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Optimal Design of District Heating Networks with Distributed Thermal Energy Storages – Method and Case Study

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ABSTRACT

District heating systems have a great potential for supporting the energy transition towards a renewable energy system, and could also be an option in less dense populated urban districts and rural communities with a medium heat density. In these cases, distributed thermal energy storages at each building could improve the overall system performance by enabling a leaner sizing of the piping systems due to peak-shaving and reducing the heat losses of the distribution grid. But how can distributed storages be included in the design of the district heating network itself? And what are the benefits with respect to the district heating piping system? This paper answers these questions and presents a novel open source optimisation framework for designing the piping network of a district heating system that is based on a mixed-integer linear programming model with a high spatial resolution. Due to its modular structure, it allows the extensibility by additional energy storage and converter units. Additionally, a novel method to consider the simultaneity of demand is introduced. Within the QUARREE100 project, the tool is demonstrated on a real world case of an existing district with 129 houses in the provincial town Heide in Northern Germany by analysing the impact of distributed thermal storages on the piping system. In the scenario with an average volume of 1 m³ heat storages, the thermal losses of the district heating network can be reduced by 10.2 % and the total costs by 13.4 %.

Keywords

District heating system;
Network optimisation;
Simultaneity;
Planning approach;
Distributed thermal energy storages;

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1. Introduction

In 2010, Lund et al. concluded that district heating systems (DHS) have a great potential for supporting the energy transition towards a renewable energy system in Denmark [1]. Continuing studies for the whole European heating sector also came to the result that DHS are in many cases an economically feasible option [2,3]. According to Möller et al., the economic potential of district heating is in total at 59 % for 14 European countries, and for Germany 66 % in relation to the total net heat demand [3]. Thus, there is a great potential of implementing and expanding DHS in Germany, as the share of DHS was only 13.7 % in 2016 [4]. The basis for potential areas for DHS can be derived from heat density maps [5,6], or analysed by applying the method for determining suitable areas presented by Knies [7]. However, not only the heat line density, but also the specific local conditions play a decisive role, and there cannot be defined absolute tipping points for heat line densities for the economic feasibility of a DHS [7].

This means that areas with a low and medium heat demand density cannot be excluded in advance. Since the heating sector needs to be coupled with other energy

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Abbreviations

CHP	combined heat and power plant
DHS	district heating system
DHW	domestic hot water
DTES	distributed thermal energy storage
LP	linear programming
MILP	mixed integer linear programming

sectors [8] in order to establish *Smart Energy Systems* for the integration of fluctuation renewable energies [9], and due to the growing importance of flexibility [10], the planning of DHS networks is also becoming increasingly complex. In addition, energy storage must be integrated, of which thermal storages will play an important role [9]. Consequently, planning methods for the design of DHS networks must be developed further to take these additional boundary conditions into account.

Especially in districts with a low and medium heat demand density, distributed thermal energy storages (DTES) at each building could have a couple of benefits for the DHS. Best presented an analysis of low temperature district heating and ultra-low temperature district heating systems for new building developments [11]. However, these low temperatures are not applicable in existing districts, where buildings demand higher supply temperatures, and DTES were not considered. It is shown in Section 2.1 that using DTES is a relevant option for DHS and they could have a number of advantages. However, with respect to the network planning, no open source modelling approach could be found, that is capable of considering DTES within the network planning approach (see Section 2.2).

This article presents a modular and flexible optimisation framework to design DHS networks. The novelty of the approach is a flexible mixed-integer linear problem (MILP) formulation based on existing open source libraries, that allows the option of considering distributed thermal energy storages (DTES) within the DHS network optimisation. In addition, a new method for the consideration of the heat demand simultaneity based on individual load profiles is introduced. The framework is published within the Python open source library *DHNx* [12,13], which permits the use and the further development by the scientific community.

The article is structured as follows: Firstly, a literature review shows the relevance of DTES for DHS, and gives on overview on existing DHS network optimisation methods. Further, it is emphasized why it is important for the scientific progress to develop open source tools. The following section explains the methodology of the optimisation approach including the procedure for modelling the simultaneity. Subsequently, the optimisation framework is demonstrated on the basis of a case study of an existing district within the project QUARREE100. The results give an indication of the influence on the investment costs of the piping system for a scenario with and without DTES. Lastly, the volume of the DTES is varied to show the influence of storage capacity of DTES on the dimensioning of the piping system.

2. Existing Scientific Work and Modelling Approaches

The following literature review examines if DTES generally provide advantages for DHS, and what they are. After that, an overview of existing planning methods for designing the DHS network is given. It is checked if there is already an approach for designing the DHS network in the presence of DTES, which is published as open source tools and can be used for further development. The importance of open source models for the scientific community is addressed in the third section.

2.1. Existing research on distributed thermal energy storages

DTES are mainly discussed regarding operating optimisation. In general, most studies focus on a supply oriented optimisation of district heating systems (DHS) rather than demand driven supply of energy. Ramm et al. and Dominković et al. aim towards the integration of high renewable energy shares [14,15], while Vandermeulen et al., Schuchardt, Johansson et al., and Vanhoudt et al. consider an economically optimal combined heat and power plant (CHP) operation [16–19].

Vandermeulen et al. name numerous benefits using DTES: decrease in running hours of peak load plants, reduced pollution, investment and operational cost. They focus on intelligent control systems discussing options to operate a CHP and heat pump more economically efficient. CHP operation can be improved by two aspects: Firstly, generating additional income by optimizing electricity sales. Secondly, the thermal and electrical efficiency can be improved by controlling the supply and return temperatures. [16]

Besides the optimisation of the system controller, two options for distributed storage systems are discussed: a) small storage vessels [17], b) thermal inertia of the building itself [15,17,18]. Using thermal inertia or the building mass as a thermal energy storage is performed by preheating the building to an upper limit of the internal room temperature and cut off of energy supply until a lower limit of the room temperature is reached. Regardless of which option is used all authors concluded benefits using DTES within their study settings.

Dominković et al. examine a study on a DHS in Sønderborg (DK) using the thermal mass of the buildings as a thermal storage to integrate solar thermal energy [15]. The storage potential of different building types is examined by a detailed building simulation model coupled with a linear optimisation model of the energy system. The results of that study show that the thermal mass of the buildings was best used as an intra-day storage. Operational cost could be reduced in the range of 0.7 – 4.7 %. [15]

Johansson et al. and Vanhoudt et al. also found that the thermal mass of buildings is beneficial for optimizing DHS [18,19]. Johansson et al. attained energy savings of about 9 % using thermal mass of buildings as a thermal storage applying a multi-agent system optimizing heat demand and supply in an DHS [18]. Vanhoudt et al. aimed at maximizing profits of a CHP selling electricity to the spot market. Three storage options are compared: a) a central buffer tank, b) small distributed storage vessels and c) thermal mass of the buildings. According to this study, the concept with distributed storage vessels is the best regarding the profits made and the concept using thermal mass is the most efficient. Since the profit of concept c) is just slightly smaller, and no costs for buffer vessels are included, the authors conclude that this concept is the most promising [19].

