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Integration of Decentralized Thermal Storages Within District Heating (DH) Networks

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Abstract **– Thermal Storages and Thermal Accumulators are an important component within District Heating (DH) systems, adding flexibility and offering additional business opportunities for these systems. Furthermore, these components have a major impact on the energy and exergy efficiency as well as the heat losses of the heat distribution system. Especially the integration of Thermal Storages within ill-conditioned parts of the overall DH system enhances the efficiency of the heat distribution. Regarding an illustrative and simplified example for a DH system, the interactions of different heat storage concepts (centralized and decentralized) and the heat losses, energy and exergy efficiencies will be examined by considering the thermal state of the heat distribution network.**

Keywords **– Thermal storages; storage concepts; energy efficiency; exergy efficiency; heat losses; district heating**

Nomenclature

A	Surface area, e.g. of storage	m^2
D	Diameter, e.g. of storage	m
E	Exergetic contents, e.g. exergetic contents delivered to / taken from the DH system	MWh
H/l	Height, e.g. of storage / Length, e.g. length of the DH system or free length for falling films	m
ND	Nominal Diameter, e.g. mean nominal diameter DN^*	mm
T	Temperature, e.g. supply flow temperature T_{supply} or ambient temperature T_0	°C
$\bar{T}/T^*$	Mean temperature, e.g. of heat supply and utilization / Minimum temperature level utilizable	°C
t	discrete time, e.g. time needed for (dis-)charging the thermal storage	h
$Q/\dot{Q}$	Heat demand, e.g. annual heat demand / Heat load, kW$_{\text{th}}$, e.g. peak heat load of the network	MWh
$\dot{q}/q_i^*$	Specific heat losses per unit area, W/m² / Specific heat losses per unit length	W/m²
s	Strength of layer, e.g. layer for stratification or steel within the wall	m
V	Volume, e.g. of thermal storage V_{Stor}	m^3
η	Efficiency, e.g. energetic or exergetic	
λ	Heat conductivity, e.g. of water or steel	W/mK
ρ	Density, e.g. of water (thermal storage media)	W/mK
τ	Typical Operational Cycle / Time Shift of storage	h

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1. INTRODUCTION

Combined-Heat-and-Power (CHP) is a common, widespread and robust system for efficiently delivering electrical power energy to heat customers. Thus, within urban areas of northern European countries, CHP is and will be a major partner for the energy turnaround [1]. Operating these systems, the main focus of operation has been on meeting the heat demands occurring in the district heating (DH) network attached. On the other hand, the revenues at the energy markets are mainly responsible for running these systems economically.

Market prices for electrical power and heat demands occurring in DH grids are not correlating. This makes the traditional operation of these systems non-profitable. Thus, a market-price-oriented operation of CHP systems becomes more and more attractive suppliers [2]–[9]. Within this context, flexibility options for the operation of CHP (thermal storages / thermal accumulators), are of interest, enhancing the economic performance of CHP, whereas operational cost diminish due to raising efficiencies [10]–[13].

Regarding the optimized integration of sensible thermal storages, operating mainly at temperatures below 100 °C and at atmospheric pressures, urgent issues remain. Especially the relevance of different heat loss mechanisms on the energetic and exergetic efficiency are mainly of interest [14]–[18]. However, these losses and efficiencies are interacting with the dimensions of the storage, the storage concept (centralized or decentralized), and a variety of operational parameters of the thermal storage taken into consideration [19], [20].

Therefore, mapping the interactions and correlations between centralized and decentralized thermal storage concepts and the energetic as well as exergetic efficiencies of the heat distribution will be the topic of the following contribution. For this purpose, typical operational parameters of an urban DH system are defined. Following, a DH system integrating different storage concepts is simulated in order to quantify the losses and efficiencies of this system. Basis for this simulation is the software tool DHEMOS, refined at the FFI [21], [22]. Relevant heat loss mechanisms within the heat distribution network and the thermal storages are approximated and evaluated.

2. STATE OF THE ART – OPERATIONAL PARAMETERS OF URBAN DH SYSTEMS

Typical operational parameters of DH systems are defined according to literature. The range of thermal and hydraulic parameters is affected by a variety of boundary conditions for DH system operation. Considering (i) the common practice in DH and (ii) future developments required in this sector according to the energy turnaround (raising efficiencies, reduced operational temperatures, etc.), pressurized hot water systems are considered in within this paper [23]. Within this hot water system, two DH network fractions are given:

- Main System including the majority of heat customers;
- Sub-Network, including a main heat customer with a high heat demand.

Generally speaking, the supply flow temperature T_{supply} of the DH system is dictated by the ambient temperature T_0($T_{supply} = T_{supply}(T_0)$). On the other hand, the temperature of the return flow T_{return} depends on the heat customers attached and fluctuates seasonally. For modelling purposes, the following assumptions are done:

- Mono-centric heat supply is assumed (spatially bundled heat sources);
- Base heat load is covered by combined heat and power plants (CHP);
- Intermediate and peak loads are mainly covered by heat only plants (heat only plant I and II) (see Fig. 1).

