10.051103/RES.260605106
Vol.5 Iss.1 pp.61-73 International Journal of Renewable Energy and Sustainability (RES)

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 a representative urban district within the city of Braunschweig as a case study. 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 is 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

The decarbonization of the building sector represents one of the key challenges for achieving Germany's target of climate neutrality by 2045 [1]. Residential buildings account for approximately one-third of the country's final energy consumption, with space heating remaining the dominant end use and still relying largely on fossil fuels [2]. Consequently, transforming urban heating systems is considered an essential component of both the German Energiewende and the European Green Deal [1]. At the international level, the Intergovernmental Panel on Climate Change (IPCC) identifies improvements in building energy efficiency, electrification of heat supply and the integration of renewable energy systems as indispensable measures for limiting greenhouse gas emissions from the built environment [1].

At the same time, cities have become the primary arenas for climate mitigation and adaptation [3]. Urban areas concentrate population, infrastructure and energy demand, while simultaneously being responsible for the majority of global energy-related greenhouse gas emissions [3]. As a result, municipalities are increasingly required to develop local heat planning strategies that combine technical feasibility with environmental effectiveness and long-term social acceptance [33]. The German Municipal Heat Planning Act (Wärmeplanungsgesetz) further underlines the growing importance of evidence-based planning approaches for identifying suitable decarbonization pathways at the district scale [36].

Recent research has identified several technological options for reducing emissions from residential buildings [1]. Building envelope retrofits, district heating expansion, heat pump deployment and rooftop photovoltaic (PV) systems are widely recognised as the principal pathways towards climate-neutral heat supply [4], [6], [7], [32]. While building retrofits reduce heat demand, electrification through heat pumps enables the substitution of fossil fuels by renewable electricity [4], [6]. Furthermore, district heating systems

ISSN: 2961-6603

10.051103/RES.260605106
Vol.5 Iss.1 pp.61-73 International Journal of Renewable Energy and Sustainability (RES)

increasingly incorporate renewable heat sources, industrial waste heat and large-scale thermal storage, thereby improving overall system efficiency and reducing greenhouse gas emissions [32]. Recent studies also demonstrate that coupling heat pumps with photovoltaic systems can significantly improve operational flexibility and reduce dependence on grid electricity, particularly in urban residential districts [34].

Alongside these technological developments, Urban Building Energy Modelling (UBEM) has emerged as an important decision-support tool for municipal energy planning [9]. Recent reviews demonstrate a clear transition from aggregated top-down approaches towards physics-based bottom-up models that explicitly represent individual building characteristics, spatial heterogeneity and local infrastructure [9]. Integrating Geographic Information Systems (GIS) with building energy simulations enables municipalities to identify spatial patterns of heat demand, evaluate alternative supply concepts and prioritise decarbonization measures according to local conditions [33].

While considerable progress has been made in modelling urban energy systems, the social dimension of the heat transition has only recently gained increasing attention [17]. Rising energy prices, demographic change and unequal investment capacities have highlighted that the transition towards climate-neutral heating may affect households differently [2]. Vulnerable groups, including low-income households, tenants and elderly residents, often face disproportionately high energy cost burdens while simultaneously lacking the financial resources to invest in energy-efficient refurbishment or renewable heating technologies [4], [12], [35]. Consequently, current research increasingly argues that successful heat transition strategies must integrate technical optimisation with broader considerations of energy justice, affordability and social equity [14], [15].

Despite these advances, an important research gap remains. Existing studies predominantly investigate either technological optimisation of heating systems or socio-economic aspects of the energy transition [9], [10]. Comparatively few approaches integrate building-level energy modelling, spatial analysis and energy vulnerability assessment within a unified framework capable of supporting municipal heat planning at the neighbourhood scale [17], [33]. As municipalities are required to develop locally adapted heat transition strategies, there is an increasing need for integrated approaches that simultaneously evaluate technical performance, environmental impacts and social implications [9], [33].

Against this background, this paper presents a spatially explicit socio-technical assessment framework for analysing urban heat transition pathways using a representative residential district in Braunschweig, Northern Germany, as a case study. Building-level energy demand is combined with geospatial information, district heating infrastructure and socio-economic indicators to evaluate four alternative decarbonization scenarios. In addition to comparing technical, environmental and economic performance, the proposed framework explicitly considers spatial patterns of energy vulnerability to identify priority areas for socially balanced municipal heat planning.

