Gas Grid Phase-Out Impacts on Building Stock Development: Incorporating Behavioural Aspects

Helen Ganal*, Martin Braun*† and Philipp Härtel*†
* Fraunhofer IEE, Fraunhofer Institute for Energy Economics and Energy System Technology, Kassel, Germany
† Sustainable Electrical Energy Systems, University of Kassel, Kassel, Germany

***Abstract*—Mannheim is the first German city to announce a complete gas grid decommissioning by 2035, presenting new challenges for building stock transformation. Rising CO_2 prices and grid costs threaten affordability, particularly for tenants. Using an agent-based model of Germany's building stock, we analyse behavioural responses to a proactive gas grid phase-out. Our findings show that regulatory decommissioning accelerates decarbonisation, reduces fossil fuel reliance, and avoids excessive cost burdens for vulnerable tenant segments. Policy measures lead to a 50% increase in air- and ground-source heat pumps compared to a business-as-usual scenario, with uptake observed across all ownership groups except commercial landlords, who disregard avoided fuel costs.**

***Index Terms*—building stock transformation, behavioural economics, heating transition, gas grid phase-out, heating sector regulation, agent-based modelling**

I. INTRODUCTION

Achieving Germany's heating sector targets [1] requires decentralised investments among diverse building owners. Financial burdens and split incentives, especially in rental properties, challenge the transition. Regulations, subsidies, and infrastructure changes shape building owners' decisions. Yet, their behaviour is not entirely rational and cannot be directly controlled. Due to the fragmented nature of the building stock and ownership, effective policy design requires a differentiated understanding of economic incentives, technical options, and behavioural drivers. Normative models often overlook owners' central role in the sector's evolution [2, 3, 4].

As gas demand declines, rising grid fees and underused infrastructure add complexity [5], unless managed through regulatory decommissioning [6].

This study examines regulated gas grid phase-out as a strategic lever for decarbonisation. Using a behavioural agent-based model, we simulate building owner decisions across socio-economic groups. Our study contributes to understanding the role of regulated gas grid decommissioning in accelerating the heating transition. We assess policy impacts on renovation and heating system choices and how they drive the actual sectoral transformation. Specifically, we analyse how proactive grid decommissioning influences heating system replacement rates and how reduced grid charges affect owner decisions. By comparing business-as-usual and a climate-protection scenario, incorporating additional market, regulatory, and subsidy mechanisms, we provide insights into the impact of systematic gas phase-outs. We find that structured gas decommissioning can accelerate fossil exit, lower long-term energy costs, and improve cost equity among tenants.

The remainder is organised as follows. Section II provides an overview of previous work. Section III explains our methodology involving the agent-based model AgentHomeID to simulate building stock evolutions, incorporating behavioural economics to model investment decisions in building envelope refurbishments and system replacements. Section IV explains key scenario assumptions and considered instruments. Section V presents and discusses the simulation results. Section VI closes with a summary and draws relevant conclusions.

II. PREVIOUS WORK

Recent research increasingly examines the interplay between energy policies, building stock dynamics, and behavioural economics. Studies highlight the economic and technical challenges of decarbonising buildings, focusing on how regulations and market incentives drive retrofits and heating system replacements [3, 4, 7, 8]. However, conventional models, often based on rational decision-making or deterministic rules, fail to capture real-world complexities, stressing the need to integrate behavioural factors into energy transition simulations [9, 10].

While many studies investigate the transformation of building heating, few explicitly consider building owners' individual renovation decisions. Agent-based modelling has provided valuable insights into their heterogeneous responses to policy and market signals [9, 11, 12]. Our approach extends this by distinguishing between landlords and self-users, who have distinct preferences and decision-making processes, offering a more nuanced perspective than previous studies.

Research on gas grid economics has shown that declining user bases can increase grid fees, while regulatory interventions like proactive decommissioning can help mitigate costs [6]. Building on this, our study integrates these insights within an agent-based framework, explicitly modelling behavioural aspects. This approach systematically analyses how gas grid phase-outs influence building owners' decisions and heating sector decarbonisation.

