Optimizing a Multi-vector Energy System with Geothermal-Powered District Heating

Natalia Kozlowska, Arthur Lefebvre, Julien Jacquemin, and Pierre Dewallef

Abstract This paper investigates optimal configurations for multi-vector energy systems, with a focus on low-temperature district heating networks (DHNs) powered by shallow geothermal energy. The system takes into account natural ground regeneration during heat extraction, which prevents borehole freezing and maintains efficiency. The study examines the balance between centralized and decentralized heat production while ensuring fair thermal energy distribution among buildings. The DHN model accounts for heat losses and inter-building distances, with a piecewise linear method used to represent pipe costs. The optimization framework evaluates both building-scale and district-scale solutions, considering various technologies, ground constraints, and temperature levels. The Renewable Energy Hub Optimizer (REHO) is employed as a basis to determine the optimal design and operation of these energy systems [7]. The case study focuses on a building stock in Belgium, incorporating building-level demands for space heating and electricity.

Keywords Optimization · Energy system · District heating network

1 Introduction

DHNs offer a cost-effective way to deliver low-carbon heat at large scale [1]. However, around 90% of district heat still comes from fossil fuels. Achieving Net Zero Emissions by 2050 requires accelerating the shift to renewable sources, such as bioenergy, solar thermal, geothermal, and large-scale heat pumps, and improving network efficiency [1]. The growing development of energy communities enables households to jointly invest in shared infrastructure for heat and electricity generation, including low-temperature DHNs that require centralized coordination. Combining centralized

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N. Kozlowska (✉) · J. Jacquemin · P. Dewallef
Universiteé de Liége, Département d'aérospatiale et mécanique, Liége, Belgium
e-mail: natalia.kozlowska@uliege.be

A. Lefebvre · J. Jacquemin
Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, Louvain-la-Neuve, Belgium

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and decentralized solutions can enhance system flexibility, resilience and efficiency. Designing such hybrid systems requires tools that integrate economic and technical considerations. This study uses a Mixed-Integer Linear Programming (MILP) model solved with Gurobi, where integer variables represent key decisions such as DHN deployment, technology selection, and nonlinear pipe cost modeling.

Various studies have addressed the optimization of district heating networks using MILP approaches, with differing scopes and limitations. For example, centralized system design and operation was focused on in [2] but excluded geothermal heat pumps and decentralized units. Another study detailed in [3] explored distributed energy systems using MILP but did not emphasize technology modeling. Several tools have been developed to support DHN design. Integrated optimization framework was proposed in [4] that includes decentralized units, though limited to heat pumps and storage, but excludes electricity and gas vectors. Similarly, MODESTO was introduced for heat configuration analysis, but did not account for the electricity vector [5]. The nPro tool extended this by incorporating multiple technologies and the electricity vector [6].

REHO offers multi-scale modeling from building to district level, supports various energy vectors, and enables centralized/decentralized configurations [7]. It introduces temperature-based selection via the heat cascade concept, but lacks spatially detailed DHN modeling, such as connection distances, heat losses, nonlinear cost functions, and pump consumption.

This study extends the REHO framework to address key gaps in district heating network design, integrate decentralized and centralized systems, incorporate geothermal heat pumps, and account for ground regeneration. An optimization tool is proposed for small-scale energy systems (up to a few dozen buildings), coupling electricity and heat vectors to capture interdependencies and constraints across both domains. The model also includes battery and thermal storage to support cost-effective and low-fossil energy systems. It enables rapid assessment of system costs, design, and operation with minimal input.

2 Problem Statement

The developed optimization tool is applied to a case study of a building stock in Belgium comprising 17 buildings with space heating and electricity demands. Objectives of the study are to determine an economically optimal mix for space heating and electricity production and distribution and decarbonize the energy system. Domestic hot water and cooling are excluded due to their minor contributions and will be addressed in future work. Heating supply options include centralized solutions, such as a 4th generation district heating network powered by a shallow, closed-loop geothermal heat pump with a field of boreholes, a gas boiler, and thermal storage, and decentralized systems located within buildings, including air-source heat pumps, gas boilers, and electric heaters. The optimization balances these approaches to minimize annual costs.

