)$$

((1.8) according to [27])

This calculation applies to both heating and cooling networks. The estimates of the changes of the two mass flows $\dot{m}_{A,1}$ and $\dot{m}_{net,1}$ as a function of the three network storage variations shall be considered in the following only for the actual storage process ($\dot{Q}_{Nst} = 0$). It is based on the assumptions that the power $\dot{Q}_{out}$ is constantly consumed before and after the temperature change, that the thermal power loss is neglected ($\dot{Q}_{loss} = 0$) and that the consumer mass flow $\dot{m}_{A,1}$ corresponds to the network mass flow $\dot{m}_{net,1}$ in its initial state (before the temperature change).

Table 1: Mass flow depending on storage variation.

Storage variation (in heat or cooling networks)	$\dot{m}_{A,2}$	$\dot{m}_{net,2}$
Storage in the network feed, network return or network feed and return flow	$\dot{m}_{A,2} = \mu * \dot{m}_{A,1}$ (1.9) with: $\mu = \frac{\vartheta_{S,1} - \vartheta_{R,1}}{\vartheta_{S,2} - \vartheta_{R,2}}$ (1.10)	$\dot{m}_{net,2} = \dot{m}_{A,2}$ (1.11)

$\dot{m}_{A,1}/\dot{m}_{A,2}$: Mass flow by/at consumer before temperature change/during network storage $[\frac{kg}{s}]$

$\dot{m}_{net,2}$: Network mass flow during network storage $[\frac{kg}{s}]$

3.2 The change in the mass flows $\dot{m}_{A,1}$ to $\dot{m}_{A,2}$ and $\dot{m}_{net,1}$ to $\dot{m}_{net,2}$ is accompanied by a change in the flow velocity $u_{m,net}$. This causes a changing pressure loss from $\Delta p_{net,1}$ to $\Delta p_{net,2}$ within the pipeline in the distribution network (primary side) and for the consumer (secondary side). The focus of the methodology is on the calculation of the pressure loss of the primary side (distribution network) due to the change of the total mass flow of the network $\dot{m}_{net,1}$. The following applies analogously for the distribution network (1) and during network storage (2):

$$\Delta p_{net,1/2} = \zeta_{1/2} * \frac{l_S + l_R}{d_{m,i}} * \frac{\rho_{m,1/2} * u_{m,net,1/2}{}^2}{2} \qquad [Pa] \qquad (1.12)$$

((1.12) according to [28])

The mean density $\rho_{m,2}$ and the mean flow velocity $u_{m,net,2}$ during storage are calculated according to equations (1.1) to (1.4). The pressure measured in front of the pump is assumed to be constant ($p_{net} = p_{net,1} = p_{net,2}$).

Together with the mean dynamic viscosity $\eta_{m,1}$ (before the temperature change) or $\eta_{m,2}$ (during storage), the mean Reynolds number is determined analogously in a simplified manner before ($Re_{m,1}$) and after ($Re_{m,2}$) the temperature change.

$$\eta_{m,1/2}(\vartheta_{m,1/2,},p_{net,1/2}) \qquad [\frac{kg}{m*s}] \qquad (1.13)$$

$$Re_{m,1/2} = \frac{u_{m,net,1/2} * \rho_{m,1/2} * d_{m,i}}{\eta_{m,1/2}} \qquad [-] \qquad (1.14)$$

((1.14) according to [28])

The pressure loss can be determined before and after the temperature change. With the two calculated network points $P_1(\dot{V}_{m,net,1} / \Delta p_{net,1})$, $P_2(\dot{V}_{m,net,2} / \Delta p_{net,2})$ and the network pressure p_{net}, the network characteristic curve can be established. Together with the network pump characteristic curve, the optimum operating point is determined. At this point, it is assumed that the existing network parameters correspond to the initial operating point P_1 before the temperature change. The variation of the volume flow changes the pressure that must be applied by the pump. The changing pressure $\Delta p_{net,2}$ can be overcome. As result, the pump is no longer operating at the optimum point.

