Impact of Pipe Cost Functions on the Optimal Design of District Heating Systems with Thermal Storage

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Abstract:

Driven by European climate policies and decarbonization targets, the building sector is required to significantly reduce its greenhouse gas emissions. District heating systems supplied by centralized heat pumps represent a promising solution to decarbonize heat supply for building stocks. The design of energy systems involving district heating networks typically relies on advanced optimization tools, often based on mixed-integer linear programming. However, the design of such systems involves important trade-offs, such as the modeling of network infrastructure costs and their influence on optimal system configurations. This paper investigates the impact of representing non-linear district heating pipe cost functions through piecewise linear formulations on the optimal design of multi-energy systems serving a small building stock. The case study consists of a heat pump-based district heating network with thermal energy storage considered under three configurations: centralized storage connected to the heat production plant, decentralized storage located at the building level, and hybrid systems combining both approaches. Rather than directly comparing the performance of these configurations, the study evaluates how the consideration of non-linear versus linearized pipe cost functions affects system design outcomes and computational time within each configuration. A sensitivity analysis is performed to assess the influence of pipe cost modeling on key design variables, including network sizing, storage deployment, and overall system cost. An energy system optimization framework is used to ensure consistent assumptions across scenarios, with a centralized geothermal heat pump and an air-source heat pump as the main heat production technologies, and no decentralized heat generation. The proposed approach provides insights into the importance of accurately representing infrastructure cost functions in optimization models and highlights their role in shaping design decisions in heat pump–based district heating systems under different storage configurations.

Keywords:

Multi-energy system optimization, mixed-integer linear programming, District heating network, piecewise linear cost formulation

1. Introduction

District heating networks (DHN) supplied approximately 10% of global final heating demand in 2025, remaining roughly stable year-on-year [1]. While they offer strong potential for the efficient and cost-effective integration of low-emission energy sources, around 90% of heat production still relies on fossil fuels. To align with net-zero goals, efforts must focus on improving energy efficiency in district heating networks and transitioning to renewable technologies, including heat pumps. Key priorities also include investing in thermal energy storage, enabling sector coupling, and developing high-efficiency infrastructure in areas with dense heat demand. To design such systems and support preliminary decision-making, multi-energy optimization tools are required, as they enable the integration of various technologies across multiple scales. District heating networks present significant implementation potential; however, economic assessment is necessary to determine how to supply the energy system, which technologies to select, how they should operate, and where they should be located. This work investigates a heat pump-based district heating network with a focus on thermal storage integration, considering both centralized and distributed storage within the energy system. Several non-linear relationships, such as cost curves and performance curves, are linearized in these kind of studies. In this work, an analysis is conducted to assess the impact of the non-linearity of distribution network pipe costs.

This study extends the REHO tool framework by incorporating detailed district heating network modeling and a more refined integration of cost functions, using either piecewise linear formulations (PWL) or appropriate linear regression techniques [2] [7]. The question of whether to implement centralized, distributed, or hybrid thermal storage configurations in heat pump-based district heating networks remains relatively underexplored as each configuration presents distinct technical and economic advantages. Jebamalai et al. [3] investigated this issue by comparing centralized thermal storage with distributed storage located at substations across a district, concluding that building-scale thermal storage represents the most cost-effective solution. More recently, Rojer et al. proposed an integrated techno-economic optimization approach with three scenarios, including the integration of seasonal and decentralized storage [5]. Their results highlighted the economic benefits of combining centralized seasonal storage with decentralized storage systems. A clear comparison between decentralized, centralized and hybrid storage configuration is needed. Concerning storage selection, Guelpa and Verda [4] reviewed thermal energy storage options for district heating systems and identified sensible heat storage using water as the most widely adopted solution. This is primarily due to its low cost, technological simplicity, favorable thermal properties, scalability, natural stratification, and the ability to use water as both the heat transfer fluid and storage medium. Regarding the integration of non-linear functions within mixed-integer linear programming (MILP) frameworks, some studies have addressed this, like Rojer [5] and Résimont [6]. However, a clear research gap remains. There is a lack of comprehensive studies comparing district heating network configurations with fully centralized storage versus fully decentralized storage at the building level. Also, the impact of incorporating non-linear cost curves versus linear approximations on the optimal system design has not been addressed in the literature.