The study addresses the following research questions:

(1) Which residential building typologies contribute most significantly to urban heat demand and CO_2 emissions?
(2) Which spatial indicators are most suitable for prioritising urban decarbonization measures at the district scale?
(3) To what extent are vulnerable population groups disproportionately affected by alternative heat transition pathways?

By integrating engineering, spatial analysis and socio-economic assessment, the proposed framework contributes to evidence-based municipal heat planning and supports the development of urban heat transition strategies that are not only environmentally effective but also socially equitable.

II. BACKGROUND AND RELATED WORK

A. Building Stock Decarbonization in Germany

Decarbonizing the existing residential building stock is considered one of the most effective measures for reducing greenhouse gas emissions in Germany [1]. Residential buildings account for a significant share of national final energy consumption, with space heating representing the dominant energy end use [2]. Since a

ISSN: 2961-6603

10.051103/RES.260605106
Vol.5 Iss.1 pp.61-73 International Journal of Renewable Energy and Sustainability (RES)

considerable proportion of German residential buildings was constructed before the implementation of modern thermal insulation standards, substantial energy-saving potentials remain within the existing building stock [18].

The residential building typology developed by Loga et al. [18] provides a standardized classification of German buildings according to construction period and representative thermal characteristics. Buildings erected between the post-war period and the late 1970s generally exhibit comparatively poor energy performance while simultaneously accounting for a large proportion of the existing housing stock [18]. Consequently, these buildings contribute disproportionately to urban heat demand and operational CO_2 emissions [18].

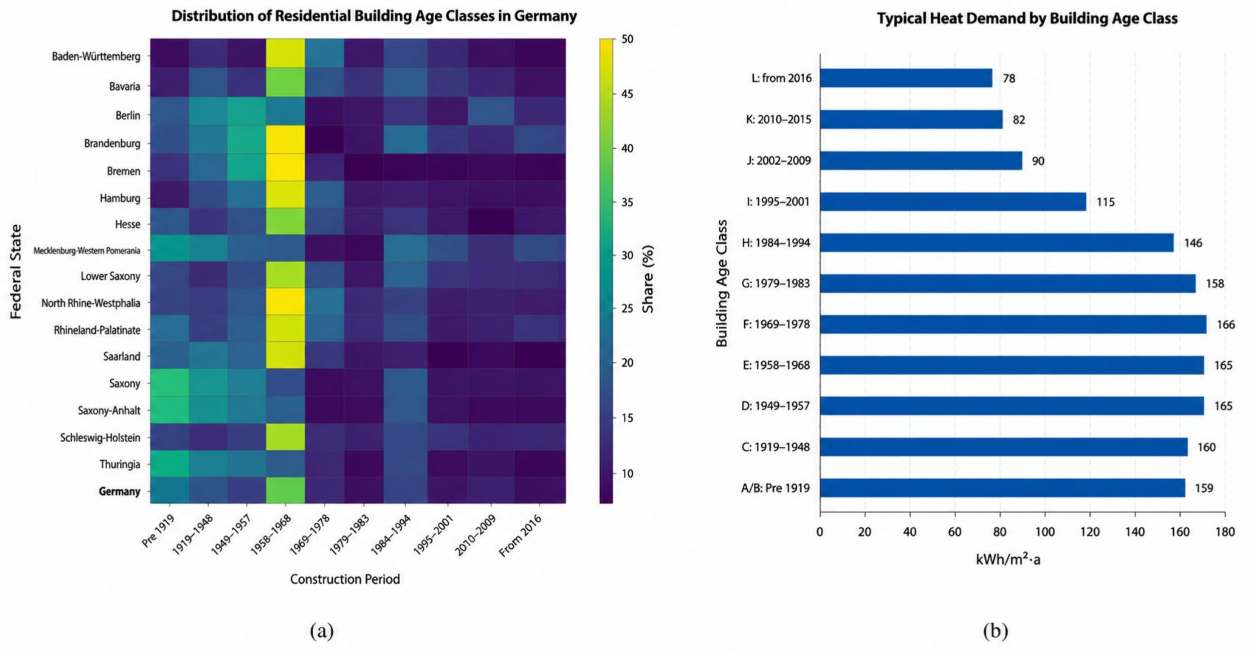

Fig 1: Distribution of residential building age classes across the German federal states (a) and representative specific heat demand by age class (b).

