EuroSun2026

CITY-SCALE IMPLEMENTATION OF CLUSTERING AND COMPETITIVE HEATING TECHNOLOGY FRAMEWORK

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Summary

Urban heating decarbonization requires coordinated planning of centralized and decentralized heating technologies while accounting for increasing local renewable electricity generation. This work presents a city-scale framework for the competitive allocation of district heating networks (DHN) and photovoltaic (PV)-supported heat pump communities. The urban area is represented as an address-level graph, and graph-based clustering is used to form spatially coherent heat pump communities that enable local PV electricity sharing. District heating subsequently competes with these communities through a techno-economic network expansion process. As buildings are connected to the DHN, affected heat pump communities are locally re-clustered to account for changes in electricity demand and PV utilization. The framework is implemented for the complete city of Oldenburg, Germany, comprising 44,421 address-level nodes. Compared with the baseline district heating planning approach, the competitive framework results in a more concentrated DHN, increasing average linear heat density from 4.03 to 7.80 $\mathrm{MWh\,m^{-1}}$ while reducing the required network length from 110.3 to 40.8 km. Community-level electricity sharing additionally increases utilized PV generation by approximately 34 GWh/year. An electricity-price sensitivity analysis further demonstrates that the resulting technology allocation responds strongly to changing techno-economic conditions, with increasing electricity prices shifting the competitive allocation towards greater DHN deployment. Overall, the results demonstrate the potential of integrated heating and electricity planning to improve both district heating infrastructure utilization and local renewable electricity use at city scale.

Keywords: district heating, heat pumps, energy communities, photovoltaic sharing, sector coupling, graph clustering, urban energy planning

Field of application for the findings: Urban heat transition planning, district heating network planning, renewable energy integration, and city-scale energy system analysis.

Addressed audience: Urban energy planners, municipalities, district heating operators, researchers, and stakeholders involved in heat transition and integrated energy system planning.

1. Introduction

Urban heating decarbonization increasingly relies on electrified technologies such as heat pumps, while district heating networks (DHN) continue to play an important role in densely populated urban areas. Rather than relying on a single heating technology, future urban energy systems are expected to combine centralized and decentralized solutions according to local techno-economic conditions. At the same time, local groups of buildings that share energy resources are emerging as an important concept for improving renewable energy integration and sector coupling. These groups are commonly referred to as energy communities or urban energy cells, as described by Perera et al. (2021) and Bartolini et al. (2020).

Within this context, we introduce the concept of heat pump communities (HPCs), defined as spatially coherent groups of buildings that share locally generated electricity, such as photovoltaic (PV) generation, to supply individual heat pumps. By aggregating electricity demand and renewable generation across neighbouring buildings, locally produced PV electricity can be utilized more effectively, reducing electricity imports from the grid and improving the economic competitiveness of electrified heating systems.

Despite the growing interest in both district heating planning and local energy communities, systematic methods for identifying spatially coherent heat pump communities and directly comparing their techno-economic suitability with district heating remain limited. Möller and Lund (2010) demonstrate that district heating expansion can be evaluated based on the economic feasibility of network extension, for which spatial heat demand and network investment costs are key determinants. The systematic review by Fouladvand et al. (2022) highlights the comparatively limited attention given to community-based heating and cooling within the broader development of energy communities. In particular, the competitive spatial allocation between alternative heating technologies remains insufficiently addressed. Furthermore, optimization-based planning approaches often become computationally demanding when applied to complete urban areas, limiting their practical applicability for city-scale studies.

This work presents a city-scale implementation of a graph-based segmentation framework for identifying and evaluating competing heating technologies at high spatial resolution. The urban area is represented as a graph in which nodes correspond to address-level building aggregations and edges capture the interaction potential between neighbouring buildings. A graph-based clustering strategy, following the approaches of Felzenszwalb and Huttenlocher (2004) and Carneiro and Zhao (2018), is employed to identify heat pump communities that maximize local PV utilization while maintaining spatial compactness. Based on these communities, a competitive heating technology selection process incrementally compares heat pump communities with district heating expansion using techno-economic criteria. As district heating expands, local electricity balances change, requiring dynamic re-clustering to continuously reassess the competitiveness of both heating technologies.

The primary contribution of this paper is the demonstration that the proposed framework can be implemented efficiently at city scale while preserving building-level spatial resolution. The methodology is applied to an urban dataset comprising 44,421 spatial nodes with hourly heat demand and PV generation profiles. A scenario analysis investigating variations in key techno-economic parameters is conducted to assess the robustness of the framework and its applicability to strategic urban heating planning. The results demonstrate that explicitly considering local PV sharing and sector coupling significantly influences heating technology selection while maintaining computational tractability for large-scale urban applications.