The goal of this article is to investigate the impact of thermal storage scale and non-linear cost functions on the design of energy systems. Three storage configurations will be analyzed within the heat-pump-based district heating network system:

- Centralized storage coupled to the centralized heat pumps powering the district heating network,
- Individual storage possibility of placement in every building while being powered by centralized heat pumps through district heating network,
- Hybrid storage configuration with the possibility of having centralized storage and individual storage in buildings.

Within each configuration, linear and piecewise linear formulation pipe costs are compared to evaluate the impact of non-linearity consideration on the system design. In particular, total system costs, district heating network pipe diameter, storage size and placement, and computational time are compared within the study. As pipe cost functions represent a key parameter in the optimal design of such systems, this study evaluates whether a piecewise linear formulation is necessary or whether a linear regression provides sufficient accuracy, considering both solution quality and computational performance.

The article is structured as follows. The introduction presents the research objectives and provides a review of the relevant literature. The second section describes the case study used to support the analysis. The third section details the methodology and input data. Finally, the last section presents the results, including analysis of the three storage configuration with linear and piecewise linear pipe costs comparison.

2. Case study

The case study considered in this work consists of a building stock in Belgium comprising 17 non-residential buildings, primarily used for offices, storage, sheds, and industrial activities. These buildings exhibit heterogeneous space heating demands, ranging from approximately 80 kW peak load to 1,850 kW for the largest building. Such a case study requires the use of appropriate cost functions, as the size of the technologies varies significantly from one building to another, and consequently, so do the associated costs. The heating demand of each building in the case study is illustrated in Figure 1. Some buildings, such as B9 and B6, exhibit relatively high annual heating demands of around 120 MWh, while others, such as B15 and B16, have much lower demands, on the order of 5 MWh.

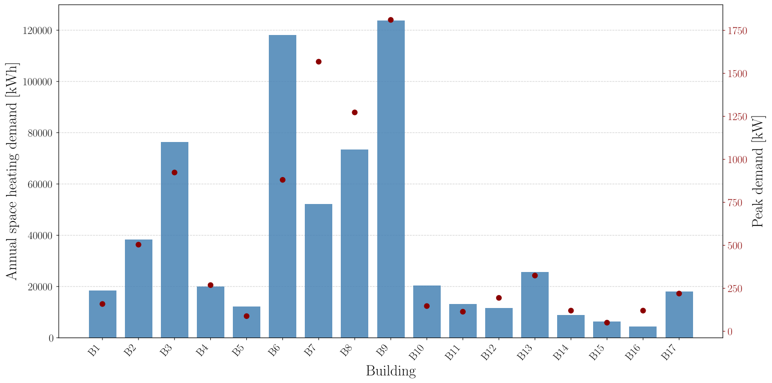

Figure 1: Annual space heating demand and associated peak power.

Figure 2 illustrates the energy system associated with the case study, in which buildings can meet their energy demands through individual systems, electricity exchange by the substation, heat supplied by a district heating network, or a combination of these options. The methodology is based on a whole energy system modeling approach, which captures all energy flows within the system along with the associated constraints and parameters. Based on the storage configuration studied, the centralized and/or individual storage are selected or not for the whole energy system optimization.

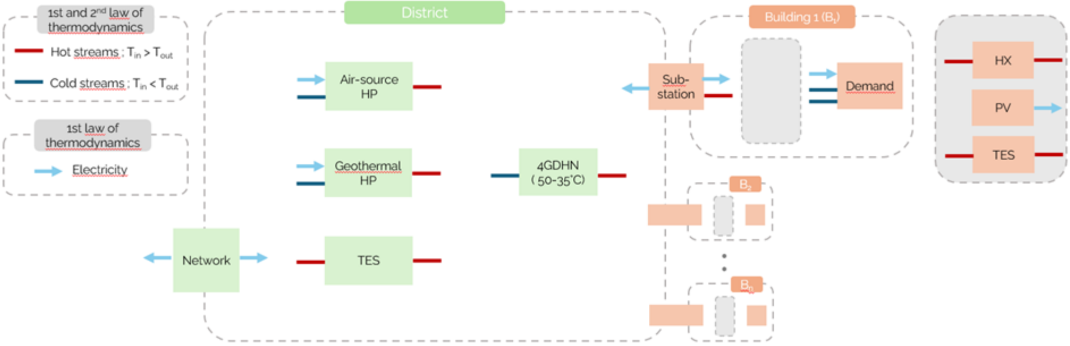

Figure 2: Multi-energy system: individual technologies in orange and centralized technologies in green with connection to the buildings by the substation.

