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Heat Transition and Decarbonization in the German Building Stock: Insights on Energy Vulnerabilities in Northern Germany

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Abstract — **Achieving climate neutrality by 2045 requires a fundamental transformation of the German building sector, where residential heating accounts for more than 65% of final energy consumption and remains largely dependent on fossil fuels. Despite increasing regulatory pressure, renovation rates remain insufficient to meet decarbonization targets. While existing research predominantly focuses on technical solutions, spatial and socio-economic dimensions are often underrepresented. This paper develops a spatially explicit and socio-technical framework to analyse urban heat transition pathways using two representative urban districts within the city of Braunschweig as case studies. Building-level energy demand, renewable energy potentials, and greenhouse gas emissions are modelled using scenario-based simulations. Decarbonization pathways include heat pump deployment, district heating expansion, photovoltaic integration, and deep renovation strategies. In addition to technical performance indicators, socio-economic data such as income distribution, tenancy ratios, and household characteristics are integrated into the analysis. This enables the identification of spatial patterns of energy vulnerability and the assessment of distributional impacts of heat transition strategies. The results reveal clusters of high-emission building typologies and socially vulnerable populations, highlighting areas where decarbonization measures can achieve both emission reductions and social co-benefits. At the same time, potential conflict zones emerge where rapid transitions may exacerbate social inequalities. The proposed methodology supports evidence-based and socially balanced urban energy planning and contributes to bridging the gap between spatial energy system analysis and the assessment of social vulnerability in urban decarbonization processes.**

***Keywords*— Decarbonization, Heat Transition, Building Energy Modelling, Energy Vulnerability, Residential Building Typologies**

I. INTRODUCTION

Achieving climate neutrality by 2045 represents a central objective of Germany's climate strategy and necessitates a profound transformation of the building sector. Residential buildings play a key role in this transition, as space heating accounts for the majority of final energy consumption in households and remains largely dependent on fossil fuels. Despite increasing regulatory pressure and financial support schemes, the annual renovation rate remains below 1%, which is insufficient to meet national decarbonization targets.

Over the past decade, research has primarily focused on technological pathways to reduce emissions in the building sector, including the electrification of heating systems, the expansion of district heating networks, and improvements in building envelope efficiency. While these approaches demonstrate considerable technical potential, they are often evaluated without sufficient consideration of spatial heterogeneity and socio-economic disparities within urban environments.

At the same time, rising energy prices have increased attention to distributional effects and energy vulnerability. Households with low income or living in inefficient buildings are particularly exposed to increasing heating costs and may be disproportionately affected by decarbonization policies.

However, integrated approaches that combine building energy modelling with spatial and socio-economic analysis remain limited. In particular, there is a lack of methodologies that allow for the identification of priority areas where emission reduction potential and social vulnerability coincide.

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This paper addresses this gap by developing a spatially explicit and socio-technical framework for analysing transition pathways using a selected urban district within the city of Braunschweig as case study. The approach integrates building-level energy modelling with geospatial and socio-economic data to assess both technical performance and distributional impacts.

The analysis is guided by the following research questions:

(1) Which residential building typologies contribute most significantly to carbon emissions?
(2) Which geospatial indicators are suitable for identifying and prioritizing decarbonization measures at the district scale?
(3) To what extent are specific societal groups disproportionately affected by energy price volatility and fossil fuel dependency?

By addressing these questions, the paper contributes to the development of more effective and socially equitable strategies for decarbonizing urban building stocks.

II. BACKGROUND AND RELATED WORK

The decarbonization of the building sector is a key component of climate mitigation strategies. In Germany, residential buildings account for a significant share of final energy consumption, with space heating as the dominant end use. Consequently, research has focused on technological pathways such as building retrofit, heating system replacement, and the integration of renewable energy technologies including heat pumps and photovoltaic systems. Urban energy system models further support the analysis of heat demand and supply configurations at district and city scales. However, these approaches often overlook spatial heterogeneity within cities. Differences in building typologies, densities, and infrastructure conditions strongly influence the feasibility of decarbonization measures, highlighting the importance of spatially explicit analyses.