2. Methodology

The proposed framework identifies suitable heating technologies at city scale by combining graph-based spatial representation, energy community formation, and competitive techno-economic evaluation. The workflow begins with the preparation of building-level geospatial data, hourly heat demand profiles, and rooftop PV generation potential. These data are aggregated into address-level entities and represented as nodes in a graph, where edges capture spatial relationships and the potential benefit of local PV sharing between neighbouring nodes. The resulting graph is subsequently partitioned into heat pump communities that enable cluster-level utilization of locally generated PV electricity. Starting from this initial community configuration, district heating networks expand from predefined heat source locations and compete with the existing heat pump communities based on their techno-economic performance. Whenever a node is assigned to district heating, its heat pump electricity demand is removed from the corresponding community and the affected community is locally re-clustered to reflect the updated electricity demand and PV utilization. This iterative process continues until no further economically favourable DHN expansion is identified, resulting in a spatially explicit allocation of the urban area between district heating and PV-supported heat pump communities.

2.1 Data Preparation

The analysis combines geospatial building information with hourly energy demand and PV generation data to establish a unified representation of the urban area. Building geometries and semantic attributes are obtained from a CityGML dataset. Different approaches have been developed to estimate building-level heat demand and corresponding load profiles from urban building data. For example, Weiler et al. (2019) demonstrate the use of the SimStadt urban energy simulation platform, where 3D CityGML building models are combined with building typologies, physical characteristics, and usage information to estimate building heat demand and derive temporally resolved demand profiles. In the present study, building-level heat demand profiles are derived following the data-driven Urban Energy Unit classification methodology developed by Blanco et al. (2024), which maps buildings to representative residential and non-residential archetypes based on their geometric and semantic characteristics to estimate energy demand at urban scale. Hourly PV generation profiles are assigned based on the available rooftop PV potential of each building.

Since individual buildings may consist of multiple building parts, all parts belonging to the same building are aggregated before graph construction. Hourly heat demand profiles, PV generation potential, and roof surface areas are summed across the corresponding building parts, while a representative geometry is retained for spatial positioning. Buildings associated with the same address are subsequently aggregated into address-level entities. The resulting dataset contains the spatial location, building characteristics, hourly heat demand, and PV generation profiles required for graph construction, community formation, and subsequent techno-economic evaluation.

2.2 Graph Representation

The urban area is represented as an undirected graph, where each node represents an address-level building aggregation and stores its associated hourly heat demand profile, PV generation profile, building characteristics, and spatial location.

Edges represent the interaction potential between neighbouring nodes. Connections are established between parcels sharing a common boundary, between parcels located directly opposite each other across roads, and, where necessary, between disconnected graph components using nearest-neighbour links to ensure a fully connected graph. Unlike conventional adjacency graphs, the constructed graph captures not only spatial proximity but also the potential for neighbouring buildings to exchange locally generated electricity and participate in a common heating supply structure. This graph therefore forms the basis for both energy community identification and district heating expansion. A comprehensive description of the graph construction, clustering formulation, and competitive technology selection algorithm is provided in a separate methodological study currently under preparation; the present paper focuses on its implementation and evaluation at city scale.

2.3 Heat Pump Community Formation

Cluster identification is performed using a graph-based greedy merging strategy, building on established graph-based segmentation and clustering approaches and the use of greedy strategies for graph-cut problems, as described by Pei et al. (2026). Initially, each node forms an individual cluster. Neighbouring clusters are then iteratively evaluated and merged whenever the objective function improves.

The clustering objective balances two competing criteria. The first maximizes local PV utilization within each cluster, where PV utilization refers to the use of locally generated electricity to supply the electricity demand of heat pumps before importing electricity from the public grid. By aggregating electricity demand and PV generation across neighbouring nodes, locally generated PV electricity can be shared more effectively, thereby reducing grid electricity consumption.

The second criterion promotes geographically compact clusters. Compact communities are expected to require less infrastructure and coordination while remaining suitable for practical implementation as local energy communities. The greedy merging process continues until no additional merge improves the clustering objective, producing spatially coherent heat pump communities that maximize local renewable electricity utilization while maintaining compact spatial structures.

2.4 Competitive Heating Technology Selection

Following cluster formation, heating technologies are selected through a competitive expansion process comparing heat pump communities and district heating networks. Potential heat sources are treated as seed nodes from which district heating expands incrementally across the graph.

For every candidate node, the annualized cost of connecting the node to the district heating network is compared with the cost of supplying the corresponding heat pump community. Whenever district heating provides the lower annualized system cost, the candidate node is permanently assigned to the district heating network. If the candidate is rejected because its direct connection is not cost-competitive, a one-step look-ahead evaluation is performed. In this step, the algorithm examines whether accepting the candidate as an intermediate expansion node enables a subsequent connection that makes the combined expansion economically preferable to the corresponding heat pump alternatives. The candidate is assigned to district heating only when this combined look-ahead pathway results in a lower projected annualized system cost; otherwise, it remains within its heat pump community.

Assigning buildings to district heating removes their electrical heating demand from the associated heat pump community. Consequently, the local balance between PV generation and electricity demand changes, directly influencing the amount of PV electricity that can be utilized within the remaining community. To capture this feedback effect, the affected community is locally re-clustered after each successful district heating expansion. This dynamic updating ensures that the techno-economic comparison continuously reflects the changing electricity balance throughout the expansion process.