Recent studies consistently demonstrate that deep building renovation combined with low-carbon heating technologies represents the most effective pathway towards climate-neutral residential buildings [1], [4, [6]. However, renovation strategies must be adapted to local building characteristics and existing infrastructure, as technical and economic boundary conditions differ considerably between urban districts [4].

B. Urban Heat Transition Technologies

The transition towards climate-neutral urban heating requires the combination of multiple complementary technologies rather than reliance on a single solution [1]. Current research identifies district heating, electrification through heat pumps, renewable electricity generation and energy efficiency improvements as the principal components of future urban heating systems [6], [7], [32].

Heat pumps have become one of the most widely discussed technologies for residential decarbonization due to their high seasonal efficiencies and their ability to utilize renewable electricity [6]. Recent review studies further demonstrate that combining heat pumps with thermal energy storage improves operational flexibility while increasing the integration of fluctuating renewable electricity generation [34].

District heating remains particularly attractive for densely populated urban neighbourhoods where high heat densities enable efficient centralized heat supply [32]. Recent developments increasingly focus on Fifth Generation District Heating and Cooling (5GDHC) systems that integrate renewable heat sources, industrial waste heat, decentralized heat pumps and thermal storage to achieve low-temperature, highly flexible energy networks [32]. Compared with conventional district heating systems, these concepts improve renewable energy integration while reducing distribution losses.

Photovoltaic systems provide an important complement to electrified heating technologies by supplying locally generated renewable electricity [7]. Their integration can substantially reduce grid electricity demand

ISSN: 2961-6603

10.051103/RES.260605106
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and improve the environmental performance of heat pump systems, particularly in residential neighbourhoods with favourable rooftop potential [34].

Overall, the literature indicates that future urban heating systems will increasingly consist of integrated energy systems combining demand reduction, renewable electricity generation, electrified heat supply and efficient heat distribution rather than isolated technological solutions [1], [32].

C. *Urban Building Energy Modelling*

UBEM has become an essential decision-support tool for analysing urban energy demand and evaluating alternative decarbonization pathways [9], [10], [22]. Unlike traditional top-down approaches that rely on aggregated energy statistics, bottom-up UBEM explicitly represents individual building characteristics and their spatial distribution.

Recent reviews classify UBEM approaches into top-down, bottom-up and hybrid methodologies while highlighting the increasing importance of physics-based bottom-up models for neighbourhood-scale applications [9], [10]. Integrating GIS with detailed building information enables municipalities to simulate energy demand at building level, identify spatial hotspots and evaluate alternative heating concepts under realistic local conditions [17], [23], [33].

Several modelling platforms have been developed for these purposes. The City Energy Analyst (CEA) provides integrated simulations of district-scale energy systems, while Citiwatts extends this concept through open-source planning tools for regional energy analyses [19], [33]. More recent research further demonstrates that combining UBEM with secure data-driven planning approaches enables municipalities to evaluate future heat transition scenarios while protecting sensitive building information [Pena].

Overall, recent developments illustrate a clear shift from purely technical building simulations towards integrated urban planning frameworks that combine building physics, spatial analysis and energy infrastructure.

D. *Energy Vulnerability and Social Equity*

Besides technical feasibility, the heat transition increasingly raises questions regarding affordability and social justice [4], [12]. Rising energy prices and unequal access to low-carbon technologies have intensified concerns about energy vulnerability, particularly among economically disadvantaged households [2], [4].

Energy vulnerability extends beyond the concept of energy poverty by considering the interaction between household characteristics, building quality, energy prices and institutional conditions [13]. Recent studies demonstrate that elderly residents, low-income households and tenants are disproportionately affected by increasing heating costs because they frequently occupy inefficient buildings while lacking the financial capacity to invest in refurbishment measures or renewable heating technologies [12], [35].

