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D-1 Executive Summary

Austria's goal to achieve climate neutrality by 2040 requires a deep transformation of the residential building sector, which accounts for around one-third of final energy use and approximately 10% of total greenhouse gas (GHG) emissions. This transformation must be both rapid and socially just: reducing emissions while ensuring that vulnerable households—particularly renters and low-income groups—are not disproportionately burdened.

This report presents findings from a research project that developed and applied a System Dynamics (SD) model to explore socially fair pathways for decarbonising Austria's residential building sector. The project combines qualitative and quantitative systems approaches to capture the complex interactions between building stock dynamics, heating systems, policy interventions, and social equity outcomes such as energy poverty.

A Causal Loop Diagram (CLD) was first developed to map reinforcing and balancing feedback loops that shape renovation behaviour, heating system transitions, political pressure, and social responses. This conceptual work informed a detailed quantitative SD model built in STELLA Architect. The model dynamically simulates:

- Building stock evolution, including construction, demolition, and renovation flows
- Energy performance improvements through renovations
- Heating system transitions from fossil fuels to low-carbon technologies
- Household energy costs, burdens, and energy poverty incidence
- Feedback mechanisms where climate and social pressures influence policy responses

The model disaggregates households into twelve groups based on building type, income level, and tenure status. This enables analysis of distributional impacts of policies and how incentives or costs are shared between landlords and tenants.

Policy Scenarios

Eight policy scenarios were developed and tested against a baseline reflecting current trends. These include:

- Economic measures (ECO1–ECO4): Increasing renovation subsidies, carbon pricing, improved landlord cost recovery, and awareness campaigns.
- Heating system decarbonisation (GHG1–GHG3): Bans on fossil fuel installations, restrictions on replacements, and full decarbonisation of electricity and district heating.
- All-policies package: Combining economic incentives, heating system bans, renewable energy deployment, and higher carbon pricing.

Key Findings

- Renovation activity: Financial incentives and carbon pricing moderately increase renovation rates (+9–10% compared to baseline). Regulatory measures allowing cost recovery in rental units further boost renovation rates (+35%). However, heating system decarbonisation policies alone have little effect on renovations.
- Energy use: Total energy use in the residential sector declines modestly (–3.4% in the all-policies scenario), with reductions driven mainly by increased renovation activity and adoption of more efficient heating systems such as heat pumps.
- GHG emissions: The all-policies package achieves the largest emissions reduction (–59% relative to baseline by 2050) but still falls short of climate neutrality. Fossil heating systems

remain in significant use by 2050, highlighting the slow turnover of building stock and heating technologies.

- Energy poverty: Carbon pricing and heating system bans slightly increase energy poverty rates (+0.1–0.3%), while subsidies modestly reduce it. A comprehensive package slightly worsens energy poverty, underscoring the need for targeted compensation or "warm rent" mechanisms.

Policy Implications

The findings suggest that:

- Comprehensive policy packages are essential. Single measures are insufficient to achieve deep decarbonisation; only combined efforts addressing both renovations and heating systems significantly reduce emissions.
- Earlier and stronger interventions—especially rapid phase-out of fossil heating systems and scaling up deep renovations—are needed to meet Austria's 2040 target.
- Socially balanced policies are crucial to prevent increases in energy poverty and ensure fairness. Bundling carbon pricing with income-based support and landlord-tenant cost-sharing mechanisms is necessary for a just transition.

Contribution and Future Outlook

This project delivers:

- The first SD model of Austria's residential building sector with a justice-oriented lens
- A structured database and modelling framework for future scenario analysis
- Qualitative and quantitative insights into policy interactions, trade-offs, and synergies
- Future work will refine model calibration, expand policy modules to include compensation schemes, differentiate renovation depths, and conduct sensitivity analyses. The model is a proof-of-concept tool that policymakers and researchers can build on to design fair, effective strategies for transforming Austria's housing sector in line with climate and social goals.

D-2 Introduction

The decarbonisation of the residential building stock is a key pillar of climate change mitigation efforts across Europe and beyond (Cabeza et al., 2022; Cabeza and Ürge-Vorsatz, 2020). In Austria, the building sector accounts for approximately 10% of national greenhouse gas (GHG) emissions, with the vast majority originating from space heating and hot water provision (Sibille et al., 2025; Umweltbundesamt, 2023). Consequently, improving the energy efficiency of buildings and transitioning away from fossil-based heating systems are critical to achieving the country's climate targets. The Federal Government's goal to achieve climate neutrality by 2040 (Bundeskanzleramt, 2025), ten years ahead of the European Union target, adds further urgency to the challenge.

Despite this policy momentum, progress in the decarbonisation of Austria's building stock remains uneven. While notable advances have been made in new building construction standards, the largest share of emissions comes from the existing building stock, much of which is thermally inefficient and heated with fossil fuels (BMK, 2023a). Around half of all buildings in Austria have an energy performance class of D or worse and are in urgent need of energy-related renovations (Sibille et al., 2025). Retrofitting these buildings and replacing outdated heating systems are not only essential for reducing emissions but also offer opportunities to improve indoor comfort, lower household energy bills, and reduce energy poverty (Eisfeld and Seebauer, 2022; Seebauer, 2021).

However, a growing body of research and policy discourse has recognised that climate policies in the building sector do not take place in a social vacuum. A 'just transition' (Heffron and McCauley, 2018; Newell and Mulvaney, 2013) lens draws attention to the social implications and distributive effects of these policies. In particular, issues of affordability, access, and equity are paramount when it comes to thermal renovations and heating system transitions. As numerous studies have shown, low-income households often lack the financial resources, information, or decision-making power needed to undertake or benefit from energy-related renovations (Bird and Hernández, 2012; Hernández and Phillips, 2015; Seebauer, 2021). These disparities are exacerbated in rental housing markets, where tenants have limited control over building infrastructure and face the risk of rent increases following energy upgrades—a phenomenon sometimes referred to as "renoviction" (Bouzarovski et al., 2018; Busà, 2024).

In Austria, this tension is particularly pronounced in the rental housing sector, which comprises around 44% of all main residences (Schöber, 2024). A large share of these rental units are located in older buildings with high energy demand and are disproportionately occupied by lower-income households (E-Control, 2013; Seebauer et al., 2019). The combination of high renovation needs, fossil-based heating systems, and socio-economic vulnerability presents a dual challenge: to reduce emissions in line with climate targets while avoiding the exacerbation of social inequalities. At the same time, current policy instruments—such as renovation subsidies or the phasing out of fossil boilers—often fail to account for these distributional aspects, thus risking an erosion of public support for the energy transition (Williams and Doyon, 2019).