III. METHODOLOGY

Considering relevant parts of the ODD protocol (Overview, Design concepts and Details) [13], we describe our agent-based simulation framework as a comprehensive approach to modelling building stock evolution, explicitly focusing on the

979-8-3315-1278-1/ 25/$31.00 ©2025 IEEE

impact of gas grid phase-out on heating sector decarbonization.

A. Overview

Our study employs AgentHomeID, an agent-based model that simulates homeowner investment decisions and building stock evolutions. While broadly applicable to building stock transformation, we use the model to assess the impact of gas grid phase-out on heating sector decarbonisation.

The model represents a regional building stock where individual agents (building owners) respond to external influences such as regulatory changes, cost trends, and fuel price dynamics. Agents fall into two main categories: private individuals and corporate entities, classified using Statistisches Bundesamt data [14]. This segmentation captures diverse decision-making behaviours under economic and regulatory influences.

The simulations runs from 2020 to 2045 in five-year intervals, using a representative sample of 50,000 buildings from the Scientific Use File of the Mikrozensus (SUF) database [15], with scaling factors applied to extrapolate results to the entire German building stock.

B. Design Concepts

1) Agent Categorisation and Decision-Making:

Agent Types: Private Individuals, namely landlords, owner-occupiers, and homeowners' associations as well as corporate entities such as private property companies, cooperatives, and public authorities. *Decision Mechanisms*

- Private Individuals: Decisions are modelled using a personal random utility model, which represents choice behaviour as utility maximisation under uncertainty, accounting for both observed and unobserved factors and incorporating socio-demographic and economic characteristics (e.g. income, gender, education, community size, and historical refurbishment behaviour) A specific willingness-to-pay (WTP) is derived from empirical discrete choice experiments conducted by the University of Kassel.
- Corporate Entities: Decisions follow an economic optimisation approach maximizing cost efficiency and long-term returns, with criteria varying by corporate group.

Prediction Approaches

- Private Individuals: Decision-making is modelled myopic, yet key attributes of refurbishment measures, such as consulting an energy advisor, are assumed to be known.
- Corporate Entities: Decisions rely on mid- to long-term economic calculations using exogenous price forecasts.

2) Dynamic Decision Triggers and Influencing Factors:

Critical Events: Investment decisions are triggered by discrete events, e.g. ownership or tenancy changes, major maintenance needs, or new regulatory requirements.

Evolving Influences: Continuous factors such as cost trends, fuel prices, and policy updates dynamically shape agents' decision-making.

Policy interaction: The model explicitly integrates policy signals, including: gas grid phase-outs, the German Building Heating Law (GEG) [16], the Building Renovation Funding Law (BEG) [17], the Communal Heat Planning Law (WPG) [18], the European Emission Trading System for Buildings and Transport (EU-ETS2) [19], and the CO_2 Cost-Sharing Law (CO_2KostAufG) [20]. Additional policies can be integrated per scenario, influencing decision frequency, renovation type/extent, and decarbonisation pace.

3) Spatial and Temporal Scope:

Spatial Scope: The simulation models 50,000 representative buildings from the SUF database, with scaling factors mapping the results to the total German building stock. It operates at the individual building level, accounting for technical potentials (e.g. district heating applicability, overall building condition).

Temporal Scope: The simulation spans 2020 to 2045 in five-year timesteps, capturing the gradual transformation and long-term building stock dynamics.

4) Building and Decision Details:

Building Attributes: Each building (i.e., the asset held by the agents) is characterised by: Envelope Condition (U-values for the roof, exterior walls, windows, and lower building parts), technical system condition (heating system type, ventilation systems with heat recovery, fuel type), construction year and component age derived from available data

Available Refurbishment Measures and Attributes: Options include various combinations of measures that achieve energy savings, CO_2 reductions, investment cost, and operating cost changes. Decisions are filtered by regulatory minimum standards, technical feasibility (considering building design or infrastructure constraints), and economic feasibility based on household income.

C. Details

1) Implementation and Calibration:

Model Environment: The simulation is built using the Mesa framework, employing a discrete-time approach with five-year timesteps to capture gradual building stock evolution.