2.5 City-Scale Implementation

The framework is applied to the complete urban area of Oldenburg, Germany, to evaluate its suitability for high-resolution city-scale heating planning. The implementation uses a unified city-wide dataset comprising building geometries, cadastral parcels, hourly heat demand profiles, and rooftop PV generation potential. After preprocessing, the complete study area is represented by approximately 40 000 address-level nodes, allowing the analysis to retain the spatial detail of individual buildings while covering the full city.

A key objective of the implementation is to assess whether the proposed framework remains computationally practical when applied to a complete urban system rather than to a limited neighbourhood or predefined planning zone. For this purpose, the full graph is processed as a single connected system, and all clustering, heating technology allocation, and district heating expansion decisions are performed directly on the city-wide representation. This avoids the loss of local interactions that may occur when the study area is divided into independent subregions.

The implementation is designed to preserve the interaction between spatial structure, heat demand, and local PV availability throughout the analysis. Consequently, the city-wide allocation is not derived from aggregated heat-density zones, but from address-level decisions that reflect both the economic suitability of district heating and the potential benefit of supplying heat pumps with locally generated PV electricity. This enables spatial variations in building density, heat demand, roof area, and renewable generation potential to influence the resulting technology distribution.

Computational performance is monitored throughout the full-city application, with particular attention given to the repeated local updates required during district heating expansion. Because only the communities affected by a new district heating assignment are updated, the framework avoids repeating the complete clustering process after every expansion step. This localized implementation strategy is essential for maintaining practical execution times while preserving the dynamic interaction between district heating growth and heat pump community formation.

The city-scale application produces a spatially explicit heating technology map for Oldenburg together with a set of planning indicators used in the subsequent scenario analysis. These include the number of buildings assigned to district heating and heat pump communities, total district heating network length, linear heat density, annualized system cost, local PV utilization, renewable electricity contribution to heat pump operation, residual grid electricity demand, and computational runtime. The results are used to evaluate how changes in techno-economic assumptions affect both the overall technology mix and its spatial distribution across the city.

2.6 Baseline District Heating Planning

To evaluate the effectiveness of the proposed framework, a baseline district heating planning approach is implemented as a benchmark. In this approach, district heating expansion is determined solely through an economic assessment of network extension without explicitly considering competition with alternative heating technologies.

Starting from the predefined heat source locations, the district heating network expands iteratively by connecting neighbouring buildings whenever the network extension is economically feasible. District heating is assumed to have unlimited heat production capacity, allowing all economically viable buildings to be connected without source capacity constraints. Unlike the proposed framework, no clustering or energy community formation is performed during the planning process.

Buildings that are not connected to the district heating network are supplied individually by heat pumps. Their rooftop PV generation is utilized only through building-level self-consumption, meaning surplus PV electricity cannot be shared with neighbouring buildings. Consequently, the benchmark does not account for community-level PV sharing, sector coupling effects arising from energy communities, or the dynamic interaction between district heating expansion and local electricity demand.

This benchmark therefore represents a conventional district heating planning strategy in which district heating and heat pumps are evaluated independently, providing a reference against which the benefits of the proposed competitive heating technology framework can be assessed.

2.7 Techno-Economic and Model Assumptions

The city-scale implementation is evaluated using a common set of techno-economic and model assumptions. District heating network investment is represented by a specific pipe cost of 1,000 EUR/m and a connection cost of 4,760 EUR per connected node, while the heat supply cost is assumed to be 0.08 EUR/kWh$_{th}$. Distribution heat losses are calculated using a linear heat-loss coefficient of 0.514 W m^{-1} K^{-1} and a temperature difference of 35 K, while additional pumping costs are neglected. For decentralized heating, the heat pump connection cost is set to 29,200 EUR per node and a seasonal coefficient of performance (sCOP) of 3.75 is assumed. No minimum linear heat density, maximum network length, maximum number of DHN connections, or heat-supply capacity constraint is imposed, allowing the resulting DHN extent to emerge from the competitive techno-economic evaluation.

District heating expansion is initialized from a seed node selected based on the highest local heat demand density within the study area, providing a demand-driven starting point for network development. The seed-node selection is, however, configurable and can be replaced by other project-specific criteria, such as the location of an existing district heating network, an available waste-heat source, or a planned heat generation facility. The subsequent extent and spatial configuration of the network are not prescribed by the seed location but are determined through the competitive expansion procedure.

The adopted techno-economic values represent modelling assumptions for demonstrating the behaviour and city-scale applicability of the proposed framework and should not be interpreted as representative of actual project or market costs. The framework itself is parameterized, allowing these assumptions, including technology costs, energy prices, seed-node locations, and capacity constraints, to be adapted to different planning contexts without changing the underlying methodology.