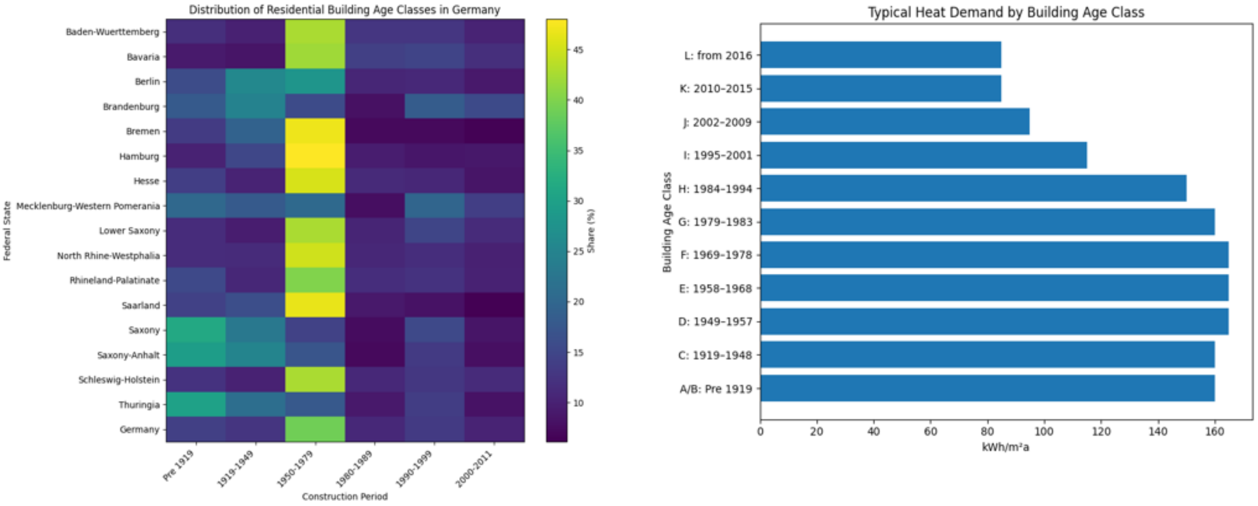

Fig 1: Distribution of residential building age classes in Germany (a) and specific building heat demands per class (b).

As illustrated, building classes D, E, and F exhibit the highest specific heat demand and, due to their large share in the building stock, represent the primary drivers of energy consumption and emissions as primary energy carriers for water and ambient heating are still largely fossil-fueled. At the same time, the social dimension of the energy transition has received growing attention. Rising energy prices and increasing awareness of energy poverty have highlighted the vulnerability of certain population groups, particularly low-income households living in inefficient buildings. These households often face disproportionately high energy costs and have limited capacity to invest in energy efficiency improvements. Despite this growing body of research, the integration of socio-economic factors into spatial energy system analysis remains limited. Many studies focus either on technical optimization or on social aspects in isolation. As a result, there is a lack of integrated approaches that allow for the simultaneous assessment of emission reduction potentials and social impacts. This paper contributes to addressing this gap by developing a spatially explicit and socio-technical

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framework that combines building energy modelling with socio-economic analysis. By linking technical performance indicators with measures of social vulnerability, the approach enables a more comprehensive assessment of urban heat transition pathways and supports the identification of priority areas for intervention.

III. METHODOLOGY

A. *Case Study Area*

The building stock is dominated by post-war typologies, particularly buildings constructed between 1969 and 1978 (class F). Due to insufficient insulation and outdated construction standards, these buildings exhibit high specific heat demand, resulting in elevated energy consumption at the district scale. This makes the area suitable for analysing decarbonization strategies in high-demand environments.