During operation, the annual heat demand Q_{Anno} of the DH system is covered by 38.5 % by the plant base load CHP-plant. Another 50.7 % are covered by the intermediate load heat only plant I and 10.7 % by the peak load heat only plant II. Summarizing the relevant operational parameters of the DH system modelled are given in Table 1.

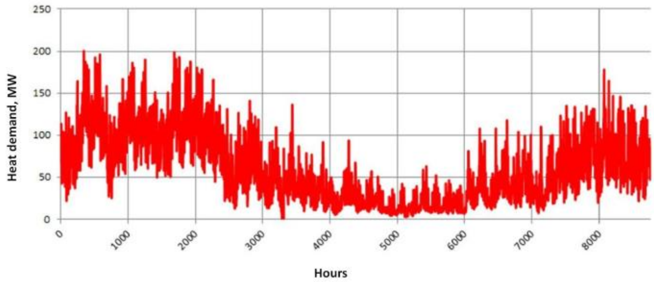

Fig. 1. Course of the Heat Demand within the DH system modelled [24].

TABLE 1. CHARACTERISTICS OF THE DH SYSTEMS MODELLED, SUBDIVIDED INTO THE DH NETWORK FRACTIONS

Parameter	Overall System	Main System	Sub-Network
Temperature Supply Flow T_{supply} Winter // Summer, °C	120 // 90		
Temperature Return Flow T_{return} Winter // Summer, °C	60 // 65		
Thermal Output CHP Q_{CHP}, MW_{th}	10…70		
Thermal Output Heat Only Plant I // II Q_I; Q_{II}, MW_{th}	60 // 70		
Length of DH network l, km	107	105	1.1
Annual Heat Demand Q_{Anno}, GWh_{th}/a	500	498.9	1.1
Peak Load $\dot{Q}_{maxth}$, MW_{th} // Mean Load per Customer $\dot{Q}$, kW_{th}	200 // 100	199.5 // 100	0.5 // 500
Customers attached	2,000	1,999	1

3. DIMENSIONS OF THE HEAT DISTRIBUTION NETWORK

Within the heat distribution network, the heat flows coming from the heat sources are distributed via the supply and return flow. Typical systems for heat distribution are, e.g., plastic bonded or steel in steel pipes.

3.1. Hydraulic Modelling of the Heat Distribution Network

The network for heat distribution is modelled according to full load operation and by assuming a maximum specific pressure drop per unit length [23], [25]. In addition the following assumptions are done:

- Pressure shocks are not considered;
- The material properties of the heat carrier (water) are approximately constant within the relevant pressure and temperature range of DH systems, e.g. density, specific heat capacity, kinematic viscosity, heat conductivity;
- Corrosive effects are neglected;

- Flow patterns occurring within the heat distribution network are stationary (parabolic flow profile);
- Inner diameters of pipes are constant / independent of pressures within the piping system (rigid body).

Basing on these assumptions, nominal diameters DN of single the single pipes I to VI are calculated according to Fig. 2. The Main System of the DH grid is aggregated within one representative heat customer, demanding a maximum heat peak load $\dot{Q}_{\mathrm{maxthMain}}$ of 199.5 MW_{th}. For this reason, the Main System is also described hydraulically by a mean (average) nominal diameter DN* [26]. These assumptions seem to be appropriate a) considering the focus of this contribution (showing the interactions of storage concepts and efficiencies for heat distribution) and b) in the light no comprehensible starting point for a more detailed modelling of the DH piping system.

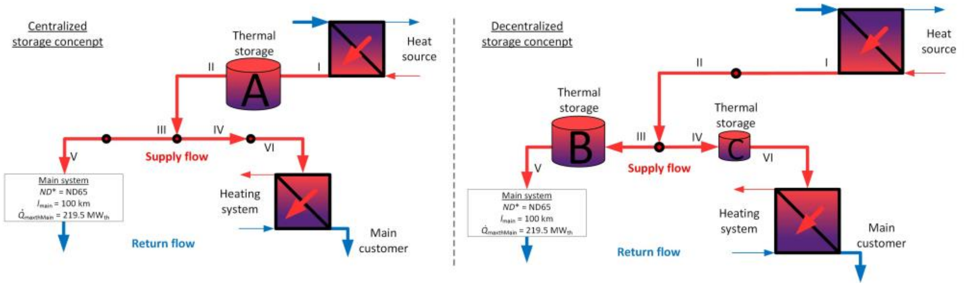

Fig. 2. Topographies of the centralized and decentralized storage concept considered.