3. Evaluation Framework

The proposed framework is evaluated at city scale using two complementary analyses. First, the resulting heating technology allocation is compared with a baseline district heating planning approach. Second, an electricity-price sensitivity analysis is performed to investigate how changes in a key techno-economic parameter influence the competition between district heating and heat pumps. All evaluations are performed for the complete city of Oldenburg using identical building data, hourly heat demand profiles, PV generation data.

For the benchmark comparison, the baseline approach evaluates DHN expansion independently of competing heating technologies and assumes unlimited heat supply capacity. Buildings for which DHN connection is not selected are supplied by individual heat pumps, with rooftop PV utilized only through building-level self-consumption. In contrast, the proposed framework considers DHN and PV-supported heat pump communities simultaneously and dynamically updates the affected communities during network expansion. The use of identical input data allows differences in the resulting technology allocation to be attributed to the respective planning approaches.

In addition to the benchmark comparison, the sensitivity of the proposed framework to electricity price is investigated. The reference electricity price is set to $p_{\text{elec}} = 0.40$ EUR/kWh, with additional simulations performed at 0.36 and 0.44 EUR/kWh. All other techno-economic and energy-system parameters are held constant. The purpose of this analysis is not to predict future electricity prices, but to evaluate how changes in the operating cost of heat pumps affect the competitive boundary between decentralized and network-based heat supply.

The evaluation focuses on indicators describing both technology allocation and infrastructure utilization. These include the number and share of nodes supplied by DHN and heat pumps, the share of annual heat demand supplied by each technology, total DHN pipe length, average linear heat density, PV utilization ratio, and the renewable share of heat pump electricity. The benchmark comparison evaluates whether explicitly considering competition between heating technologies and community-level PV sharing changes the resulting urban heating configuration, while the sensitivity analysis evaluates the stability and responsiveness of this allocation under changing electricity-price assumptions.

4. Results

The results demonstrate the application of the proposed framework to the complete city of Oldenburg. First, the city-wide graph representation and the initial formation of heat pump communities are presented. The subsequent results illustrate how these communities evolve during the competitive heating technology selection and show the resulting spatial allocation between district heating and heat pumps. Finally, the proposed approach is compared with conventional district heating planning to assess differences in network deployment, infrastructure utilization, and the use of locally generated PV electricity.

4.1 Graph Representation and Initial Heat Pump Communities

The proposed framework was applied to the complete city of Oldenburg, resulting in a connected graph comprising 44,421 address-level nodes. Figure 1 illustrates the initial heat pump communities obtained from the graph-based clustering procedure before the competitive heating technology selection process begins. For clarity, only the ten largest communities are highlighted, while the remaining smaller communities are shown in lighter colours. The resulting communities closely follow the spatial structure of the city and are not

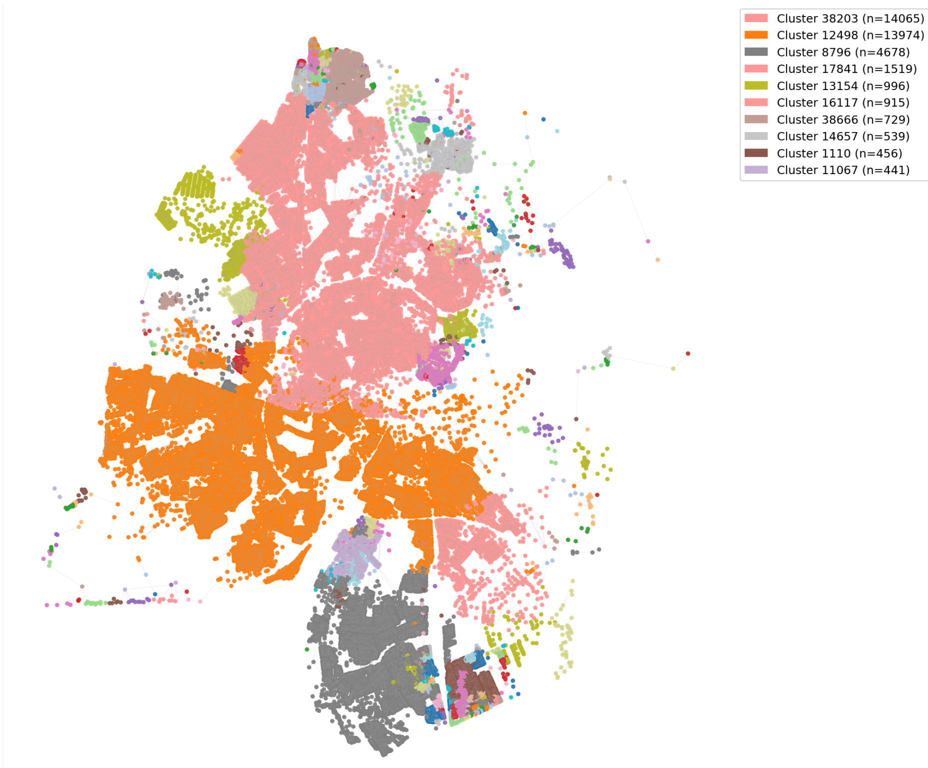

Fig. 1: Initial heat pump communities obtained from the graph-based clustering procedure for the complete city of Oldenburg. Each colour represents a distinct community.

constrained by predefined administrative boundaries or regular spatial grids. Instead, community boundaries emerge naturally from the underlying graph topology and the clustering objective, which balances local PV utilization and spatial compactness. Large communities are primarily observed in densely developed urban regions where neighbouring buildings provide greater opportunities for local energy sharing, whereas smaller communities occur predominantly in peripheral and less densely populated areas.