The technologies available to power the building stock are at district-scale: a geothermal heat pump, an air-source and a large-scale water tank energy storage, and at building-scale in every building: photovoltaic panels, an individual water tank energy storage, and a heat exchanger to transfer heat from the distrct heating network to the building through the substation. The power of the geothermal heat pump is limited as borehole geothermal energy requires lots of space. The area available for boreholes placement is $13440m^2$.

3. Methodology

The optimization problem aims to minimize the total annual cost, consisting of capital (CAPEX) and operational expenditures (OPEX) associated with each building's technologies, centralized technologies, district heating network pipes and primary energy use:

$$min\ Obj = CAPEX + OPEX \tag{1}$$

The cost of thermal storage and district heating network pipes plays a key role in this study. In particular, district heating pipes account for a significant share of total investment costs, which justifies investigating the impact of their non-linear cost function. Moreover, hybrid configurations, where centralized and decentralized technologies coexist within a district heating network, make the system design especially sensitive to pipe costs. The sensitivity analysis conducted in this work highlights the need to represent pipe costs using a piecewise linear formulation, as illustrated in Figure 3.

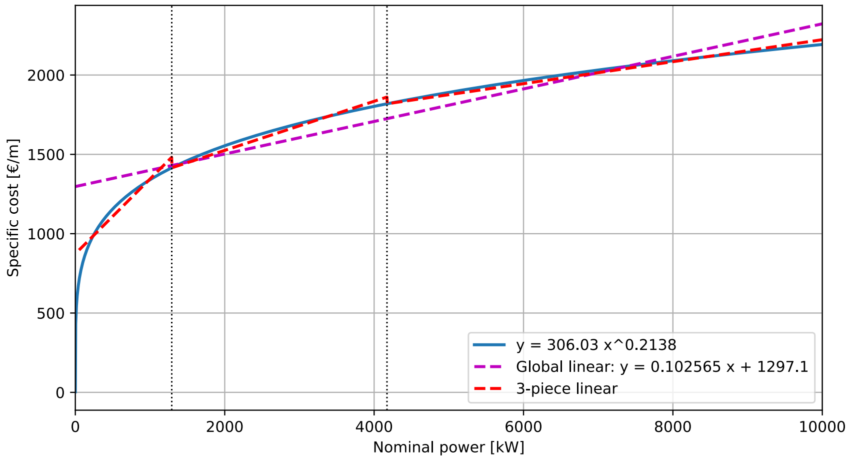

Figure 3: Pipes cost: piecewise linear formulation.

The methodology for piecewise linearization is introduced in previous work by the same author [7], although the cost data are updated here using more accurate values [8]. The cost curve is approximated using three linear segments, providing a balance between modeling accuracy and computational efficiency.

Considering a multi-scale energy system and the possibility to choose between having either a centralized storage coupled with a heat pump or either individual storages in every building, it is important to scale correctly the cost of storage. Two different sources are used to do a polynomial fit, as illustrated in Figure 4, and approximate the storage as accurately as possible [8] [9]. A storage cost function is associated to each building based on the necessary storage volume in order to cover 20% of the mean daily heating demand. For the centralized storage tank, it is estimated that the necessary storage volume is designed to cover 10% of the annual heating demand.

