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Integrated planning of grids and energy conversion units in municipal multi-energy carrier systems

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Abstract

The ongoing energy transition requires the planning of low-emission municipal energy supply systems. These systems comprise distribution grids for electricity, gas, and heat, as well as energy conversion units such as heating systems. This paper presents a linear optimization model considering these elements in order to identify the cost-minimizing system design while achieving a given CO₂ emission limit. The model is applied to an exemplary test case comprising 900 buildings. In order to increase scalability of the model to larger system sizes, the effect of reducing the spatial resolution on the optimization results is analyzed. The results show that the effect is small and that spatial aggregation is indeed a valid approach to reduce problem complexity and to allow significant speedups, reaching a factor of 200 for the given case study.

Keywords: Municipal energy supply, Multi-energy carrier systems, Sector coupling

Introduction

The ongoing energy transition requires the reduction of emissions attributed to the energy consumption of buildings, bringing municipal energy supply systems into focus. These systems include infrastructures for energy carriers such as electricity, gas, and heat, as well as conversion units such as heating technologies within the buildings. The holistic planning of municipal energy supply systems with numerous decision options requires mathematical optimization tools, which consider the expansion of infrastructures and conversion units in an integrated approach.

Modeling of municipal energy supply systems

The concept of energy hubs (Geidl 2007; Geidl et al. 2007) introduced the combination of multiple interconnected energy carriers into the optimization of energy systems. Since then, a wide variety of optimization models for municipal energy systems has been developed (Weinand et al. 2020; Keirstead et al. 2012; van Beuzekom et al. 2015; Allegrini et

al. 2015; Mancarella 2014). These models can be differentiated based on their consideration of individual technologies or integrated systems, their focus on grid operation or grid expansion, their degree of abstraction in the modeling of grids, and the energy carriers considered.

A first group of models focuses on the integration of individual technologies such as thermal storages, CHP units, or heat pumps into a given cross-sectoral energy system (Bachmaier et al. 2015). The expansion of energy infrastructures is not considered. A second group of models focuses on the operational optimization of multi-energy carrier grids, again without consideration of their expansion planning (Geidl and Andersson 2007; Widl et al. 2015; Moeini-Aghaie et al. 2014; Fichera et al. 2018; Martinez Cesena and Mancarella 2019). A third group of models considers the expansion of energy distribution capacities, but abstracts from realistic grid structures (Mainzer 2019; Eggers et al. 2015; Juroszek and Kudelko 2016; Ko et al. 2017; Jennings et al. 2014), so that for example the study area is divided into sub-areas, between which energy exchange capacities can be expanded. Different grid levels and the routing on those are neglected. In a fourth group with more detailed focus on the grid structure, some models plan the grid expansion for a subset of energy carriers like heat (Falke et al. 2016; Falke and Schnettler 2016), electricity and gas (Saldarriaga et al. 2013), or electricity and heat (Lu et al. 2017). Models such as DISTRICT-HP (Saad Hussein 2018) consider the expansion of distribution grids for electricity, gas, and heat, as well as the expansion of conversion units (Lu et al. 2017; Wouters et al. 2014; Mehleri et al. 2013; Wakui et al. 2014; Shabanpour-Haghighi and Seifi 2015). However, these models are only exemplarily applied to small study areas, which do not represent municipal scales and can therefore not answer questions for the overall system design.

Contributions of this paper

This paper follows two objectives. First, it introduces an optimization model for municipal energy supply systems, which considers the infrastructures for electricity, gas, and heat on different grid levels as well as the conversion units linking them. This model is applied to an exemplary test case including 900 buildings. Second, as the further scaling to even larger systems quickly leads to impractical computation times, this paper explores what effects the reduction in spatial resolution has on the overall system design results. In the following sections, the optimization model including its objective function and constraints is introduced and the spatial aggregation approach is described. Afterwards, the model is applied to a test case and the design results with and without spatial aggregation are compared.