3.2. Thermal Modelling of the Heat Distribution Network

Basing on the hydraulic model of the heat distribution network, a thermal model is implemented into the DH system simulation. Due to the general aim of this contribution, as well as the agglomeration of the Main System within one representative heat customer, any implementation of a sophisticated thermal model is not possible [27]–[29]. Thus, a basic thermal model is utilized considering typical specific heat losses per unit length q_{i}^{*} in dependence of the geometry as well as the temperature of the supply T_{supply}, return T_{return}, ambient T_0 and soil T_{soil} [30]. Specific heat losses per unit length $\dot{\mathrm{q}}_{\mathrm{supply}}(\mathrm{DN}, \mathrm{T}_{\mathrm{supply}}, \mathrm{T}_{\mathrm{return}}, \mathrm{T}_0, \mathrm{T}_{\mathrm{soil}})$ and $\dot{q}_{\mathrm{return}}(DN, T_{\mathrm{supply}}, T_{\mathrm{return}}, T_0, T_{\mathrm{soil}})$ are considered. The losses of the return flow decrease in the winter due to lower return flow temperatures T_{return} (see Table 2).

TABLE 2. THERMAL PARAMETERS OF THE HEAT DISTRIBUTION NETWORK ACCORDING TO FIG. 2

Pipe	Length, m	*ND*	$\dot{q}_{\mathrm{supply}}$, W/m		$\dot{q}_{\mathrm{return}}$, W/m	
			Summer $T_{\mathrm{soil}} = 10$ °C	Winter $T_{\mathrm{soil}} = 0$ °C	Summer $T_{\mathrm{soil}} = 10$ °C	Winter $T_{\mathrm{soil}} = 0$ °C
I	100	700	45.4	61.2	31.2	30.6
II	800	700	45.4	61.2	31.2	30.6
III	5000	700	45.4	61.2	31.2	30.6
IV	1000	65	18.6	25.2	12.8	12.6
V	Σ_{ges} 100 000	ND^{*} = ND65	18.6	25.2	12.8	12.6
VI	100	65	18.6	25.2	12.8	12.6

4. DIMENSIONS OF THE THERMAL STORAGE

Thermal storages will play a major role for the economic and efficient operation of DH and CHP systems. Integrating storages will generate different advantages for DH systems, e.g. (i) increase in full-load hours for CHP plants, and (ii) decrease in operational costs of the overall DH system, due to:

- Enhanced primary energy efficiencies of all heat sources attached;
- Decreased operational hours of fossil intermediate/peak load heat only plants with high fuel related costs;
- Decreased electrical energy demands of pumps within the piping network;
- Diminished efforts for maintenance (e.g. CHP plants, pipes, valves) as thermal load cycles decrease.

Within this context, the calculation of the heat losses are described and quantified for typical operational cycles τ (typical time shift for heat production and allocation) of thermal storage systems [31].

4.1. Capacity of Thermal Storages

The heat capacity of thermal storages considers the different loads of the heat sources and the heat customers. Integrating storages, peak loads will increasingly be supplied by intermediate and base load heat sources. Therefore, the storage capacity Q_{stor} must be adjusted according to the demands under peak load conditions (see Fig. 3).

According to the course of the heat demand within the DH system modelled, the peak load heat only plant supplies up to 70 MW_{th} (or 35 % of $\dot{Q}_{\text{maxth}}$) and up to 260 MWh_{th} [24]. These heat contents shall be replaced by heat contents from the thermal storage system (coming from base or intermediate load heat sources). Thus, the thermal storages must be adjusted according to different DH network topologies and storage concepts (centralized or decentralized). Furthermore, Q_{stor} of each single storage depends on the seasonal temperature difference between the supply and return flow (see Table 1). Resulting, Q_{stor} is diminished for the operational conditions of the summer period (see Table 3). However the volume of the thermal storages V_{stor} must be adjusted to the peak load (winter).

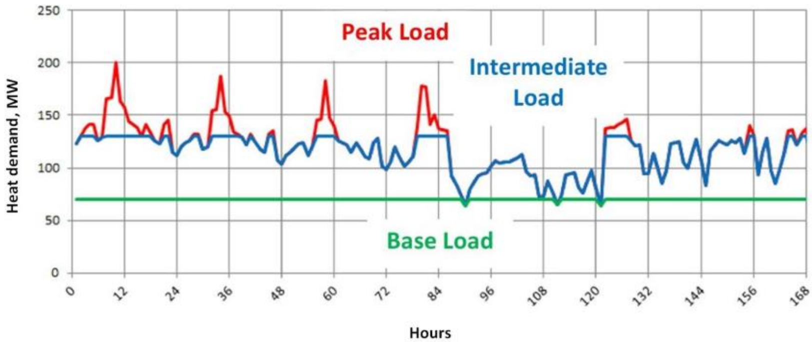

Fig. 3. Sequestration of Heat Loads occurring within the DH system modelled into peak, intermediate and base load [26].