Initial Conditions: The model initializes with the current building stock distribution, including ownership structures and socio-demographics, based on SUF data and the Statistisches Bundesamt. The refurbishment state of buildings (building envelope and technical systems) is inferred from construction year and component lifespans.

Parameterisation: Key parameters include: Probability distributions for random utility in private decision-making, cost trends for maintenance and renovation, fuel price trajectories, regulatory intervention schedules (e.g. timing and scope of the gas grid phase-out) and availability of heat sources and grid infrastructure. These parameters are calibrated using available statistical data and historical trends from the building and energy sectors.

Stochasticity: Missing inputs (e.g. landlord characteristics, WTP, construction years, component ages) are stochastically assigned to reflect data uncertainty and real-world variability.

Data Gaps and Assumptions: For instance, while SUF data details current heating system status, it lacks rental property ownership data. Ownership is thus probabilistically assigned based on income and rental revenue indicators.

2) Simulation Process and Output:

Event-Driven Dynamics: Every five-year timestep, the model evaluates critical events for each agent, thereby supporting computational efficiency. When triggered (e.g. tenancy change, maintenance need), the corresponding decision process – random utility based for private individuals, optimisation-based for corporate entities – is executed.

Data Collection and Analysis: The simulation tracks key metrics, including: Renovation and heating system replacement timing and frequency, final energy and heat demand, CO_2 emission impacts, Investment costs and monthly fuel expense changes, Landlord funding and cost allocation. Sensitivity analyses assess transition dynamics by varying parameters such as fuel prices, cost trends, and regulatory stringency.

Validation: Model outputs are validated against historical refurbishment rates and energy consumption data, using quantitative measures (e.g. correlation coefficients) to ensure consistency with observed trends.

IV. CASE STUDY DESCRIPTION

Reducing greenhouse gas emissions in the building sector relies on two key strategies: enhancing energy efficiency and decarbonising energy sources by replacing fossil fuels with renewables. We compare a business-as-usual (BAU) scenario with a more ambitious climate protection (ACP) scenario, emphasising gas grid phase-out as a key driver of heating sector decarbonisation. AgentHomeID is used to analyse these scenarios. The following sections outlines the key German regulatory instruments considered, the general scenario assumptions and the key scenario differences.

A. Regulatory Framework

The regulatory framework comprises four key instruments:

Building Energy Act (GEG – 09/2023) [16], which requires new heating systems to use at least 65 % renewable energy, mandates the EH 55 energy efficiency standard for new buildings, and integrates municipal heating planning.

Heating Planning Act (WPG – 12/2023) [18], which sets renewable energy and waste heat targets for heating networks (2030/2045) and mandates municipal heating plans by June 2026 (cities >100,000 inhabitants) and June 2028 (smaller municipalities).

Fuel Emissions Trading Act (BEHG – 12/2019, revised 12/2023) [19], which introduces greenhouse gas pricing for fuels, rising from 25 €/t to 55 €/t CO_2 by 2025, with a transition to the EU ETS II in 2027.

Federal Funding for Energy-Efficient Buildings (BEG – 12/2023) [17], which supports full-scale renovations, renewable heating subsidies, climate bonuses, and income-based incentives for owner-occupiers, with extra aid for worst-performing buildings and phased renovations.

B. General scenario assumptions

Below, we discuss key scenario simulation assumptions.

Socio-demographics: The simulation is based on the SUF from the German Mikrozensus (70 % household sub-sample) [15], providing representative data on building characteristics, technical installations, and socio-demographics. Population ageing is modelled by incrementing occupants' ages at each time step, with departures simulated probabilistically. Household parameters, including financial status, building technology, move-in years, dwelling units, and refurbishment status, are derived from the SUF and statistically enriched (e.g. mapping income classes to uniformly distributed values). We estimate investment budgets for private owners as functions of net household income, with absolute thresholds (below which no investments occur without subsidies) and income-dependent limits. For modelling decision-making, WTP metrics quantify monetary and qualitative trade-offs for refurbishment attributes. These characterise decision-maker typologies through regression analyses based on representative surveys and discrete-choice experiments, informing agent renovation choices.