Optimization model

Model overview

The target of the presented model is to identify the cost-optimized design of a municipal energy supply system. The model is formulated as a linear optimization problem (van Beeck 1999) minimizing the overall system costs, including costs for investment into grids and conversion units as well as costs for energy consumption during operation. It takes the perspective of a central planner, who has control of all investment and operational decisions within the municipal energy system. The optimization variables therefore comprise installed capacities for central and decentral conversion units, electric cables and

transformers, gas pipes and pressure regulators, and heat pipes. Furthermore, the system operation, described by the input and output of conversion units as well as flows on grid elements, is optimized. This approach enables the identification of optimized system designs from a holistic perspective neglecting the barriers of split ownership and the influence of frequently changing energy regulations.

The investments and operation are subject to various constraints as further introduced in “[Constraints](#)” section. The model allows for a brown field approach by considering existing grid capacities in the optimization, or a green field approach by neglecting those.

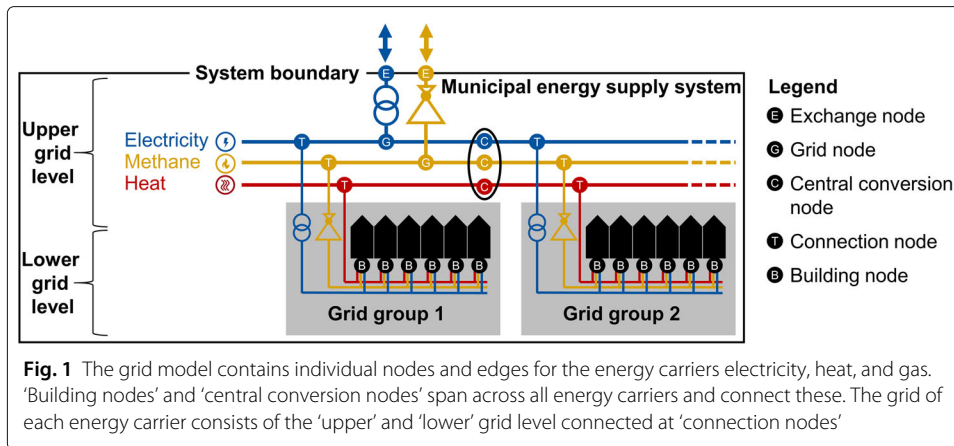
The input comprises the geo-referenced grid structure, the supply task, weather data, as well as technical and economic parameters. The *grid structure*, defined as a graph with nodes and edges, describes possible infrastructure connections for each energy carrier. In case of a brown field optimization, existing capacities for each edge are defined. The grid structure also contains nodes for all buildings to be supplied. The *supply task* defines demand time series for electricity, space heat, and warm water to each building. The *weather data* contains time series for the global radiation and ambient air temperature. The *technical and economic parameters* include electric and thermal efficiencies and investment costs of energy conversion units as well as investment costs for grid elements such as cables, pipes, transformers, and pressure regulators. Furthermore, specific emission factors and price time series for each energy carrier are included. All aforementioned input time series are full-year data sets with a time resolution of 15 minutes per time step.

Grid model

Municipal energy supply systems contain grids for different energy carriers as well as conversion units such as heating technologies. These are either located in central locations to feed into the grid, or in buildings, where the demand occurs. The grid of each energy carrier comprises different grid levels. The electricity grid relies on the low voltage level to connect buildings with distribution stations, and the medium voltage level for linking those with substations (Sillaber 2016). Similarly, the gas system comprises a low pressure and the overlaid high pressure level (Cerbe 2016). Heating grids can be split into main and final distribution levels (Nussbaumer et al.). These two grid levels, in the following referred to as ‘upper’ and ‘lower’ level, are connected using transformers (electricity), pressure regulators (gas), and heat pipes (heat). Within the optimization model, the grid information for each energy carrier is described by a graph with nodes and edges, as visualized in Fig. 1. The nodes are classified as building nodes, central conversion nodes, grid nodes, connection nodes, and exchange nodes.

Building nodes are present in the lower grid level of each energy carrier and have a demand for electricity and heat, which must be fulfilled by the overall system. In a building node, conversion units can be installed to directly serve the demand, such as heat pumps, electric or gas heaters, pellet heaters, small cogeneration units, solar thermal units, and photovoltaic systems.