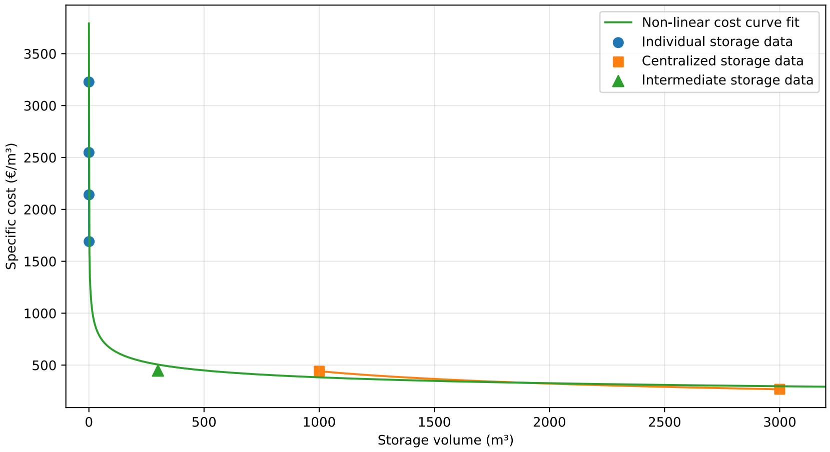

Figure 4: Storage cost curve.

For the thermal power production technologies, it is attempted to develop more precise cost functions for each technology. It is either in the form of a function $c(x) = A * x^b$ or a fixed investment cost. In the case of the power function assigned to a building-level technology, it is preprocessed and sized to the space heating peak power of each building of the case study in order to have an adequate approximation. For district-scale technologies, the power function is sized to the peak power of the sum of every building's hourly consumption. As every building's technology has a different cost due to their different peak demand and the non-linear cost function, only the sources are cited for all the technology costs [8] [10] [11].

The thermal losses of the storage systems differ between individual water tanks and large-scale storage units. The large-scale water tank has a fixed diameter of 10.8 m and a heat transfer coefficient of 0.3 W/m²K, while individual water tanks have a diameter of 0.98 m and a heat transfer coefficient of 1.3 W/m²K [12]. The efficiency of these storage systems is therefore determined based on the heat transfer coefficient, the tank diameter, the temperature difference within the storage, and the ambient temperature. The storage model is based on [12], in which mass exchange occurs between two temperature levels. For the sake of simplicity, the storage tank is discretized into only two temperature levels, each operating at a fixed temperature. These temperature levels correspond to virtual tanks, each with its own mass balance.

The district heating network is modeled by incorporating both thermal losses and the distances between connected households, while relying on a predefined network topology. Decisions regarding whether to build the network and how to size the pipes are optimized by balancing centralized and decentralized energy solutions. Energy balance equations are applied across both the network's arcs and nodes, allowing for the representation of any topology. Within this system, nodes are classified into three types: those linked to production and/or storage units, those connected to building heat demand, and those that solely facilitate energy transfer without associated production or demand. The details of the modelling has been previously detailed by the same author [7].

To ensure computational tractability, the analysis is based on a set of 10 representative days selected from the full year using a k-medoids clustering approach, supplemented by 4 critical days corresponding to the two hottest and two coldest days of the year. Each representative day corresponds to a cluster of similar days characterized by comparable hourly profiles of building energy demand, solar irradiance, outdoor air temperature, and electricity prices. In total, 14 representative periods are considered within the optimization framework.

The optimization tool is formulated based on a set of constraints specific to each technology, as well as on the overall energy balance of the system. Both the district and building scales are subject to their own constraints, while being interconnected through energy flows within the substation. The proper functioning of the system is ensured by enforcing energy balance equations at multiple levels: for each building connected to the network and at the district scale, where centralized technologies interact with the grid. Two main energy carriers, electricity and heat, are distributed from the district level to individual buildings. These energy flows are either generated by local technologies or, in the case of electricity, imported from external sources. At the point of end use, heat is ultimately converted into space heating to meet building demand.

4. Results

Energy systems with centralized and distributed storage differ in several key aspects. Centralized storage offers simpler operation, lower unit costs, and higher efficiency in terms of ambient heat losses, but relies on a single location and may lead to higher distribution losses. In contrast, distributed storage enhances flexibility and reduces peak loads in the district heating network, thereby lowering pipe diameters and associated costs. This work does not aim to directly compare these storage configurations. Instead, it focuses on analyzing and comparing system design characteristics under linear and non-linear pipe cost formulations for each configuration. Detailed results on installed capacities and technology sizing are not presented, as they fall outside the scope of this study.