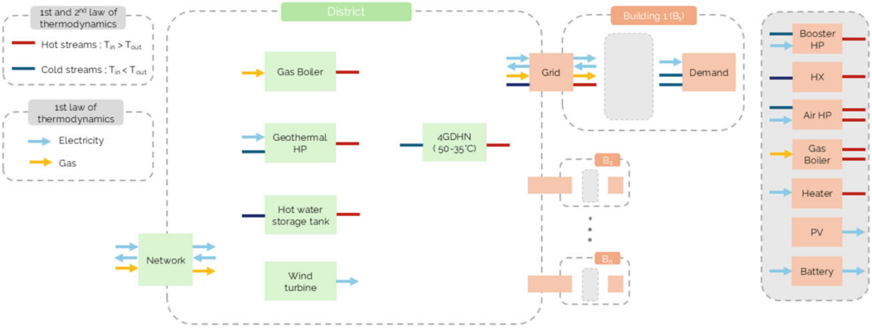

Fig. 1 Multi-vector energy system: individual technologies in orange and centralized technologies in green with connection to the buildings by the grid

Heat delivery from the DHN to buildings is provided via either heat exchangers or booster heat pumps, depending on temperature requirements. The geothermal system accounts for seasonal ground temperature variations, considering both heat extraction and natural regeneration. Figure 1 illustrates an energy system where buildings may meet their energy needs through individual systems, grid-connected electricity exchange, DHN heat, or a hybrid of these options. Electricity demand can eventually be satisfied by PV panels, a wind turbine, a connection to a battery and electricity import.

2.1 Problem Formulation

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, and primary energy use:

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

To ensure computational tractability, the analysis is based on a set of 10 representative days selected from the full year using a k-medoid clustering approach [9]. Each representative day corresponds to a cluster of similar days characterized by comparable hourly profiles of building energy demand, solar irradiance, outdoor air temperature, wind speed, and electricity and gas prices.

The model incorporates a range of technologies, for both heat and electricity generation, as well as energy storage. These technologies are subject to their own technical constraints, but also capacity limits and energy balance requirements, including thermal and electrical coupling. A comprehensive overview of these constraints is provided in [8]. Investment and maintenance cost data for the decentralized and centralized technologies were found in the EU Joint Research Centre[1] and the Danish Energy Agency[2] reports. Fixed and variable investment costs are used to discourage very small installed capacities and better approximate the cost functions.

To accurately capture long-term energy shifting capabilities, interseasonal storage is incorporated into the model. This allows surplus energy generated during periods of high renewable availability to be stored and later used during periods of high demand or low generation. The model achieves this by reconstructing the full-year timeline from the set of typical days, enabling sequential hourly tracking of the state of charge across the entire year. This approach allows the model to capture the temporal flexibility offered by large-scale thermal storage systems, which is essential for evaluating seasonal energy balancing strategies.

In shallow, closed-loop geothermal heat pump systems with borehole (BH) fields, ground temperatures around each borehole must remain above 0 °C to avoid freezing and ensure efficiency. Each 100 m-deep BH has a radius of 0.068 m, with U-pipe outer and inner radii of 0.016 and 0.013 m, respectively. Typical thermal conductivity values were used [10]. An analytical solution was applied to determine the temperature distribution, yielding a maximum extractable power of 4.23 kW per borehole under the 0 °C constraint [10]. BH interactions and seasonal ground temperature variations were neglected as a first approximation.

2.2 District Heating Network

The district heating network is modeled to account for both heat losses and distance-based household connections. The network topology is predefined, while the decisions to construct the DHN and determine the pipe capacities are optimized based on the trade-off between centralized and decentralized solutions. Energy balance equations are applied at both the arcs and nodes of the network, enabling the modeling of any type of network topology. Each node in the DHN is categorized as one of the following:

- connected to production and/or storage units,
- connected to building heat demand,
- enabling energy flow without associated production or demand.

The energy balance on each node n, and for every time and period, is:

$$\forall n, \forall p, \forall t \sum_{i,j \in A_n} \left(P^{\mathrm{in}}_{\mathrm{i,j,p,t}} - P^{\mathrm{out}}_{\mathrm{i,j,p,t}} \right) = \dot{Q}^{\mathrm{heat}}_{\mathrm{n,p,t}} + \dot{Q}^{\mathrm{ch}}_{\mathrm{n,p,t}} - \dot{Q}^{\mathrm{disch}}_{\mathrm{n,p,t}} - \dot{Q}^{\mathrm{dem}}_{\mathrm{n,p,t}} \qquad (2)$$

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[1] EU Research Centre Report: https://data.europa.eu/doi/10.2760/110433.