Central conversion nodes, linking the different energy carrier grids, are present in the upper grid level. They can convert energy from one carrier to another using similar technologies as used in building nodes, but in large scale, and with the difference that generated heat is fed into the heat grid.



Grid nodes and the edges between them exist on both grid levels and for each energy carrier individually. They perform the task of transporting their respective energy carrier between import nodes, central conversion nodes, and building nodes.

Connection nodes connect the upper and lower grid level of each energy carrier and represent electric transformers, gas pressure regulators, and heat connections.

The *exchange nodes* for the energy carriers electricity and gas are located in the upper grid level and allow the energy exchange between the modeled system and the outside. There is no exchange node for heat, as the heat grid is considered as being entirely local within this model.

The part of a grid on the lower level located under one connection node is referred to as 'grid group', as shown in Fig. 1. A building node belongs to the same grid group for all energy carrier grids.

Objective function

The objective function describes the minimization of annualized overall system costs with investment into grid and conversion units as well as operation, as stated by

$$Z = C_{grid,total}^{inv} + C_{conversion_units,total}^{inv} + C^{operation} \quad (1)$$

$$= \sum_c \sum_k C_{c,k}^{inv} + \sum_j \sum_n C_{j,n}^{inv} + \sum_c \sum_t P_c^{exchange} p_{t,c} \quad (2)$$

The first term $\sum_c \sum_k C_{c,k}^{inv}$ describes the annualized grid investment costs as sum across all energy carriers c and all grid edges k of the annualized investment costs per edge. These are derived based on the installed edge capacity, edge length, and annualized specific investment costs for the respective edge type. The second term $\sum_j \sum_n C_{j,n}^{inv}$ describes the annualized investment costs for conversion units as sum across all units j in all nodes n of the annualized investment costs per unit. These result from the installed unit capacity and annualized specific investment costs for the respective technology. The third term $\sum_c \sum_t P_{c,0}^{exchange} p_{t,c}$ describes the operational costs for energy carrier consumption. These are defined as the sum across all time steps t and energy carriers c of the energy exchange at the exchange node multiplied by the price of the respective energy carrier. As the model takes the perspective of a central system planner, no charges related to energy regulations,

such as network charges and energy taxes, are considered. The prices for the energy carriers therefore represent wholesale market prices, which in addition in the case of electricity inherently imply scarcity or abundance in the overall national system.

Constraints

Technology constraints

For each conversion unit j in each node n at each time step t , the energy carrier input and output are linked via the efficiency $\eta_{t,n,j}^c$ with

$$P_{t,n,j}^{c,out} = P_{t,n,j}^{c,in} \cdot \eta_{t,n,j}^c \quad \forall t, n, j \quad (3)$$

The output of the unit j in node n is further limited by its installed capacity with

$$P_{t,n,j}^{c,out} \leq \hat{P}_{n,j}^{c,out} \quad \forall t, n, j \quad (4)$$

For heat pumps, the time-varying coefficient of performance (COP) replaces $\eta_{t,n,j}$. It is calculated based on time series for the flow temperature and evaporation temperature. For decentral air to water heat pumps, estimated building-specific flow temperatures and the outside air temperature are used in combination with the COP curve of a definable heat pump. For central water to water heat pumps, the flow temperature of the heating grid is regulated based on the outside temperature. The evaporation temperature, describing the temperature of the heat source such as ground water, waste water, or river water, is set at a constant value. A large-scale heat pump available on the market is used as basis for the COP curve.

Node constraints

Similar to the transport model described in Saad Hussein (2018), each grid node n of each energy carrier c must be in balance regarding incoming and outgoing edge flows $F_{t,mn}^c$, infeed $P_{t,n}^{c,infeed}$, and withdrawal $P_{t,n}^{c,withdrawal}$ in each time step t :

$$\sum_{(m,n)} F_{t,mn}^c - \sum_{(n,m)} F_{t,nm}^c + P_{t,n}^{c,infeed} - P_{t,n}^{c,withdrawal} = 0 \quad \forall t, n, c \quad (5)$$