If the newly determined operating point P_2 is above the pump characteristic curve (see Figure 3, required operation point 1), this means that the existing circulating pump cannot provide the required pressure drop height or that its efficiency deteriorates. At this point it should be assumed that the given pump characteristic curve stands for the maximum speed of the pump and that for this reason the pump cannot apply the pressure loss height with its delivery height. A more powerful pump must hence replace the pump.

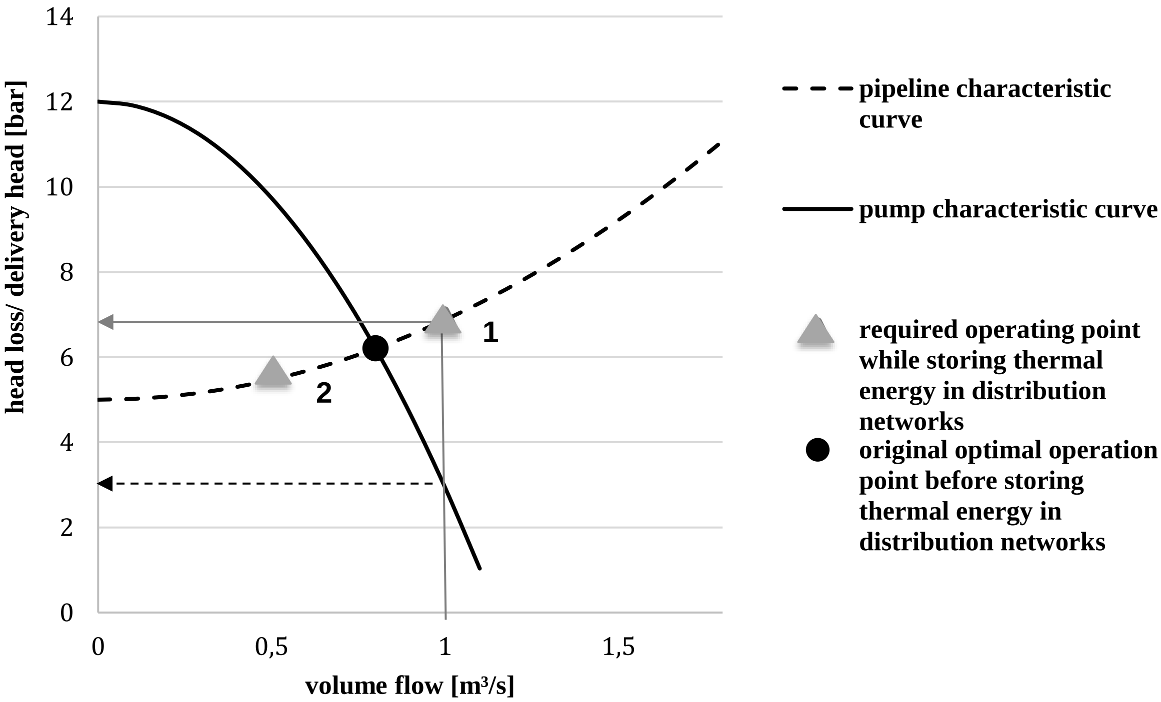

Figure 3: Pump and pipeline characteristic curve with required operation points

If the resulting operating point P_2 is below the pump characteristic curve (see Figure 3, required operation point 2), the required delivery head can be implemented, but the pump does not operate at its optimum efficiency. It must be decided individually whether the losses in efficiency are to be accepted with minimal reductions in the volume flow, or whether the pump should also be replaced in the event of major reductions. The gray arrow in the diagram shows exemplary which pressure would be required for the new volume flow $\dot{V}_{m,net,2}$.

The changing mass flow and pressure loss within the pipeline is of great importance for estimating the investment costs associated with network storage, as the circulating pump in the network may have to be replaced.