Roberto et al. studied the benefits of DTES in an existing DHS for improving the economic profit and reducing the net CO_2 emissions by applying different operation strategies [20]. They concluded little benefits in case of flexible heat generator units. However, mainly fossil fuel driven heat generators like gas fired CHP and boilers were considered in their study. Thus, the authors also state that DTES should be applied in DHS with non-flexible generation options and when intra-day electricity prices show higher fluctuations [20], which is a realistic scenario for the upcoming years due to the increasing share of fluctuating renewable energy sources within the power system. The authors further conclude that DTES could decrease the demand peak of the DHS network [20]. Altogether, the potential impact of DTES on the DHS network design itself and the associated savings of investment costs for the piping system costs were not analysed.

Using DTES seems to be a promising solution to operate a DHS more efficiently and more profitable. A potential of reducing costs through smaller piping is mentioned for example by Gadd and Werner [21], and by Vandermeulen et al. [16], but it is not part of recent studies. Most of the before mentioned literature dealing with the benefits of DTES did not include an examination of the actual influence of DTES on sizing the district heating grid. Thus, the literature of published approaches for DHS network planning has been reviewed to screen if and how DTES are considered within the planning of DHS networks.

2.2. District heating networks planning tools

The THERMOS project provides a free to use and very user-friendly web-based DHS planning tool [22]. It is based on a high level of detail using a buildings-wise representation of the heat demand. The tool also includes a bottom-up method for estimating the heat demand of the buildings. The main feature of the THERMOS-tool is the DHS network design. This includes the selection of the heat supply site, the cost-efficient connection of buildings, and the routing and dimension of the piping network. Two different objectives are implemented, which represent two different perspectives on the planning problem: the maximisation of the net present value for the network operator, and the maximisation of the whole-system net present value. The modelling background of the THERMOS-tool is based on Kuriyan and Shah [23]. The THERMOS-tool is a very powerful and practical planning tool. However, the examination of DTES within the planning of a DHS network is not possible, and, as the source code is not public, it is not possible to extend it.

Weinand et al. developed a combinatorial optimisation approach to design district heating networks based on deep geothermal energy [24]. Here, the cost optimal location of a geothermal plant is determined, taking into account the location and characteristics of several settlements, a specification of the heat coverage by the district heating network, and restrictions by geographical conditions like forests. An optimisation approach is compared with a heuristic method. The authors conclude that the heuristic method outmatches the optimisation approach by a significantly shorter computing time with a deviation of the investment costs of less than 5 percent [24]. Though, this approach does not include a detailed representation of the district heating network within the settlements themselves.

Bording et al. also presented a linear integer approach including the piecewise linear approximation of the relation of mass flow and pressure drop [27]. This publication also focuses on the connection of new customers to an existing district heating network and therefore maximizes the overall net profit. The stationary peak load case is considered and the global – i.e. a same factor for all consumers – simultaneity factor is applied. However, the approach is limited to networks having a tree configuration with a single plant, and the network itself is an input for the optimisation process and not a result based on a larger network with all potential routing options. [27]

Lambert et al. present a multi-stage stochastic programming formulation for the optimal phasing of DHS networks to minimize the investment risk [28]. The term phasing refers to the expansion decisions when a DHS network is developed from a 'seed' network and evolves over time [28], which is a very important aspect of the planning of future DHS. The authors also state that the approach could be used to show local authorities and planners how their district heating network might expand over the investment period.

Li and Svendsen propose a district heating network design approach using a mixed-integer non-linear optimisation (MINLP) formulation and a genetic algorithm for solving [29]. This includes a detailed representation of the thermal and hydraulic relations. Similar to Weinand et al., the location of the district heating plant is optimized on a discrete grid (compare [24]). A mathematical formulation using the design peak heating load as basis and 8 time steps representing the different load states during the year is performed. The approach considers a tree-shaped structure without isolated loops. [29]

Also using genetic algorithm technique, Razani and Weidlich published a modelling approach for analysing different DHS layouts including thermal storages [30]. A small virtual district heating network supplied by a CHP is analysed with three different storage configurations: a central storage, semi decentral storages, and full decentral storages [30]. To the knowledge of the authors, this is the only modelling approach that considers thermal energy storages within the network planning. However, the approach can be neither used nor extended by others as it is not published as open source package. Furthermore, it is based on a single heat supply, and the impact of DTES on the piping system is not evaluated.

For the task of designing and sizing district heating networks, Dorfner presented in his PhD Thesis the open source models *DHMIN*, originally published in 2014 [25], *dhmin* (seasonal), and *rivus* [26]. This could be identified as the only fully open source planning tools. The main feature of *dhmin* (seasonal) is the consideration of redundancy of multiple heat generation sites by using multiple time steps. As the title of the 2014's publication already indicates, the *dhmin* family focuses on large scale districts. Therefore, the spatial resolution follows a street-wise aggregation by mapping the buildings to the graph edges. The simultaneity factor (concurrence effects) is considered via a global factor by downscaling the cumulated peak power at each source node. [25,26] Although the code is open, there is a lack of modularity for reasonably expanding the model. In addition, the spatial resolution of this model follows a different design concept. Therefore, this model was not considered for further development.

The literature research shows that there are numerous published modelling approaches for the design and planning of district heating networks. It also shows that most of the models are proprietary and the source code is not published. Certainly, most articles about proprietary models provide important information on the methodological approach. But in most cases, it is neither possible to use the model nor to extend it. However, this aspect is crucial for scientific progress as shown in the following section.

2.3. Open source model development

Publishing the source code of a scientific model is not an addition but essential to meet scientific standards [31]. DeCarolis et al. pointed out the importance of reproducibility and shows that describing the software in a journal paper is not enough to make analysis repeatable [32]. General statements based on model results will influence the scientific discussion and even policy decisions and should therefore be as transparent as possible [33]. Nevertheless, publishing the source code is necessary but insufficient to meet the standards as there are requirements on readability, documentation and version control [34]. Therefore, in the scientific process, an open model is only limitedly comparable to a proprietary model.

During the development of the presented software, the transparency rules of DeCarolis et al. [32] and Pfenninger et al. [34] were followed to ensure reusability. Where possible, existing packages are used. Proprietary models, even if the functional scope may exceed that of the presented tool could not be considered as explained above.

Hence, the optimisation is based on the *oemof.solph* package which already has a relevant impact on the scientific community [35], and thereby accelerates scientific progress. The *oemof.solph* package already shows that community based development increases the code quality by code reviews and ensures that errors are detected more likely, as the software is used by several people.

The software is published within the open source Python software package DHNx [12], which is part of an existing scientific community. By practising open source development on the platform github [13], the connectivity is granted and the expandability is facilitated. This enables a collaborative development, and avoids duplicated work in science.

3. Methods

In the following sections the methodological approach is discussed. At the beginning, an overview is provided followed by the description of the underlying topological model and the mathematical background of the core elements of the model. Lastly, a new method for considering the simultaneity of heat demand is introduced.

