URBAN CLIMATE FUTURE LAB (UCFL): ASSESSING URBAN RESOURCE USAGE AND CLIMATE VULNERABILITIES IN LOWER SAXONY

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Abstract

Reaching climate neutrality by 2045 in Germany requires the decarbonisation of the building sector and its associated energy supply systems. The interdisciplinary research project Urban Climate Future Lab (UCFL) focuses on the investigation of the complex interactions between urban environment, energy and climate change and adaption. Especially the sub project RES ("resources") within UCFL addresses building resource usage in terms of embodied and operational energy and their emission implications. In the first project phase characteristic urban structures are investigated through scenario driven building energy modelling and embodied energy analysis within case study areas in Lower Saxony. In addition, social and societal aspects shall be integrated and investigated to derive insights to energy and climate vulnerabilities of specific societal groups. The aim is to derive useful metrics to quantify the degree of climate change affectedness and adaption readiness of the case study areas as well as the energy and climate change vulnerabilities of affected social groups.

Kurzfassung

Zur Erreichung des Klimaneutralitätsziels bis 2045 in Deutschland, müssen der Bausektor und die damit verbundenen Energieversorgungssysteme vollständig dekarbonisiert werden. Das interdisziplinäre Forschungsprojekt Urban Climate Future Lab (UCFL) untersucht die komplexen Wechselwirkungen zwischen urbaner Umwelt, Energie und Klimawandel sowie -anpassung. Das Teilprojekt RES („Ressourcen") innerhalb des UCFL befasst sich mit der Ressourcennutzung von Gebäuden in Bezug auf graue Energie und Betriebsenergie sowie deren Auswirkungen auf die Emissionen. In der ersten Projektphase werden charakteristische urbane Strukturen durch szenariobasierte Gebäudeenergiemodellierung und -analyse der grauen Energie in exemplarischen Fallstudien in Niedersachsen untersucht. Darüber hinaus sollen soziale und gesellschaftliche Aspekte integriert und untersucht werden, um Erkenntnisse über die Energie- und Klimavulnerabilität spezifischer Gesellschaftsgruppen zu gewinnen. Ziel ist es, geeignete Messgrößen abzuleiten, um den Grad der Betroffenheit durch Auswirkungen des Klimawandels und die Anpassungsfähigkeit der untersuchten Fallstudien sowie die Energie- und Klimawandelvulnerabilität betroffener sozialer Gruppen zu quantifizieren.

Introduction

Germany is aiming to reach climate neutrality by 2045 (Federal ministry for the environment, climate action, nature conservation and nuclear safety, 2019), while the federal state of Lower Saxony has set ambitions even higher to become carbon emission free already by 2040 (Lower Saxony, 2020). This requires the rapid decarbonisation of the building sector and its associated energy supply systems, while simultaneously strengthening adaptation to climate change impacts. The interdisciplinary research project UCFL investigates the complex interactions between urban environments, energy systems, and climate change and adaptation. This article focuses on the UCFL sub-project RES (Resources), which addresses building-related resource use in terms of both embodied and operational energy and their associated emission implications.

In the ongoing second year of the first project phase, characteristic urban structures are analysed using scenario-driven building energy modelling and embodied energy assessments in selected case study areas in Lower Saxony. To move beyond a purely technical perspective, social and societal dimensions are systematically integrated in order to identify patterns of energy and climate vulnerability among specific social groups. Methodologically, the paper combines multi-scalar energy modelling at the city, neighbourhood, and building levels with socio-demographic indicators and participatory insights.

The aim is to derive robust and policy-relevant metrics that quantify (1) the degree of climate change affectedness and adaptation readiness of urban case study areas, and (2) the energy- and climate-related vulnerabilities of affected social groups. By linking resource-oriented energy analysis with social vulnerability perspectives, the work contributes to energy social science debates on just and resilient urban transitions.