At the urban scale, climate adaptation research similarly emphasizes that socially vulnerable neighbourhoods often experience higher environmental risks while benefiting less from climate mitigation and adaptation measures [14], [15]. Consequently, recent literature argues that urban heat planning should integrate technical analyses with socio-economic indicators to ensure equitable distribution of costs and benefits during the energy transition [12], [14].

In addition, sustainable urban development frameworks, including Sustainable Development Goal 11 (SDG 11), stress that climate-neutral cities require the simultaneous consideration of environmental sustainability, economic resilience and social inclusion [16], [26]. These findings underline that successful heat transition strategies must extend beyond technical optimisation towards integrated socio-technical planning.

E. *Research Gap*

Although substantial progress has been achieved in urban energy modelling and low-carbon heating technologies, important research gaps remain [9], [10]. Existing studies frequently investigate technological optimisation, spatial energy analysis or socio-economic vulnerability separately [17], [33]. Comparatively few approaches combine building-level energy modelling, district-scale spatial analysis and energy vulnerability assessment within a unified framework capable of supporting evidence-based municipal heat planning.

This paper addresses this gap by developing a spatially explicit socio-technical assessment framework that integrates technical, environmental and social indicators for the evaluation of alternative heat transition pathways. Using a representative residential district in Braunschweig as a case study, four decarbonization

ISSN: 2961-6603

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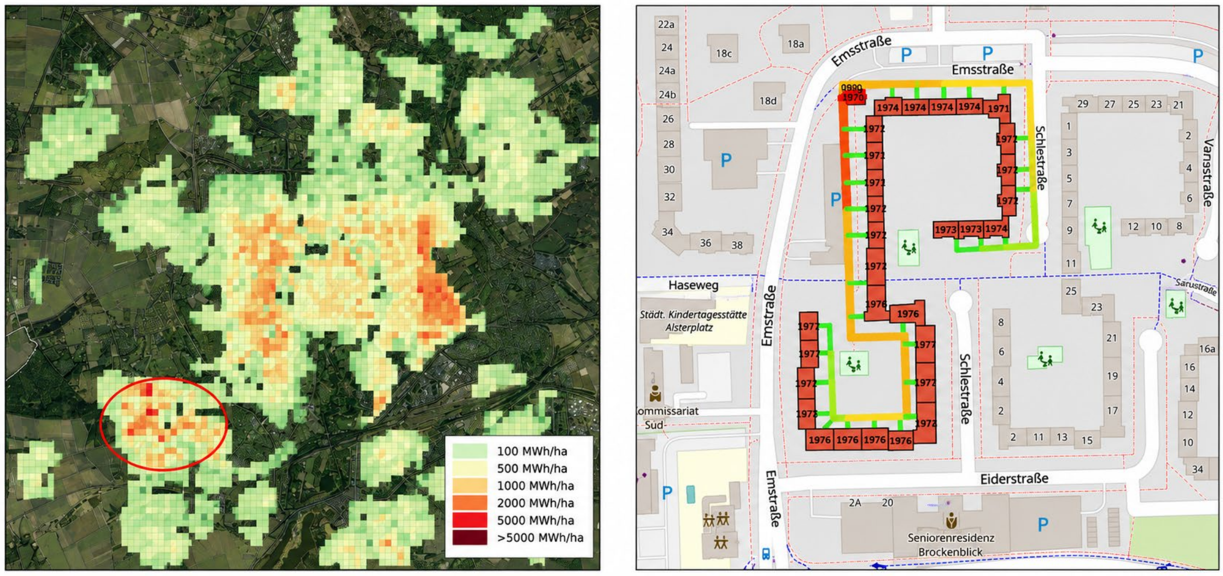
scenarios are analysed with respect to their technical performance, environmental impacts and implications for energy vulnerability. The proposed framework supports municipalities in identifying priority intervention areas and contributes to the development of climate-neutral and socially equitable urban heat transition strategies.

III. METHODOLOGY

To address the identified research gap, this study develops a spatially explicit and socio-technical framework for evaluating urban heat transition pathways at the district scale. The methodology combines building-level energy modelling with geospatial information and socio-economic indicators to assess both the technical performance and the distributional impacts of alternative decarbonization strategies.