3.1. Overview optimisation approach

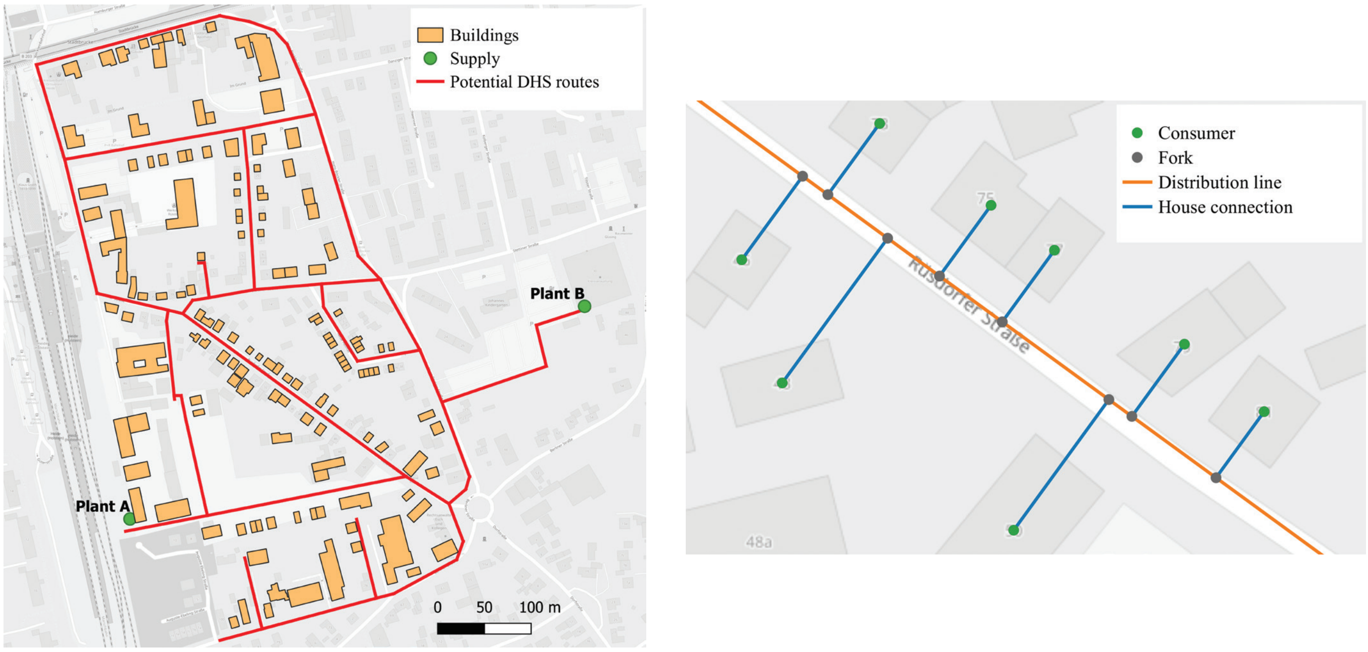
The aim of the techno-economic optimisation approach is to find the most cost-efficient district heating network with the option of considering DTES. This includes the optimal network routing and the sizing of the district heating pipes. The description of the model can be formulated as follows: Given are the heat demand of each consumer of an urban district, the option of DTES at the customers, and a cost-function for the heat distribution pipes. The heat demand is given by individual load profiles. The optimisation problem is concerned with deciding on where to build the pipeline system, and how to dimension it, while minimizing the overall costs. Additionally, the DHS optimisation approach is designed to consider the case of complete redundancy of multiple supply options. The optimisation follows two stages: First, the best routing option is found by two time step optimisation formulated as mixed-integer linear problem (MILP) applying a global simultaneity factor. Second, a linear programming model (LP) is applied to determine the optimal sizing of the piping system for the case with and without distributed storage options. In the second stage, the three coldest days of the year with the maximum heat load with a time resolution of a quarter of an hour are used as heating demand profiles to be satisfied. The modelling approach is implemented in Python as open source tool within the package *DHNx* [12,13]. For building up the optimisation model, the library *DHNx* itself makes use of the open source package *oemof.solph* [35–37], which uses *pyomo* [38] for creating the MILP model. For solving the optimisation model, *gurobi* is used as solver [39]. However, other solvers, like *CBC* [40], can be used as well.

3.2. Topological input data

The base of this design approach consists of two georeferenced data layer: a line layer containing all potential routing options for DHS, which e.g. can be derived from *OpenStreetMap* [41], and a polygon or point layer containing all buildings, which are supplied by the DHS. Figure 1 (a) illustrates the starting basis.

Based on the given geometry, a consistent nodes-edges structure is generated. This means that the distribution lines are prepared for the optimisation model builder, and the connections of the buildings are created. This implies splitting and merging the distribution lines, adding nodes at the ends of all edges, and categorizing the nodes according their representation: consumer, supply, and fork. Figure 1 (b) shows the result of the geometry processing, and illustrates the detailed representation of the district heating grid. Each building is connected to the distribution network.

After processing the geometry (see Figure 1 (b)), an *oemof.solph* energy system is created [36]. For all edges, a DHS pipeline component named *HeatPipeline* was developed and will be explained in detail in Section 3.3. Besides, the following classes from the *oemof.solph* library are used in the energy system model: *Bus, Source, Sink, GenericStorage*. For all nodes, an *oemof.solph Bus* is generated. A *Bus* creates an energy balance. The heat demand is given by an individual time series of the coldest period of the year for each building, and modelled by a *Sink*. For the scenario with DTES, a *GenericStorage* is added to each building node. At each DHS supply plant, a *Source* represents the heat generation units and ensures the heat feed-in to cover the heat demand of the district heating system. The detailed mathematical background of the *oemof.solph* components is provided by the *oemof.solph* documentation [36]. In the following, the two most important components



(a) (b)

Figure 1: (a) Geometry input of the district planning and optimisation approach. Red: possible district heating routes; orange: considered buildings. (b) Result of the geometry processing and input for the optimisation model builder. Source background map: [41].

HeatPipeline and *GenericStorage* are explained in detail.

3.3. Model of district heating pipelines

For the DHS pipelines, a MILP model called *HeatPipeline* was developed and is published within the *DHNx* library [12]. The mathematical formulation is based on [25]. However, this model differs in the level of detail and the way how the heat demand is considered. The forward and return pipes are not modelled separately, but are represented by one component. All edges of the district heating network (see Figure 1 (b)) are modelled by a *HeatPipeline* component (see also [12]). Figure 2 outlines the concept.

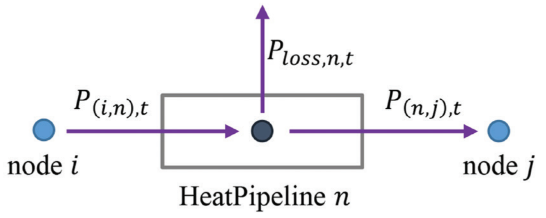


Figure 2: Scheme of the DHS pipeline model.