3.3 Depending on the extent of the temperature changes and the share of the power loss in the generator output, estimates can be made about the accuracy of the previous neglect in the former steps and the general purpose of the integration of network storage.

As in the previous determination of the pressure loss, the mean temperature between flow and return ($\vartheta_{m,1}$ and $\vartheta_{m,2}$) and the network pressure p_{net} are used to calculate the mean thermal conductivities ($\lambda_{m,1}$ and $\lambda_{m,2}$) and Prandtl numbers ($Pr_{m,1}$ and $Pr_{m,2}$). The mean Nusselt numbers $Nu_{m,1}$ and $Nu_{m,2}$ can be determined in the following. By calculating the characteristic values, the mean internal heat transfer coefficient can be defined before ($\alpha_{m,i,1}$) and after the temperature change ($\alpha_{m,i,2}$) in the pipeline.

$$\alpha_{m,i,1/2} = \frac{Nu_{m,1/2} * \lambda_{m,1/2}}{d_{m,i}} \qquad [\frac{W}{m^2 * K}] \tag{1.15}$$

((1.15) according to [28])

To determine the mean external heat transfer coefficients $\alpha_{m,a,1}$ and $\alpha_{m,a,2}$, a distinction is made between pipelines inside buildings and ducts with steady ambient air and pipelines outside buildings.

With the calculated values, the average heat loss or heat gain before ($\dot{Q}_{m,loss,1}$) and after ($\dot{Q}_{m,loss,2}$) the temperature change can be determined analogously for the entire pipeline.

$$\dot{Q}_{m,loss,1} = \frac{\pi * (l_S + l_R) * (\vartheta_{m,1} - \vartheta_a)}{\frac{1}{\alpha_{m,i,1} * d_{m,i}} + \frac{\ln\left(\frac{d_{m,i} + s_{m,pipe}}{d_{m,i}}\right)}{2 * \lambda_{pipe}} + \frac{\ln\left(\frac{d_a}{d_{m,i} + s_{pipe}}\right)}{2 * \lambda_D} + \frac{1}{\alpha_{m,a,1} * d_a}} \qquad [W] \tag{1.16}$$

with $d_a = d_{m,i} + 2 * s_{m,pipe} + 2 * s_D$ $[m]$

(1.17)

$s_{m,pipe}$: mean wall thickness of the piping system $[m]$

((1.16) according to [29]

4. The calculations carried out in the third method step with regard to the effects on the mass flow and the pressure loss can be used to estimate the investment costs for the implementation of the network storage. These should be compared with the investment costs for the integration of a coupled sensible thermal storage with the same storage capacity.

Application example the methodical approach of this work was applied to practical examples, whereby the respective results for an industrial and a public example are listed below. The table provides information on the existing network parameters before the temperature change and the respective maximum and minimum supply and return temperatures of the producers with regard to network storage.

Table 2: Existing network parameters of application examples

	Hot water network	Cold water network	Solar local heating network
Temperature	Supply: 95 °C Return: 50 °C	Supply: 6 °C Return: 12 °C	Supply: 65 °C Return: 35 °C
Pressure	4,5 bar	4,5 bar	5 bar
Flow velocity	1 m/s	1 m/s	1 m/s
Mass flow	80,38 kg/s	105,92 kg/s	5,7 kg/s
	Condensing boilers, CHP plant	Absorption chiller	Solar thermal collector
Temperature	Supply: max. 98 °C Return: max. 55 °C	Supply: min. 5 °C Return: min 9 °C	Supply: max. 95 °C Return: max 35 °C
		Compression refrigeration machine	
Temperature		Supply: min. 3,3 °C Return: min. 6,1 °C	