Economics: All prices and incomes are inflation-adjusted. Real incomes and rents remain constant, while building system and renovation costs follow an inflation-adjusted construction price index, accounting for learning curves and economies of scale. A dedicated tool is used to compute levies on the total energy costs, thereby capturing the financial burden on consumers within the system. CO_2 prices, reflecting ETS II uncertainties, are incorporated into fuel cost projections and allocating costs between tenants, landlords, and self-occupiers. Gas network charges are scenario-dependent, reflecting differences in connection densities and planned decommissioning measures, and thus significantly influence overall cost structures. Differences between the scenarios in CO_2 prices and gas grid tariffs are described in IV-C.

Infrastructure, system, and building technology: Retrofit potential varies by building type and location. The model accordingly assigns technical potentials and infrastructure connectivity options (e.g. district heating, hydrogen networks). By 2045, approximately one-third of buildings, particularly in urban and densely populated areas, are assumed to be integrated into district heating networks, with mandatory connection rates varying by scenario. Hydrogen network expansion is capped at 10 % of residential buildings, representing a relatively generous estimate [21, 22]. No gas network expansion is assumed for existing buildings, and selective decommissioning may necessitate boiler replacements with alternative systems. National biomass consumption is limited to 65 TWh (wood equivalent) annually, with an additional 15 TWh for biomethane/hydrogen applications. All retrofits comply with the Building Energy Act (GEG), with further technical constraints—such as air-source heat pump installations being restricted to buildings with fewer than nine dwelling units and adequate energy efficiency.

C. Key Scenario Differences

Key policy instruments and main exogenous assumptions that differ between the scenarios are summarised in Table I.

Policy instrument	**Business-as-Usual (BAU)**	**Ambitious Climate Protection (ACP)**
Gas grid decommissioning	No regulated decommissioning	Regulated decommissioning (legal framework)
Regulation on gas/oil boilers	No additional restrictions	No additional restrictions; targeted campaigns
Grid fee development	Moderate increasing times 2 by 2045	substantially times 12 by 2045
Biomass and hydrogen use	No restrictions	Limited use
Mandatory retrofitting	No mandatory measures	Mandatory for selected buildings
Subsidy policy	Fixed until 2045 according to BEG	Stricter requirements for new buildings; no subsidies for biomass boilers; otherwise, BEG remains constant
Investment support (low-income)	No investment in building envelope for HHs with an income $<$ 2,000 €/month	HHs with an income $<$ 2,000 €/month receive an 80% subsidy rate
Loan duration	10 yrs.	20 yrs.
Investment budget allocation	HHs $>$ 2,000 €/month: 30 % of income over 10 yrs. HHs $<$ 2,000 €/month: 0	HHs $>$ 2,000 €/month: 30 % of income over 20 yrs.. HHs $<$ 2,000 €/month: Self-users: 10 % over 20 yrs. Landlords: 30 % over 20 yrs.
CO_2 pricing mechanism	High, increasing over time	Moderate, below BAU dynamic

Table I: Comparison of policy instruments in the BAU and ACP scenarios (HH: Household).

In the ACP scenario, gas networks are fully decommissioned between 2030 and 2045, with a linearly increasing phase-out rate. A fixed proportion of buildings is randomly selected for disconnection, requiring those with gas heating to transition to alternative technologies. In the BAU scenario, network charges remain relatively low, roughly doubling by 2045 due to the absence of rapid gas boiler and gas network connection phase-outs and the consequently slow decline in connection density. In contrast, the ACP scenario features two opposing effects: network charges rise due to a sharp decline in gas connections driven by climate policies, which is partially offset by decommissioning low-density network segments. This leads to costs projected to be twelve times higher by 2045 compared to today. These assumptions are based on [6]. In the BAU scenario, CO_2 prices (in real 2020 euros) increase sharply to €182 per tonne in 2027 following the introduction of ETS2, driven by a high allowance shortage in the absence of ambitious climate policies. Prices continue to rise, reaching €277 per tonne by 2045, whereas in the ACP scenario, characterised by significantly lower CO_2 emissions, the price rises more moderately, reaching €166 per tonne by 2045. Price assumptions are based on analyses in [23]. The ACP scenario combines multiple regulatory instruments. The analysis examines the specific impact of gas network decommissioning.