The following equations describe the constraints of the *HeatPipeline* component, which represents a single element of the pipeline network:

$$C_n = P_{(n,j),invest} \cdot c_{invest} + y_{(n,j)} \cdot c_{investfix} \tag{1}$$

$$P_{loss,n,t} = P_{(n,j),invest} \cdot f_{loss,t} + y_{(n,j)} \cdot f_{lossfix,t} \tag{2}$$

$$P_{(n,j),t} = P_{(i,n),t} - P_{loss,n,t} \tag{3}$$

$$P_{(i,n),invest} = P_{(n,j),invest} \tag{4}$$

$$P_{(n,j),investmin} \cdot y_{(n,j)} \leq P_{(n,j),invest} \leq P_{(n,j),investmax} \cdot y_{(n,j)} \tag{5}$$

$$-P_{(i,n),invest} \leq P_{(i,n),t} \leq P_{(i,n),invest} \tag{6}$$

$$-P_{(n,j),invest} \leq P_{(n,j),t} \leq P_{(n,j),invest} \tag{7}$$

$$y_{n,j} \in \{0,1\} \tag{8}$$

with the following decision variables:

C_n Investment costs of DHS pipe n [€]

$P_{(n,j),invest}$	Heat transport capacity of DHS pipe n [kW]
$P_{(n,j),t}$	Heat flow from the DHS pipe n at time step t [kW]
$P_{(i,n),t}$	Heat flow into the DHS pipe n at time step t [kW]
$P_{loss,n,t}$	Thermal loss of DHS pipe n at time step t [kW]
$y_{(n,j)}$	Investment decision variable of DHS pipe n [-] (0 = no investment; 1 = investment)

and the following parameters:

c_{invest}	Capacity dependent investment costs [€/$\text{kW}_{\text{transport}}$]
$c_{investfix}$	Fix investment costs [€]
f_{loss}	Capacity dependent investment costs [kW_{loss}/$\text{kW}_{\text{transport}}$]
$f_{lossfix}$	Fix investment costs [kW_{loss}]
$P_{(n,j),investmin}$	Minimum pipe capacity [$\text{kW}_{\text{transport}}$]
$P_{(n,j),investmax}$	Maximum pipe capacity [$\text{kW}_{\text{transport}}$]

The binary variable $y_{(n,j)}$ is used to create an y-offset in the linear function of the investment costs and thermal losses (see equations (1), (2), and (8)), in order to better approximate the real costs and thermal losses of the DHS pipelines. Hereby, an investment of zero is possible as well by equation (5). The time dependent actual heat outflow $P_{(n,j),t}$ results from the inflow $P_{(i,n),t}$ minus the thermal loss $P_{loss,n,t}$ (see equation (3)). The invested capacity of the in- and outflow are set equal (4) to generate a symmetry within the component independently of the physical mass flow. Thus, the flow direction does not affect the invested pipe capacity, and bidirectional heat flow values can be allowed ((6) and (7)). For all consumers' connections, only directed heat-pipe components are used so that in the case with storages, no heat feed-in from a consumer is possible.

For the parametrization of the DHS pipe component, a pre-calculation is performed to transfer the hydraulic design criteria and parameters into capacity dependent parameters for the optimisation model. The following scheme in Figure 3 clarifies the approach.

The starting point is a maximum length-specific pressure drop, which is a common criterion for designing DHS pipelines [42]. Furthermore, the roughness of the pipelines' inner surface, and the temperature level the DHS is operated at needs to be given. By using an iterative calculation approach, the maximum flow velocity is calculated for each DN number. Within this iterative approach, the empirical formulas of Blasius, Prandtl, Colebrook and Kármán are used to calculate the pressure drop according to the usual state of the art depending on the flow type and whether a smooth or a rough flow regime is present in case of a turbulent flow regime (for further information, see [43,44]). The maximum heat transport capacity of each DN number results from the forward and return temperature, the DHS is operated. The maximum heat transport capacity thus determined is the magnitude to which the costs and the thermal losses are referred to for the optimisation model. Section 4.1 provides the parameters applied in the case study.

3.4. Model of thermal energy storage

The distributed thermal energy storages (DTES) are modelled by the *GenericStorage* given by the *oemof.solph* library [36]. The constraints created by the *GenericStorage* depend on the attributes used to instantiate the model. Figure 4 illustrates the model of the thermal energy storage.

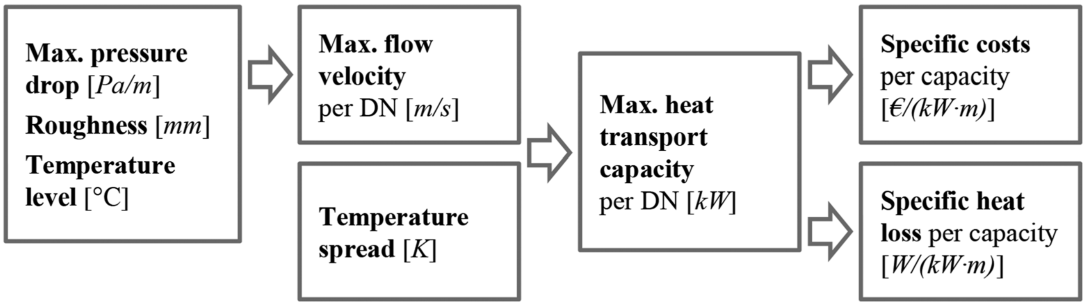


Figure 3: Derivation of capacity dependent optimisation parameters from hydraulic design guidelines.

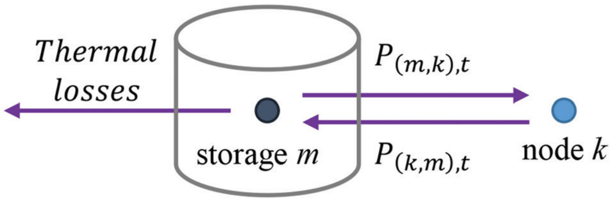


Figure 4: Scheme of the thermal energy storage model.

The deployed storage model represents an ideal stratified thermal energy storage. The thermal loss consists of a fix loss term depending on the nominal storage capacity, and a variable loss term depending on the actual state of charge of the storage. The constraints of the storage model are described by the following equations (see also [36]):

$$\begin{aligned} W_{m,t} = {} & W_{m,t-1} \cdot (1-\beta)^{\Delta t} - W_{nominal} \cdot \gamma \cdot \Delta t \\ & -P_{(m,k),t} \cdot \Delta t + P_{(k,m),t} \cdot \Delta t \end{aligned} \tag{9}$$

$$W_{m,t_{last}} = W_{m,t_{zero}} \tag{10}$$

$$0 \leq W_{m,t} \leq W_{nominal} \tag{11}$$

with the following decision variables:

$W_{m,t}$	Energy stored at time step t [kWh]
$P_{(m,k),t}$, $P_{(k,m),t}$	Heat in- and outflow at time step t [kW]

and the following parameters:

$W_{nominal}$	Nominal capacity [kWh]
β	Variable loss factor [-]
γ	Fix loss factor [-]
Δt	Duration of time step as fraction of 1 h [-]

Equation (9) describes the energy balance of the storage. The thermal energy of the storage results from the energy of the previous time step minus losses and the outflow plus the inflow. In order to meet the overall energy balance the stored thermal energy of the time step zero and the last time step must be equal (10). The maximum thermal energy of the storage is restricted by the given capacity of the storage (11).

3.5. Simultaneity of heat demand

In planning and dimensioning district heating networks, the consideration of the simultaneity of demand plays an important role. In many district heating network optimisation models, the simultaneity is taken into account by downscaling the maximum winter heating load of the consumers globally with a fix factor, often called the simultaneity factor [45]. Since the simultaneity factor depends on the kind and number of heat consumers, the sizing of distribution lines with few customers might be inappropriate by using a global simultaneity factor. For example, in case of a simultaneity factor of 0.6 for 200 customers of a district, and a simultaneity factor of 0.9 for five particular customers, which are supplied by one distribution line, a global downscaling of the consumers' loads leads to an underestimation of the actual heat load in this distribution line.