[2] Danish Energy Agency, Technology Catalogues: https://ens.dk/en.

where $P^{\mathrm{in}}_{\mathrm{i,j,p,t}}$ and $P^{\mathrm{out}}_{\mathrm{i,j,p,t}}$ represent thermal power entering and leaving pipe (i, j) at node n, $\dot{Q}^{\mathrm{heat}}_{\mathrm{n,p,t}}$ is the heat produced, $\dot{Q}^{\mathrm{ch}}_{\mathrm{n,p,t}}$ and $\dot{Q}^{\mathrm{disch}}_{\mathrm{n,p,t}}$ are storage charging and discharging powers, and $\dot{Q}^{\mathrm{dem}}_{\mathrm{n,p,t}}$ is the heating demand.

The arcs connecting each node, which represent the pipes, are subject to thermal losses along their length. These heat losses are a significant drawback in district heating networks and must be accounted for to ensure accurate sizing. Manufacturer data express heat losses [kW/m] as a function of pipe diameter, following a quadratic trend. To avoid introducing nonlinearities into the model, heat losses are instead approximated as a function of nominal pipe capacity (Fig. 2a) by assuming a constant flow velocity of 1 m/s. This allows the use of the relation $P^{\mathrm{nom}} = \rho v c_p A \Delta T$ where P is the nominal thermal capacity. Two linear regressions were then performed on this transformed data for a DHN with a supply temperature of 50 °C and a return temperature of 35 °C. The reference heat loss values [kW/m] are given for a temperature difference of 65 °C, corresponding to an 85 °C/55 °C network and a 5 °C ambient temperature. In our model, the actual ΔT is dynamically calculated as $\frac{T_{\mathrm{supply}}+T_{\mathrm{return}}}{2} - T_{\mathrm{amb,p,t}}$, where ambient temperature varies hourly based on meteorological data. Given that the pipe capacities remain below 2 MW in the studied cases, only the first regression is applied to reduce computational complexity.

The corresponding energy balance on arcs is expressed by the following equation:

$$\forall i, j \in A, \forall p, \forall t \quad P^{\mathrm{out}}_{\mathrm{i,j,p,t}} = P^{\mathrm{in}}_{\mathrm{i,j,p,t}} - Q^{\mathrm{loss}}_{\mathrm{i,j,p,t}} \times L_{\mathrm{i,j}} \tag{3}$$

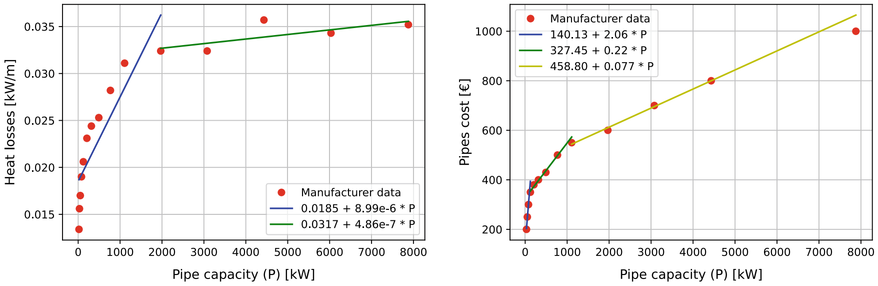
The cost of DHN pipes generally increases with pipe diameter, but this relationship is inherently nonlinear. Since cost is a critical driver in the optimal design of DHNs, accurately capturing this nonlinear cost behavior is essential. To preserve tractability within the optimization model while approximating the nonlinearity, a piecewise linear (PWL) cost formulation is employed. This approach discretizes the capacity domain into a set of predefined intervals. For each arc of the network, binary variables ($\mathrm{Y}^{\mathrm{int}}_{\mathrm{i,j,k}}$) are introduced to activate one and only one interval, corresponding to the selected pipe capacity. Continuous variables then define the actual capacity ($\mathrm{P}^{\mathrm{nom,int}}_{\mathrm{i,j,k}}$) within the bounds of the selected interval. The total pipe cost is thus modeled as a PWL function of the installed capacity, as shown in Fig. 2b, maintaining a linear structure compatible with MILP solvers. The formulation is expressed by the following constraints:

$$\sum_{k=1}^{n_{\mathrm{cost,int}}} \mathrm{P}^{\mathrm{nom,int}}_{\mathrm{i,j,k}} = \mathrm{P}^{\mathrm{nom}}_{\mathrm{i,j}} \quad \forall (i, j) \in \mathcal{A} \tag{4}$$

$$\mathrm{Y}^{\mathrm{built}} \geq \sum_{k=1}^{n_{\mathrm{cost,pipe}}} \mathrm{Y}^{\mathrm{int}}_{\mathrm{i,j,k}} \quad \forall (i, j) \in \mathcal{A} \tag{5}$$