Energy systems are deeply entangled with social structures, everyday practices, and questions of justice. Climate change intensifies these entanglements by reshaping energy demand, amplifying exposure to heat stress, and increasing the risk of unequal adaptation outcomes (Kim et al., 2021;

Ye & Niyogi, 2022). As emphasized by energy social science research, technical transitions alone are insufficient; they must be understood within broader socio-economic and institutional contexts.

Lower Saxony provides a compelling case for examining these dynamics. The region combines coastal and inland cities, aging building stocks, and pronounced socio-spatial inequalities. Municipalities are expected to contribute to ambitious climate mitigation targets while also protecting residents from climate-related risks such as overheating and energy poverty. This dual challenge foregrounds the need for integrated analytical frameworks that bridge engineering-based energy research with social vulnerability perspectives.

UCFL responds to this need by fostering transdisciplinary collaboration between energy researchers, social scientists, planners, and local stakeholders. This article contributes to debates by focusing on the project's work package RES and by explicitly connecting building energy modelling with concepts of energy and climate vulnerability.

Climate change, energy demand, and social inequality in Lower Saxony

Climate change and urban energy implications

Climate projections for Lower Saxony indicate increasing average temperatures and a marked rise in the frequency and intensity of heat waves. These trends have direct consequences for urban energy systems, particularly through higher cooling demand and increased risks of indoor overheating. At the same time, energy systems are undergoing structural transformations driven by decarbonization, electrification, and volatile energy prices.

From an energy social science perspective, these developments are not merely technical challenges. They affect households differently depending on income, housing quality, tenure status, and access to adaptive resources. Buildings thus become critical sites where climate change, energy systems, and social inequality intersect.

Energy and climate vulnerability

Energy vulnerability refers to the likelihood that households are unable to attain adequate levels of energy services without compromising other basic needs (Bardazzi, R., Pazienza, M.G., 2023). Climate change exacerbates this vulnerability by increasing energy demand for cooling and by exposing residents to health risks during extreme heat events (Relvas, H., Monjo, R., Coelho, S. et al., 2025).

In Lower Saxony, energy and climate vulnerability often overlap spatially. Low-income households and elderly residents are more likely to live in poorly insulated buildings with limited adaptive capacity. Without deliberate policy interventions, climate adaptation measures may reinforce existing inequalities—for example, when energy-efficient retrofits lead to higher rents or when cooling technologies remain inaccessible to vulnerable groups.

The Urban Climate Future Lab and the Work Package "Resources"

UCFL is designed as a transdisciplinary research platform that integrates energy research, climate science, urban studies, and social sciences. Its overarching objective is to co-produce actionable knowledge for climate-resilient and socially inclusive urban development.

The work package RES adopts a broad understanding of resources, encompassing not only energy and material flows but also social, economic, and institutional capacities. Central research questions include: - How does climate change reshape urban energy demand and resource use? - How can buildings and neighborhoods be adapted to climate impacts while advancing energy justice? - Which social groups are disproportionately affected by climate-related energy risks, and how can adaptation strategies address these disparities?

Methods: A multi-level, socio-technical research approach

This study adopts a mixed-methods and multi-level research design. The methodological framework integrates quantitative building energy modeling with socio-spatial vulnerability analysis and participatory insights across three interlinked analytical levels: city, quarter (neighbourhood), and building. This vertical integration enables the systematic exploration of how climate change impacts, energy demand, and social vulnerability interact across scales.

At the city level, the analysis focuses on strategic energy and climate policy contexts, urban form, and large-scale exposure to climate risks. Municipal data, climate projections, and aggregated building stock information are used to assess overall trends in heating and cooling demand under current and future climate scenarios.

This level primarily addresses decision-making by municipalities, planners, housing companies, and policy-makers. Analytical objectives include evaluating decarbonization pathways, identifying priority areas for large-scale retrofitting, and assessing the distributional implications of city-wide energy strategies. The city scale thus provides the governance and policy framework within which lower-scale interventions are embedded (Figure 1).