Therefore, a multi time step approach is proposed using individual load profiles of the period around the peak load, e.g. the coldest three days of a year. The idea is that the simultaneity effect is already included in individual load profiles to imitate a real diversified load. Consequently, within the optimisation approach for dimensioning the piping network itself no additional effort must be made for considering the simultaneity effect. The particular load profiles can be achieved by individual modelling of the heat load of the buildings, or by applying a normal distributed time shift to load profiles types. Within this study, a combination of both approaches is conducted, which is explained in detail in Section 4.2. The following Figure 5 illustrates the principal approach based on three exemplary normed load profiles. The peaks of the load profiles occur on a different time step. In the optimisation process, the whole 3-days load profiles are used for dimensioning the DHS piping system.

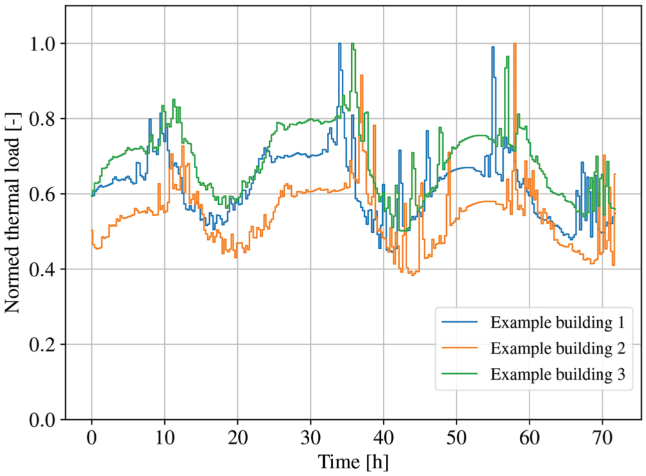


Figure 5: Exemplary heat load of three buildings showing the shift in heat load peak, which imitates the simultaneity effect.

4. Parameters and Case Study

The parameters of the district heating pipelines applied in the case study are provided in the first part of this section. The second part introduces the existing district considered in the case study, and explicates the calculation of the heat demand profiles.

4.1. Parameters of the district heat pipelines

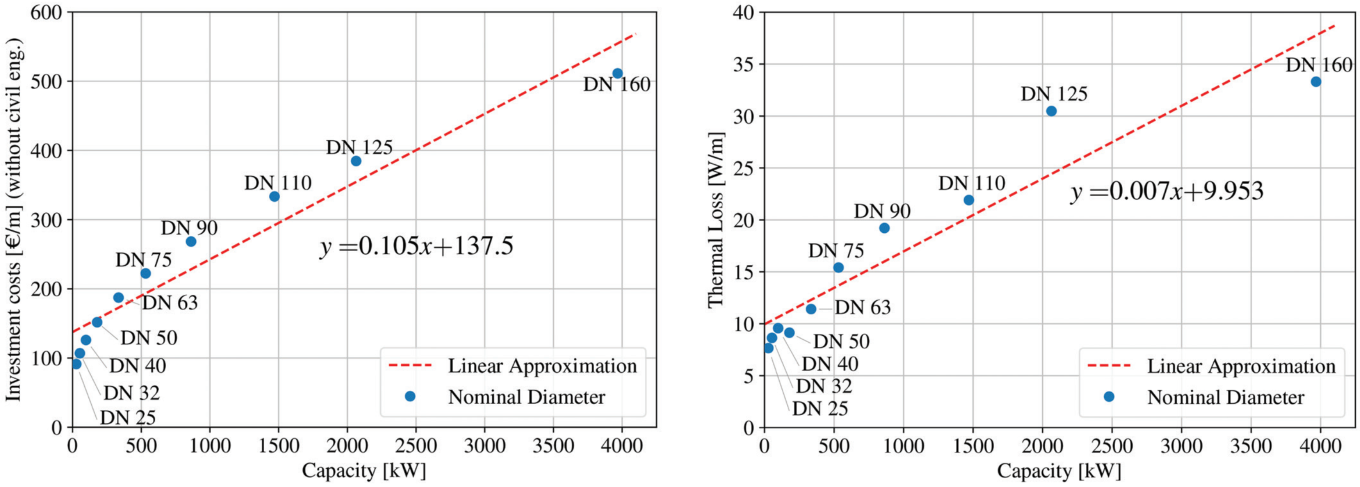
In reality, only discrete pipe diameters are commercially available. Hence, the discrete parameters of individual costs for each pipe with a specific nominal diameter are linearized to obtain a mathematical problem that can be calculated in a reasonable computing time. For each nominal diameter, the maximum heat transport capacity is calculated as described in Section 3.3.

According to Best et al., the recommendations for the specific pressure drop per meter pipe length range from 70 to 350 Pa/m [46]. In this analysis, the conservative value of 100 Pa/m is used as design guideline. Next, a roughness of 0.01 mm for the inner pipe surface, a forward temperature of 80 °C, and a return temperature of 50 °C are assumed as design criteria for the district heating grid due to the existing buildings stock. A ground temperature of 10 °C is assumed for the calculation of the thermal losses. The investment costs for district heating pipes depend on many individual factors, and the data given in literature vary depending on the country and the year of publication (compare [47–49]). In this analysis, the cost function $50\,\text{€}/m + (700\,m^{-1} \cdot DN)^{1.3}\,\text{€}/m$ given by the THERMOS-tool is used [22]. The costs include installation and exclude costs for civil engineering. The heat losses are based on public technical data sheets of the manufacturer *Enerpipe* [50]. Figure 6 provides the data for the piping network, and illustrates the results of the linearization.

In both costs and thermal losses, the linearization leads to slightly higher values for the small pipe diameters, whereas the values for the nominal diameter of DN 75 to DN 125 results in lower values (Figure 6).

4.2. Characterization of the district

The approach for optimizing the district heating network with DTES is applied to a case study of the research project QUARREE100. The district is placed in the town Heide in the German state Schleswig–Holstein (geographical coordinates 54.1951764 9.1019015). The region is characterized by a high number of wind power plants, which need to be curtailed on a regular basis due to congestions in the electricity grid [51–53]. DTES could also make a positive contribution to the flexibility of the overall system (see also [54]). The building structure within that district is a diverse mixture of existing building types. It includes single family houses, row houses, apartment buildings, commercial properties, and industrial buildings. Most of the buildings were built in the fifties and sixties, some of them even in the early 20th century. In many cases, the energetic standard of the buildings is low, and an energy-oriented refurbishment is



(a) (b)

Figure 6: Optimisation parameters of the district heating pipelines; Transport capacity is based on a temperature spread of 30 K and a maximum specific pressure drop of 100 Pa/m. (a) Costs of the district heating pipes per trench length [22]. (b) Thermal losses of the district heating pipes based on [50].

overdue. In addition to the existing building stock, a densification by residential buildings is planned. In order to provide a renewable heat supply, a DHS is planned which needs to be operated with a forward temperature of 70 °C to 80 °C in the first years due to the existing building stock.