A. Case Study Area

The proposed framework is applied to a representative residential district located in the southwestern part of Braunschweig, Lower Saxony, Germany. The study area is characterized by a compact urban structure dominated by multi-family residential buildings constructed primarily between the 1950s and the late 1970s. These post-war buildings exhibit comparatively high heat demand and therefore represent considerable potential for energy-related CO_2 reduction.



(a) (b)

Fig 2: Residential heat demand density within the city of Braunschweig (a) and selected case study district including residential building construction years and the existing district heating infrastructure (b).

The district was selected because it reflects typical characteristics of many German residential neighbourhoods developed during the post-war period. All buildings are connected to an existing district heating network, providing a realistic basis for evaluating centralized heat 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 heat demand and social constraints makes the area particularly relevant for assessing the distributional impacts of alternative heat transition pathways.

B. Data Collection and Spatial Database

The analysis is based on an integrated spatial database combining building-specific, technical and socio-economic information. Building data include construction year, gross floor area, building type and spatial location. Construction periods were assigned according to the German residential building typology proposed by Loga et al. [18], enabling representative thermal properties to be assigned to each building.

ISSN: 2961-6603

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Geospatial information was processed within a GIS to analyse building distribution, district heating infrastructure and heat demand density. In addition, socio-economic indicators—including household income, tenancy structure and demographic characteristics—were incorporated to identify areas with elevated levels of energy vulnerability.

The integration of technical and socio-economic information within a GIS environment enables a spatially differentiated assessment of both decarbonization potential and social vulnerability, consistent with recent developments in urban energy planning and UBEM [9], [10], [33].

C. Building Energy Modelling

Annual heat demand was determined using a bottom-up modelling approach in which each residential building was analysed individually before aggregating the results at district level. Compared with aggregated statistical methods, bottom-up approaches provide a more realistic representation of urban energy demand by explicitly considering building age, geometry and thermal characteristics [9], [10].

Representative specific heat demand values were assigned according to the respective construction period using the German residential building typology [18]. Total annual heat demand was calculated as the sum of space heating and domestic hot water demand.

Based on the calculated heat demand, primary energy consumption and operational CO_2 emissions were determined using technology-specific conversion factors and emission coefficients. This approach enables a consistent comparison of alternative heating concepts under identical boundary conditions.

The modelling approach follows recent recommendations for physics-based UBEM applications that combine detailed building information with spatial analysis to support municipal heat planning and urban decarbonization [9], [10], [23], [33].

D. Scenario Definition

Four representative decarbonization scenarios were developed to evaluate alternative heat transition pathways under identical boundary conditions.

(1) District heating (baseline scenario):

The existing district heating network is maintained and represents the current state of the energy system.

(2) Heat pump integration:

The centralized heat supply is replaced by decentralized air-source heat pumps installed at building level. Heat generation is fully electrified using the public electricity grid.

(3) Heat pump and photovoltaic integration:

This scenario extends Scenario 2 through the integration of rooftop photovoltaic systems. Locally generated electricity is preferentially used to operate the heat pumps, thereby reducing electricity imports and improving environmental performance.

(4) District heating with building retrofit:

The existing district heating network is retained while reducing heat demand through improvements to the building envelope. This scenario represents a demand-side strategy focusing on energy efficiency rather than changes to the heating technology.

All scenarios are evaluated using identical technical, environmental and economic performance indicators, including annual heat demand, electricity demand, primary energy consumption, greenhouse gas emissions and the levelized cost of heat (LCOH). The comparative results are presented and discussed in Chapter IV.

E. Assessment of Energy Vulnerability

In addition to the technical assessment, the proposed framework incorporates socio-economic indicators to evaluate the potential distributional impacts of alternative heat transition pathways. Energy vulnerability is assessed by combining building-related energy demand with spatial socio-economic characteristics.

The assessment considers six key indicators: (i) energy demand intensity, (ii) building age structure, (iii) household energy cost burden, (iv) the share of residents aged over 60 years, (v) exposure to energy price volatility and (vi) renovation rate and building condition.