4.1. Centralized storage: linear vs non linear pipes cost consideration

A heat-pump-based district heating network with a centralized storage is studied in this section. A whole design of the system is performed with linear pipes cost and piecewise linear pipes cost. As all the thermal production is centralized and heating demand is fixed, the pipes size is not changed for the two scenarios.
Concerning the economic performance of the storage configuration resumed in Table 1, it presents a real total costs of around 3109 kEUR/year and there are no difference between the two scenarios of pipes cost formulation. The real TOTEX is calculated with the pipes nominal design values based on the real non-linear cost function of the pipes.

Table 1: Economic performance comparison for centralized storage configuration with linearized and non-linearized cost curves.

	cen. storage	cen. storage pwl
CAPEX (tech) [kEUR/year]	710	710
CAPEX (dhn) [kEUR/year]	388	388
OPEX [kEUR/year]	2008	2008
TOTEX [kEUR/year]	3105	3105
Real TOTEX [kEUR/year]	3109	3109

Around 5 minutes of computational time are needed for both scenarios, which allows to have a quick decision for preliminary design of multi-energy energy systems. Even though the difference in time between the two scenarios is negligible, it is not necessary to use piecewise linear costs as investment costs and pipes diameter are unchanged.

4.2. Individual storage: linear vs non linear pipes cost consideration

In this section, the heat-pump-based district heating network has decentralized storage distrbuted accross buildings. Every building has the possibility in the optimizer to install a storage.

In the individual storage configuration, most pipe diameters are affected by the cost formulation, with differences reaching up to 40% between linearized and piecewise linear pipe cost models, as shown in Figure 5. As illustrated in Figure 6, the size and location of decentralized storage units also change significantly, with five units being modified. The introduction of piecewise linear pipe costs leads to a different optimal system design, where some building-level storage units are removed while others are newly introduced.

These results highlight that, in multi-scale energy systems, such as those combining centralized production with decentralized storage, the optimal design is highly sensitive to cost modeling assumptions, and therefore requires a more detailed representation. In contrast, for single-scale systems, such as configurations with only centralized storage, linearized cost functions appear sufficient to provide a reliable approximation of both system design and operation.

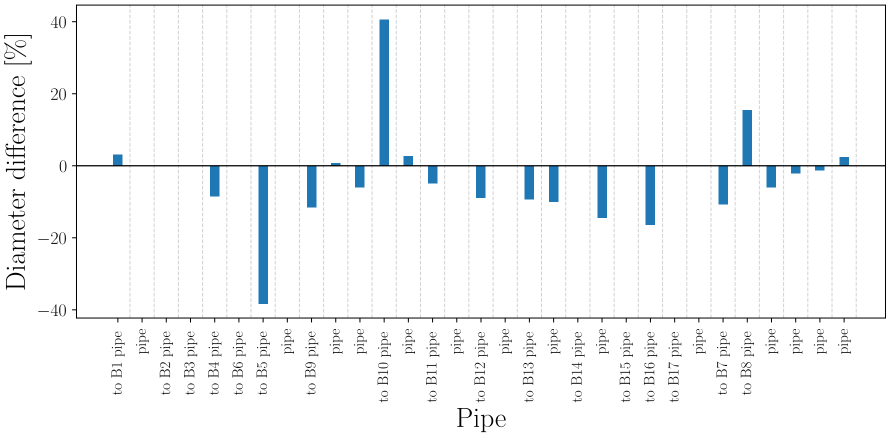

Figure 5: Pipe diameter difference between linearized and non-linearized pipes costs scenario for indivdual storage configuration.

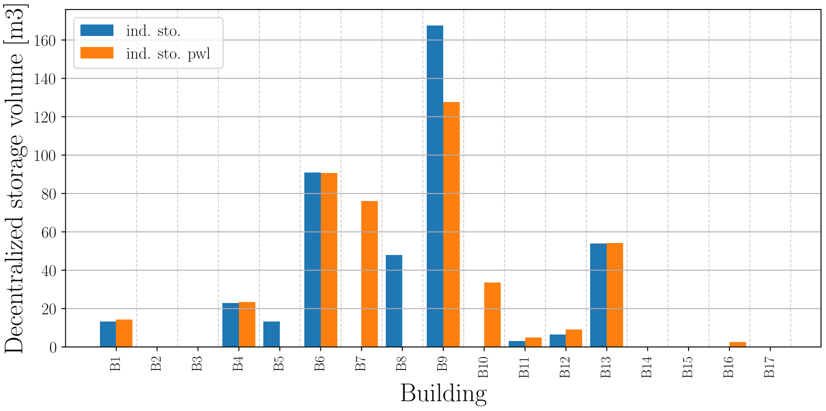

Figure 6: Storage volume in every buildings for indivudal storage configuration: linearized vs piecewise linear pipes cost.