TABLE 3. OPERATIONAL PARAMETERS OF (DE-)CENTRALIZED THERMAL STORAGES WITHIN THE DH SYSTEM MODELLED

Thermal Storage Concept (Fig. 2)	Centralized	Decentralized	
	Overall System	Main System	Sub-Network
Max. Operational Temperature Winter // Summer T_{maxstor}, °C	98 // 90		
Min. Operational Temperature Winter // Summer T_{minstor}, °C	60 // 65		
Typical Operational Cycle / Time Shift τ, h	12		
Storage Capacity Q_{stor} Winter // Summer, MW_{th}	260 // 171.1	259.35 // 170.60	0.65 // 0.40
Storage Volume V_{stor}, m³	5.865	appr. 5.850	15

4.2. Thermal Losses Within Thermal Storages

Within thermal storages, most different heat loss mechanisms must be considered in order to operate these systems in an optimized way. Therefore, the following losses will be described qualitatively and approximated for operational conditions of the winter season (worst case conditions):

- Conductive effects via the wall and insulation of the thermal storage;
- Conduction within thermal short circuits;
- Convective heat transfer due to falling films at the interior side of the storage wall;
- Conduction within the thermal storage media itself in between a high and low temperature layer at the head and bottom of the storage.

On the other hand, (i) energetic and exergetic losses induced by turbulences occurring from (dis-)charging cycles (operation of the storage), (ii) thermal inertia of the storage infrastructure and (iii) heat radiation / radiative effects between the roof and bottom of the storage systems (at high and low temperature levels) are not considered. Summarizing, the heat losses occurring are given in Table 4. Especially within the decentralized storage concept, considerable losses occur within the storage attached to the (small) Sub-Network. The relevant physical mechanisms and assumptions done for approximating the heat losses are described within the following paragraphs.

4.3. Heat Conduction via the Wall

The conductive heat loss via the wall is minimized by the insulation. The specific heat losses per unit area $\dot{q}_{\text{wall}}$ are well below 15 W/m² [32]. The influence of the soil below the thermal storage is of minor importance for the overall heat losses occurring via the wall. Thermal boundary layers within and outside the thermal storage and the insulating effect of the steel casing are irrelevant for quantifying the heat losses [14], [19], [20]. For the given thermal storage systems, temperature drops occurring due to heat losses via the wall ΔT_{wall} are low (see Table 4).

4.4. Heat Conduction in Thermal Storage Media

Within DH system, thermal storages are mainly operated as (atmospheric) sensible storage systems, stratifying high and low temperature fluids due to density gradients $\rho = \rho(T)$. Heat flows due to vertical temperature gradients occur within the thermal storage media. The vertical heat flows occurring are mainly influenced by the strength of the thermal layer for stratification at the beginning of the load cycle $s_{\text{lay}}(t_0)$ as well as the typical time shift for heat production and allocation τ. While $s_{\text{lay}}(t_0)$ is increasing ($s_{\text{lay}}(t_0 + \tau) > s_{\text{lay}}(t_0)$), the energetic contents utilizable diminish ($Q_{\text{stor}}(t_0 + \tau) < Q_{\text{stor}}(t_0)$). In addition, the energetic contents within the thermal storage are bound to a minimum temperature level $T_{\text{minsupply}}$ utilizable directly within the DH system attached [14], [19], [20]. $T_{\text{minsupply}}$ strongly depends on economic, ecologic and technological target parameters of DH system operation.

In the course of the simulations, heat losses occurring due to conductive effects within the thermal storage media itself are approximated by a numerical model. Assumptions done in order to quantify these losses are:

- Loading status of the thermal storages 40 %;
- Strength of thermal layer for stratification $s_{\text{lay}}(t_0) = 0.5$ m, cf. also the charging/discharging cycle of the thermal storages according to chapter 5;
- Minimum temperature level directly utilizable within the DH system attached $T_{\text{minsupply}} = (T_{\text{maxstor}} + T_{\text{minstor}})/2$.

Especially the last assumption is very conservative and maximizes the decrease of the energetic contents due to conductive effects within the thermal storage media (worst-case approximation). In comparison to conductive effects via the wall, temperature drops ΔT_{H2O} occurring due to heat flows within the thermal storage media are comparatively high (see Table 4). This is mainly bound to a small strength of the thermal boundary layer $s_{\text{lay}}(t_0)$.

4.5. Heat Conduction Thermal Short Circuits

Resulting from a high heat conductivity of some parts of the infrastructure within the thermal storage, especially in comparison to the heat conductivity of the thermal storage media itself ($\lambda_{\text{H2O}} \ll \lambda_{\text{Steel}}$), additional vertical heat flows occur, e.g. within the wall. Due to analytic considerations, the vertical heat flows within the short circuit $\dot{Q}_{\text{shortcirc}}$ and thermal storage media $\dot{Q}_{\text{H2O}}$ are related basing on similar the following assumptions [14]:

- Similar temperature gradients for short circuit $\Delta T_{\text{shortcirc}}$ and storage media ΔT_{H2O} ($\Delta T_{\text{shortcirc}} \approx \Delta T_{\text{H2O}}$);
- Similar strengths of thermal layer for stratification with the short circuit $s_{\text{layshortcirc}}$ and the storage media s_{laymedia} ($s_{\text{layshortcirc}} \approx s_{\text{laymedia}}$);
- Small relative strength of the wall $s_{\text{wall}} \ll D_{\text{stor}}$;
- Small heat conductivity of the storage media λ_{H2O} in comparison to heat conductivity of the short circuit λ_{Steel}.