Linking these indicators with the spatial building database enables the identification of neighbourhoods where high decarbonization potential coincides with increased socio-economic vulnerability. The resulting

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framework supports evidence-based municipal heat planning by integrating technical system performance with social equity considerations.

IV. RESULTS AND DISCUSSION

A. *Baseline Scenario: District Heating*

The baseline scenario represents the current heat supply of the case study district, where all residential buildings are connected to an existing district heating network. Based on the building-level energy model, the district exhibits an annual heat demand of approximately 2,150.6 MWh, consisting of 1,657.7 MWh for space heating and 493.0 MWh for domestic hot water preparation.

The district heating network operates with a linear heat density of approximately 2.27 MWh/m, indicating favourable conditions for centralized heat supply. Nevertheless, the environmental performance of the existing system remains limited. Annual operational greenhouse gas emissions amount to 358.8 t CO_2, corresponding to 166.9 g CO_2/kWh supplied heat.

Network distribution losses of approximately 218.5 MWh account for around 10 % of the total supplied energy. Although these losses are typical for conventional district heating systems, they increase overall primary energy demand and reduce system efficiency. The results therefore indicate that maintaining the existing heat supply without further decarbonization measures will not be sufficient to achieve long-term climate targets.

Overall, the baseline scenario provides the reference against which the alternative heat transition pathways are evaluated.

B. *Heat Pump Scenario*

Replacing the centralized district heating system with decentralized air-source heat pumps substantially changes both the energy supply structure and the environmental performance of the district.

Using a seasonal coefficient of performance (COP) of 4.09, annual electricity demand amounts to approximately 526.3 MWh, while operational greenhouse gas emissions decrease to 184.2 t CO_2. Compared with the baseline, this corresponds to an emission reduction of approximately 49 %.

Specific emissions decrease from 166.9 g CO_2/kWh to 85.7 g CO_2/kWh, illustrating the considerable mitigation potential of building electrification. These findings are consistent with recent studies demonstrating that heat pumps represent one of the most effective technologies for reducing emissions from existing residential buildings when supplied by an increasingly decarbonized electricity system [1], [6].

However, the scenario also reveals important limitations. Complete electrification increases dependence on the electricity grid and may require reinforcement of local distribution infrastructure during peak heating periods. Consequently, large-scale heat pump deployment should be accompanied by demand-side management, flexible electricity markets and increasing shares of renewable electricity generation.

C. *Heat Pump and Photovoltaic Scenario*

The integration of rooftop photovoltaic systems with decentralized heat pumps further improves the environmental performance of the district.

Annual photovoltaic electricity generation reaches approximately 9,843 MWh, substantially exceeding the electricity demand of the heat pumps. Consequently, only 304.0 MWh of electricity must be imported from the public grid, while surplus renewable electricity can be exported.

Annual greenhouse gas emissions decrease to 106.4 t CO_2, representing a reduction of approximately 70 % compared with the baseline scenario and approximately 42 % compared with the heat pump scenario. Likewise, primary energy demand decreases to 547 MWh, representing the lowest value among all analysed scenarios.

Besides achieving the lowest environmental impacts, the combined heat pump and photovoltaic scenario also increases resilience against future electricity price volatility through local renewable electricity generation. Nevertheless, implementation depends on suitable rooftop areas, ownership structures and investment capacity. In addition, the considerable mismatch between electricity generation and heating demand throughout the year highlights the importance of storage technologies and smart energy management for future urban energy systems [Quiros].

ISSN: 2961-6603

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D. District Heating with Building Retrofit Scenario

The fourth scenario investigates a demand-side strategy in which the existing district heating infrastructure is retained while reducing heat demand through improvements to the building envelope.

Building retrofit measures substantially reduce transmission losses and overall heating demand, thereby lowering operational greenhouse gas emissions without fundamentally changing the existing heat supply infrastructure. Compared with technology-based approaches, this scenario addresses the underlying cause of excessive energy consumption by improving building efficiency.

From a long-term perspective, reduced heat demand also decreases household energy expenditures and increases resilience against future energy price increases. However, comprehensive refurbishment requires comparatively high upfront investments and long implementation periods. Furthermore, retrofit potential differs considerably between individual buildings depending on construction period, structural condition and ownership characteristics.