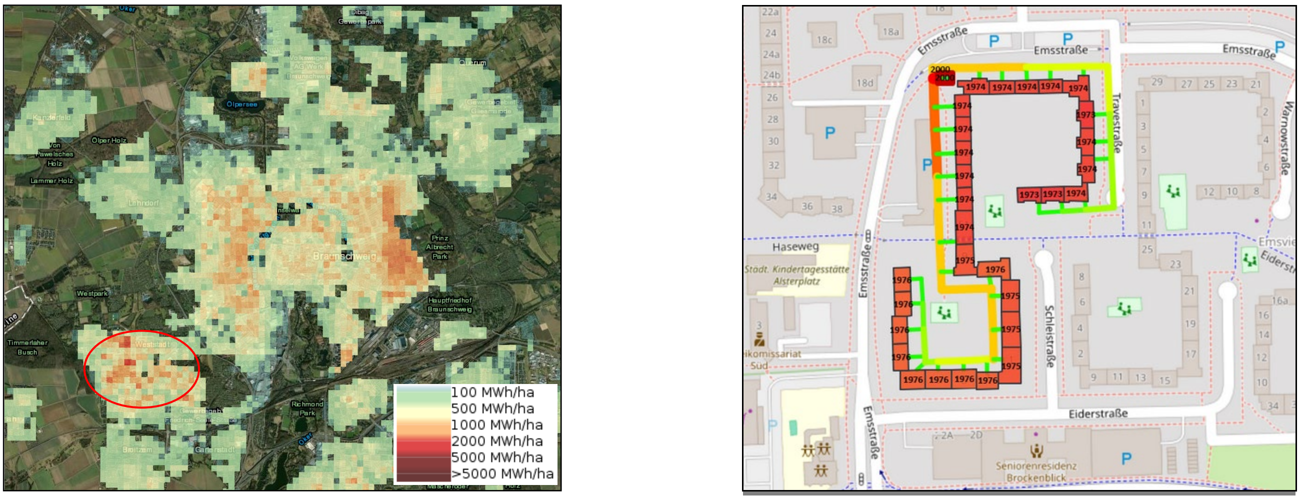

Fig 2: Residential heat demand density of city of Braunschweig (a) and selected case study quarter (b).

All buildings are connected to a district heating network, providing a basis for evaluating centralized supply strategies. The district also exhibits socio-economic vulnerability, including lower income levels, a high share of tenants, and limited investment capacity. This combination of high demand and social constraints makes the area particularly relevant for assessing distributional impacts.

B. *Data Basis and Integration*

The analysis is based on an integrated dataset combining geospatial, building-specific, and socio-economic information. The building dataset includes 32 residential buildings with a total floor area of approximately 23,455 m².

For each building, key attributes such as construction year, building typology, and floor area are available. These attributes are used to assign representative thermal properties and derive building-specific heat demand values. The classification of buildings into age-based typologies allows for a consistent mapping of thermal performance characteristics across the district. In addition to building data, infrastructure-related information is incorporated, including the layout and operational parameters of the district heating network. This includes indicators such as linear heat density and network losses, which are essential for evaluating the efficiency of centralized heat supply. Socio-economic data is integrated at the district level, including indicators such as income distribution, tenancy ratios, and household characteristics. These variables are used to assess energy vulnerability and to analyse the distributional impacts of different decarbonization pathways. The integration of these heterogeneous datasets enables a multi-dimensional analysis that captures both technical system performance and socio-economic conditions.

C. *Energy Modelling Approach*

The energy modelling approach follows a bottom-up methodology, where heat demand is calculated at the building level and subsequently aggregated to the district scale. This approach allows capturing the heterogeneity of the building stock and its influence on overall energy demand.