$$\frac{\dot{Q}_{\text{shortcirc}}}{\dot{Q}_{\text{H2O}}} = \frac{2 s_{\text{wall}}}{D_{\text{stor}}} \cdot \left(\frac{\lambda_{\text{Steel}}}{\lambda_{\text{H2O}}}\right). \tag{1}$$

Basing on these assumptions, thermal short circuits cause high temperature drops $\Delta T_{\text{shortcirc}}$ for typical time shifts τ between heat production and allocation, compare $\Delta T_{\text{shortcirc}}$ with ΔT_{H2O} or ΔT_{wall} (see Table 4).

4.6. Convective Effects Due to Falling Films

Resulting from radial temperature and density gradients of the thermal storage media, vertical falling films occur at the inside of the storage wall. Mass flows from the top of the thermal storage penetrate the layer for stratification. Due to changing boundary temperatures surrounding the falling film, buoyancy and the vertical velocity of the falling film decrease. Therefore, the falling film from the head of the thermal storage is integrated (implemented) into the thermal layer. On the other hand, within the thermal layer for stratification itself, and below this layer, additional falling films occur due to analogous effects. Falling film velocities of these falling films are smaller than the falling film velocity from the head of the storage. Resulting, the thermal layer for stratification is growing.

Within this context, energetic losses resulting from falling films are calculated basing on an approximate solution for describing the flow boundary layer near the wall. Considering the coupling of the flow and thermal boundary layer (velocity and temperature field near the wall), the strength of the flow boundary layer is approximated [19], [20], [33]. Main parameter influencing the flow boundary layer is the free length for vertical flows at the wall $\mathrm{l_{fall}}$. However, l_{fall} strongly depends on the loading status of the thermal storage, as well as the internal structure of the wall (e.g. circumferential obstacles). Due to convective heat flow mechanisms, comparatively high temperature drops occur ΔT_{fall}, compare ΔT_{fall} with ΔT_{H2O} or ΔT_{wall} (see Table 4).

5. IMPACT OF STORAGE CONCEPT ON THE EFFICIENCY OF HEAT DISTRIBUTION

Basing on the heat loss mechanisms described, approximated and quantified, the DH systems implementing different thermal storage concepts are described and evaluated by energetic and exergetic efficiencies η_{en} and η_{ex} of the heat distribution. In addition to the load of the DH system itself, the operational condition of the thermal storage must be considered (discharging or charging).

5.1. Operational Modes of the Thermal Storage

During the operation of the (Overall) DH System, the thermal storages are cyclically charged and discharged. While charging the thermal storages, the maximum volume (mass) flow hydraulically possible for upstream piping systems of the DH network enter the thermal storage. Thus, the DH network demands peak load, disregarding the heat load necessary for meeting the demands of the customers attached. In Parallel, the thermal storage delivers heat to the heat customers attached (Overall DH System or Main System / Sub-Network). On the other hand, while discharging the thermal storage, merely the volume (mass) flows necessary for meeting the demands of the customers attached are taken from the thermal storage, whereas no heat contents enter the thermal storage.

Thus, within the centralized storage concept (see Fig. 2 left), the central thermal storage (A) supplies heat to the Overall DH System. Within the decentralized storage concept, each thermal storage (B and C) supplies heat to the networks associated (Main System and Sub-Network (see Fig. 2 right). Resulting from these operational modes, the time needed for charging the storage t_{in} is smaller than the time needed for discharging the storage t_{out}.

5.2. Operational Modes of the Heat Distribution

The energetic operational condition of the heat distribution is described by the energetic and exergetic efficiencies η_{en} and η_{ex}. These are derived from the relations of heat contents supplied by the heat sources Q_{in} and heat contents utilized at the customer's sites Q_{out}. Furthermore, Q_{in} and Q_{out} must consider a full charging and discharging cycle of the thermal storages ($t_{\mathrm{in}}/t_{\mathrm{out}} = 0.4$). Depending on the storage concept, the energetic and exergetic efficiencies of the centralized and decentralized storage concept are calculated. However, considering the exergetic efficiency η_{ex}, the mean temperature of heat supply and utilization $\bar{T}_{\mathrm{in}}$ and $\bar{T}_{\mathrm{in}}$ as well as the minimum temperature level utilizable T^*. Unfortunately, due to the agglomeration of the heat customers attached in the Main System of the DH system modelled, merely an exact calculation of η_{ex} is possible for the Sub-Network:

$$\eta_{\mathrm{en}} = \frac{\sum Q_{\mathrm{out}}}{\sum Q_{\mathrm{in}}}; \tag{2}$$

$$\eta_{\mathrm{ex}} = \frac{\sum E_{\mathrm{out}}}{\sum E_{\mathrm{in}}} = \frac{\sum\left(1-\frac{T^*}{T_{\mathrm{out}}}\right)\cdot Q_{\mathrm{out}}}{\sum\left(1-\frac{T^*}{T_{\mathrm{in}}}\right)\cdot Q_{\mathrm{in}}}. \tag{3}$$