The given information show that the temperature of the industrial hot water network can be increased by a maximum of 3 °C in the supply line and by a maximum of 5 °C in the return line. For the industrial cooling network, the supply temperature can be lowered by a maximum of 1 °C and the return temperature by a maximum of 3 °C. The supply temperature of the solar local heating network can be raised by 30 °C, whereas the return temperature cannot be raised. The return flow temperature has a significant influence on the performance of the solar collectors and is therefore actively limited to 35°C. For the distribution networks, the total pipe lengths (hot water network: 9,280 m; cold water network: 4,540 m, solar local heating network: 17,880.94 m) and the respective internal diameters can be used to calculate a total pipe volume of 763.52 m³ for the hot water network, a total capacity of 481.36 m³ for the cooling network and a volume of 103.14 m³ for the solar local heating network. These values are important when calculating the additional maximum energy that can be stored by changing the temperature to the maximum (heating network) or minimum (cooling network) temperature limit values. The results are presented in Table 3:

Table 3: Additional storable energy.

Network	Additional storable energy in the feed [kWh]	Additional storable energy in the return [kWh]	Additional storable energy in total [kWh]
Hot water	1285	2187	3473
Cold water	281	842	1123
Solar local	1740	0	1740

Table 4 summarizes the effects on mass flow, pressure drop and thermal power consumption including heat losses and gains by showing the respective values before and after the temperature change.

Table 4: Effects of network storage on the network parameters.

Network parameters		before temperature change	after temperature change / during storage
Hot water network	Network mass flow [kg/s]	80,38	84,12
	Pressure loss [bar]	1,69	1,81
	Thermal power consumption [W]	434 090	464 454
Cold water network	Network mass flow [kg/s]	105,92	158,88
	Pressure loss [bar]	0,92	1,94
	Thermal power consumption [W]	32 278	43 046
Solar local network	Network mass flow [kg/s]	11,4	5,7
	Pressure loss [bar]	16,94	4,69
	Thermal power consumption [W]	190 867	272 719

The power loss of the hot water network has risen by around 7%, the cooling network by around 33% and the solar local heating network by around 43%. The significantly higher increase in the power loss of the cooling network can be explained by the higher temperature difference to the environment and the stronger increase in the network mass flow. Consequently, network storage is associated with an increase in losses due to temperature changes.

The effects of network storage on mass flow, volume flow and pressure loss are exemplary shown in the following diagram of the pump and network characteristics of the hot water network. Table 4 indicates that the volume flow and the pressure loss during energy storage in the industrial hot water network only increase at minimum rate. This fact can be explained by the low mass flow change factor μ. However, the pump characteristic curve is below the required operating point during network storage. The existing network pump cannot compensate the pressure loss height by its delivery head. The same applies to the cold water network. It however shows a stronger change in the volume flow and the pressure loss level during energy storage. The reason for this is the significantly higher mass flow change factor. In the solar local heating network, volume flow rate is considerably reduced due to the higher temperature spread between supply and return flow. The required operating point during network storage is therefore below the pump characteristic curve. For this reason, the existing network pump can compensate the required pressure loss height by its delivery head.

The characteristic curves lead to the conclusion that the network pumps must be resized and retrofitted for dynamically operation. Depending on the demand, this requires a replacement of the complete existing pump, which is of particular importance for estimating the investment costs of network storage. This topic is discussed in more detail in the following chapter.