Specific heat demand values are assigned based on building age classes, reflecting differences in thermal performance and construction standards. These values are derived from representative benchmarks for German residential buildings and account for variations in insulation quality, building geometry, and system efficiency. The total annual heat demand of the district amounts to approximately 2,150.6 MWh, consisting of space heating (1,657.7 MWh) and domestic hot water demand (493.0 MWh). These values serve as the baseline for all scenario calculations. Energy supply systems are modelled according to scenario-specific configurations. In the district heating scenario, heat supply is centralized, and network losses are explicitly considered. In the heat pump scenarios, electricity demand is calculated based on a seasonal coefficient of performance (COP), reflecting realistic operating conditions. Primary energy consumption and CO_2 emissions are calculated using scenario-specific emission factors and conversion parameters. This allows for a consistent comparison of environmental performance across all scenarios.

D. Scenario Definition

Four decarbonization scenarios are defined to represent different strategic approaches for transforming the urban heating system:

(1) District heating (baseline scenario):

The existing centralized heat supply system is maintained without major structural changes. This scenario serves as a reference case and reflects current system performance, including network losses and emission intensity.

(2) Heat pump integration:

The centralized district heating system is replaced by decentralized air-source heat pumps at the building level. This scenario represents a fully electrified heating system and allows for assessing the impact of electrification on energy demand, emissions, and infrastructure requirements.

(3) Heat pump + photovoltaic integration:

This scenario extends the electrification pathway by integrating on-site photovoltaic systems. The locally generated electricity is used to partially cover the electricity demand of the heat pumps, thereby reducing grid dependency and improving the carbon balance.

(4) District heating + building retrofit:

In this scenario, the existing district heating system is retained, while building envelope improvements are implemented to reduce heat demand. This represents a demand-side intervention strategy that focuses on improving energy efficiency rather than changing the supply system. The selected scenarios cover a broad spectrum of decarbonization strategies, including supply-side transformation, electrification, renewable integration, and demand reduction. This allows for a comprehensive assessment of trade-offs between technical performance, environmental impact, and socio-economic feasibility.

E. Socio-Economic Assessment

Socio-economic indicators are linked to the building stock to assess energy cost burdens and vulnerability to price increases. This enables the identification of areas where technical and social challenges overlap.

IV. RESULTS AND DISCUSSION

A. Baseline Scenario: District Heating

In the baseline scenario, the total heat demand of 2,150.6 MWh is supplied via the existing district heating network. A high linear heat density of 2.27 MWh/m indicates favourable conditions for centralized supply. However, environmental performance remains limited. Total CO_2 emissions amount to 358.8 t (166.9 g/kWh), mainly driven by the carbon intensity of the heat supply and high demand levels. Network losses of 218.5 MWh (≈10%) further increase system inefficiencies. These results show that even well-developed district heating systems do not inherently ensure low emissions and depend strongly on supply decarbonization and demand reduction.

B. Heat Pump Scenario

Replacing district heating with decentralized air-source heat pumps reduces emissions to 184.2 t (−49%). The specific emission intensity decreases to 85.7 g/kWh, reflecting higher system efficiency. Electricity demand amounts to 526.3 MWh, with a seasonal COP of 4.09. However, primary energy consumption increases to 947 MWh due to electricity conversion factors. Additionally, electrification introduces strong dependency on the electricity grid, potentially increasing peak loads and infrastructure requirements.

C. Heat Pump + Photovoltaic Scenario

Integrating photovoltaic systems significantly improves performance. Emissions decrease to 106.4 t (−70% vs. baseline), with the lowest specific emissions (49.5 g/kWh). PV generation (9,843 MWh) exceeds demand, leading to substantial grid feed-in and reduced electricity imports (304.0 MWh). Primary energy decreases to 547 MWh, making this the most efficient scenario. However, mismatches between generation and demand require grid interaction, and feasibility depends on roof availability and ownership structures.

D. District Heating + Retrofit Scenario

This scenario reduces heat demand through building envelope improvements while maintaining centralized supply. Lower demand decreases both energy use and network losses, improving overall efficiency. Unlike supply-side strategies, retrofit addresses structural inefficiencies and increases resilience to energy price fluctuations. However, high investment costs and long implementation times remain key barriers.