The distribution of community sizes reflects the heterogeneous urban morphology of Oldenburg. A small number of large communities cover the majority of the urban area, while numerous smaller communities represent isolated neighbourhoods and suburban developments. This hierarchical structure enables the framework to capture both dense city centres and sparsely populated regions within a unified graph representation without imposing artificial zoning.

These initial heat pump communities form the baseline configuration for the subsequent competitive heating technology allocation. During district heating expansion, buildings assigned to the district heating network are removed from their respective communities, and only the affected communities are locally re-clustered to account for the updated electricity demand and PV utilization. Consequently, the initial clustering provides the starting point for the dynamic interaction between decentralized heat pump communities and centralized district heating networks.

4.2 Competitive Heating Technology Selection

The competitive heating technology selection modifies both the spatial extent of the heat pump communities and the final distribution of heating technologies across the city. Figure 2 shows the resulting heat pump communities together with the nodes assigned to the DHN and the corresponding network connections. In contrast to the initial clustering shown in Figure 1, the community structure changes as the DHN expands and nodes are removed from heat pump operation.

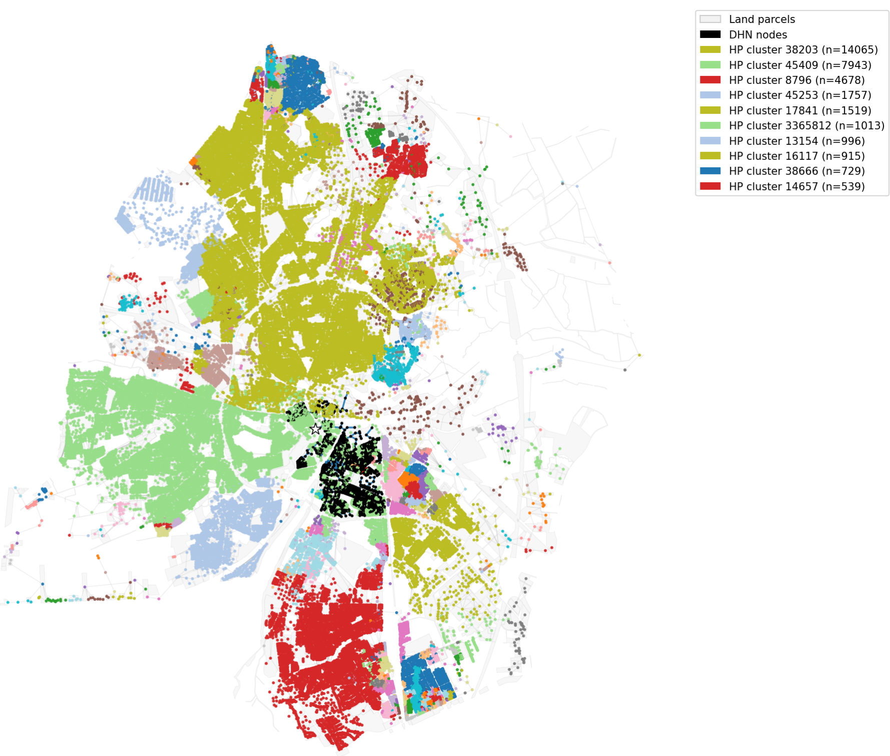

Fig. 2: Final heat pump communities after competitive heating technology selection. Coloured nodes represent the remaining heat pump communities, black nodes indicate buildings assigned to district heating.

The change in community structure is particularly visible in the size of the largest clusters. Before DHN expansion, the two largest initial communities contained 14,065 and 13,974 nodes, respectively. Following competitive technology selection and local re-clustering, the largest remaining heat pump community contains

14,065 nodes, whereas the second-largest community decreases to 7,943 nodes. Other communities also change in size and spatial extent. This demonstrates that the initial clustering does not impose a fixed community structure on the subsequent technology selection. Instead, the communities adapt locally as buildings are assigned to district heating and the corresponding heat pump electricity demand is removed.

Figure 3 presents the resulting city-wide heating technology allocation in a simplified form, distinguishing only between DHN- and heat-pump-supplied nodes. Of the 44,421 address-level nodes considered in the analysis, 1,456 nodes (3.3%) are assigned to district heating, while 42,965 nodes (96.7%) remain supplied by heat pumps. In terms of heat demand, the DHN supplies approximately 5.9% of the total annual heat demand, while the remaining 94.1% is supplied by heat pumps.