The economic performance of this configuration presents a real total cost of around 3122 kEUR/year and shows almost no variation in investment costs between the two scenarios, despite significant changes in the size and placement of decentralized storage units, as detailed in Table 2. The investment cost of the district heating network remains nearly unchanged, as do the technology investment costs, resulting in an almost identical total expenditure. Similarly, the real TOTEX, calculated using the original non-linear pipe cost function, exhibits negligible differences.

These results suggest that the primary impact don't lie in overall system cost, but in the sizing and spatial distribution of individual storage units, highlighting the sensitivity of the design results and the need for more detailed post-processing analysis for practitioners aiming to design multi-scale energy systems, particularly in the context of 4th- and 5th-generation district heating networks where multi-scale systems are more and more developed.

Table 2: Economic performance comparison for individual storage configuration with linearized and non-linearized cost curves.

	dec. storage	dec. storage pwl
CAPEX (tech.) [kEUR/year]	738	740
CAPEX (dhn) [kEUR/year]	366	367
OPEX [kEUR/year]	2015	2016
TOTEX [kEUR/year]	3119	3123
Real TOTEX [kEUR/year]	3123	3122

The computational time required for the linear cost scenario is approximately 5 minutes, compared to around 2 hours for the piecewise linear pipe cost formulation. Multi-scale energy system scenarios thus become significantly more computationally demanding when introducing integer variables associated with piecewise linearization. However, for the design of multi-scale energy systems, particularly when determining the placement, installed power, and capacities of technologies, a more accurate representation of non-linear pipe costs may be necessary. Other non-linearities could also play an important role in improving design accuracy, but their investigation falls beyond the scope of this study.

4.3. Multi-scale storage: linear vs non-linear pipes cost consideration

In this section, the heat pump–based district heating network is allowed to operate with a hybrid storage configuration, combining centralized storage with distributed storage at the building scale. In this configuration, many pipe diameters are affected by the piecewise linear cost formulation, with differences reaching up to 20% between the two pipe cost scenarios, as illustrated in Figure 7.

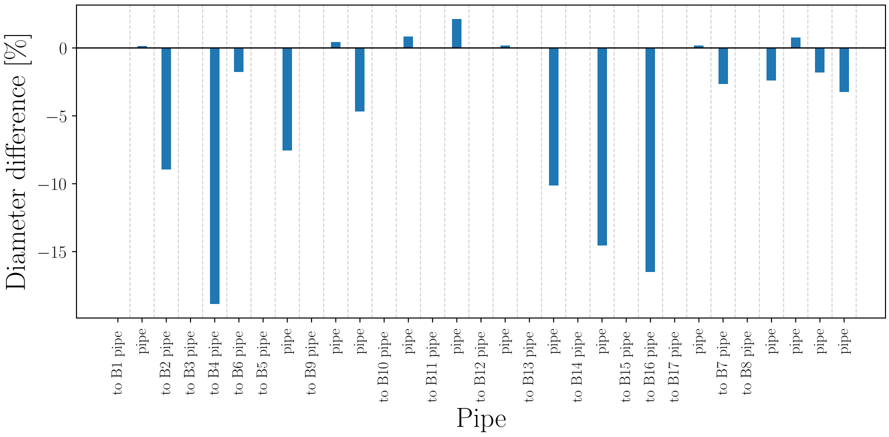

Figure 7: Pipe diameter difference between linearized and non-linearized pipes costs scenario for hybrid storage configuration.

The size and location of individual storage units also change significantly, with nearly all units being modified except for building B7, as shown in Figure 8.