$$\mathrm{P}^{\mathrm{nom,int}}_{\mathrm{i,j,k}} \leq c^{\mathrm{max,cost}}_{\mathrm{k}} \times \mathrm{Y}^{\mathrm{int}}_{\mathrm{i,j,k}} \quad \forall (i, j) \in \mathcal{A}, \forall k \in \{1, \ldots, n^{\mathrm{cost}}_{\mathrm{pipe}}\} \tag{6}$$

$$\mathrm{P}^{\mathrm{nom,int}}_{\mathrm{i,j,k}} \geq c^{\mathrm{min,cost}}_{\mathrm{k}} \times \mathrm{Y}^{\mathrm{int}}_{\mathrm{i,j,k}} \quad \forall (i, j) \in \mathcal{A}, \ \forall k \in \{1, \ldots, n^{\mathrm{cost}}_{\mathrm{pipe}}\} \tag{7}$$



(a) Heat losses [11].

(b) Pipe costs [12].

Fig. 2 Linear regression for PWL programming as a function of pipe capacity

$$\mathrm{Cost}_{i,j} = \tau^{\mathrm{pipe}} \times L_{\mathrm{i,j}} \times \sum_{k=1}^{n_{\mathrm{cost,pipe}}} \left(\alpha_{\mathrm{k}} \times \mathrm{Y}^{\mathrm{int}}_{\mathrm{i,j,k}} + \beta_{\mathrm{k}} \times \mathrm{P}^{\mathrm{nom,int}}_{\mathrm{i,j,k}}\right) \quad \forall (i, j) \in \mathcal{A} \tag{8}$$

where $c_{\mathrm{k}}^{\mathrm{min,cost}}$ and $c_{\mathrm{k}}^{\mathrm{max,cost}}$ are lower and upper pipe capacity bounds of each interval, $L_{\mathrm{i,j}}$ is the length of each arc (pipe), τ^{pipe} is the annuity factor for pipe construction, α_{k} and β_{k} are the intercept and slope of the linear equation.

The electricity consumption of the circulation pump in the district heating network is considered by calculating the mass flow rate (9), assuming a constant pressure drop of 100Pa per meter of pipe, a pump efficiency of 75% and a critical path of length L:

$$\dot{m}_{\mathrm{i,j,p,t}} = \frac{P^{\mathrm{in}}_{\mathrm{i,j,p,t}}}{c_{\mathrm{p}} \times \left(T^{\mathrm{supply}} - T^{\mathrm{return}}\right)} \quad \forall (i, j) \in \mathcal{A},\ \forall p \in \mathcal{P},\ \forall t \in \mathcal{T}_p \tag{9}$$

$$\mathrm{Elec}^{\mathrm{dhn}}_{\mathrm{p,t}} = \sum_{i \in \mathcal{N}^{\mathrm{prod}},\ (i,j) \in \mathcal{A}} \dot{m}_{\mathrm{i,j,p,t}} \times \frac{\Delta P \times L}{\rho \times \eta_{\mathrm{pp}}} \quad \forall p \in \mathcal{P},\ \forall t \in \mathcal{T}_p \tag{10}$$

2.3 Case Study

The case study evaluates a single optimization scenario that minimizes annual total system cost to determine the optimal energy mix. The analysis balances centralized and decentralized technologies to identify the most cost-effective configuration. If economically viable, a low-temperature district heating network (50 °C–30 °C) would require 7.8 km of piping (supply and return) to connect all buildings, with centralized heat production located at a single node. The study uses electricity pricing and weather data for the Liége region. The primary goal is to present a design tool needing minimal input to help decision-makers develop integrated energy systems for heating, domestic hot water, electricity, and cooling, emphasizing the economic viability of electrification, particularly via geothermal heat pumps.

3 Results

The optimal energy mix in the reference scenario combines centralized and decentralized technologies. A DHN is selected, with heat exchangers installed in substations to transfer heat to individual buildings.

On the centralized side, a 1019 kW geothermal heat pump is implemented, coupled with a thermal storage tank of 344kWh. The system includes 241 boreholes, each 100 m deep and spaced 8 m apart, covering a geothermal field of 13440 m^2. With an 8 m borehole spacing, thermal interference is negligible, and ground temperature remains above 0 °C, confirming sufficient natural regeneration. As shown in Fig. 3, the heat pump charges the storage tank during off-peak hours in low-demand periods, which is then discharged during peak hours. On low-demand days, storage is mainly charged during daylight using PV electricity, compensating for night-time heat losses in the DHN. Despite the presence of a central plant, a significant portion of demand is still covered by decentralized systems.