V. RESULTS AND DISCUSSION

A. Energy Carrier Consumption Trends

Final energy consumption trends in Fig. 1 show a gradual decline in fossil fuel use (gas and heating oil) through 2045, with a corresponding rise in renewable energy sources (district heating, electricity, biomass, and hydrogen/biomethane). In the BAU scenario, the building sector will still consume about 92 TWh of gas and oil by 2045 despite the legal ban taking effect that year. The ACP scenario achieves a complete fossil fuel phase-out through regulated gas network decommissioning, forcing a shift to renewable heating. The ACP scenario limits hydrogen and biomethane use. In contrast, under the BAU scenario, gas boilers remain installable with balance-sheet certification of hydrogen/biomethane use. While these alternatives have lower capital expenditures, they result in higher operating costs, increasing tenants' burdens. The ACP scenario mitigates financial risks and promotes sustainable resource allocation by prohibiting such solutions. Additionally, the ACP setting enforces stricter biomass and hydrogen constraints, encouraging district heating expansion and heat pump adoption. BAU's excessive reliance on hydrogen/biomethane and biomass indicates a high dependence on imports.

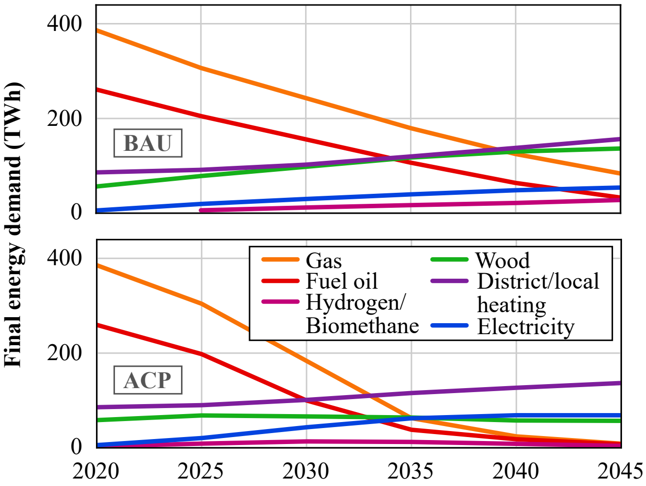

Figure 1: Energy carrier consumption trends over time.

B. Development of Heating Technologies

Between 2015 and 2045, the residential heating system stock undergoes a substantial transformation from combustion-based systems (gas and oil boilers) to a diversified technology stack, as shown in Fig. 2, which depicts the evolving shares of heating technologies. In the ACP scenario, gas network decommissioning accelerates replacing fossil-fuel systems, which, combined with restrictions on biomass and hydrogen/biomethane, drives the rapid adoption of heat pumps (air- and ground-source). Moreover, Minimum Energy Performance Standards (MEPS) mandate building envelope improvements, further supporting air-source heat pump deployment. In contrast, the BAU scenario sees a slower transition, allowing combustion-based systems to remain for longer.

C. Investment Behaviour by Ownership Structure

Fig. 3 shows that heating system investment decisions vary considerably across different ownership groups, including cooperatives, homeowners' associations, private owner-