Figure 1: Multilevel analysis scoping to meet diverse stakeholder objectives

The quarter (or neighbourhood) level acts as a critical intermediary between city-wide strategies and individual buildings. At this scale, aggregated building energy models are combined with socio-demographic indicators such as income levels, age structure, and housing tenure to identify spatial patterns of combined energy and climate vulnerability.

Building typologies and construction periods are analysed to benchmark energy performance and overheating risks across neighbourhoods. This scale is particularly relevant for stakeholders such as building owners, energy consultants, and planners, as it supports the development of targeted retrofitting strategies, energy-saving measures, and community-based approaches such as shared energy infrastructures.

At the building level, detailed dynamic building energy modelling (BEM) is conducted to simulate heating and cooling demand, indoor thermal comfort, and the impacts of adaptation measures under future climate conditions. Representative residential building types typical for Lower Saxony are modelled based on construction age classes, material properties, and energy systems.

This level allows for high-resolution analysis of overheating frequency, peak loads, and demand–load interactions with the electricity grid. It directly informs decisions by building owners, utilities, municipalities, and grid operators regarding demand-side management, grid stability, and the integration of renewable energy systems.

Data integration and modeling workflow

Across all three analytical levels, the study follows a consistent modelling workflow comprising data pre-processing, model generation, simulation, and post-processing (Figure 2). Geometric data (e.g. CityGML, shapefiles), non-geometric data (e.g. statistical and open municipal data), building-specific information (materials, energy systems), climate data, and socio-economic indicators are systematically integrated into the modelling environment. Simulations are performed by simulation engine platform citiwatts (Pena-Bello, A., Jeannin, N., Wyrsch, N., Wannier, D., Rager, J. 2025.) Simulation outputs are post-processed to derive indicators relevant for both technical performance (energy demand, overheating) and social analysis (exposure of vulnerable groups). This workflow enables the translation of detailed simulation results into policy-relevant insights and supports the identification of socially just adaptation pathways.

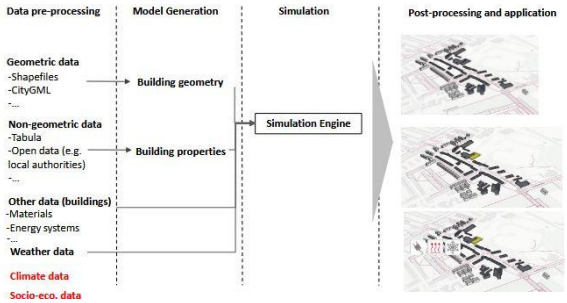

Figure 2: Multilevel analysis scoping to meet diverse stakeholder objectives

Key performance indicators for energy and climate vulnerability

To operationalise the concept of energy and climate vulnerability across scales, UCFL proposes a set of key performance indicators (KPIs) that combine physical exposure, energy system performance, and social sensitivity. These indicators are designed to function as decision-support metrics for municipalities, planners, and housing providers.

At the **city level**, KPIs focus on systemic exposure and distributional effects, including:

- Average and peak cooling demand per capita under current and future climate scenarios;

- Share of population exposed to critical heat stress days (e.g. number of days above indoor or outdoor temperature thresholds);

- proportion of residential floor area in low energy efficiency classes;

- spatial overlap between heat exposure and socio-economic disadvantage (composite vulnerability index);

- energy cost burden at the urban scale (average household energy expenditure as a share of income).

At the **quarter (neighbourhood) level**, KPIs capture socio-spatial differentiation and intervention priorities, such as:

- neighbourhood-level overheating frequency and duration in residential buildings;

- aggregated heating and cooling energy demand per square metre;

- share of vulnerable households (e.g. low-income, elderly) living in buildings with poor thermal performance;

- retrofit potential index combining energy savings, heat risk reduction, and social vulnerability;

- access to adaptive resources, such as green spaces, shading, or shared energy infrastructures.