The basis for dimensioning the DHS network are the thermal load profiles of the buildings, which are comprised of domestic hot water (DHW) demand and heating-energy demand. The heating-energy demand series for every building are obtained by a detailed simulation of the different building types using the software EnergyPlus [55]. Profiles for DHW are generated from VDI 4655 [56], which provides normalized daily profiles for typical days. (It also provides profiles for heating-energy, in case the effort of a dedicated building simulation is not desired.) All energy load profiles are individually scaled to the actual annual energy demand of the corresponding building, which is based on data provided by the local utility company. Now, simply adding all those profiles up to a total load profile of the whole district would reveal unrealistically high peaks of power, because of the limited number of unique source profiles. To circumvent this issue, the following approach for creating a simultaneity effect is applied:

For each building, a time shift value is randomly drawn from a normal distribution with a given standard deviation σ and the profile is shifted in time by this amount of time steps. This can be interpreted as one household starting their day e.g. an hour earlier than their neighbour. Figure 7 shows the histogram of this process. For a time series with a time step of 15 min, the standard deviation of σ = 5.753 results in approximately 68 % of profiles being shifted up to ±1.5 h. The mean μ is near zero, which ensures that the quality of the original profiles is retained. In Figure 8, an aggregated reference profile (without shift) and the far smoother aggregation of shifted profiles is presented. Division of the maximum thermal powers yields the simultaneity factor, which results in this case to 67.3 %, and correspondents very well to [45].

By applying this time shift method, a simultaneity effect is already considered within the demand time series, in contrast to the common approach of scaling the nominal power of each house by a global simultaneity factor (see also [54]). This improves the usability of these profiles for simulations of the district heating system. It is important to note, however, that there is no common rule for choosing the standard deviation, which is the user input for this method. Instead, the resulting simultaneity factor has to be calculated and checked for plausibility.

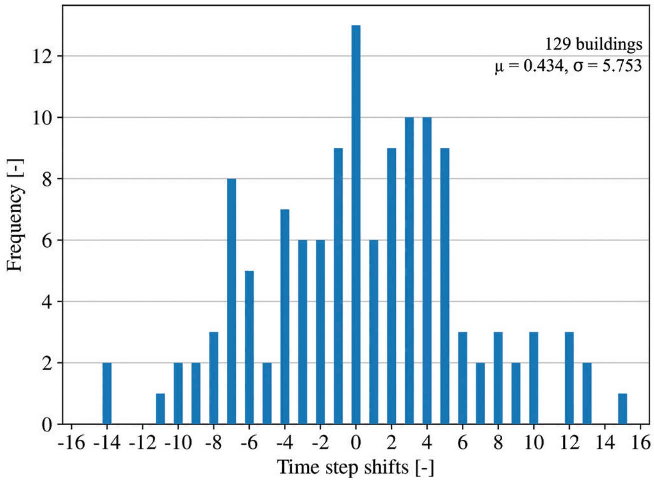


Figure 7: Histogram of time shifts drawn from a normal distribution with a given standard deviation σ = 5.753 for 129 buildings; mean value μ = 0.434.

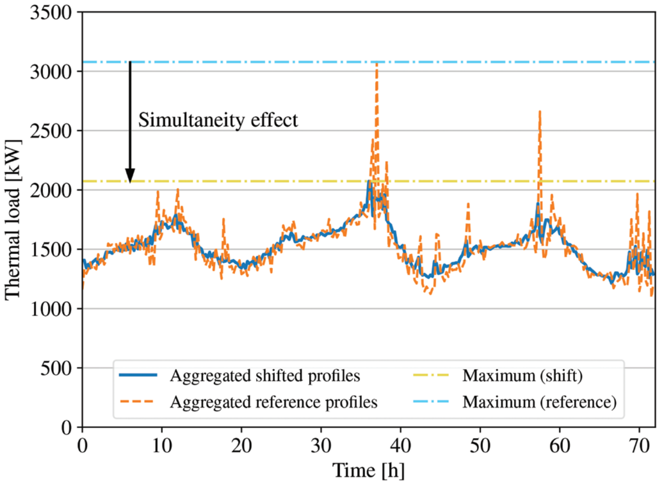


Figure 8: Three day thermal load profiles for dimensioning the DHS network. Applying the time shift method reduces the maximum heat load compared to the aggregated original reference loads profiles.

5. Results

The DHS network optimisation is performed for two scenarios: In the first scenario, regular heat exchange units without any additional thermal storage are assumed. In the second scenario, every building is equipped with a thermal storage. For each building individual storage volumes were used that are proportional to the annual heat demand. The thermal storages supply both the heating demand and the domestic hot water. In both scenarios, the DHS is designed for the case of redundancy of the two given heat supply options in order to improve the reliability and resilience of the DHS. The calculations can be performed on a current computer within a reasonable computing time[1].

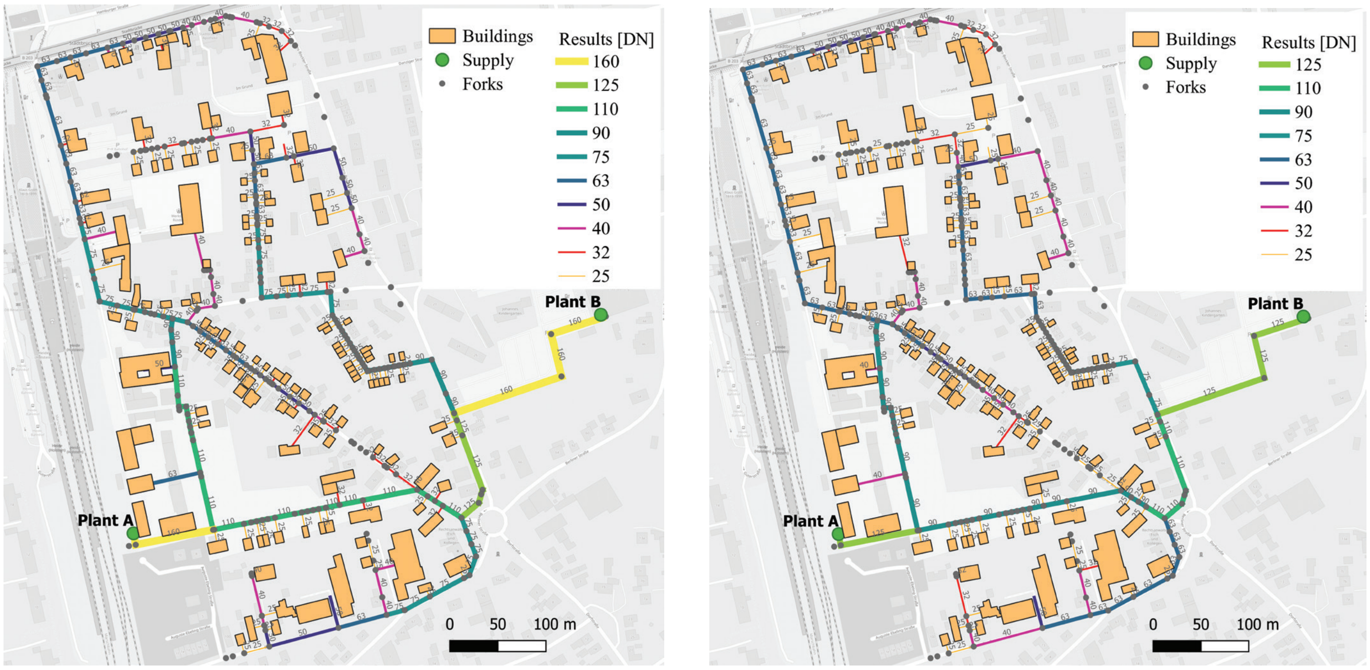
After contemplating the dimensioning results, the impact on the investment costs of the piping system is analysed. Finally, the results are compared for different storage volumes. The aim of the case study is not to provide an overall assessment of the benefits of DTES, which is a very project specific issue, but to demonstrate the optimisation tool, and to provide an indication of the impact on the piping system when using DTES.