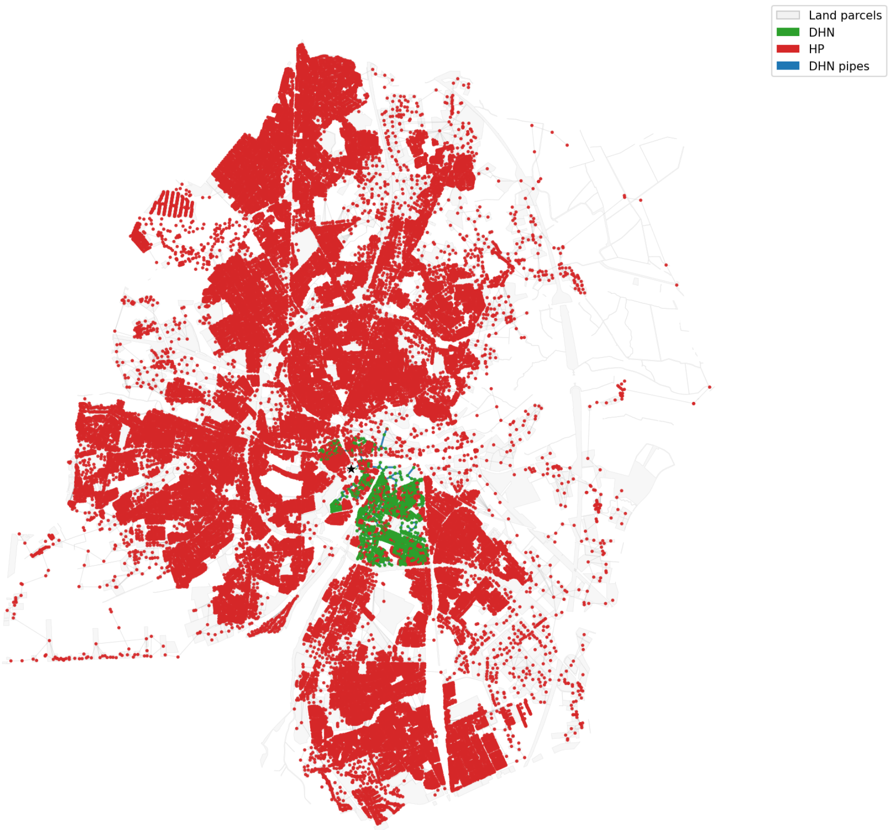

Fig. 3: Final city-wide heating technology allocation obtained using the competitive framework. Green nodes represent buildings assigned to the district heating network, red nodes represent buildings supplied by heat pumps.

The resulting allocation shows that district heating is concentrated within a relatively compact part of the urban area surrounding the predefined heat source, rather than expanding extensively across the complete city. The majority of the city remains supplied by decentralized heat pumps organized within energy communities. The resulting DHN has a total pipe length of approximately 40.8 km and achieves an average linear heat density of 7.80 $\mathrm{MWh\,m^{-1}}$, indicating that the network is concentrated in areas where the installed infrastructure can serve comparatively high heat demand.

The spatial allocation therefore illustrates the central principle of the competitive framework: district heating is not treated as the default technology wherever network expansion is possible. Instead, DHN expansion competes with PV-supported heat pump communities, while the communities themselves adapt as the technology allocation evolves. The resulting configuration combines a spatially concentrated district heating network with widespread decentralized heat pump communities across the remaining urban area.

4.3 Comparison with Baseline District Heating Planning

The proposed competitive heating technology selection is compared with the baseline district heating planning approach described in Section 2.6. Figure 4 shows the resulting heating technology allocation for the conventional approach. In this case, DHN expansion is determined without explicit competition with PV-supported heat pump communities, while buildings remaining outside the network are supplied by individual heat pumps with building-level PV self-consumption.