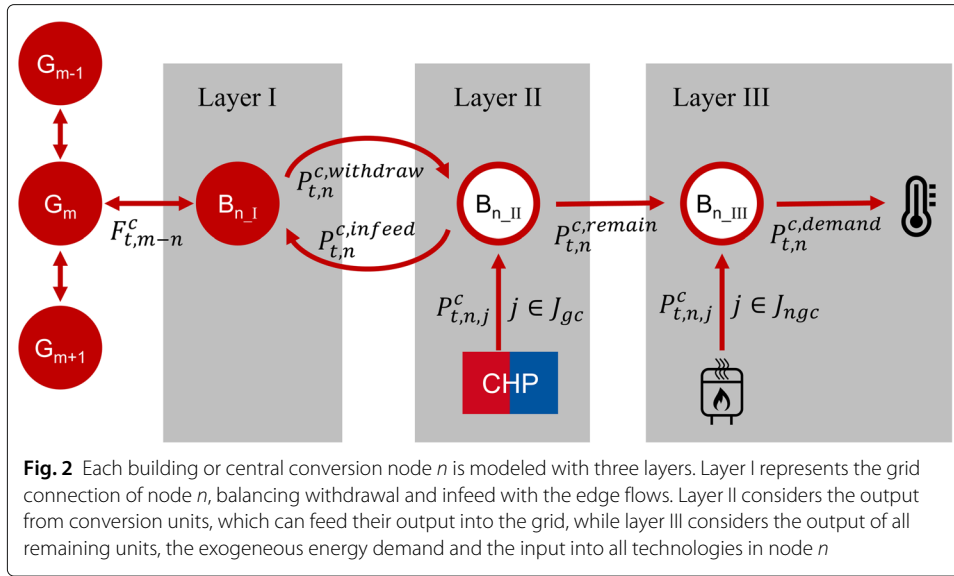
In a building or central conversion node, multiple conversion, renewable energy, and storage units can be installed. Some units can feed their output into the grid, others can only supply within the same node. Therefore, a multi-layer node model is chosen, as shown in Fig. 2. Each building or central conversion node in each energy carrier grid is made up of three layers, whereby each layer has its own energy balance constraint.

Layer I represents the connection with the grid and is subject to Eq. 5. The balance equation of layer II considers the output from the subset $J_{n,gc}$ of conversion units in node n , which can feed their output back into the grid:

$$\sum_{j \in J_{n,gc}} P_{t,n,j}^{c,out} + P_{t,n}^{c,withdrawal} - P_{t,n}^{c,infeed} - P_{t,n}^{c,remain} = 0 \quad \forall t, n, c \quad (6)$$

The term $P_{t,n}^{c,remain}$ describes the energy transferred from layer II to layer III. The balance equation of layer III considers the output from the subset $J_{n,ngc}$ of conversion units in node n , which cannot feed their output into the grid.

$$\sum_{j \in J_{n,ngc}} P_{t,n,j}^{c,out} + P_{t,n}^{c,remain} - \sum_{j \in J_n} P_{t,n,j}^{c,in} - P_{t,n}^{c,demand} = 0 \quad \forall t, n, c \quad (7)$$



This layer balances the energy demand of the building $P_{t,n}^{c,demand}$ and the fuel input into conversion units within the same node $P_{t,n,j}^{c,in}$ on the one side with the energy transferred from layer II and the output of conversion units in layer III on the other side. The restriction of energy transfer between layer II and layer III to positive values hinders units installed in layer III from feeding their output into the grid.

$$P_{t,n}^{c,remain} \geq 0 \quad \forall t, n, c \quad (8)$$

Grid constraints

The flow $F_{t,mn}^c$ on each edge of energy carrier c connecting nodes m and n and on each transformer (electricity) and pressure regulator (gas) is modeled as power flow neglecting parameters such as voltage, pressure, and temperature level, as well as losses. It is limited by its installed capacity:

$$F_{t,mn}^c \leq \hat{F}_{mn}^c \quad \forall m, n, c, t \quad (9)$$

CO₂ emission limit

The overall system operation in all time steps is constrained by a CO₂ emission limit, considering the emissions resulting from the consumption of energy carriers. For electricity and gas, the exchange across the system boundary at the exchange nodes is taken into account. A reverse electricity flow out of the system results in a CO₂ credit. For pellets, the consumption at all nodes is considered. The specific emission factors for these energy carriers depend on the overall scenario parametrization.