Consequently, building renovation should be regarded as a complementary measure that enhances the effectiveness of low-carbon heating technologies rather than replacing them.

TABLE I
COMPARISON OF THE INVESTIGATED DECARBONIZATION SCENARIOS

Indicator	**District Heating**	**Heat Pump**	**Heat Pump + PV**	**District Heating + Retrofit**
Heat Demand (MWh)	2,150.6	2150.6	2,150,6	**1,321.8**
Grid electricity import (MWh)	9.8	526.0	**304.0**	10.8
District heating demand (MWh)	2,369.1	-	-	**1,539.3**
Renewable electricity generation (MWh)	-	-	**9,843.0**	-
CO_2 emissions (t/a)	358.8	184.2	**106.4**	234.7
Specific CO_2 emissions (g/kWh)	166.8	85.7	**49.5**	177.5
Primary energy (MWh)	657.4	947.4	547.1	**435.1**
Network heat losses (MWh)	218.5	-	-	217.5
Electricity demand (MWh)	9.9	526.3	526.3	10.8
Seasonal COP	-	4.09	4.09	-
Dominant technology	District heating	Air-source heat pump	Heat pump + PV	District heating + retrofit

Table I summarizes the principal technical, environmental and economic performance indicators of all analysed scenarios. While the combined heat pump and photovoltaic scenario achieves the lowest operational greenhouse gas emissions and primary energy demand, the retrofit scenario provides the largest reduction in heat demand. In contrast, the existing district heating system represents the economically established reference but exhibits the highest environmental impacts.

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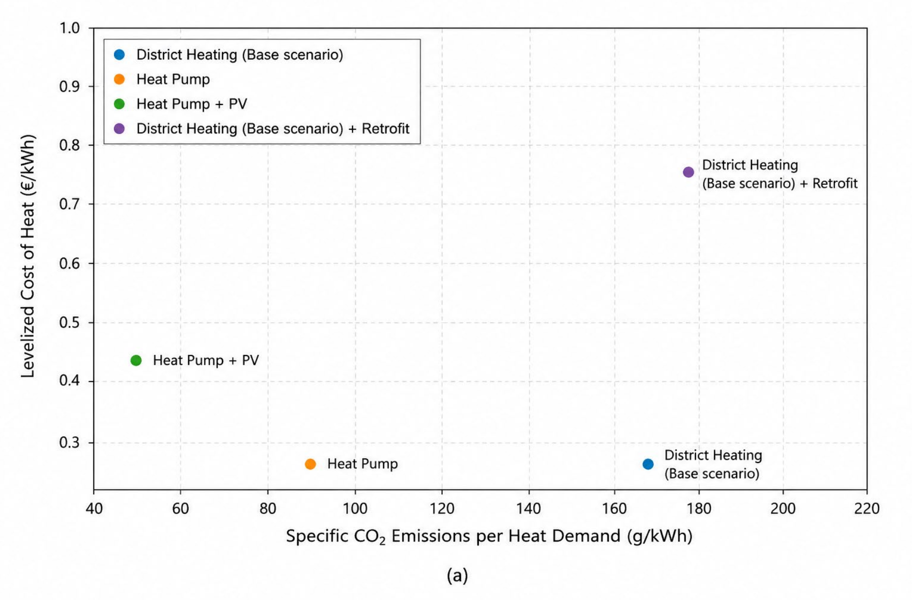

Fig 3: Comparison of the analysed decarbonization scenarios with respect to specific CO_2 emissions and levelized cost of heat (a).

E. Comparative Assessment of Decarbonization Scenarios

Figure 3 illustrates the trade-offs between economic and environmental performance across all analysed scenarios. Although the existing district heating system provides comparatively low investment requirements, it also exhibits the highest specific greenhouse gas emissions. Electrification through heat pumps substantially improves environmental performance while maintaining moderate heat generation costs.

The combination of heat pumps and photovoltaic systems represents the environmentally most favourable solution, achieving both the lowest CO_2 emissions and the lowest primary energy demand. Nevertheless, this scenario requires favourable local conditions, including sufficient rooftop availability and substantial initial investments.