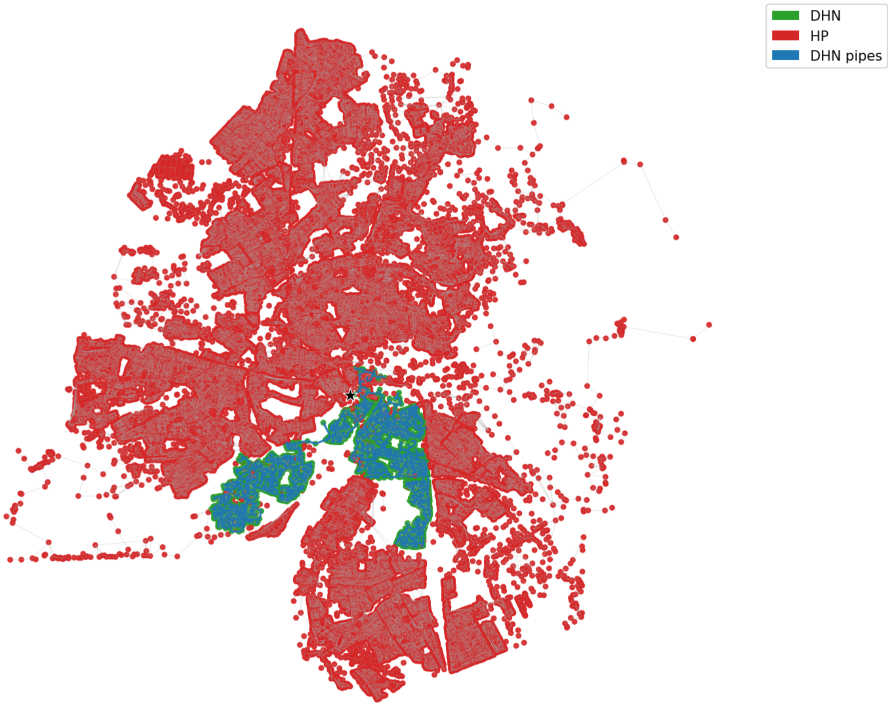

Fig. 4: Heating technology allocation obtained using the baseline district heating planning approach. Green nodes represent buildings connected to the district heating network, red nodes represent buildings supplied by individual heat pumps.

The quantitative differences between the two planning approaches are summarized in Table 1. A clear difference can be observed in the extent and utilization of the resulting district heating infrastructure. Under the baseline approach, 3,795 of the 44,421 address-level nodes are connected to district heating, compared with 1,456 nodes under the proposed competitive framework. The corresponding share of annual heat demand supplied by district heating increases from 5.9% to 8.2%. However, achieving this additional coverage requires the total DHN pipe length to increase substantially from 40.8 km in the competitive framework to 110.3 km in the conventional approach.

This difference is particularly evident in the average linear heat density. As shown in Table 1, the proposed framework achieves 7.80 $\mathrm{MWh\,m^{-1}}$ compared with 4.03 $\mathrm{MWh\,m^{-1}}$ for the baseline approach. Thus, although fewer buildings are assigned to district heating in the competitive framework, each metre of installed network supplies substantially more heat on average. The resulting DHN is therefore more concentrated in areas where the infrastructure can be utilized effectively.

Tab. 1: Comparison of the proposed competitive framework and baseline district heating planning for the city-scale case study.

Indicator	**Competitive**	**Baseline**
DHN nodes	1,456	3,795
HP nodes	42,965	40,626
DHN heat share (%)	5.9	8.2
DHN pipe length (km)	40.8	110.3
Linear heat density (MWh/m)	7.80	4.03
PV utilized (GWh/year)	1,114.8	1,080.8
PV utilization ratio (%)	70.6	68.4
Renewable share of HP electricity (%)	82.2	81.7

The interaction with local PV generation provides an additional distinction between the two planning strategies. As summarized in Table 1, the competitive framework utilizes approximately 1,114.8 GWh/year of PV generation, compared with 1,080.8 GWh/year under the baseline approach. Since total PV generation is identical in both cases at approximately 1,579.4 GWh/year, this corresponds to approximately 34.0 GWh/year of additional locally utilized PV electricity, or a relative increase of approximately 3.1% in utilized PV generation. Consequently, the overall PV utilization ratio increases from 68.4% to 70.6%.

The renewable contribution to heat pump electricity also increases from 81.7% in the baseline approach to 82.2% in the competitive framework. Although the percentage-point differences in these indicators appear moderate, their absolute magnitude becomes relevant at city scale. In particular, the additional utilization of approximately 34 GWh/year of PV electricity demonstrates the benefit of considering community-level electricity sharing together with heating technology selection rather than treating the electricity and heating sectors independently.

Overall, the comparison shows that greater DHN coverage does not necessarily imply more effective utilization of district heating infrastructure. The baseline approach connects approximately 2.6 times as many nodes and requires approximately 2.7 times the pipe length, while its average linear heat density is substantially lower. In contrast, the proposed framework combines a more concentrated DHN with greater utilization of locally generated PV electricity in the remaining heat pump communities. The resulting technology allocation therefore reflects both the efficient use of district heating infrastructure and the potential for local renewable electricity to support decentralized heating.

4.4 Electricity Price Sensitivity

The sensitivity analysis shows that electricity price has a pronounced influence on the competitive allocation of heating technologies. At the reference electricity price of 0.40 EUR/kWh, the framework assigns 1,456 nodes to district heating. Reducing the electricity price by 10% to 0.36 EUR/kWh results in no DHN connections, as heat pumps become more competitive under the applied techno-economic assumptions. In contrast, increasing the electricity price by 10% to 0.44 EUR/kWh increases the number of DHN nodes to 3,475, corresponding to approximately 7.8% of all 44,421 address-level nodes compared with 3.3% in the reference case. As illustrated in Fig. 5, the resulting increase in DHN deployment indicates a clear shift in the competitive boundary between decentralized heat pumps and district heating as electricity prices increase. Rather than prescribing a fixed technology allocation, the framework therefore responds dynamically to changes in the techno-economic conditions of the investigated scenario.