This report is situated at the intersection of climate mitigation, adaptation and social justice in the Austrian housing sector. It explores the potential trade-offs and synergies resulting from feedbacks related to barriers and policy options involved in decarbonising the residential building stock in a socially just and politically feasible manner. The focus lies particularly on the rental sector, where the so-called "tenant-landlord dilemma" (Ástmarsson et al., 2013; George et al., 2023; Kühn et al., 2024) and the associated "split incentive" problem—where landlords must bear the costs of renovation while tenants reap the benefits—poses a persistent obstacle to action (Bird and Hernández, 2012, 2012; Melvin, 2018). In this context, a just transition perspective not only calls for effective policy tools but also demands careful consideration of who bears the costs, who benefits, and whose voices are heard in the process (Newell and Mulvaney, 2013).

The empirical and analytical foundation of this report draws on a combination of qualitative and quantitative methods. First, we conducted a review of literature and policies. Insights from this were synthesised into a qualitative causal loop diagram (CLD) highlighting the dynamic interactions between technical, economic, and social drivers of the heating transition. The CLD served as a conceptual basis for the development of a system dynamics (SD) model, which aims to simulate alternative policy pathways and their implications for emissions reduction and social equity.

While the final version of the model is still under development, the modelling framework offers a structured and flexible approach to analyse, assess, and explore different policies and combinations thereof, such as carbon pricing, renovation subsidies, warm rent mechanisms, and targeted income support. The model can endogenously represent socio-economic dynamics by capturing feedback loops, such as the influence of energy poverty on social policy pressure, or the impact of rising carbon prices on heating costs and subsequent retrofit incentives. Moreover, it distinguishes between different household groups based on income, tenure status, and dwelling characteristics, thus allowing for a disaggregated analysis of equity outcomes.

Importantly, the approach adopted in this project aligns with a growing recognition in the academic literature and policy circles that the decarbonisation of buildings must be both rapid and just. As Carley and Konisky (2020) argue, the transition to a low-carbon future should not merely be efficient but also equitable, ensuring that vulnerable populations are not left behind or further marginalised. Similarly, McCauley et al. (2013) emphasise the importance of “energy justice” as a framework for evaluating the fairness of energy systems and policies, including dimensions of recognition, participation, and distribution.

In addition to offering an analysis of the intricacies linked to decarbonising Austria's residential building sector for Austria, this report seeks to contribute to the broader discourse on sustainable transitions. It speaks to several strands of research, including socio-technical transitions research, environmental justice, and energy policy. In doing so, it echoes calls for more integrated and interdisciplinary approaches that consider not only the technical feasibility but also the social acceptability and political viability of climate mitigation strategies (Abram et al., 2022; McCauley et al., 2019).

The structure of the report is as follows. After this introduction, section 2 situates the project within the existing policy context and literature. Section 3 outlines the theoretical anchors and methodological approach of this study. Section 4 presents the model itself, while section 5 gives an overview of the policy scenarios the model intends to simulate. In section 6, we reflect on insights from the modelling process so far. Finally, section 7 provides and outlook and plan of the next steps.

Overall, this report underscores that a successful transformation of the Austrian housing sector hinges not only on technological innovation and financial investment but also on deliberate efforts to address structural inequalities. Without such efforts, the energy transition risks deepening existing fault lines rather than bridging them. Conversely, if carefully designed, policies for building decarbonisation can yield substantial co-benefits for climate, public health, and social cohesion. The challenge lies in crafting strategies that harness this potential without reproducing or reinforcing patterns of exclusion and disadvantage.

D-3 Policy Context and Literature Review

D-3.1 The Building Sector in Climate and Energy Policy

The residential building sector is a critical arena for both climate change mitigation and social policy. Globally, buildings account for around 36% of final energy consumption and nearly 40% of energy-related CO_2 emissions when upstream power generation is included (Dahiya and Laishram, 2024). This makes the sector central to efforts to meet the objectives of the Paris Agreement. Yet decarbonising buildings is especially complex due to long lifespans, diverse ownership structures, and the embeddedness of buildings in everyday social practices (Amann et al., 2023; D'Oca et al., 2018). These challenges are compounded in Europe, where a large share of the building stock is old and energy inefficient, and where energy use for space heating constitutes a substantial share of household energy demand, particularly in colder climates.

The European Union has made the building sector a key pillar of its climate strategy. The European Green Deal (European Commission, 2019) and the Fit-for-55 package set out a trajectory toward climate neutrality by 2050. Within this framework, the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED) aim to raise renovation rates and improve building energy performance. These policies are complemented by the EU Renovation Wave Strategy, which explicitly targets a doubling of renovation rates over the next decade (European Commission, 2020). The European Climate Law has enshrined the 2050 climate neutrality target into binding legislation.

Austria, as an EU member state, is committed to these targets. The Austrian federal government has adopted the European goals in its own national climate and energy strategy, the #Mission2030 framework, and the subsequent "National Energy and Climate Plan" (NEKP) (BMK, 2024). Austria's targets include a 100% share of renewable electricity by 2030 and climate neutrality by 2040 (Bundeskanzleramt, 2025). Given that buildings are responsible for around one third of final energy consumption and roughly 10% of total greenhouse gas (GHG) emissions in Austria (Umweltbundesamt, 2023), the sector's transformation is essential for reaching national targets.

A central concern for both Austrian and EU climate policy is the decarbonisation of heat—often referred to as the "heat transition" (Abbasi et al., 2021). This involves both the replacement of fossil-fuel heating systems and the energetic refurbishment of buildings to reduce heat demand (D'Oca et al., 2018; Galimshina et al., 2024). In Austria, the installation of fossil heating systems in new buildings is no longer permitted (EWG, 2023), however, a clear pathway to phase-out existing oil and gas heating systems is lacking. Overall, the policies reflect a broader shift toward electrification and district heating, supported by a surge in subsidies and regulatory tightening (BMK, 2023b).

D-3.2 Decarbonising the Building Stock: Instruments, Levers and Barriers

Decarbonising the existing building stock typically rests on two primary levers: improving building energy efficiency (through insulation and envelope upgrades) and switching to low-carbon heating systems (e.g. heat pumps, biomass, district heating) (Cabeza and Ürge-Vorsatz, 2020; Kapeller et al., 2024). In both cases, a combination of regulatory and economic instruments is commonly applied.

Regulatory instruments include building codes, mandatory energy performance certificates, and, more recently, phase-out deadlines for specific heating systems. In Austria, federal and state governments jointly define minimum standards for new construction and major renovations. Economic instruments include subsidies, tax incentives, and carbon pricing. Notably, Austria introduced a carbon tax on fossil fuels in 2022 as part of its eco-social tax reform, along with a climate bonus (Klimabonus)[1] to redistribute revenues and cushion impacts on vulnerable households (Parlament Österreich, 2022).