The retrofit scenario occupies an intermediate position. While reducing overall heat demand, its comparatively high investment costs result in the highest levelized cost of heat among the investigated pathways. These findings demonstrate that technical optimisation alone cannot determine the most appropriate decarbonization strategy. Instead, municipalities must balance environmental performance, economic feasibility and local implementation conditions.

Overall, the comparison confirms that integrated solutions combining renewable electricity generation, electrification and targeted building renovation provide the greatest long-term decarbonization potential.

F. Energy Vulnerability and Social Implications

Beyond technical system performance, the results demonstrate that socio-economic characteristics substantially influence the feasibility and distributional impacts of urban heat transition strategies.

Neighbourhoods characterized by comparatively low household incomes, a high proportion of tenants and older residential buildings exhibit increased vulnerability to rising energy prices. Although heat pumps combined with photovoltaic systems provide the greatest environmental benefits, their comparatively high upfront investment costs may limit implementation within financially constrained households. Likewise, extensive building retrofits may improve long-term affordability but can also increase housing costs through modernization-related rent increases.

The spatial integration of technical and socio-economic indicators therefore enables municipalities to identify priority intervention areas where high decarbonization potential coincides with elevated energy vulnerability. Such integrated assessments support targeted funding programmes and socially balanced municipal heat planning by ensuring that environmental benefits are achieved without disproportionately burdening vulnerable population groups.

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These findings reinforce recent research emphasizing that successful urban heat transition strategies require not only technological innovation but also equitable governance structures, inclusive planning processes and targeted policy support for vulnerable households [12], [13], [14], [16].

Overall, the presented framework demonstrates that combining building energy modelling, spatial analysis and socio-economic assessment provides municipalities with a robust decision-support tool for prioritizing heat transition measures according to both technical effectiveness and social equity.

V. CONCLUSIONS

This paper presented a spatially explicit socio-technical framework for analysing urban heat transition pathways using a representative residential district in Braunschweig, Northern Germany, as a case study. By integrating building-level energy modelling, geospatial analysis and socio-economic indicators, the proposed approach enables a comprehensive evaluation of alternative decarbonization strategies while explicitly considering their technical, environmental and social implications.

The results demonstrate that post-war residential buildings constitute the largest contributors to urban heat demand and operational greenhouse gas emissions, confirming their importance as priority targets for municipal decarbonization strategies. The comparative scenario analysis further shows that no single technological solution is capable of simultaneously maximizing environmental performance, economic feasibility and social acceptance. While decentralized heat pumps combined with photovoltaic systems achieve the greatest reduction in greenhouse gas emissions and primary energy demand, building retrofits effectively reduce heat demand but require substantial upfront investments. Existing district heating systems remain an important option for densely populated urban areas, particularly when progressively supplied by renewable and low-carbon heat sources.

Beyond the technical assessment, the study highlights the importance of incorporating socio-economic indicators into municipal heat planning. The spatial integration of energy demand, building characteristics and indicators of energy vulnerability enables municipalities to identify neighbourhoods where high decarbonization potential coincides with increased social vulnerability. Consequently, future heat transition strategies should combine technological optimization with targeted policy measures that ensure affordable and socially equitable implementation.

The proposed framework contributes to the growing body of research on integrated urban energy planning by linking engineering-based energy modelling with spatial analysis and social vulnerability assessment. In doing so, it supports evidence-based decision-making for municipalities and demonstrates how technical and social objectives can be addressed simultaneously within local heat planning processes.

Although the presented framework is applied to a single case study district, its methodological approach is transferable to other urban contexts. Future research should extend the analysis by incorporating dynamic building operation, hourly energy demand profiles, future electricity market developments, thermal storage systems and renewable district heating concepts such as Fifth Generation District Heating and Cooling. In addition, applying the framework to multiple municipalities would further improve its generalizability and support the development of standardized decision-support tools for climate-neutral and socially equitable urban heat transition planning.

ACKNOWLEDGMENT

The authors extend their gratitude to the funding and collaborative efforts that made this research possible. The results were developed within the "Urban Climate Future Lab" (UCFL), funded by zukunft.niedersachsen, a funding program of the Lower Saxony Ministry of Science and Culture and the Volkswagen Foundation.

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ISSN: 2961-6603

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ISSN: 2961-6603