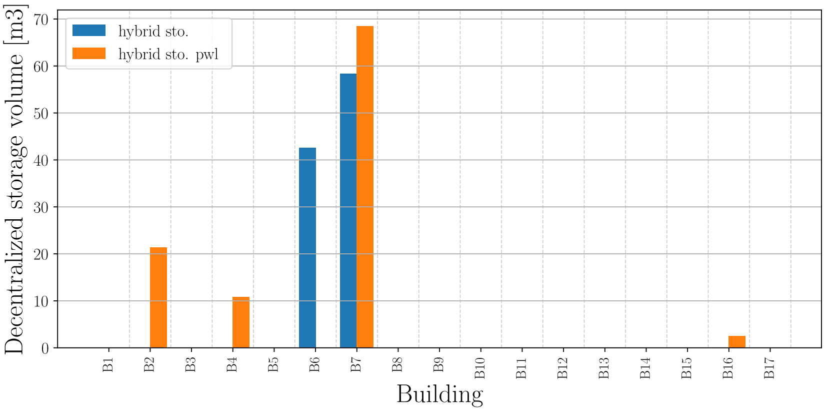

Figure 8: Storage volume in every buildings for hybrid storage configuration: linearized vs piecewise linear pipes cost.

These results further confirm that multi-scale energy systems are highly sensitive to pipe cost modeling and require accurate cost representations to properly capture storage design decisions. However, the availability of both centralized and decentralized storage options provides greater flexibility in distributing energy flows, resulting in smaller design differences compared to the fully decentralized configuration. In particular, centralized storage partially absorbs these variations, leading to a more robust overall system design.

The economic performance of this configuration presents a real total cost of around 3089 kEUR/year and shows only a 1% difference in district heating network investment costs between the two scenarios, which remains negligible. Similarly, variations in other cost components are minimal. As observed in the previous section, the piecewise linear formulation has little impact on the total system cost. However, the size and placement of storage units are still significantly influenced by the pipes cost formulation, highlighting the need for accurate cost modeling to obtain a reliable system design.

Table 3: Economic performance comparison for hybrid storage configuration with linearized and non-linearized cost curves.

	hybrid	hybrid pwl
CAPEX (tech.) [kEUR/year]	712	713
CAPEX (dhn) [kEUR/year]	368	372
OPEX [kEUR/year]	2004	2005
TOTEX [kEUR/year]	3084	3090
Real TOTEX [kEUR/year]	3089	3089

The computational time required for the linear cost scenario is approximately 15 minutes, compared to around 5 hours for the piecewise linear pipe cost formulation. The integration of multi-scale storage significantly increases computational complexity. Depending on the level of detail required for system design and decision-making, it may be necessary to incorporate non-linear cost representations to obtain more realistic and reliable results.

5. Conclusion

This work investigated the impact of non-linear district heating pipe cost representations on the optimal design of multi-energy systems, considering centralized, decentralized, and hybrid thermal storage configurations.

For fully centralized systems, where both production and storage are located at the district level, linearized pipe cost functions are sufficient. These configurations, typical of 3rd- and 4th-generation district heating networks, show no differences in pipe sizing or total system costs between linear and piecewise linear formulations. This indicates that non-linear cost modeling is not required for such centralized designs.

In contrast, when storage is distributed at the building scale, as in more advanced 4th- and 5th-generation district heating networks, the representation of pipe cost non-linearities becomes important. While total system costs remain largely unchanged, the optimal design is significantly affected, with notable differences in pipe diameters, reaching 40%, as well as in the size and placement of storage units. Hybrid configurations lead to similar conclusions: although centralized storage introduces additional flexibility and absorbs some variations, system design remains sensitive to pipe cost modeling. Decentralized heat pumps in a thermal network, as currently studied in 5th-generation district heating networks, would also probably lead to sensitivity to non-linear pipes costs.

Finally, the inclusion of piecewise linear cost formulations significantly increases computational time, from minutes to several hours, especially in hybrid storage systems due to the presence of centralized and individual storage. Therefore, for individual and hybrid storage configurations, while linear cost functions are adequate for estimating total costs, more detailed non-linear representations are recommended when accurate design decisions, such as technology placement and sizing, are required.

Future works could include the comparison of the three different configurations, centralized, decentralized and hybrid storage configurations, in terms of feasibility and economic profitability.

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