Aggregation of lower grid levels

The “Grid model” section introduced the grid model of municipal energy supply systems with an upper and lower grid level. Results on the lower level allow for a detailed analysis of the optimal design for individual buildings and streets. Results for the upper level support assessments of the optimal overall cross-sectoral system design and are therefore in focus. The mere neglect of the lower level in the optimization, however, is not possible, as both levels interact with each other. At the same time, the full consideration of

Table 1 Investment costs and thermal efficiencies for heat pumps (HP), electric heaters (EH), gas condensing heaters (GH), pellet heaters (PH), and combined heat and power units (CHP)

	EH	GH	HP_c	CHP_c	EH_c	GH_c	PH_c
Inv. costs [EUR/kW]	37	123	1200	359	17	58	210
Thermal efficiency	0.99	0.98	f(t)	0.43	0.99	0.98	0.94

The ‘_c’ represents central conversion technologies. The thermal efficiency of HP_c varies with time based on the COP curve of a commercial model (Emerson Climate Technologies 2012), the electric efficiency of CHP units is assumed as 43%. The life span of all technologies is assumed to be 20 years

the lower level increases problem complexity significantly. The aggregation of information and thereby reduction of resolution on the lower level can help to bridge this conflict. The aggregation chosen in this work selects one representative building node for each grid group on the lower level and assigns the aggregated characteristics of all buildings within this grid group to it. For additive values such as the demand time series, the sum is calculated. For non-additive values such as the COP time series, the weighted average is calculated, with the heat demand time series used as weighting factors. The length of the new edge between the representative building and the connection node is calculated as the weighted average of all individual distances between the buildings and the connection node, with the annual energy demand as weighting factor.

Exemplary application and results

Description of the test case

The introduced model is exemplarily applied to a test case based on a district in Aachen, Germany, including 900 multi-family houses, as visualized in Fig. 3a. The degrees of freedom include the installation of those conversion technologies introduced in Table 1, the grid expansion for electricity, heat, and gas, and the system operation. As the test case is located in a city center, heat pumps and pellet heaters in buildings are not provided as technology options. Furthermore, no storages are considered in this exemplary application. The technology parameters introduced in Table 1 have been defined based on a research of publicly available manufacturer data. Table 2 displays the parameters for grid expansion.

The synthetic grid data is created based on Open Street Map. The number of buildings, which can be supplied by one distribution station, is set to 50 based on standard transformer sizes and assumed electric power requirements of buildings. This results in 18 grid groups and connection nodes, which are spread across the study area, and to which the buildings are assigned based on proximity. On the lower grid level, possible grid connections between building nodes and their respective connection node are defined based on a shortest path algorithm. These possible connections are assumed identical for all three energy carriers. On the upper grid level, possible electric connections in the form of

Table 2 Investment costs and life span for electric, gas, and heat edges in lower and upper grid level as well as transformers (electric) and pressure regulators (gas)