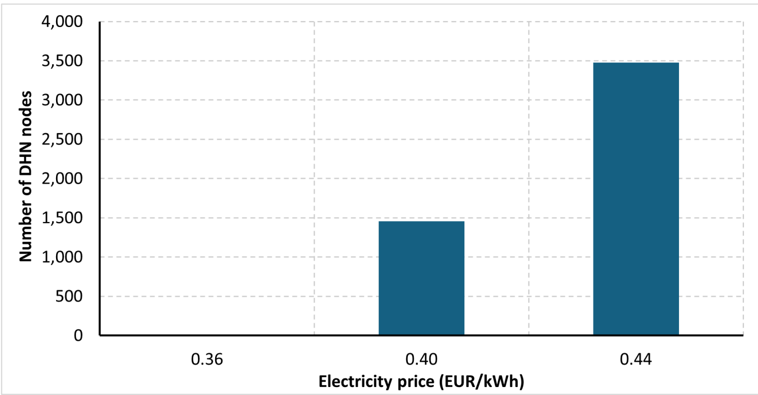

Fig. 5: Sensitivity of district heating allocation to a ±10% variation in electricity price around the reference value of 0.40 EUR/kWh.

5. Discussion and Conclusions

This study demonstrates the city-scale implementation of a graph-based framework for the competitive allocation of district heating and PV-supported heat pump communities. Rather than determining heating technologies independently, the proposed approach considers the interaction between centralized heat supply, decentralized heat pumps, and locally generated PV electricity. Applying the framework to the complete city of Oldenburg demonstrates that this interaction can be represented at address level while retaining the spatial structure of the urban area.

The comparison with baseline district heating planning highlights an important consequence of the competitive approach. Expanding the DHN wherever connection is economically feasible results in substantially greater network coverage, but does not necessarily lead to more effective use of the installed infrastructure. The proposed framework assigns fewer nodes to district heating and concentrates the network in areas where heat demand can be served with considerably higher linear heat density. The resulting average linear heat density increases from 4.03 to 7.80 $\mathrm{MWh\,m^{-1}}$, while the required network length decreases from 110.3 to 40.8 km. This indicates that considering the alternative value of decentralized heating during network expansion can lead to a more selective utilization of district heating infrastructure.

The results also demonstrate the importance of coupling heating technology selection with the local electricity balance. Buildings remaining within heat pump communities can share locally generated PV electricity, while the community configuration is dynamically updated as district heating expansion removes heat pump electricity demand. At city scale, this interaction increases utilized PV generation from approximately 1,080.8 to 1,114.8 GWh/year compared with the conventional case, corresponding to approximately 34 GWh/year of additional PV utilization. Although the increase in the overall PV utilization ratio from 68.4% to 70.6% appears moderate, the absolute difference demonstrates the relevance of community-level electricity sharing when applied across a complete urban area. The framework therefore provides a mechanism for simultaneously considering efficient DHN deployment and renewable electricity utilization rather than optimizing the heating and electricity sectors independently.

The resulting technology allocation should not be interpreted as a fixed prescription for the future heating system of Oldenburg. The spatial distribution of DHN and heat pump communities depends on the techno-economic assumptions, available heat sources, PV potential, and technology characteristics used in the analysis. Instead, the main contribution is the planning framework itself, which enables these interacting factors to be evaluated consistently at city scale. The comparison further illustrates that indicators such as network coverage alone are insufficient for evaluating urban heating strategies; infrastructure utilization, local renewable energy use, and interactions between competing technologies should also be considered.

The current implementation considers district heating, heat pumps, and rooftop PV generation. Future work will extend the framework to additional heating technologies, renewable energy sources, and electrical and thermal storage options. Heat-source capacity constraints can also be introduced to represent situations in which district heating expansion is limited by the available thermal generation capacity. Another planned extension is the development of a cluster-level prioritization metric that quantifies the potential system improvement associated with interventions in individual energy communities. Such a metric could support staged urban energy planning by identifying communities where infrastructure or technology changes provide the greatest benefit when city-wide transformation cannot be implemented simultaneously.

Further work will also focus on improving the computational implementation of the iterative clustering and network-expansion procedure. The present study demonstrates the applicability of the framework to a city-wide graph containing 44,421 address-level nodes; however, a systematic assessment of computational performance has not been undertaken. Algorithmic optimization and runtime benchmarking across urban datasets of different sizes will therefore be investigated to quantify scalability and identify opportunities for further computational improvement.

Overall, the results demonstrate that competitive heating technology planning can provide information beyond that obtained from independent district heating expansion. By explicitly accounting for the interaction between DHN deployment, heat pump communities, and local PV sharing, the proposed framework produces a more concentrated district heating network while simultaneously increasing the utilization of locally generated renewable electricity. This integrated perspective provides a basis for spatially resolved urban heating transition planning in which centralized and decentralized technologies are treated as complementary and competing components of the same energy system.

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