5.1. Pipeline dimensioning

Figure 9 illustrates the results of the sizing of DHS for both scenarios. The storage volume was chosen so that it corresponds to an average storage volume of 1 m^3 per building, which is equivalent to a thermal capacity of 35 kWh at a temperature spread of 30 K. In this case study, this equates to an energy equivalent of 7.2 h of the average annual heat load, or to 1.4 h of the maximum heat load on average per building, respectively.

The DTES permit a smaller diameter at many distribution lines due to peak-shaving (see also Figure 11). The topology itself remains the same due to restricting the available distribution lines according to the results of the optimisation with two time steps. Especially the main distribution lines starting from the heat supplies can be reduced by one DN number. Some house connections are designed leaner as well, even though the effect is smaller, since the smallest DN number 25 is already sufficient in the case without storages for many buildings. Figure 10 illustrates the results of the accumulated length of each pipe dimension in detail for the distribution lines.

In the scenario without DTES, no pipe with a nominal diameter of 160 is necessary to meet the design criterion of a maximum pressure drop of 100 Pa/m. Instead, the accumulated length of the smaller pipe diameter increases. This becomes particularly clear at the nominal diameters of 25, 40, 63, 90 and 125.



(a) (b)

Figure 9: Results of the DHS network optimisation with two energy supply plants. DN: nominal diameter. (a) Sizing of the piping system without DTES. (b) Sizing of the piping system with DTES with a volume of 1 m^3 at each customer. Background map: [41].

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[1] The solving time of a single scenario of the case study with DTES ranges between 15 and 60 minutes on a Windows machine with Intel® Core™ i7-8550U CPU @ 1.80 GHz and 16 GB RAM using the gurobi solver v9.0.2.

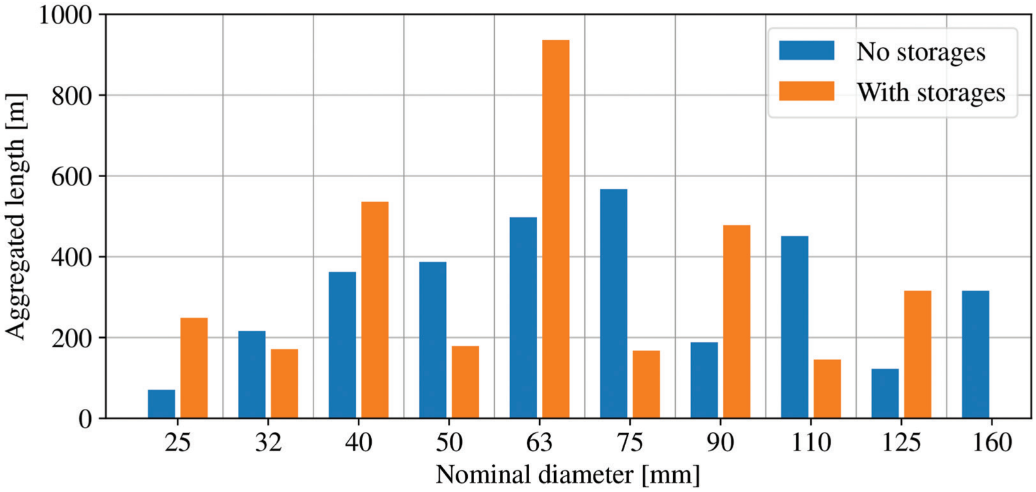

Figure 10: Accumulated length of each DN number of the distribution lines for the scenario with and without DTES.

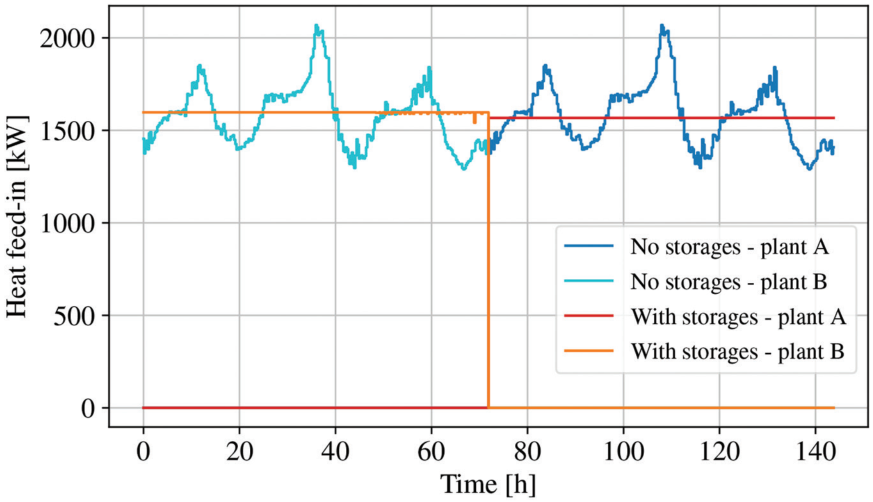

Figure 11: Heat feed-in of the two district heating plants compared for the case with and without DTES. The heat load at the supply can be smoothed almost completely with DTES.

The resulting design can be met with an appropriate commitment of the DTES. This leads to a reduction and flatting of the peaks of the heat supply of the district heating grid. An average volume of 1 m³ almost lasts for fully smoothing the feed-in profile. Figure 11 shows the heat feed-in of the two supply options for the scenario with and without DTES. The optimisation period includes twice the coldest three days of the year. In the first half of the period, district heating plant A needs to supply the total heat demand, in the second half of the period, plant B. Hereby, the sizing is optimized for the failure of one of the district heating plants at any time of the year.

5.2. Comparison of costs

Table 1 summarizes the resulting investment costs for the mechanical engineering and the thermal losses of the DHS piping system for an average storage volume of 1 m^3 per building. For each scenario, the results for the discrete nominal pipe diameter are calculated by rounding the results of the model to the next feasible DN number using a linear approximation for pipe diameter in order to ensure that a maximum pressure drop of 100 Pa/m is maintained. In addition to the linearization, this also leads to the deviations between the results of the linear approximation and the next DN number. Nevertheless, the DTES enable a leaner piping system.

Table 1: Investment costs and thermal losses of the DHS network with two energy supply plants for the case with and without DTES. The storage volume relates to the average storage volume of 1 m^3 per building. The results are given for the raw pipeline capacities of the linear approximation and the rounded-up values to the next DN number.