Despite these instruments, the transformation of the building stock has been slow. Renovation rates in Austria remain well below the 2% per annum needed to meet climate targets (IIBW and Umweltbundesamt, 2023). Empirical research identifies multiple barriers: high upfront costs, long payback periods, lack of knowledge or trust in energy-saving technologies, and the "split incentive" problem in rental housing (Amann et al., 2023; Amann and Mundt, 2021; Peer et al., 2025; Seebauer et al., 2019). The latter refers to a misalignment of costs and benefits between landlords (who would pay for retrofits) and tenants (who would benefit from lower energy bills), which undermines incentives for investment in energy efficiency.

These barriers are particularly pronounced in Austria's rental sector, which accounts for around 44% of all main residences (Schöber, 2024). A large share of these are older buildings with poor energy performance, often in the hands of small private landlords or institutional housing providers (Sibille et al., 2025; Statistik Austria, 2023). At the same time, households with low incomes are overrepresented in poorly insulated rental dwellings, exacerbating both energy poverty and emissions intensity (Seebauer, 2021; Wegscheider-Pichler, 2022).

D-3.3 Social Dimensions of the Heat Transition

The decarbonisation of buildings is not only a technical and economic challenge—it is also a deeply social one. Retrofitting the housing stock affects people in many ways, among others how people live, what they pay for energy, and their ability to feel comfortable at home also during cold periods and heatwaves. As such, there is growing recognition that energy transitions must be socially just and inclusive. This has led to a growing literature on "energy justice" and "just transitions," which frame the energy transition in terms of fairness in distribution, recognition, and decision-making (Heffron and McCauley, 2018; Jenkins et al., 2016; Sovacool and Dworkin, 2015)

In the building sector, social inequalities manifest in different ways. Low-income households are more likely to live in inefficient dwellings, lack the capital or legal agency to improve their situation, and face disproportionate exposure to cold homes or energy-related debt (Bouzarovski and Petrova, 2015). Tenants are often unable to influence heating systems or insulation levels, while owners in multi-apartment buildings may face collective action problems (Ástmarsson et al., 2013; Melvin, 2018).

Moreover, the structure of existing policy instruments can reinforce inequalities. Subsidies for retrofitting are often only accessible to owner-occupiers with upfront capital, leaving tenants and low-income households behind (Lekavičius et al., 2020). Carbon pricing, if not accompanied by adequate redistribution, may also place a greater burden on those who have the least flexibility to adjust their energy use. As a result, poorly designed climate policy can inadvertently increase energy poverty or reduce public support for climate action (Belaïd, 2022; Martin and Islar, 2021).

In Austria, these concerns have become more salient as heating costs have risen in recent years due to both international energy market developments and the introduction of carbon pricing. The climate bonus - which has since been abolished - was originally introduced to mitigate the burdens from increased energy prices. While recycling of carbon pricing revenues is generally found to be progressive (Kirchner et al., 2019; Mayer et al., 2021), public debates have intensified around the fairness of phase-out targets and subsidy allocation. The phase-out path for gas heating systems contained in the original draft of the Renewable Heat Act (EWG) (Austrian Parliament, 2022) was removed from the final bill, and the subsidy programs "Raus aus Öl und Gas" (which subsidised replacements of fossil heating

[1] Though the coalition government led by Christian Stocker abolished the "Klimabonus" revenue redistribution mechanism in spring 2025.

systems with low-carbon alternatives) as well as the "Sanierungsbonus" (which subsidised building retrofits) have also been discontinued in the meantime.

D-3.4 Existing Studies and Research Gaps

The decarbonisation of the residential building sector has been the subject of increasing attention across a range of scientific disciplines. These include techno-economic modelling of transition pathways, analyses of social and political feasibility, and more recently, a growing literature on energy justice and distributional effects. The following subsection briefly synthesizes the state of research across these strands and outlines the contributions and innovations of the present study.

D-3.4.1 Techno-economic modelling of building decarbonisation

A robust body of literature exists on techno-economic transition pathways, that assesses the effects of different policy packages on technical and economic factors such as energy demand, CO2 emissions and costs in the building sector, especially in the context of national and EU-level climate goals. In Austria, the Invert/EE-Lab model (Müller, 2015; Müller et al., 2024; Steinbach, 2016) has played a central role in informing such pathways, with scenarios for phasing out fossil fuels in space heating and domestic hot water supply, and reaching high thermal efficiency standards in the building stock. For example, the ACRP-funded “Decarb-Inclusive” project developed detailed decarbonisation pathways that also considered affordability and social differentiation (Kranzl et al., 2020). More recently, the ACRP-funded "TransFair-AT" project assessed various policy options aimed at decarbonising the housing and mobility sectors regarding their socioeconomic effects, and identified pathways for a socially fair decarbonisation (Kettner et al., 2025).

D-3.4.2 Systems modelling and SD applications in the building sector

While energy system models based on mathematical optimization are well-established, relatively few studies have applied System Dynamics (SD) to the decarbonisation of the residential building stock (Che et al., 2023; Fazeli and Davidsdottir, 2017; Onat et al., 2014; Zhou et al., 2020). In contrast to optimization models, which typically aim to identify optimal economic or technological conditions (such as minimizing cost or achieving market clearing for electricity), SD models adopt a more dynamic and exploratory approach, often assessing the system-wide impacts of "what-if" scenarios. Where SD models exist, they are often used at national or regional levels to evaluate long-term renovation strategies and measures aimed at increasing energy efficiency. However, they rarely integrate distributive or procedural justice concerns, nor do they model social feedbacks, such as between household energy burdens, political support for climate policies, and investment decisions. This presents a critical gap, particularly for countries like Austria where the rental housing sector comprises a large share of the stock and is shaped by distinct governance and ownership patterns. The current project addresses this gap by combining SD modelling with insights from the energy justice and just transition literature.

D-3.4.3 Socio-political studies on housing and retrofit in Austria

A growing number of studies address the socio-political dimensions of building renovation and climate policy in Austria. For instance, Seebauer (2021) investigated how low-income renters in Graz perceive fairness in renovation processes, revealing strong preferences for shared cost models and inclusive decision-making. Other studies have highlighted barriers related to the landlord-tenant dilemma (Berger and Höltl, 2019), financialization of real estate, and the political economy of housing provision (Litschauer and Friesenecker, 2021). Others outline institutional barriers to and policy options for accelerating energy renovations (Amann, 2019; Amann et al., 2023; Amann and Mundt, 2021). In a recent study, Müller et al. (2024), provided a model-based analysis of different policies promoting decarbonization in light of their socio-economic and justice-related effects. These works provide valuable contextual insights but do not offer a system-based account of how these factors dynamically interact over time or in response to different policies. This project seeks to bridge that gap by linking such qualitative factors to a simulation-based model capable of testing different intervention scenarios.