TABLE 4. SUMMARY OF HEAT LOSSES OCCURRING WITHIN THE (DE-)CENTRALIZED THERMAL STORAGES

Thermal Storage Concept (see Fig. 2)	Centralized	Decentralized	
Storage	A	B	C
Heat Conduction via the Wall			
Specific Heat Loss $\dot{q}_{\mathrm{wall}}$, W/m²	15		
Height / Diameter Storage $H_{\mathrm{stor}} = D_{\mathrm{stor}}$, m	19.50	19.50	2.65
Surface Area A_{stor}, m	1,800	1,800	33.2
Heat Loss via Wall $\dot{Q}_{\mathrm{wall}}$	27.0	27.0	0.5
Relative Heat Loss within τ $Q_{\mathrm{loss}}/Q_{\mathrm{minstor}}$, %	<0.20	<0.20	<0.35
Temperature Drop within the Storage ΔT_{wall}, K	<0.05	<0.05	<0.35
Heat Conduction in Thermal Storage Media			
Strength of Thermal Layer for Stratification $s_{\mathrm{lay}}(t_0)$, m	0.50		
Storage Capacity $Q_{\mathrm{stor}}(t_0)$, MWh$_{\mathrm{th}}$	62.92	62.92	0.124
Strength of Thermal Layer for Stratification $s_{\mathrm{lay}}(t_0+\tau)$, m	0.59		
Storage Capacity $Q_{\mathrm{stor}}(t_0+\tau)$, MWh$_{\mathrm{th}}$	62.56	62.56	0.117
Relative Heat Loss within τ $1-[Q_{\mathrm{stor}}(t_0+\tau)/\ Q_{\mathrm{stor}}(t_0)]$, %	<0.05	<0.05	<5.3
Temperature Drop within the Storage ΔT_{H2O}, K	<0.08	<0.08	<0.61
Heat Conduction in Thermal Short Circuits			
Strength of Thermal Layer for Stratification $s_{\mathrm{lay}}(t_0)$, m	0.50		
Strength of Wall s_{wall}, m	0.05		
$\dot{Q}_{\mathrm{shortcirc}}/\dot{Q}_{\mathrm{H2O}}$, %	37	37	270
Relative Heat Loss within τ: $1-[Q_{stor}(t_0+\tau)/\ Q_{stor}(t_0)]$, %	<0.02	<0.02	<14.3
Temperature Drop within the Storage $\Delta T_{shortcirc}$, K	<0.03	<0.03	<1.64
Convective Heat Transfer due to Falling Films			
Strength of Thermal Layer for Stratification $s_{lay}(t_0)$, m	0.50		
Strength of Thermal Layer for Stratification $s_{lay}(t_0+\tau)$, m	0.59		
Relative Heat Loss within τ: $1-[Q_{\mathrm{stor}}(t_0+\tau)/\ Q_{\mathrm{stor}}(t_0)]$, %	<0.03	<0.03	<2.95
Temperature Drop within the Storage ΔT_{fall}, K	<0.05	<0.05	<0.34
Sum of Losses Occurring			
Sum of Relative Heat Losses within $\boldsymbol{\tau}$: $\boldsymbol{Q_{\mathrm{stor}}(t_0+\tau)/\ Q_{\mathrm{stor}}(t_0)}$, %	**<0.03**	**<0.03**	**<24.0**
Sum of Temperature Drops within the Storage $\boldsymbol{\Delta T_{\mathrm{stor}}}$, K	**<0.30**	**<0.30**	**<3.00**

Within these calculations T^* is not the meteorological ambient temperature, but the minimal supply flow temperature necessary for heat supply, e.g. for industrial purposes (highly variable T^*), heating purposes via floor heaters ($T^* \approx 30 \ldots 50$ °C), radiators ($T^* \approx 60 \ldots 80$ °C) or for tap water supply ($T^* \approx 70 \ldots 80$ °C).

In consideration of the widespread utilization of radiators, the minimum temperature level utilizable is defined $T^* \approx 70$ °C. Summarizing, Table 5 gives the results of the DH system simulation applying different storage concepts for a full charging/discharging cycle. The maximum heat load is 22 MW_{th} (approximately 11 % of the maximum heat load). Especially within the Sub-Network, η_{en} and η_{ex} strongly depend on the storage concept. In addition, the efficiencies of the Main System considerably depend on the storage concept as well.