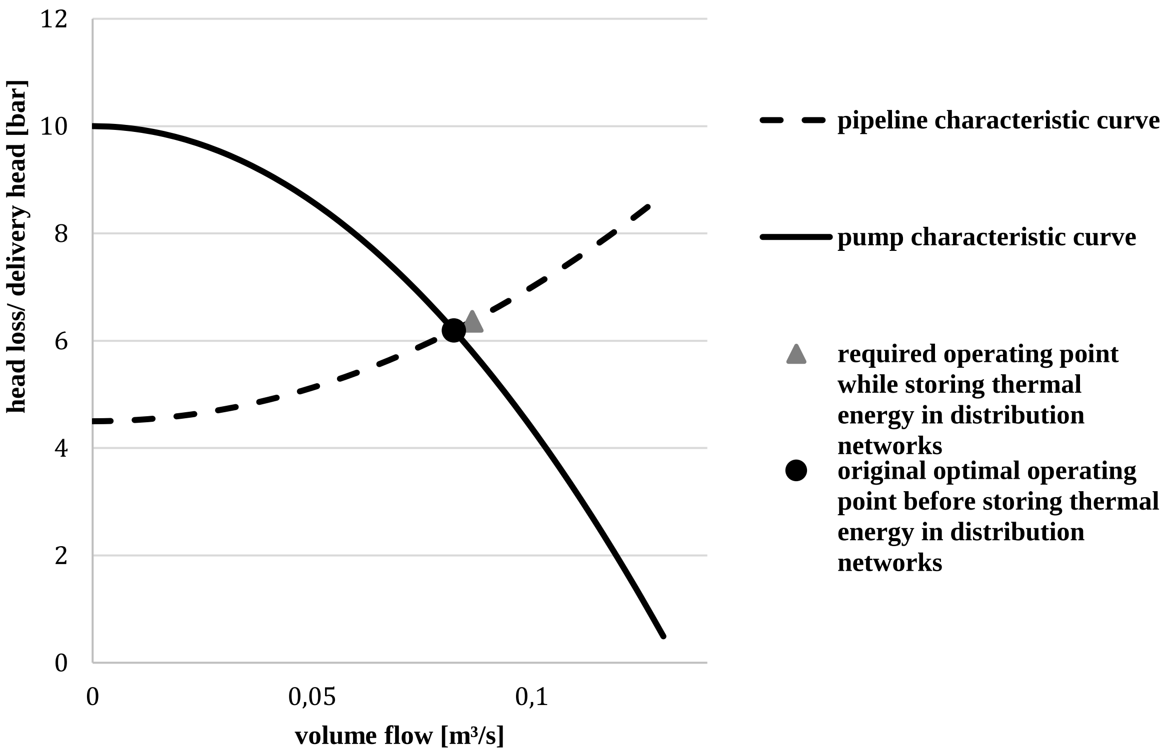

Figure 4: Pump and pipeline characteristic curve of the hot water network.

4 Economic comparison

In this chapter, network storage is economically assessed with regard to the results of the practical examples examined in the industrial and public sectors. A comparison is made with the costs for coupled sensible water storage systems from literature values of projects carried out with similar storage capacity. Investment and control costs are incurred for the implementation of network storage and for the integration of coupled storage facilities. Since the control costs for both types of storage are alike, the focus is on the investment costs.

The costs incurred for network storage can be explained using the pump and network characteristics listed in the respective practical examples. During network storage, the required operation point changes. Depending on whether it is above or below the pump characteristic curve and to what extent the change impacts the pump efficiency, it may have to be replaced or new pumps might need to be added. Maintenance costs (about two percent of the investment cost of the pump) are neglected, as they are part of the previous operational costs. The investment costs for a new network pump depend, among other things, on the maximum delivery head, the maximum flow rate and the output. The network pumps of the industrial hot and cold water network need to be replaced for network storage which causes – based on offers – investment and installation costs of 14.000 € resp. 15.000 €. In addition, it becomes clear that the required operating point for network storage in the solar local heating network is below the pump characteristic curve. The pressure drop head, that needs to be overcome, can thus compensate the existing main pump by its delivery head. A replacement of the pump is therefore not necessary under this scenario. There are no extra investment costs for the implementation of network storage.

The following section examines the costs to be expected for coupled storage instead of network storage. It is assumed that the same energy ($Q_{S,S}$ or $Q_{S,R}$) can be stored in the coupled storage system at the same temperature as in the supply or return flow of the network.