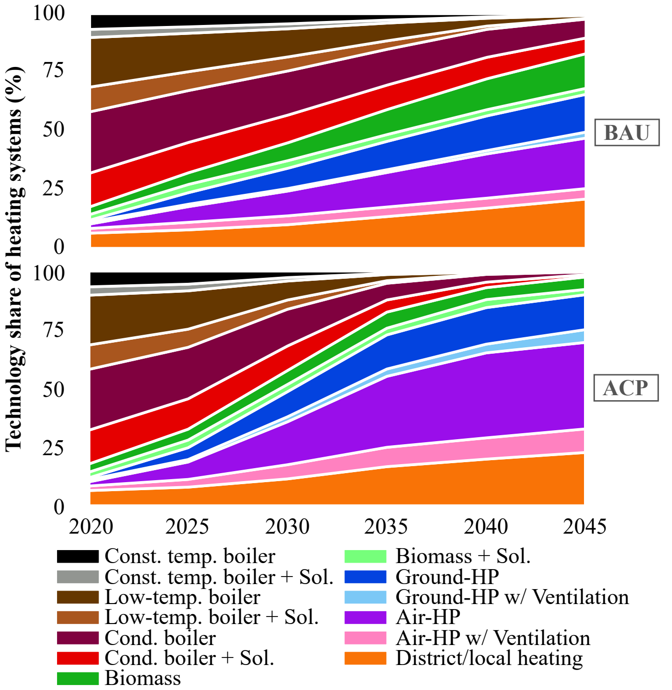

Figure 2: Development of technology shares in the building stock over time.

occupiers, private landlords, private commercial entities, and public sector owners. Private owners, mainly of smaller residential buildings, base decisions on individual WTP: owner-occupiers prefer high-efficiency systems (e.g. ground-source heat pumps) despite higher upfront costs, while landlords opt out for lower-cost solutions (e.g. pellet boilers) with higher operating expenses. Institutional owners, managing multi-family buildings, follow economic objectives: private commercial owners prioritise CAPEX efficiency and cost transfer to tenants, while cooperatives and public entities also weigh avoided fuel costs and long-term profitability. Investment behaviour also differs by scenario. In the BAU scenario, private commercial and public institutional owners initially favour new gas-condensing boilers. Still, a 2024 regulation requiring 65 % renewable energy gradually reduces fossil fuel-based installations. In the ACP scenario, gas network decommissioning prohibits hydrogen/biomethane boilers, accelerating the shift to heat pumps. This policy-driven phase-out curbs fossil system reliance and limits hydrogen/biomethane use, exposing ownership-specific responses to regulatory interventions.

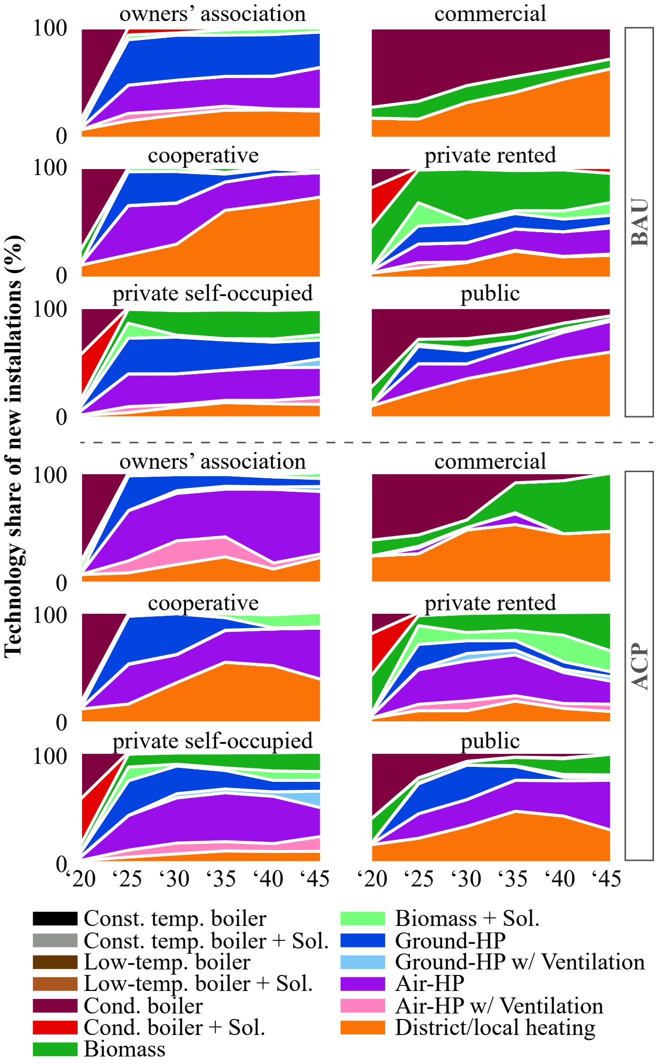

Figure 3: Technology shares of new installed systems over time for different ownership groups for BAU and ACP.