TABLE 5. ENERGETIC PARAMETERS OF (DE-)CENTRALIZED THERMAL STORAGE CONCEPT

Parameter	Centralized Concept			Decentralized Concept		
	Main System	Sub-Network	Overall	Main System	Sub-Network	Overall
Q_{in}, MWh_{th}	307.7	0.93	308.8	303.4	0.74	304.1
Q_{out}, MWh_{th}	263.4	0.60	264.0	263.4	0.60	264.0
η_{en}, %	**85.6**	**64.4**	**85.6**	**86.8**	**80.7**	**86.8**
T^*, °C	70	70	NaN	70	70	NaN
$\bar{T}_{out}$, °C	77.3	70.7	NaN	77.5	73.4	NaN
E_{in}, MWh_{th}	6.66	0.0022	6.67	6.67	0.0072	6.68
E_{out}, MWh_{th}	5.49	0.0012	5.49	5.62	0.059	5.63
η_{ex}, %	**82.4**	**54.1**	**82.4**	**84.2**	**82.2**	**84.2**

6. SUMMARY AND PROSPECT

Thermal storages will play a major role for optimizing the operation of CHP plants, as well as intermediate and peak load heat only plants. Adding flexibility to existing DH systems, thermal storages must be adjusted according operational needs, e.g. enhancing the stability of heat supply or the efficiency of heat distribution. For this purpose, the major heat loss mechanisms of the heat distribution system as well as the thermal storages have to be considered and quantified. Summarizing the results of the system simulations conducted on different thermal storage concepts, the integration of decentralized thermal storages offers several advantages:

- Major shift in energetic and exergetic efficiencies for the heat distribution, especially regarding ill-conditioned sub-parts of the DH system;
- Major shift of the supply flow temperatures available within ill-conditioned sub-parts of the DH system, generally enhancing the quality and safety of DH supply;
- Highly efficient decoupling of heat production and allocation / utilization of heat at the customer's site, especially for thermal storage systems applying low (i) Surface areas per heat content (hot water volume) stored, (ii) Vertical heat flows within the thermal storage media, (iii) Vertical heat flows within thermal short circuits and (iv) Radial temperature and density gradients.

Main design guideline for DH systems is the application of decentralized heat storages in the vicinity of the heat customers in order to obtain high flow velocities for the high temperature thermal media within the heat distribution network. Thus, thermal storages are integrated most efficiently, high efficiencies within the heat distribution may be achieved and heat losses are diminished. In addition, the efficiency of thermal storages may be enhanced by implementing thermal insulations, as well as a stable layer for thermal stratification, low relative strengths of the wall and maximized volumes of "near-customer-storages".

Besides economic (e.g. increasing costs for increasing decentralization) and legal aspects, a technological and ecological optimum between "near-customer" installation of thermal storage systems and the energy efficiency of the heat distribution network must be found. Prospecting, the influence of additional energetic and exergetic losses within thermal storages, such as turbulences induces while (dis-)charging / operating the storage, thermal inertia of the storage infrastructure as well as effects of heat radiation (in between the head and bottom of the storage) have to be considered within future examinations. The impact of these losses will enhance for decreasing storage capacities. Thus, the optimum for a decentralized storage strategy and diminished heat losses is influenced.

REFERENCES

[1] AGFW. Der Energieeffizienzverband für Wärme, Kälte, KWK e. V. Die 70/70-Strategie Konzept und Ergebnisse. AGFW-Projektgesellschaft für Rationalisierung. Institut fur Energiewirtschaft und Rationelle Enerfieanwendung der Universtat Stuttgart, 2015.

[2] Dubois R. Optimale Tageseinsatzplanung von Kraft-Wärme-Kopplungssystemen unter Berücksichtigung von Kurzzeitspeichern. Dissertation, Düsseldorf: 1986.

[3] Gustafsson S-I., Karlsson B. Heat Accumulators in CHP networks. *Energy Conversion and Management* 1992:33:1051–1061. doi:10.1016/0196-8904(92)90002-E

[4] Ito K., Yokohama R., Shiba T. Optimal operation of a diesel engine cogeneration plant including a heat storage tank. *Journal of Engineering for Gas Turbines and Power* 1992:114:687–694. doi:10.1115/1.2906643

[5] Pakere I., Purina D., Blumberga D., Bolonia A. Evaluation of thermal energy storage capacity by heat load analyses. *Energy Procedia* 2016:95:377–384. doi:10.1016/j.egypro.2016.09.040

[6] Van Ruth N. J. L. New type of valve for solar thermal storage tank stratification. *Energy Procedia* 2016:91:246–249. doi:10.1016/j.egypro.2016.06.212

[7] Ziemele J., Gravelsins A., Blumberga A., Blumberga D. The effect of energy efficiency improvements on the development of 4th generation district heating. *Energy Procedia* 2016:95:522–527. doi:10.1016/j.egypro.2016.09.079

[8] Masatin V. Latosev E., Volkova A. Evaluation factor for district heating network heat loss with respect to network geometry. *Energy Procedia* 2016:95:279–285. doi:10.1016/j.egypro.2016.09.069

[9] Li H., Wang J. S. Load management in District Heating operation. *Energy Procedia* 2015:75:1202–1207. doi:10.1016/j.egypro.2015.07.155

[10] Pfeiffer R., Verstege J. Committing and dispatching power units and starage devices in cogeneration systems with renewable energy sources. *Power System and Control Management* 1996:21–25. doi:10.1049/cp:19960230

[11] Huhn R. Beitrag zur thermodynamischen Analyse und Bewertung von Wasserwärmespeichern in Energiewandlungsketten. Dissertation. Stuttgart: 2006.