	Investment Costs [k€]		**Thermal Losses [kW]**	
	Linear Approximation	**Next DN number**	**Linear Approximation**	**Next DN number**
No DTES	833	901	59.2	62.9
DTES with 1 m³	783	780	55.8	56.5

Looking at the results of the next DN numbers, the cost difference is 121 k€, which is 13.4 %. The thermal losses are reduced by 10.2 %.

5.3. Variation of storage volume

In this section, a variation of the thermal storage volume is performed. As before, the storage volume is proportional to the annual heat demand of each building. Figure 12 illustrates the impact on the mechanical engineering costs and the thermal loss of DHS.

Already small storages with a usable thermal storage volume of 100 l on average per building is able to smooth the highest peak of the DHS. In this case, the investment costs decrease by 9.6 %, and the thermal losses are reduced by loss by 7.5 %. By increasing the storage volume, the benefits of additional storage capacity decrease, relatively. At an average storage volume greater than 1000 l the DHS piping network cannot be designed leaner anymore, because the whole three-day demand profile is flattened almost completely (see also Figure 11).

6. Discussion

An integrated optimisation approach for the design of district heating networks with DTES has been introduced and demonstrated in a case study. However, there are limits within the approach. The results have uncertainties and the tool does not aim to replace a detailed thermo-hydraulic simulation. Nonetheless, the introduced approach is an adequate proceeding in the planning process of hydraulic systems, and it is useful to compare the effect of different concepts on the pipeline system. It is based on recommendations for dimensioning DHS especially in conceptual stages [30,43]. For this purpose, the design criterion of a maximum pressure drop for all DHS pipelines is applied. Depending on the general conditions the maximum pressure drop of the

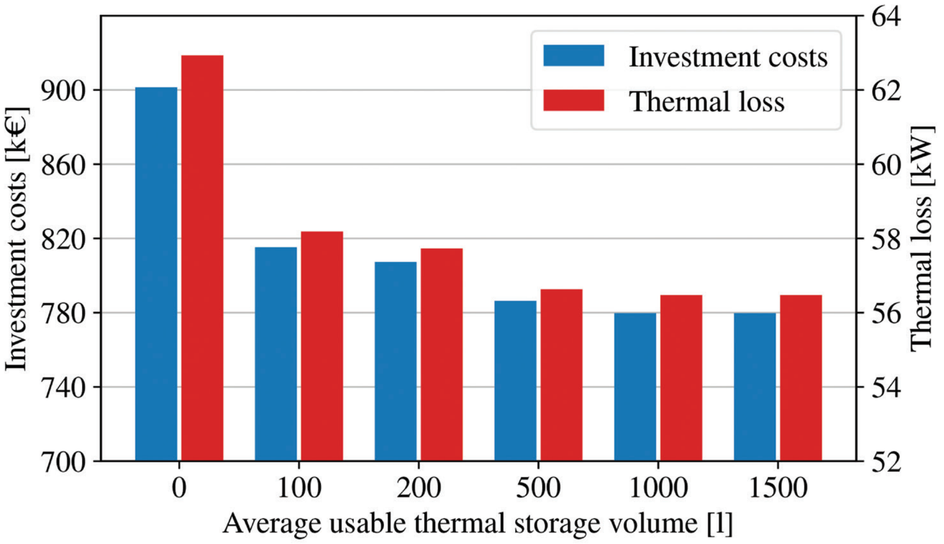

Figure 12: Impact of the thermal storage volume of DTES on the DHS network design. The x-axis shows the average storage volume per building. Left y-axis: Mechanical engineering costs; Right y-axis: Thermal loss.

pipes should be within 100 to 300 Pa/m [42,46]. The results of this optimisation method can then be used in the second step as input for a detailed thermo-hydraulic simulation.

The costs of the DHS pipelines are estimated to be in proportion to the heat transport capacity (see Figure 6). Hence, the costs of large pipes are underestimated while the costs of small pipes are overestimated. In most cases this will not affect the optimal routing. Nevertheless, to get a more exact result a linearization including the two neighbouring points could be used for each DN number. In a recursive approach, starting with the linear results each pipeline section gets the linearized cost from the results of the previous run. Also, rounding up to the next higher DN number leads to an additional inaccuracy. For the subsequent planning process, a mandatory review of the raw optimisation results of the transport capacity of the pipelines would reveal these errors. Alternatively, rounding to the next (either smaller) DN number could also be an appropriate proceeding, since the rounding-up causes a systematic additional safety factor, which might not be necessary.

The optimisation problem is solved with the perfect foresight approach. Therefore, the storages are used in an optimal way knowing the exact demand which will result in the smallest possible diameters. Even though, the weather forecast for the next three days is quite reliable nowadays, an uncertainty will always remain. Furthermore, taking into account that the demand of the district is assumed for a specific year with exemplary weather conditions. Due to both effects the flow in a real DHS could be higher under cold weather (highest demand) conditions.

So far, the cost and benefits in operating of the DTES for the overall DHS are not assessed, since the focus of this work is the design of an optimal topology and dimension of DHS networks. Though, DTES are often used to achieve a reduced peak load, a decoupling of demand and generation as well as to optimise heat generation plant. DTES are also able to increase the reliability and failsafe performance in case of short term breakdowns of the heat generation plant and to alleviate stress in critical parts of the DHS grid in case of increased loads due to e. g. grid expansion [42]. Kleinertz et al. found DTES to be more efficient regarding heat losses but less favourable due to slightly higher investment cost and increased operation complexity [57]. However, these results are always related to the specific use case, and the evaluation of the overall benefits of DTE needs to be executed for each project individually. The introduced modelling approach provides a starting point for studies regarding the overall benefits of DTES.

7. Conclusions and Outlook

An optimisation approach for DHS networks has been introduced, that allows the consideration of DTES within the design and planning process, and that includes a novel method to consider simultaneity. The optimisation framework fills the gap of a flexible open source tool for DHS network optimisations and is published within the open source Python library *DHNx* [12,13]. Hereby, the package sets the basis for further complex DHS optimisation models with the option of adding further additional energy converter and storage units at the heat generation site and at the buildings.

The optimisation approach is demonstrated by a case study of an existing urban district in northern Germany with 129 buildings connected to the DHS network. A DHS network optimisation is performed for the cases of equipping the buildings with DTES and without DTES. The results show that DTES with a usable storage volume of 1 m^3 enable a leaner piping by savings of 13.4 % of mechanical engineering costs, and a reduction of thermal losses by 10.2 %. It also could be demonstrated that already a small storage volume can have a significant impact on the piping system.

The purpose of the case study is to showcase the optimisation tool, which is capable of performing DHS network optimisation for complex future energy system configuration. The tool can be used by others within project individual settings, and it creates a remedy for modelling the effect on the investment costs of the piping system in the presence of DTES. With regard to the case study, the costs benefits in operation, like savings of thermal losses and pumping costs by temporarily shutting down in summer, and effects on the plant equipment, like a reduction of the peak load capacity, are subject of further analysis. In the end, these aspects are highly dependent on project individual parameters, like heat production costs, and need to be assessed individually in each project in any case. The development of a method for the determination of the optimal storage size dependent on the heat load of the buildings is also an interesting task for further research. Therefore, the *DHNx* library provides an adequate place for further joint development [13].

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