VI. CONCLUSION

Our study examines the impact of regulated gas grid decommissioning on accelerating the heating transition, evaluating sector specific policy targets under different policy frameworks. Using an agent-based modelling approach, we simulate heating system replacement rates and investment decisions across diverse ownership groups, capturing behavioural responses to policy and market signals. By comparing a Business-as-Usual (BAU) scenario with an Ambitious Climate Protection (ACP) scenario, integrating additional market, regulatory, and subsidy measures, we find that ACP drives a rapid shift from fossil fuels to renewable heating systems. The additional stringent measures introduced in the ACP scenario, particularly the regulated decommissioning of gas networks, significantly accelerate the uptake of heat pumps, increasing their share by 50% compared to the BAU scenario. Requirements for the renovation of inefficient building envelopes especially incentivise the installation of air-source heat pumps, which can be operated more efficiently and cost-effectively in well-insulated buildings. As a result, their share increases by 84% relative to the BAU scenario. Such analyses can inform the design of policy instruments by evaluating incentive effects and distributional outcomes across building types and income levels, thereby supporting a targeted and socially balanced transition. A promising direction for further research based on the agent-based modelling results is the analysis of distributional impacts and cost burdens across different owner and user groups, particularly with respect to household income.

ACKNOWLEDGMENT

The work of this paper has been performed as part of the project *Soziale Wärmewende (Socially just heat transition)*, commissioned by Agora Energiewende.

REFERENCES

[1] Federal Ministry of Justice, "Bundes-klimaschutzgesetz: Ksg," 2024-07-15. [Online]. Available: https://www.gesetze-im-internet.de/ksg/BJNR251310019.html

[2] P. Jochum, J. Lawrenz, S. Böttcher, D. Stelter, T. Krenz, P. Mellwig, M. Pehnt, A. von Oehsen, S. Blömer, and H. Hertle, "Anlagenpotenzial: Ableitung eines korridors für den Ausbau der erneuerbaren wärme im gebäudebereich," 2017. [Online]. Available: https://www.ifeu.de/fileadmin/uploads/BeuthHS_ifeu_Anlagenpotenzial_Endbericht_2017.pdf

[3] S. Braungardt, M. Bei der Wieden, T. Hesse, T. Kenkmann, M. Koch, and S. Krieger, "Großbaustelle Gebäudesektor. Lokal und sozial die Wärmewende entfachen," 2023. [Online]. Available: https://www.oeko.de/fileadmin/oekodoc/WWF_OEko-Institut_Waermewende.pdf

[4] Boston Consulting Group, "Klimapfade 2.0: Ein wirtschaftsprogramm für klima und zukunft," 2021. [Online]. Available: https://www.bcg.com/germany/klimapfade

[5] D. Then, C. Spalthoff, J. Bauer, T. M. Kneiske, and M. Braun, "Impact of natural gas distribution network structure and operator strategies on grid economy in face of decreasing demand," *Energies*, vol. 13, no. 3, p. 664, 2020.

[6] S. M. J. Oberle, "Die Rolle der Gasverteilnetze im Energiesystem der Zukunft in Deutschland," Ph.D. dissertation, Karlsruher Institut für Technologie (KIT), 2023.

[7] "Klimaneutrales Deutschland. Von der Zielsetzung zur Umsetzung." [Online]. Available: https://www.agora-energiewende.de/fileadmin/Projekte/2023/2023-30_DE_KNDE_Update/A-EW_344_Klimaneutrales_Deutschland_WEB.pdf

[8] D. Then, P. Hein, T. M. Kneiske, and M. Braun, "Analysis of dependencies between gas and electricity distribution grid planning and building energy retrofit decisions," *Sustainability*, vol. 12, no. 13, p. 5315, 2020.