The necessary volume of the coupled storage system and the approximate investment and installation costs are compared for three practical examples. The costs are based on already implemented projects with similar water storage volumes. The calculation is based on the information given in Table 2. In the industrial hot water network about 3.500 kWh at 45 K correspond to about 67 m^3. For the industrial cold water network 1.100 kWh at 6 K equal 157 m^3 and for the public solar local heating network 1.750 kWh at 30 K equal 50 m^3.

A comparison of the costs for the implementation of network storage with the costs for a coupled storage facility (see Table 6) in which the same thermal energy can be stored shows that the investment costs for network storage are significantly lower. Operating and maintenance costs are not taken into account, as these are incurred with both storage methods. Interest rates and cost increases are not taken into account in the cost calculation. The service life of the pumps is assumed to be 10 years, of the coupled sensible storage to be 25 years [32, 33]. Even though the pumps for the network storage have to be replaced three times, they would still cost 50 % less than the coupled sensible storage. This result is of great importance since the economic side is decisive for the actual implementation of the integration of thermal energy storage.

Table 6: Comparison of costs.

Type of distribution network	Costs (investment and installation) [€]	
	Network storage	coupled, sensible storage(based on [30, 31])
industrial hot water network	14.000	128.000
industrial cold water network	15.000	85.000
public, solar local heating network	-	35.000

5 Conclusion and Outlook

The results of this feasibility study have confirmed the advantages of network storage over coupled storage. These are particularly evident regarding economic and space-saving aspects. As the storage of energy takes place in already existing structures, no additional infrastructure must be built, which is reflected in the lower investment costs. The feasibility study carried out on network storage provides the basis for further scientific work in this field. One approach, for example, would be to carry out a time-dependent, dynamic simulation of network storage and a calculation of the storable energy within the networks in the course of the consumption and generation loads. This would enable to optimize the operation of the heat and cooling generators. In addition, it is possible to optimize the capital and operative expenditures (CAPEX and OPEX). The network storage should therefore be improved in such a way that CAPEX and OPEX are as low as possible and at the same time supply security is as high as possible. Furthermore, the costs or storage capacity of sensible storage within existing networks could be optimized and compared with coupled thermal storage.

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Acknowledgements

The authors would like to thank the BMBF and the project management organization Jülich, which supported the Synergie research project and this work.

Short CV

Alexander Emde, M.Eng.

Alexander Emde, M.Eng., geb. 1993, studierte an der Hochschule für Technik und Wirtschaft des Saarlandes und ist seit 2017 als wissenschaftlicher Mitarbeiter am Institut für Energieeffizienz in der Produktion (EEP) der Universität Stuttgart und am Fraunhofer-Institut für Produktionstechnik und Automatisierung IPA tätig. Er arbeitet an nationalen und internationalen Projekten. Sein Schwerpunkt ist die Erforschung von hybriden Energiespeichersystemen.

Bianca Haehl, B. Eng.

Bianca Haehl schloss im Juni 2018 ihr Wirtschaftsingenieur-Studium mit einer Bachelorarbeit am Fraunhofer-Institut für Produktionstechnik und Automatisierung (IPA) in Stuttgart ab. Seit Oktober 2018 ist Sie bei Netze BW als Gasnetzmanagerin tätig.

Prof. Dr.-Ing. Dipl.-Kfm. Alexander Sauer

Alexander Sauer, geb. 1976, studierte an der RWTH Aachen Maschinenbau und Betriebswirtschaftslehre und promovierte am WZL der RWTH Aachen. Er ist Leiter des Instituts für Energieeffizienz in der Produktion (EEP) der Universität Stuttgart und Leiter des Fraunhofer-Instituts für Produktionstechnik und Automatisierung (IPA).

Verena Lampret, M. Sc.,

Verena Lampret, geb. 1995, studierte an der Ruhr-Universität Bochum und ist seit 2021 als wissenschaftliche Mitarbeiterin am Institut für Energieeffizienz in der Produktion der Universität Stuttgart und am Fraunhofer-Institut für Produktionstechnik und Automatisierung tätig.