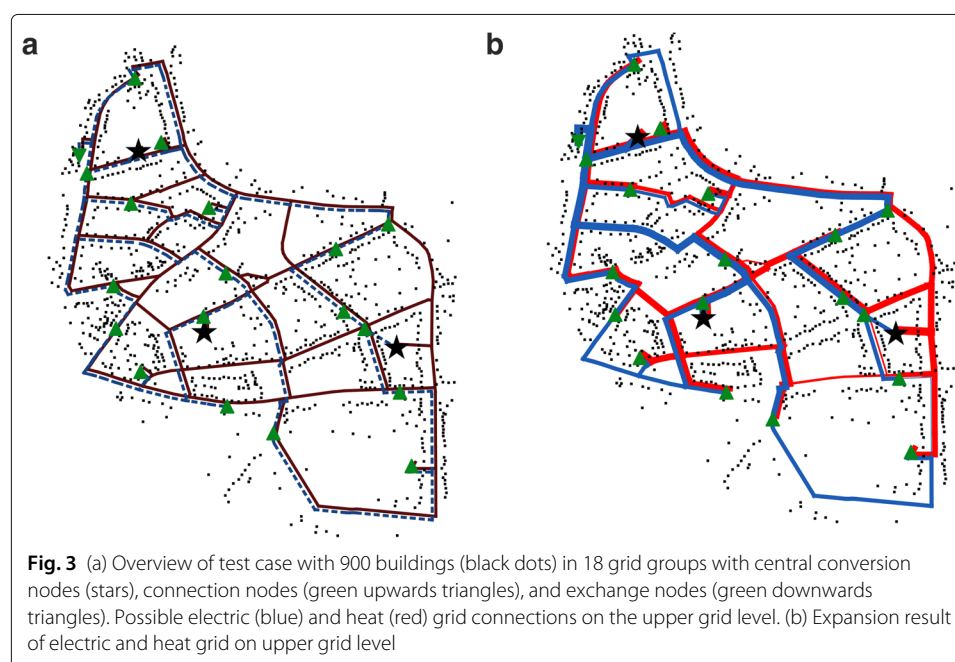
	el_lv	el_mv	gas_lp	gas_hp	heat_low	heat_up
Inv. costs [EUR/(kW km)]	630	23	79	4	242	60
Life span [a]	45	45	50	50	40	40
	el_mv_lv		gas_hp_lp			
Inv. costs [EUR/kW]	40		6			
Life span [a]	35		45			

rings to link connection nodes with the exchange node are determined based on a traveling salesman algorithm. For gas, the same rings are defined and meshing edges added. The possible connections for heat on the upper grid level are determined based on the complete street network. Within the grid, three central conversion nodes are defined.

For the electric and hot water demand, probabilistic load profiles are generated for each building based on an estimated number of households, occupants' behavior, and the appliances in operation. Within this case study, the hot water demand is considered to be supplied by electric water heaters and is therefore added to the electric demand. For space heating, a thermal building model is applied, which translates the building's characteristics into an equivalent RC network.

The surrounding environment of the test case system is assumed as scenario 'TM80' in the German Energy Agency's 'dena Leitstudie' (Bründlinger et al. 2018) with a CO₂ emission reduction target of 80% compared to 1990. Accordingly, the specific emissions for electricity, gas, and pellets are set to 0.05, 0.24, and 0.01 kg CO₂-eq/kWh, respectively (Hecking et al. 2017). The emission reduction target of the test case system is assumed as comparably more ambitious and set to 95% (base year 1990). The emissions in 1990 are calculated based on an assumed heating technology distribution dominated by gas and oil heaters (BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. 2019) and the specific emissions for electricity, gas, and oil in 1990 with 0.76, 0.24, and 0.31 kg CO₂-eq/kWh (Bründlinger et al. 2018; Umweltbundesamt 2020). The CO₂ limit results as 2.74 Mt/a.

Using time series aggregation approaches (Teichgraeber and Brandt 2018; 2019), the annual input time series with a resolution of 15 min per time step are clustered to identify 120 representative time steps with a resolution of one hour per time step. These are considered in the optimization and their objective function coefficient is multiplied with a factor, which describes the number of original time steps represented.



The optimization is performed as greenfield approach, once with high resolution with each building as individual node ('Disaggregated'), and once with low resolution with aggregated grid groups ('Aggregated'). The results are introduced in the following.