D-3.4.4 Energy poverty, justice, and fairness in transitions

The link between energy efficiency policy and energy poverty has become a key concern, particularly in light of rising energy prices and inflation. Both international and Austria-specific studies point to a risk that renovation and fuel-switch policies, if poorly designed, may deepen inequalities by shifting costs onto vulnerable households or excluding them from the benefits of the transition (Anguelovski et al., 2022; Bouzarovski et al., 2018; Grossmann, 2019; Woods et al., 2024). For example, Kettner et al. (2025) found that targeted compensation and inclusive governance mechanisms are needed to avoid regressive effects of climate policies. The justice literature also emphasizes procedural aspects, such as participation and access to information, which are seldom incorporated in quantitative policy models.

D-3.4.5 Synthesis and contribution of this project

In summary, while prior work has significantly advanced our understanding of technical feasibility, policy instruments, and social acceptability, these strands remain largely disconnected. The novelty of this project lies in integrating these dimensions within a unified system dynamics framework. By doing so, the model can account for multiple feedbacks, including those related to social dynamics: for instance, how energy poverty might increase political pressure for redistribution, or how carbon pricing can drive both retrofit activity and affordability concerns. Moreover, the model enables the testing of justice-sensitive scenarios (e.g., warm rent schemes or targeted subsidies) that go beyond cost-optimal pathways and engage with questions of distribution and fairness.

Hence, the project contributes to a small but growing literature that approaches building sector decarbonisation not only as a technical or economic challenge, but as a socially embedded process requiring attention to power, equity, and institutional complexity. It also adds to a very limited number of studies that apply SD to housing transitions in a way that incorporates justice perspectives.

D-4 Theoretical and Methodological Approach

D-4.1 Energy Justice and Just Transition: Theoretical Anchors

The transition to a low-carbon society entails significant socio-economic and distributive consequences, especially in sectors such as housing, where energy use is intimately linked to essential needs, affordability, and infrastructure. Within this context, the concepts of energy justice and just transition have gained prominence as both normative and analytical frameworks to interrogate and guide policy and system change. Energy justice is commonly conceptualised as comprising three interrelated dimensions: distributive justice (who benefits or suffers from energy policies), recognitional justice (whose needs, identities, and vulnerabilities are acknowledged), and procedural justice (who participates in decision-making processes) (Jenkins et al., 2016; Sovacool and Dworkin, 2015). In the housing sector, these dimensions manifest in debates around how retrofitting policies affect different income groups, whether vulnerable tenants are represented in planning processes, and how the burdens and benefits of decarbonisation are shared.

Closely related, the concept of a just transition emerged historically in the labour movement and has evolved into a broader framework addressing the social implications of environmental and climate policies (Healy and Barry, 2017; Wang and Lo, 2021). It seeks to ensure that the costs of structural change—such as phasing out fossil fuels or mandating building renovations—do not fall disproportionately on already disadvantaged groups. Scholars such as Newell and Mulvaney (2013) argue that a just transition must involve contesting incumbent power relations and shaping low-carbon pathways that are not only technologically feasible but also socially equitable and democratically accountable.

This perspective is particularly relevant in the context of Austria's housing sector, where a large proportion of the population are tenants, many of whom reside in buildings with poor energy performance (Seebauer, 2021; Wegscheider-Pichler, 2022). Policies aimed at reducing emissions through mandatory renovations, carbon pricing, or phase-outs of fossil heating systems may exacerbate existing inequalities if they do not incorporate justice considerations. Accordingly, this research adopts an energy justice and just transition perspective as a guiding normative lens to evaluate and design transition pathways in the residential building sector.

D-4.2 A Systems Perspective on Building Sector Decarbonisation

Decarbonising the building stock is a complex challenge involving technical, behavioural, economic, and institutional factors (D'Oca et al., 2018). As outlined above, significant improvements in energy performance and emissions reduction are technically possible. However, numerous barriers hinder widespread uptake of retrofitting measures and the adoption of low-carbon heating technologies. These include split incentives between landlords and tenants, limited access to finance, lack of skilled labour, regulatory hurdles, and informational gaps (Bird and Hernández, 2012; Cabeza and Ürge-Vorsatz, 2020; Castellazzi et al., 2017; D'Oca et al., 2018; Kettner et al., 2025; Lang et al., 2021).

Understanding and addressing these interrelated obstacles requires a systems perspective—one that moves beyond linear cause-effect reasoning and instead focuses on feedback loops, stock-flow dynamics, time delays, and policy interactions (Meadows, 2009; Sterman, 2000). Buildings are long-lived capital goods, and both the physical stock and the socio-institutional structures surrounding them evolve differently over time. Therefore, policy interventions can have delayed effects, and unintended consequences such as rebound effects (Motavasseli, 2024), gentrification and displacement (Bouzarovski et al., 2018) or increased inequalities (Lekavičius et al., 2020) are common. Moreover, policies do not operate in a vacuum but are part of a socio-political structure: their effectiveness depends on behavioural responses, socio-political acceptance, and interactions with other measures.

A systems perspective enables researchers and policymakers to explore how different system structures influence developments over time, how reinforcing or balancing feedbacks can accelerate or inhibit change, and where leverage points for effective intervention might lie. It is particularly useful in the context of the Austrian housing sector, where multi-faceted technological challenges (such as renovating an old and inefficient building stock or replacing a large volume of fossil heating systems with low-carbon alternatives in short time) intersect with complex social challenges (such as the tenant-landlord dilemma or equity concerns linked to access to subsidies for energy efficiency and low-carbon technologies).

D-4.3 System Dynamics as an Integrative Methodological Approach

The transition to a low-carbon housing sector represents an example of a complex, dynamic system—marked by long time horizons, interdependent actors and sectors, delays between policy inputs and system responses, and feedbacks that can either reinforce or counteract change. To explore such systems, a method is required that can accommodate dynamic complexity, integrate qualitative insights with quantitative data, and offer structured ways to investigate policy interventions under uncertainty. SD modelling is well suited to meet these needs.

Pioneered by Jay Forrester in the 1960s to address industrial and urban planning problems, SD has since evolved into a broadly used methodology in fields as diverse as sustainability transitions, public health, education, and energy systems (Barbrook-Johnson and Penn, 2022; Meadows, 2009; Pruyt, 2013; Sterman, 2000). Its core strength lies in its ability to model feedback-rich systems over time, representing how variables interact within and across sectors, and how these interactions shape the trajectory of the system.

