CITY-SCALE IMPLEMENTATION OF CLUSTERING AND COMPETITIVE HEATING TECHNOLOGY FRAMEWORK

Summary

This paper presents a city-scale implementation of a segmentation framework which assigns competing heating technologies to groups of buildings with a high spatial resolution. Building land parcels are aggregated into spatial nodes and grouped using a clustering strategy that enhances local solar self-consumption while maintaining spatial compactness. Heating technologies are selected through a competitive expansion process comparing heat pump communities and district heating networks (DHN) under techno-economic constraints. The method is evaluated at full urban scale. A scenario analysis on varying cost inputs demonstrates the applicability of the framework for early-stage planning tasks at the city level. Results show that the framework works reliably and efficiently at city scale and how considering solar-electric interactions and local sector coupling has a strong impact on the choice between technologies, enabling more integrated infrastructure planning.

Keywords: city-scale implementation, heating technology selection, clustering strategy, district heating networks, heat pump communities, solar-electric interactions, techno-economic analysis, sector coupling.

Field of application for the findings: Strategic planning of urban heating infrastructure, identification of heat pump communities, district heating expansion assessment under sector coupling considerations.

Addressed audience: Researchers in urban energy systems and solar integration, district heating planners and utilities, municipal energy strategy departments, and policymakers involved in heating transition planning.

1. Introduction

Urban heating decarbonization increasingly relies on electrified technologies such as heat pumps, while district heating networks (DHN) remain important in dense urban areas. In future urban energy systems, local groups of buildings that share energy resources are expected to play a central role, often described as energy communities or energy cells (Perera et al., 2021). In this context, we introduce the concept of heat pump communities (HPC), defined as spatially aggregated building groups that share locally produced electricity, such as photovoltaic (PV) generation, to operate individual heat pumps. As of now, systematic methods to identify such spatially coherent groups in urban environments and compare the techno-economic suitability of alternative heat supply solutions remain limited. This work, therefore presents a city-scale implementation of a simplified segmentation approach to define and evaluate such building groups. The method uses a graph-based clustering strategy and explicitly considers the economic competition between HPC and DHN as alternative heat supply structures.

As PV deployment increases, locally generated electricity can partially supply the electricity demand of heat pumps, reducing reliance on the grid and affecting the competitiveness of heat pumps with respect to DHN. Planning approaches that do not consider this local solar coupling may lead to suboptimal technology choices across urban areas.

This method identifies the most suitable heating technology for groups of buildings. It uses a graph-based clustering (Carneiro and Zhao, 2018) strategy and explicitly accounts for the economic competition between different heating technologies. In this case, spatial aggregation of buildings to improve local PV utilization by heat pumps is compared with heat supply through DHN. The method, therefore, combines spatial clustering with an incremental techno-economic comparison between different heating solutions. Overall, the approach demonstrates that city-scale heating technology selection and cluster identification can be achieved without compromising spatial resolution while remaining computationally feasible.

2. Method Overview

The urban area is represented as a graph $G = (N, E)$, where nodes correspond to land parcels aggregated at address level after basic data cleaning to remove non-relevant use types. Each node is characterized by building attributes such as hourly heat demand profiles, PV generation potential, and spatial location. Edges represent the economic interaction potential between neighboring nodes, reflecting the benefit or cost of grouping nodes together to share a common heat supply structure (Felzenszwalb and Huttenlocher, 2004).

Cluster identification is performed using a greedy merging strategy (Pei et al., 2026). In the first step, spatial clusters are formed to maximize local PV sharing while maintaining spatial compactness. Here, PV utilization refers to the use of locally generated electricity within the cluster before drawing electricity from the grid. By aggregating electricity demand and PV generation across neighboring nodes, locally produced solar energy can offset heat pump electricity demand beyond individual building boundaries.

Once clusters are established, a competitive heating technology selection process is applied. Starting from predefined seed nodes at possible heat sources, DHN expansion is evaluated incrementally against cluster-based electric heat supply. Whenever a node is assigned to DHN, its electrical heating demand is removed from the cluster electricity balance. This change affects PV utilization within the remaining cluster and therefore triggers a local re-clustering step to update electricity balances and techno-economic evaluation.