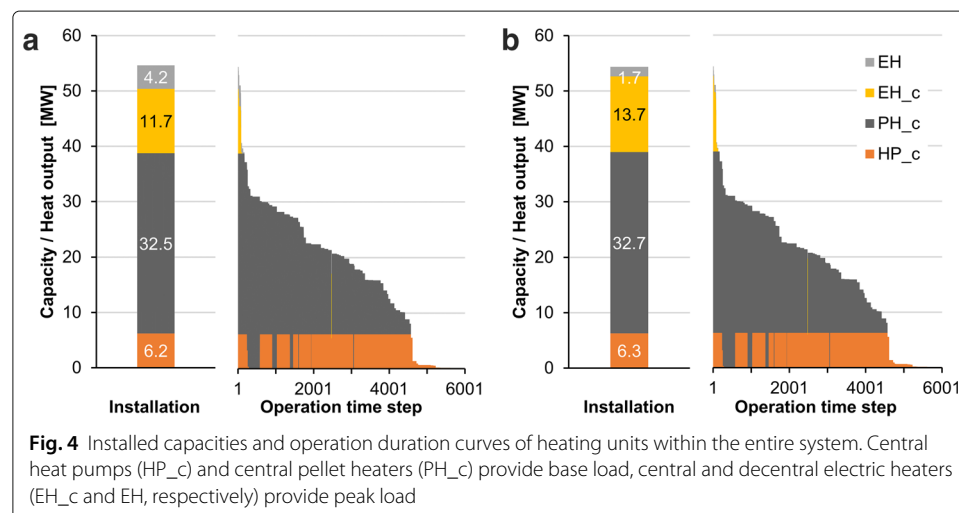
Optimization with disaggregated grid

The optimization with disaggregated grid results in an objective function value of 7.16 Million Euro and exhausts the emission limit fully. The resulting grid expansion on the upper grid level is visualized in Fig. 3b. The technology installation and operation for the entire system is visualized in the bar chart and duration curve in Fig. 4a. The base load is covered by central heat pumps and pellet heaters in combination with the heat grid, keeping CO₂ emissions low. However, the installation of these technologies to cover peak loads would increase overall system costs significantly, so that central and decentral electric heaters are instead installed for this purpose. The share of central and decentral electric heaters is the result of a trade-off between additionally required heat and electric grid capacities as well as differing technology costs. No gas-fired technologies are installed, as the utilization of these would exceed the emission limit due to the specific emissions of methane in the above-introduced system scenario. The overall system design, combining different central and decentral technologies, demonstrates the benefits of hybrid heating systems.

The resulting heat grid starts from the central conversion nodes with capacities of up to 22 MW. The capacity decreases, as heat connection points to the lower grid groups are passed and supplied. The chosen network structure resembles a combination of meshes in the center and branches in the outer area. The electric grid capacities are expanded up to 12 MW and are especially high between the exchange node and central conversion nodes with installed electric heaters. Since there are no gas-fired technologies installed, no gas grid is expanded.

Optimization with aggregated grid and comparison of results

The optimization with aggregated grid groups only requires 0.45% of computation time, a speedup by a factor of 200. It completes with an objective function value of 7.05



Million Euro, a deviation by 1.5% in comparison to the optimization with disaggregated grid, and also exploits the CO₂ limit fully. The system design shows the utilization of the same heating technologies, as displayed for the installation and operation in Fig. 4b. While the selected heating technologies and their overall installed capacity is not affected by the aggregation to grid groups, the installed capacities for each technology differ. For central base load technologies, the aggregated optimization leads to 0.1 MW and 0.2 MW higher central heat pump and pellet heater capacities. It also results in 2 MW higher central and 2.5 MW lower decentral electric heating capacity. Regarding the grid expansion, the same edges are used and similar capacities are installed across all energy carriers.

Conclusion

This paper presented a detailed model for the planning of municipal energy supply systems, including the distribution grids for electricity, gas, and heat, as well as the central and decentral energy conversion units. It is formulated as a linear optimization problem minimizing the overall system costs, while restricting the CO₂ emissions to a predefined limit. To reduce problem complexity, an approach for spatial aggregation of buildings within the same grid group has been optionally applied. The application of this model to an exemplary test case comprising 900 buildings has shown the benefits of hybrid heating systems, utilizing multiple central and decentral conversion units. The comparison of optimization results with and without spatial aggregation has shown the same technology installations with small deviations in the installed capacities, as well as similar grid expansion results, while achieving a speedup by a factor of 200. Therefore, the reduction of problem complexity with spatial aggregation is a possible approach, if the optimization purpose is the identification of design characteristics on the overall system level. Future work will introduce binary decision variables for grid expansion to the model and will present its application to larger system scales.

About this supplement

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Authors' contributions

CH developed the model, conducted the exemplary application, and wrote the manuscript. AU provided valuable feedback to the manuscript draft. AM supervised the development process. All authors read, edited, and approved the manuscript.

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Availability of data and materials

N.A.

Declarations

Competing interests

The authors declare that they have no competing interests.

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