E. Scenario Comparison: Cost and Emissions

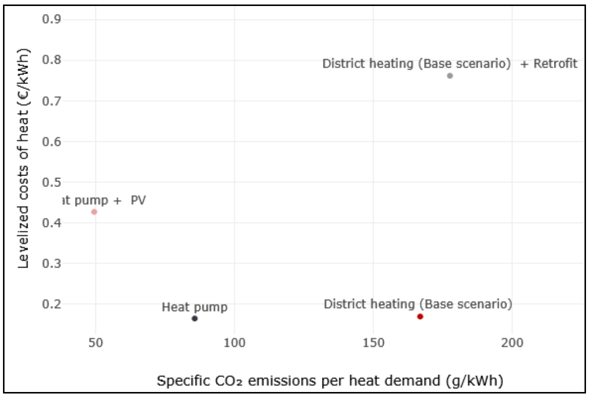

Fig 3: Scenario comparison in cost and emissions dimension.

Fig. 3 provides a comparative overview of the analysed scenarios in terms of specific CO_2 emissions and levelized cost of heat. The results reveal clear trade-offs between economic and environmental performance. The baseline district heating scenario is characterized by relatively low costs but high emissions. The heat pump scenario significantly reduces emissions while maintaining moderate cost levels. The heat pump + PV scenario achieves the lowest emissions, demonstrating the effectiveness of combining electrification with renewable energy generation. In contrast, the district heating + retrofit scenario improves emission performance compared to the baseline but is associated with the highest costs due to investment in building upgrades. Overall, the results indicate that no single scenario simultaneously minimizes both emissions and costs. Instead, decision-making requires balancing environmental objectives with economic feasibility.

F. Energy Vulnerability and Social Implications

The results show that socio-economic conditions strongly influence both the feasibility and distributional impacts of decarbonization pathways. In particular, low-income households and tenants are disproportionately affected by energy price volatility due to higher relative energy expenditures and limited investment capacity. In the baseline scenario, the dependence on district heating systems creates structural vulnerability, as households have limited control over energy sources and are directly exposed to centralized pricing mechanisms. Electrification strategies and renewable integration, while effective in reducing emissions, require significant upfront investments and are therefore often less accessible to financially constrained

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households. Similarly, building retrofit measures may lead to rent increases, creating potential conflicts between decarbonization and housing affordability.

To address these challenges, spatially explicit indicator systems are essential for identifying priority areas where high emission reduction potential coincides with socio-economic vulnerability. Relevant indicators include (a) energy demand intensity (kWh/m²), (b) building age structure (e.g. dominance of class F), (c) energy cost burden (% of income), (d) people age higher than 60 years (% of population), (e) exposure to energy price volatility, (f) renovation rate and building condition. These indicators enable the targeted prioritization of interventions and highlight the need for socially balanced policy measures to ensure that the heat transition does not exacerbate existing inequalities.

V. CONCLUSIONS

This paper presented a spatially explicit and socio-technical framework to analyse urban heat transition pathways using a representative case study district in Braunschweig. By integrating building-level energy modelling with geospatial and socio-economic data, the study enables a combined assessment of technical performance and distributional impacts. The results show that post-war residential buildings, particularly those constructed between 1969 and 1978 (class F), are the dominant drivers of heat demand and CO_2 emissions due to their high specific energy consumption and large share in the building stock. Spatial indicators such as energy demand intensity, building age structure, CO_2 emission density, and socio-economic characteristics enable the identification of priority areas where high emission reduction potential coincides with social vulnerability. The analysis further demonstrates that socially vulnerable households are disproportionately affected by energy price volatility and have limited capacity to invest in decarbonization measures. At the same time, capital-intensive solutions such as heat pumps and photovoltaic systems may reinforce existing inequalities if not supported by targeted policies. Scenario results indicate that electrification and renewable integration offer substantial emission reductions, while retrofit measures reduce demand. However, trade-offs between environmental performance and economic feasibility remain. Overall, decarbonizing urban heating systems requires integrated strategies that combine technological transformation with social considerations to ensure both effectiveness and equity.

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