[9] C. Nägeli, M. Jakob, G. Catenazzi, and Y. Ostermeyer, "Towards agent-based building stock modeling: Bottom-up modeling of long-term stock dynamics affecting the energy and climate impact of building stocks," *Energy and Buildings*, vol. 211, p. 109763, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0378778819324569

[10] C. Senkpiel, A. Dobbins, C. Kockel, J. Steinbach, U. Fahl, F. Wille, J. Globisch, S. Wassermann, B. Droste-Franke, W. Hauser, C. Hofer, L. Nolting, and C. Bernath, "Integrating methods and empirical findings from social and behavioural sciences into energy system models—motivation and possible approaches," *Energies*, vol. 13, no. 18, p. 4951, 2020.

[11] E. Özer, L. Kranzl, A. Müller, and B. Zakeri, "The impact of energy prices in decarbonizing buildings' energy use in the EU27," *Energy and Buildings*, vol. 323, p. 114814, 2024.

[12] A. Akhatova and L. Kranzl, "Agent-based modelling of building retrofit adoption in neighbourhoods," *Energy and Buildings*, vol. 328, p. 115172, 2025.

[13] V. Grimm, S. F. Railsback, C. E. Vincenot, U. Berger, C. Gallagher, D. L. DeAngelis, B. Edmonds, J. Ge, J. Giske, J. Groeneveld, A. S. Johnston, A. Milles, J. Nabe-Nielsen, J. G. Polhill, V. Radchuk, M.-S. Rohwäder, R. A. Stillman, J. C. Thiele, and D. Ayllón, "The ODD protocol for describing agent-based and other simulation models: A second update to improve clarity, replication, and structural realism," *Journal of Artificial Societies and Social Simulation*, vol. 23, no. 2, 2020.

[14] Statistisches Bundesamt, "Zensus 2022." [Online]. Available: https://ergebnisse.zensus2022.de/datenbank/online/statistic/3000G/details

[15] Forschungsdatenzentren der Statistischen Ämter des Bundes und der Länder, "Mikrozensus 2012, SUF, version 0."

[16] Federal Ministry of Justice, "Gebäudeenergiegesetz (Building Energy Act) of August 8, 2020 (Federal Law Gazette I p. 1728), last amended by Article 1 of the Act of October 16, 2023 (Federal Law Gazette 2023 I No. 280): GEG," 2020-08-08. [Online]. Available: https://www.gesetze-im-internet.de/geg/

[17] ——, "Richtlinie für die Bundesförderung für effiziente Gebäude (Guideline for the Federal Funding for Efficient Buildings) of December 21, 2023 (Reference: Federal Gazette AT 29.12.2023 B1): BEG." [Online]. Available: https://www.bafa.de/SharedDocs/Downloads/DE/Energie/beg_richtline_beg_em_20231221_PDF.html

[18] ——, "Wärmeplanungsgesetz (Heat Planning Act) of December 20, 2023 (Federal Law Gazette 2023 I No. 394): WPG." [Online]. Available: https://www.gesetze-im-internet.de/wpg/

[19] European Commission, "Directive 2003/87/ec of the european parliament and of the council of 13 october 2003 establishing a system for greenhouse gas emission allowance trading within the union and amending council directive 96/61/ec (text with eea relevance): Ets2." [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02003L0087-20240301

[20] Federal Ministry of Justice, "Kohlendioxidkostenaufteilungsgesetz (Carbon Dioxide Cost Allocation Act) of December 5, 2022 (Federal Law Gazette I p. 2154): CO2KostAufG." [Online]. Available: https://www.gesetze-im-internet.de/co2kostaufg/CO2KostAufG.pdf

[21] J. Thomsen, N. Fuchs, R. Meyer, N. Wanapinit, J. Ulffers, B. Bavia Bampi, D. J. Lohmeier, E. Prade, G. Gorbach, N. Sanina, P. Engelmann, S. Herkel, C. Kost, M. Braun,

M. Lenz, and :unav, “Bottom-up studie zu pfadoptionen einer effizienten und sozialverträglichen dekarbonisierung des wärmesektors. endbericht.”

[22] M. Wietschel, B. Weißenburger, M. Rehfeldt, B. Lux, L. Zheng, J. Meier, and :unav, “Preiselastische wasserstoffnachfrage in deutschland - methodik und ergebnisse.”

[23] L. Nesselhauf and S. Müller, “The carbon price for buildings and road transport. a concept for the transition from national to eu emissions trading.”