Installed capacities per building are shown in Fig. 4. Gas boilers and air-source heat pumps are selected in nearly all buildings with decentralized systems, often operating in parallel with the DHN through heat exchangers. Two buildings (B4 and B8) include electric resistance heaters as backup for peak loads. However, the high number of technologies installed in some buildings, particularly B4 and B8, suggests future work such as using a piecewise linear formulation for investment costs to better account for economies of scale, or performing sensitivity analyses on demand and primary energy prices to improve the realism of the design.

The annual total system cost for the reference scenario is 2085 k €(648 k€for CAPEX, 1259 k€for OPEX, 58 k€for piping costs). Table 1 summarizes the district heating network performance, showing moderate heat losses (13.3%) and efficient pump operation with 79MWh of annual electricity use.

Total electricity demand, including both building and heating technologies, is partly covered by a 2 MW wind turbine and 4778 kW of PV panels. Remaining

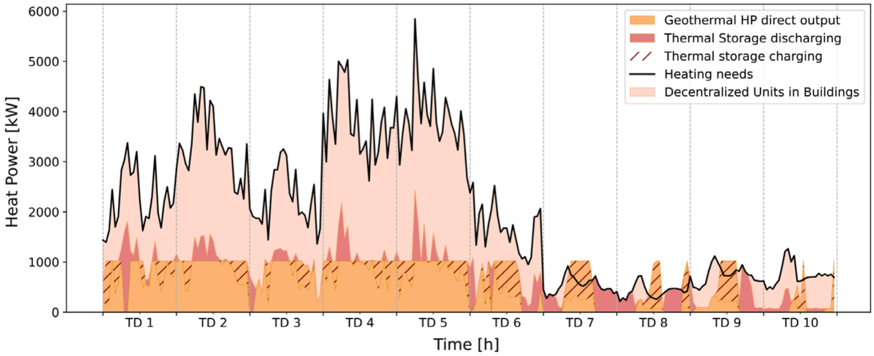


Fig. 3 Load curve of centralized and decentralized technologies

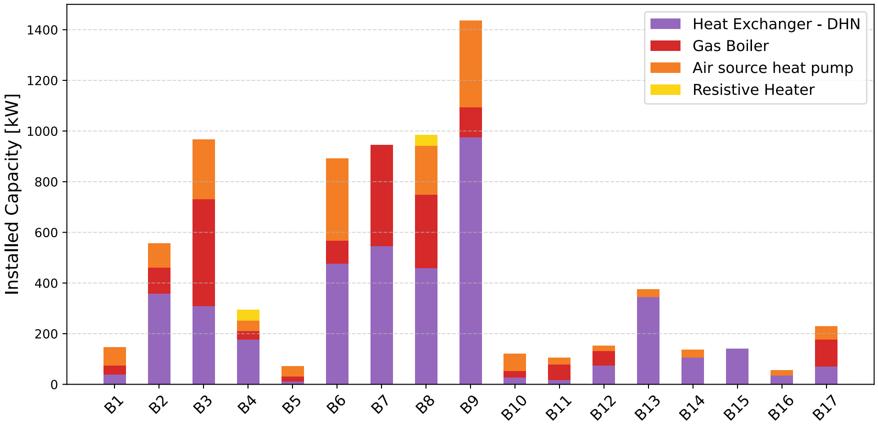


Fig. 4 Installed decentralized technologies in every building

Table 1 District heating network indicators

Indicator	Value
Annual DHN thermal energy [MWh_{th}]	4633.85
Annual heat losses [MWh_{th}]	615.16
Share of heat losses [%]	13.28
Linear heat density [MWh/m/an]	0.58
Pump consumption [MWh_{el}]	78.99

demand (6274 MWh/year) is met by grid imports. Due to renewable intermittency, some locally generated electricity is exported back to the grid.

4 Conclusion

This work proposes a methodology for the preliminary design of multi-vector energy system, enabling the identification of an economically optimal energy mix combining centralized and decentralized technologies, supported by a low-temperature district heating network (50–35 °C). The geothermal system comprises 241 boreholes 100 m deep spaced 8 m apart, ensuring sufficient heat extraction without ground freezing. Significant decentralized capacity remains to be integrated alongside the DHN, which shows 13.28% thermal losses and a circulation pump consumption of 79 MWh. DHN pipe costs are approximated through a piecewise linear formulation to better capture their nonlinear behavior. The proposed tool enables early-stage design and operation with minimal input data. Future works will address cooling needs and artificial ground regeneration integration and the inclusion of electrical network modeling to capture combined thermal and electrical design constraints.

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