D-4.3.1 Core Elements of the System Dynamics Approach

At its heart, SD modelling focuses on three key elements (Sterman, 2000):

- Feedback loops – causal structures where variables influence each other in circular ways. These can be reinforcing (positive) or balancing (negative), and they determine how systems behave over time.
- Stocks and flows – stocks represent accumulations (e.g., the number of residential buildings, cumulative emissions), while flows represent the rate of change into or out of those stocks (e.g., construction, renovation, demolition). These structures describe how the state of the system evolves over time. Importantly, stocks are not limited to physical or material infrastructures but can also represent institutional or informational stocks such as (levels of) trust in public authorities, public awareness of climate issues, or political pressures.
- Delays and non-linearities – many real-world processes exhibit time lags between cause and effect (e.g., the delay between policy adoption and actual emission reductions due to construction times). In addition, systems often exhibit non-linear behaviour, such as diminishing effects of subsidies or threshold effects ("tipping points") in political support. These behaviours result from the interaction of feedback loops and stock-flow structures and are essential to understanding complex, path-dependent dynamics.

Together, these elements enable the construction of dynamic models that simulate the dynamic complexity of real-world problems. SD models can capture how behaviours, infrastructure, and policies interact and evolve over time, making them particularly useful for exploring transition pathways and the potential unintended effects of policy interventions. Unlike static assessments or optimisation-based approaches, SD enables researchers and decision-makers to examine how systems behave under alternative scenarios, accounting for delays, resistance, and potential unexpected effects.

D-4.3.2 *Qualitative System Dynamics: Causal Loop Diagrams*

A common entry point into SD modelling is the development of Causal Loop Diagrams (CLDs) (Bala et al., 2017; Barbrook-Johnson and Penn, 2022; Sterman, 2000). These are qualitative tools used to visualise and discuss the major dynamics of a system by eliciting underlying cause-and-effect relationships. CLDs represent key variables and show how they influence one another via feedback loops, from which possible system behaviour can be drawn. For instance, increasing energy efficiency may reduce emissions, which in turn could affect political will, subsidy levels, or household behaviour.

CLDs are particularly useful in the early stages of system analysis, as they allow researchers and stakeholders to visualise their understanding of the system, identify potential leverage points, and discuss where interventions might lead to unintended consequences. In participatory settings, they can also be used to elicit, compare and merge mental models among actors (Sedlacko et al., 2014).

While CLDs do not include numerical data, they provide a conceptual foundation for quantitative model development, helping to ensure that any mathematical representation is grounded in a coherent theory of system structure and behaviour. As a starting point for this, reference modes are often employed. Reference modes are set of graphs and other descriptive data showing the historical behaviour of the key concepts and variables (Sterman, 2000). On this basis, relevant factors influencing the indicator or proxy in question and the causal relationships among them are identified.

D-4.3.3 *Quantitative System Dynamics: Stock-Flow Modelling and Simulation*

Once a CLD has been established, the next step in the SD approach is to translate its structure into a quantitative stock-flow model, typically implemented in dedicated software platforms such as STELLA. These models consist of:

- Stocks: accumulations or state variables, such as the number of renovated dwellings, cumulative emissions, or households in energy poverty.
- Flows: rates that change the size of stocks over time, such as renovation flow, demolition, or fuel switching.
- Converters and parameters: auxiliary variables and constants that influence flows (e.g., renovation rates, subsidy rates, energy prices).
- Graphical functions or equations: representations of relationships, including thresholds, saturation effects, or elasticities.

Quantitative SD models operate by simulating the behaviour of the system over decades, enabling analysts to explore how the system responds to different initial conditions, parameter values, and policy scenarios. One key advantage is their ability to test “what-if” scenarios and compare policy mixes in a consistent, transparent framework.

These models are not predictive in the narrow sense but are exploratory tools that understand how different assumptions and interactions shape future trajectories. They are especially useful when dealing with high uncertainty, long timeframes, and deep societal change—as is the case with the decarbonisation of the housing sector.

D-4.3.4 *Integration of Quantitative and Qualitative Insights*

SD is largely grounded in conceptual clarity and qualitative insight and not a purely quantitative or data-driven approach. Gaps in the data are addressed through different ways of supplementing data as well as testing and validating the model structure and its quantitative aspects (i.e., equations and numerical data) based on literature, stakeholder knowledge and expert judgment. The emphasis is not on precision, but on structure, transparency, and insight into system behaviour (Sterman, 2000).

This makes SD particularly well suited for transition modelling in areas where social, economic, and technical dimensions intersect, and where the effects of policy depend heavily on timing, feedback, and acceptance. While social dynamics were important from the very beginning of SD, in recent years, the approach has gained increasing attention in the field of sustainable transitions, including energy and climate policy, due to its capacity to integrate behavioural dynamics, distributional aspects, and institutional change (Allen et al., 2021; Collste et al., 2017; Dixson-Declève et al., 2022)