At the **building level**, KPIs enable high-resolution assessment of technical and social performance, including:

- annual and peak heating and cooling demand (kWh/m²);

- number of hours exceeding thermal comfort thresholds;

- sensitivity of indoor comfort to occupant behaviour and ventilation strategies;

- energy cost burden at the household level;

- flexibility and load-shifting potential relevant for grid stability.

Together, these KPIs will allow a differentiated assessment of climate and energy vulnerability across scales. By linking them to specific stakeholder responsibilities and policy levers, they serve as concrete decision determinants for prioritising adaptation measures, designing funding schemes, and evaluating socially just energy transitions. The usage and application of the proposed KPI set will be topic of the second and third year of the project, which have just begun.

Integrating social vulnerability into energy modeling

Linking quantitative and qualitative data

A distinctive contribution of the Resources work package lies in integrating building energy modelling with socio-demographic and qualitative data. Spatially explicit modelling outputs—such as cooling demand or overheating frequency—are combined with indicators including income, age structure, household composition, and housing tenure.

This integration allows for the identification of "energy and climate vulnerability hotspots," where technical risks and social disadvantages coincide. Such insights move beyond average energy indicators and foreground distributional effects, a core concern of energy justice research.

Participation and co-production

In line with social science approaches to energy transitions, UCFL emphasizes participatory methods. Workshops and interviews with residents and local administrations are used to contextualize modelling outcomes and to capture experiences of heat stress and energy insecurity.

These co-production processes are intended to reveal non-technical barriers to adaptation, such as limited agency of tenants, lack of trust in institutions, or competing policy priorities. They also may help translate abstract modeling results into narratives that resonate with local stakeholders.

Case study applications in Lower Saxony and preliminary results

To illustrate the applicability of the proposed multi-scalar framework and key performance indicators, the proposed appraoch is applied to three exemplary urban case studies in Lower Saxony: **Salzgitter**, **Vechta**, and **Oldenburg**. The cities were selected to reflect contrasting urban structures, socio-economic conditions, and climate-related challenges, thereby enabling comparative insights into energy and climate vulnerability.

Salzgitter

Salzgitter is characterised by a polycentric urban structure, a strong industrial base, and neighbourhoods with a relatively high share of post-war residential buildings. These characteristics make the city a relevant case for studying the interaction between industrial energy systems, residential energy demand, and climate adaptation needs. At the city level, modeling results indicate comparatively high absolute energy demand and emissions linked to both industrial activity and an aging residential building stock (Figure 3).

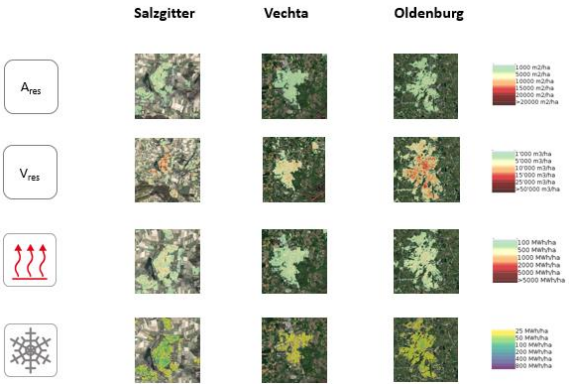

Figure 3: Gross floor area of residential buildings (A_{res}), volumes of residential buildings (V_{res}), annual heating and cooling demand densities for case studies (source: simulations citiwatts platform).

Climate change projections show increasing risks of summer overheating (expressed as urban heat island (UHI) index), particularly in dense quarters (Figure 4).