This two-stage procedure provides a simplified yet scalable framework for identifying spatial heating structures at city scale.

3. City-Scale Implementation

The method is applied to a city comprising approximately 40,000 spatial nodes. Hourly heat demand profiles and hourly PV generation time series are used to evaluate annual performance. The spatial graph representation enables selection among competitive heating technologies across the entire urban area.

The segmentation algorithm is executed for the full city, producing a spatially explicit allocation of HPC and district heating connections. Key performance indicators include DHN penetration rate, total network length, annualized system cost, residual grid electricity consumption, and spatial distribution of heating technologies.

Conventional district heating planning approaches are typically based on heat density thresholds and pipe investment economics. These methods rely on spatial averaging of demand over predefined areas and assess network feasibility primarily through aggregated heat density and infrastructure cost indicators. As a result, they do not perform an explicit node-by-node comparison between alternative heating technologies and generally neglect interactions with distributed electricity generation at building level.

In contrast, the proposed framework evaluates heating technology choices at node level and explicitly integrates PV generation into the decision process. Cluster-level PV sharing allows locally generated electricity to reduce the effective operating cost of heat pumps, and this benefit is reassessed dynamically during network expansion. Importantly, assigning a node to district heating alters the local electricity balance and changes the availability of PV within the remaining cluster. This feedback effect is explicitly taken into account through iterative updating of PV utilization. The framework therefore enables a technology-neutral, system-level assessment that captures sector coupling effects rather than relying on density-based averaging.

4. Scenario Analysis

Scenario analysis is conducted to evaluate the robustness of the framework under variations in key techno-economic parameters such as electricity price and district heating pipe investment cost. Beyond expected economic shifts, the analysis demonstrates the stability and computational performance of the algorithm at full city scale.

The framework provides spatially explicit, node-level heating technology allocation rather than density-based averaging across predefined zones. This higher resolution supports the identification of building-level energy communities and is aligned with emerging energy cell concepts. In contrast to traditional density-based planning, the method explicitly captures sector coupling effects and dynamically updates local electricity balances during the identification of suitable DHN customers.

The algorithm is fully deterministic and reproducible, with transparent decision rules based on techno-economic comparison rather than black-box optimization. For the investigated urban dataset comprising several thousand nodes, the full pipeline executes within a practical runtime on standard computing hardware, making it suitable for scenario exploration and planning studies. Compared to large-scale mathematical design optimizations, which often become computationally prohibitive at city scale, the proposed approach offers a tractable and scalable alternative.

These characteristics demonstrate that the framework is not only economically meaningful but also computationally efficient and practically deployable for urban heating transition analysis.

5. Results and Conclusions

The city-scale implementation shows that the proposed clustering and competitive heating technology framework can be applied consistently to a complete urban dataset. By incorporating PV generation into heating technology selection, the method captures solar-electric interactions and supports sector-coupled infrastructure assessment at a high resolution.

The algorithm performs reliably at city scale. Computational performance mainly depends on the number of DHN nodes, since each new integration step requires a localized re-clustering. As the network grows, execution time increases due to the iterative nature of expansion and re-clustering. For a full urban dataset comprising several thousand nodes, the complete pipeline executes within a few hours on standard desktop hardware. Despite this iterative behavior, the framework remains computationally manageable for full urban deployment and scenario analysis.

The clustering structure developed in this study provides a scalable baseline for future urban energy system design and operational optimization. The defined clusters function as modular energy communities that enable coordinated operation and support the integration of additional renewable energy sources. As a next step, a ranking mechanism could be introduced to evaluate and prioritize clusters according to their suitability for development as HPCs, for example based on PV potential, demand characteristics, and techno-economic performance. This would allow planners to systematically identify the most promising areas for decentralized electrified heat supply. The framework therefore establishes a foundation for extended multi-energy system analysis and design at city scale.

References

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