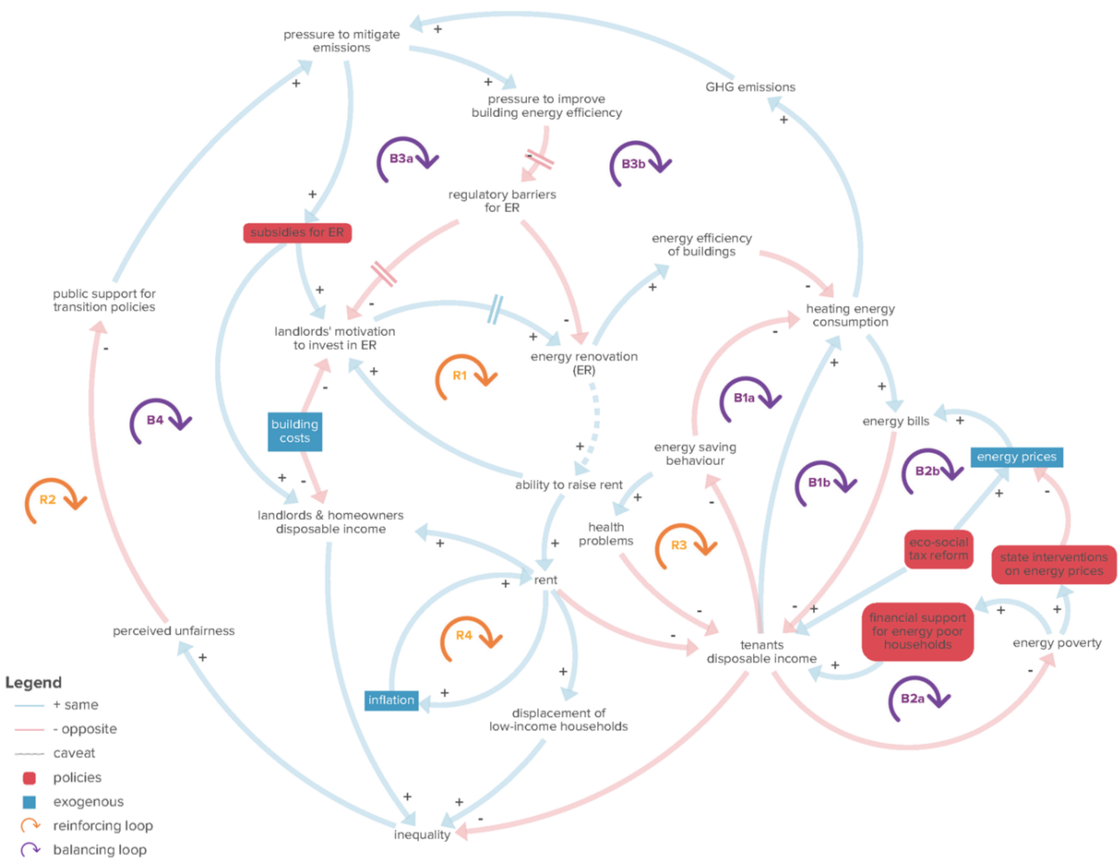
In this project, SD provides the methodological backbone for linking housing system structure, energy use, emissions, policy incentives, and social outcomes such as energy poverty. The next section presents the actual model developed for this purpose, including both a CLD to map key dynamics and a stock-flow simulation model built in STELLA Architect.

D-5 Model Overview: From Qualitative Insights to Dynamic Simulation

D-5.1 From Causal Loop Diagram to Model Structure

The modelling effort in this project was informed by a systems perspective on the socio-technical transformation of Austria's rental housing sector. As a first step, a qualitative CLD was developed to map the key interdependencies, feedback effects, and leverage points shaping the interplay between decarbonisation efforts, social justice concerns, and policy instruments in the building sector. This diagram was developed through a mixed method approach, including literature review, expert interviews, and partly drawing on previous project findings (Klingler et al., 2025).

Abb. D-1: CLD visualising the problem dynamics



The CLD highlights the interactions between various factors, policies, and exogenous variables that influence this transition. Blue arrows indicate positive polarity (+), where a change in one variable causes a change in the same direction in another variable. Red arrows indicate negative polarity (-), where a change in one variable leads to an opposite change in another. Two parallel crossing lines on arrows indicate delays i.e. a time-lag in the reaction. Balancing loops are either reinforcing (R) or balancing (B), meaning they amplify and stabilize the dynamics within the system, respectively. Current policies are highlighted as red rectangles with rounded corners, variables that are predominantly shaped by factors outside of the CLD are in petrol boxes.

The CLD maps the complex interactions between technical, economic, and social drivers of energy renovation (ER) in Austria's residential building stock. The CLD was developed to guide the transition from qualitative understanding to quantitative modelling and to ensure that key feedback loops, behavioural mechanisms, and trade-offs were captured in the formal model structure. At the core of the CLD is the interplay between building energy efficiency, renovation activity, energy costs, and socio-political feedbacks. Energy renovation reduces heating energy consumption by improving building energy efficiency, which in turn lowers energy bills. However, the pathway to increased renovation activity is mediated by a range of balancing and reinforcing feedback loops.

Balancing feedback loops:

- *B1 – Income–Consumption Loop*: Higher household incomes typically result in larger dwellings (Statistik Austria, 2022), more appliances (Poblete-Cazenave and Pachauri, 2021), and less energy-saving behaviour (Umit et al., 2019), all of which increase energy consumption and therefore reduce disposable income. This creates a balancing loop where increases in income are partially offset by increased energy costs.
- *B2 – Energy Poverty Mitigation Loop*: This loop consists of two mechanisms. B2a captures how state subsidies targeting energy-poor households (e.g., for heating costs) mitigate energy poverty. B2b reflects how broad interventions in energy pricing (e.g. the electricity price brake (BMF, 2024)) help reduce household energy bills, thereby lowering energy poverty levels.
- *B3 – Climate Policy Response Loop*: Increases in GHG emissions from buildings raise political pressure, triggering policy interventions such as subsidies for replacing fossil heating systems (B3a) or funding for energy renovations (B3b) (BMK, 2023b, 2023a). These in turn reduce emissions, completing a balancing feedback loop.
- *B4 – Justice Erosion Loop*: A less direct but politically relevant loop: when subsidies primarily benefit homeowners and landlords (rather than tenants) - which is typically the case, as evidence from other country suggests (Lekavičius et al., 2020; Macintosh and Wilkinson, 2011) - they may contribute to perceived injustice and inequality, which could erode public support for transition policies.

Reinforcing feedback loops:

- *R1 – Landlord Profitability Loop*: Landlords are more likely to invest in building renovation when this allows them to raise rents (Lang et al., 2021; Mjörnell et al., 2019), which increases income and makes further renovations attractive. However, this dynamic is moderated in Austria by rent regulation and construction-period-specific legal constraints (Morawetz and Klaiber, 2024; MRG, 1981).
- *R2 – Inclusive Retrofit Support Loop*: When energy efficiency refurbishments lower tenants' heating costs, disposable income increases. If subsidies are perceived as fairly distributed, this may boost public support for energy transition policies, potentially creating a reinforcing loop between fairness, support, and policy implementation (Thaller et al., 2023; Williams and Doyon, 2019).
- *R3 – Health–Income Trap Loop*: Households in energy poverty often resort to limiting heating (Brunner et al., 2012; Eisfeld and Seebauer, 2022), which may lead to health problems (Ormandy and Ezratty, 2012). This in turn can reduce productivity or increase sick leave, reinforcing poverty and reducing ability to pay energy costs (Khullar and Chokshi, 2018).
- *R4 – Inflation–Rent Spiral Loop*: Widespread use of value-protection clauses in rental contracts allows rents to rise with inflation. Since rent is part of the consumer price index (CPI) (Statistik Austria, 2024), this creates a self-reinforcing relationship between inflation and rental prices.

Overall, the CLD informs the structure of the system dynamics model by identifying key causal relationships and leverage points, many of which are not purely technical in nature. It draws attention to the co-evolution of: technological change (e.g., heating system replacement, insulation), behavioural responses (e.g., energy-saving efforts, renovation decisions), socio-economic impacts (e.g., energy poverty, rent dynamics), and policy feedbacks (e.g., changing carbon price, shifting public support).