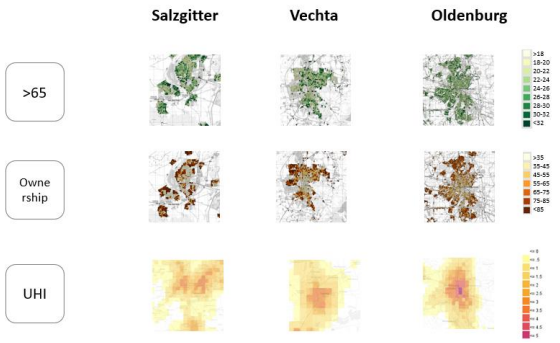

Figure 4: Percentage of people aged over 65 years [%], ownership ratio [%] and distribution of UHI for case studies [K] (source: Zensus20222, DWD).

Furthermore, figure 4 reveals that the percentage share of people aged 65 or older is high in city quarters that are like to be affected by summer overheating in the future.

At the quarter level, socio-spatial analysis reveals overlaps between older building typologies, lower-income households, and elevated heat exposure. Building-level simulations highlight significant potential for reducing both operational energy demand and overheating through targeted retrofitting measures. From a vulnerability perspective, Salzgitter exemplifies how climate and energy risks are closely tied to structural economic conditions, underlining the need for socially targeted adaptation and renovation programmes.

Vechta

Vechta represents a rapidly growing medium-sized city with a comparatively young population and ongoing residential development. While the overall building stock is newer than in many larger cities, socio-economic heterogeneity and rising housing demand create specific energy and climate challenges.

City-level analysis shows moderate current heating demand (Figure 3), but a strong relative increase in cooling demand under future climate scenarios. At the quarter scale, differences between newly developed residential areas and older neighbourhoods become apparent, particularly with regard to overheating risks and access to adaptive resources such as shading and green spaces (Figure 4).

Building-level modeling demonstrates that even relatively modern buildings can be vulnerable to summer heat if passive cooling strategies are insufficient. Social analysis suggests that households with limited financial flexibility may face increasing energy cost burdens as cooling demand rises. Vechta thus illustrates how climate vulnerability can emerge not only from poor building quality but also from rapid urban growth and changing energy needs.

Oldenburg

Oldenburg, as a larger and denser urban centre in Lower Saxony, combines a historic core with compact residential neighbourhoods and a diverse socio-demographic structure. The city has comparatively advanced climate and energy strategies, making it a suitable case for examining the limits and distributional effects of existing policies.

At the city level, modelling highlights pronounced urban heat island effects (Figure 4) and increasing cooling demand in central areas (Figure 3). Quarter-level analysis reveals strong socio-spatial differentiation: densely built inner-city neighbourhoods with a high share of rental housing show elevated exposure to heat stress and limited adaptive capacity.

Building-level simulations indicate that retrofitting measures can substantially improve thermal comfort and reduce energy demand, but social indicators point to potential risks of displacement or rent increases. Oldenburg therefore exemplifies the tension between technical adaptation potential and social equity, reinforcing the importance of coupling energy modelling with vulnerability analysis in decision-making.

Discussion: Energy Justice and Resource-Oriented Adaptation

The three case studies demonstrate how energy and climate vulnerability manifest differently depending on urban structure, building stock, and socio-economic context. While Salzgitter highlights the role of industrial legacies and structural disadvantage, Vechta underscores the challenges of growth and emerging cooling demand, and Oldenburg illustrates distributional conflicts in dense urban settings.
Together, the cases confirm the added value of a multi-scalar, resource-oriented approach that integrates building energy modelling with social vulnerability perspectives. They also show that meaningful adaptation pathways must be context-specific and socially differentiated, rather than relying on one-size-fits-all solutions.

Conclusion

Climate change adaptation in urban energy systems requires analytical approaches that bridge technical and social dimensions. Using Lower Saxony as a case study, this article has shown how UCFL, and particularly its work package RES, integrates building energy modelling with concepts of energy and climate vulnerability.

By aligning engineering-based simulations with social science insights, the project contributes to debates on energy justice and socially inclusive adaptation. The results suggest that resource-oriented, transdisciplinary research can support urban energy

transitions that are not only low-carbon but also resilient and equitable.

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