[12] Verda V., Colella F. Primary energy savings through thermal storage in district heating networks. *Energy* 2011:36:4278–4286. doi:10.1016/j.energy.2011.04.015

[13] Dittmann A., Nestke C. Wärmespeicherung erhöht die Effizienz der Kraft-Wärme-Kopplung. *EuroHeat & Power* 2010:39:34–41.

[14] Schuchardt G. K., Holler S. Wärmetransportprozesse und energetische Verluste in thermischen Speichern für Fernwarmenetze. Dresden: Kraftwerkstechnischen Kolloquim, 2015.

[15] Nelson J. E. B., Balakrishnan A. R., Srinivasa Murthy S. Parametric studies on thermally stratified chilled water storage systems. *Applied Thermal Engineering* 1999:19:89–115. doi:10.1016/S1359-4311(98)00014-3

[16] Ismail K. A. R., Leal J. F. B., Zanadri M. A. Models of liquid storage tanks. *Energy* 1997:22:805–815. doi:10.1016/S0360-5442(96)00172-7

[17] Kumana J. D., Kothari S. P. Predict storage-tank heat transfer precisely. *Chemical engineering* 1982:127–132.

[18] Jack M. W., Wrobel J. Thermodynamic optimization of a stratified thermal storage device. *Applied Thermal Engineering* 2009:29:2344–2349. doi:10.1016/j.applthermaleng.2008.11.021

[19] Bestrzynski G. K., Holler S., Olbricht M. Energetic Performance of Short Term Thermal Storage in Urban District Heating Networks. Presented at 14th. Int. Symp on District Heating and Cooling, Stockholm, Sweden, 2014.

[20] Bestrzynski G. K., Holler S., Luke A. Anpassung verbrauchernaher thermischer Speicher an die individuellen Betriebscharakteristiken von Wärmesenken. Presented at NEIS Konferenz, Hamburg, 2014.

[21] Johansson C. Towards Intelligent District Heating. Dissertation, Blekinge Institute of Technology, Karlskrona, 2010.
[22] Bestrzynski G. K., Razani A. R., Janßen H., Luke A., Scholl S. Dynamic Modell for Small Scale District Heating Networks in Rural Areas. Presented at 4th IIR Conference on Thermophysical Properties and Transfer Processes of Refrigeration, Delft, 2013.
[23] AGFW. Der Energieeffizienzverband für Wärme, Kälte, KWK e. V. (Hrsg.). Transformationsstrategien Fernwärme. AGFW-Projektgesellschaft für Rationalisierung, Information und Standardisierung.
[24] Bundesverband der deutschen Gas- und Wasserwirtschaft (BGW, heute BDEW). Abwicklung von Standardlastprofilen. Praxisinformation P 2007/13 Gastransport/Betriebwirtschaft, Berlin, 2007.
[25] Verein Deutscher Ingenieure VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen Hrsg. VDI Wärmeatlas, zehnte, bearbeitete und erweiterte Auflage. Düsseldorf: Springer, 2006.
[26] Loewen A. Entwicklung eines Verfahrens zur Aggregation komplexer Fernwärmenetze. Fraunhofer IRB 2001.
[27] Claesson J., Bennet J. Multipol Method to Compute the Conductive Heat Flows to and Between Pipes in a Cylinder, Notes on Heat Transfer. Universität of Lund, 1987.
[28] Grigull U., Franz G. Wärmeverluste erdverlegter Rohrleitungen. *Wärme-, Klima und Sanitärtechnik* 1970.
[29] Franz G., Grigull U. Wärmeverluste von beheizten Rohrleitungen im Erdboden Heat Loss of Buried Pipes. *Wärme- und Stoffübertragung* 1969:2:109. doi:10.1007/BF01089055
[30] District heating pipes - Preinsulated bonded pipe systems for directly buried hot water networks - Steel valve assembly for steel service pipes, polyurethane thermal insulation and outer casing of polyethylene; German version EN 488:2015. Berlin: Beuth Verlag, 2009.
[31] Schuchardt G.K. (née Bestrzynski). Beitrag dezentraler Speicher zur Erhöhung der Effizienz bei der Wärmeverteilung, IRO 2016.
[32] Leitfaden zum Nachweis der Speichereffizienz im Rahmen des Kraft-Wärme-Kopplungsgesetzes. Bundesamt für Wirtschaft und Ausfuhrkontrolle, 2014.
[33] Incropera F. P., DeWitt D. P., Bergamnn T. L., Lavine A. S. Heat and Mass Transfer. 6th Edition. Wiley and Sons Inc., 2007.

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