This systemic perspective allows for a better understanding of how specific policies—such as renovation subsidies, carbon pricing, or support for energy-poor households—interact with one another and with broader social structures over time. This systems mapping exercise served as a conceptual bridge to the development of a formal System Dynamics (SD) model that simulates key dynamics over time and allows for policy testing.

D-5.2 Model Purpose and Boundaries

The primary purpose of the SD model is to explore potential trade-offs and synergies between climate mitigation and social justice objectives related to different policies in Austria's rental housing sector under different scenarios. More specifically, the model aims to answer questions such as:

- How do different fuel switching and building decarbonisation policies compare to each other with regard to their emissions reduction potential?
- How do these strategies impact household energy costs and energy poverty across different tenant groups?
- What policy mixes can help reduce emissions while improving or at least safeguarding affordability?

The model focuses on long-term dynamics (2020–2050) and includes both technical and socio-economic dimensions. The geographical scope is Austria, a special focus is put on the rental sector. The model does not aim to produce precise forecasts, but rather to serve as an exploratory tool to understand systemic interactions, identify leverage points, and inform policy debates on useful policy mixes.

Key simplifications and boundaries include:

- Focus on main residences only; vacation homes, secondary and vacant residential units are omitted from the analysis.
- Concentration on space heating as the dominant energy service in the residential sector. Other domestic energy services such as electricity for lighting or appliances are omitted.
- The model does not yet include cooling needs, carbon emissions linked to construction materials and activities, or land use effects.
- Political dynamics are stylized and captured via feedbacks from climate/social pressure to policy effort.

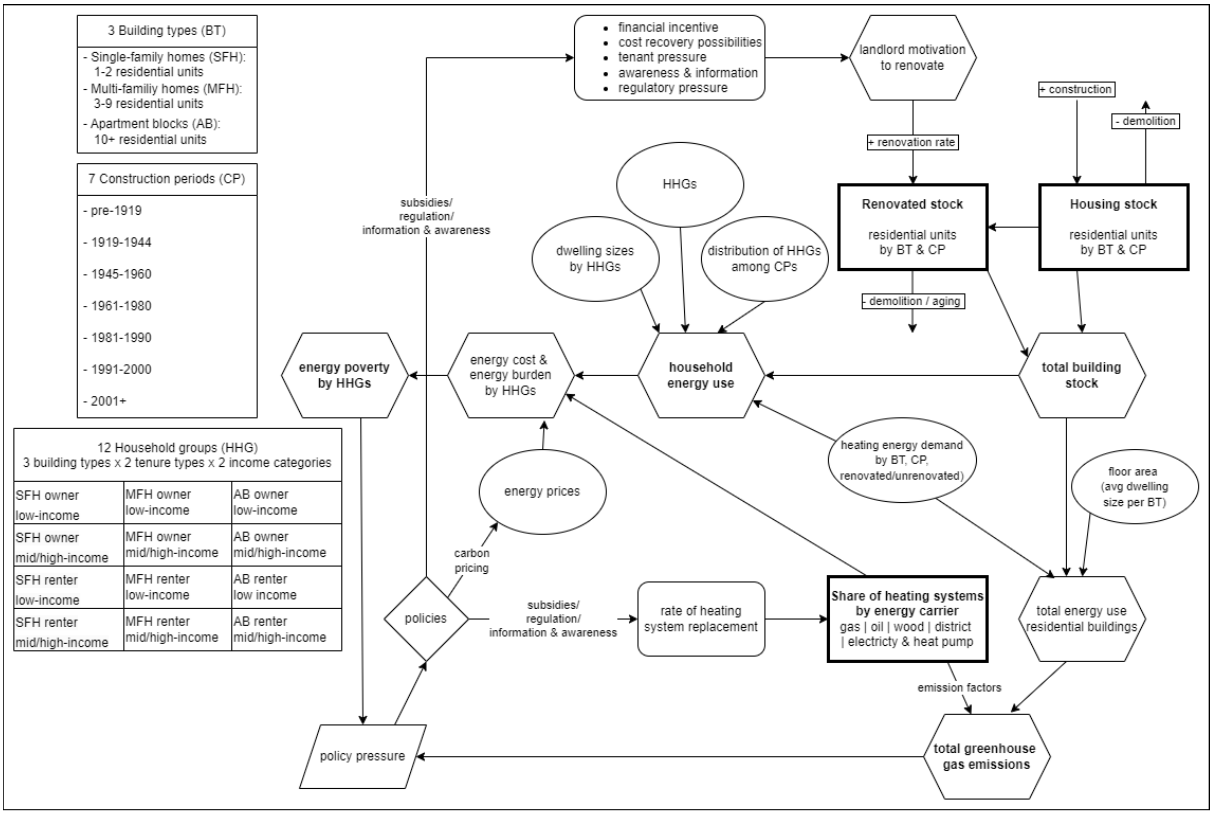
D-5.3 Main Model Dynamics and Structure

The quantitative SD model was built using STELLA Architect and consists of six interconnected modules:

1. Building stock dynamics
2. Heating systems and fuel switching
3. Energy demand and GHG emissions
4. Households and energy poverty
5. Renovation dynamics

Feedback loops ensure that changes in one module dynamically influence others, capturing the complex interactions and delayed responses typical in building sector transitions.

Abb. D-2: Conceptual overview of the system dynamics model of the Austrian residential building sector.



The model integrates housing stock dynamics, heating system transitions, household energy use, energy cost and burden, and resulting greenhouse gas (GHG) emissions. It differentiates between three building types (BT), seven construction periods (CP), and twelve household groups (HHG) defined by building type, tenure and income. Household energy use is influenced by energy prices, dwelling size, and building performance. Policy interventions—such as subsidies, carbon pricing, and regulation—affect renovation and fuel-switching behaviour, shaping both energy poverty outcomes and total emissions. Feedback loops capture the interdependencies between energy burden, policy pressure, and decarbonisation efforts.

Overall, the model structure consists of over 200 variables and their respective equations, and an arrayed logic across building types, vintages, heating systems, and household groups. It combines a sector-wide building model with a justice lens, including households, policies and feedbacks based on careful structuring and literature analysis. In addition, it integrates key justice considerations linked to energy poverty and tenant-owner differences.

D-5.3.1 Building Stock and Renovation

The model tracks the number of residential units across building types (single-family houses, multi-family houses, and apartment blocks) and construction periods (seven vintage categories). The typology is drawn from the TABULA project (Loga et al., 2016, 2012), which provides a classification scheme according to building size, age and further parameters and a set of exemplary buildings representing these building types.

Three main processes govern stock evolution:

- New Construction: Adds newly built residential units into the youngest construction cohort (2001+). The rate of construction is a function of total stock and a construction rate parameter.
- Demolition: Removes buildings from the stock at rates that vary by construction period, with older buildings having higher demolition rates.
- Renovation: Moves units from non-renovated to renovated sub-stocks, improving energy efficiency (reducing heating energy demand per m²). Renovation rates depend on policy incentives, landlord motivation, regulatory barriers, and social/political pressures.

This structure captures the slow turnover of the building stock, reflecting the long lifetimes of buildings. Renovation has a cumulative effect: as more buildings are renovated, average heating energy demand (HWB) decreases, lowering overall energy use and emissions. The model distinguishes between renovated and non-renovated stocks internally and computes a weighted HWB for each building type and construction cohort.

D-5.3.2 Heating System and Fuel Switching

The model includes five primary heating energy carriers (gas, oil, wood, district heating, and electricity/heat pumps).[2] These are represented as shares for each building type and construction period. A stock-flow structure models how these shares evolve:

- Heating System Replacement: Households replace heating systems at defined lifetimes or when incentives/regulations make switching attractive.
- Fuel Switching Dynamics: Transition rates between carriers (e.g., from oil to heat pumps) depend on base switching rates, policy pressure effects, and bans on new fossil installations. These elasticities are calibrated to observed historical data.

This module allows testing of policies such as:

- Subsidies for renewable heating
- Gradual or immediate bans on fossil heating system replacements
- Awareness campaigns influencing technology adoption

Changes in heating system composition directly affect both GHG emissions (through emissions factors) and household energy costs (through carrier-specific energy prices).

D-5.3.3 Energy Demand and GHG Emissions

Total energy demand is determined by the energy performance of buildings and the total floor area, which is computed from the building stock and average dwelling sizes. The heating energy demand (Heizwärmebedarf, HWB) per building type and vintage are taken from the TABULA project (Loga et al., 2016, 2012), which provides HWB values for a typology of a total of 21 different building types differentiated by three buildings types: single- and two family homes (SFH), multi-family homes (MFH) i.e. buildings with 3-9 residential units, and apartment blocks (AB) i.e. buildings with 10+ residential units) and vintages (pre-1919, 1919-1945, 1945-1960, 1961-1980, 1981-1990, 1991-2000, 2001+). Renovated buildings are assumed to have substantially lower HWB values, using data from BMK (2023a), and their growing share over time reduces total energy use. Final energy demand is linked with the heating share and multiplied with emissions factors to calculate annual GHG emissions.

Total sectoral energy use is the sum across all building types and cohorts. This energy demand is multiplied by heating system shares and emissions factors to compute total GHG emissions from the residential sector. These annual emissions are contrasted with exogenously determined target emissions (compliant with climate neutrality goals) to compute an emissions gap, which in turn influences compliance cost (due to necessary compensation payments), and subsequently climate policy pressure.

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[2] This classification comes with some limitations, as many households use more than one energy carrier (e.g., combine a wood pellet heating in one room with electric or gas heating systems in other rooms). Yet the modelling structure requires to assign only one energy carrier as primary source for space heating for each residential unit. Another challenge arises from the fact that heating energy costs for households using electric heating systems are difficult to estimate because in the EU-SILC only the sum of overall electricity bills is reported.

D-5.3.4 Households and Energy Poverty

Household are disaggregated into twelve groups building type, tenure and income level. The twelve household groups are intended to differentiate households according to building types (SFH, MFH, AB), tenure (owner/renter) and income (low-income vs. medium/high income). The rationale behind this differentiation is to account for differences in dwelling sizes, heating system energy carrier, HWB, and income. This allows the model to estimate household energy costs, energy burdens (costs as a share of income), and energy poverty risk.

For each group, the model computes:

- Energy Use: Based on average dwelling size, energy efficiency (HWB), and energy-saving behaviour.
- Energy Cost: Derived from energy use, carrier-specific prices, and heating system shares.
- Energy Burden: Energy cost relative to disposable household income.
- Energy Poverty Indicator: Share of households in each group exceeding a 10% energy burden threshold.

Energy-saving behaviour is endogenized through feedback from past energy costs to current demand.

This energy poverty component is also linked to policy feedbacks resulting from this the social dimension: If energy poverty increases, social policy pressure rises, influencing redistributive measures (e.g., heating cost subsidies, tax rebates). However, subsidies that lower energy costs can reduce the incentive for fuel switching, creating trade-offs between affordability and decarbonisation.

This module captures equity concerns and the risk of policy backlash if decarbonisation policies disproportionately harm vulnerable groups.

D-5.3.5 Renovation Dynamics

Renovation of existing buildings is represented as a flow from the non-renovated building stock to the renovated stock for each building type and construction cohort. The renovation rate is calculated as a weighted function of multiple behavioural and policy factors. At its core, a base renovation rate reflects historic renovation activity, which is then modified by:

- Policy incentives (e.g., subsidies, cost recovery rules),
- Landlord motivation and barriers (such as regulatory constraints or tenant pressure),
- Climate policy pressure derived from the emissions gap,
- Social policy pressure arising from high energy poverty.

These influences are combined with delay functions to capture planning and implementation times for renovations. Renovation improves a building's heating energy demand (HWB), thus reducing energy use and emissions. The module also calculates a weighted renovation rate, aggregating across household groups and allocating renovation flows to building cohorts based on their distribution in the stock. Demolitions and renovations interact, as heavily degraded buildings are more likely to be either renovated or demolished. Over time, the renovated share of the building stock accumulates as a stock variable, directly influencing sector-wide energy intensity and mitigation outcomes.

D-5.3.6 Policy Instruments and Feedback Mechanisms

The model includes several policy levers that can be switched on or off or varied in strength for scenario analysis:

- Carbon pricing and associated revenue recycling mechanisms (with includes an endogenous component: carbon prices rise in response to growing policy pressure resulting from gaps between target and actual emissions),
- Renovation subsidies (differentiated by household group and modifiable by scenario),
- Cost recovery regulations (for landlords), which determine to what extent landlords are able to recover costs for energy renovation investments by means of increasing rents,
- Bans and mandatory phase-outs on fossil heating systems
- Awareness and information campaigns aimed at increasing landlord willingness to retrofit

Two main feedback pressures drive policy evolution:

- Climate policy pressure, which is based on the gap between actual and target emissions, influences carbon pricing and renovation incentives
- Social policy pressure, which is based on the level of energy poverty, influences compensation measures.

Total policy pressure is a weighted combination of these, which modulates renovation rates, switching rates, and energy prices.

D-5.3.7 Calibration, Validation and Data Sources

Calibration in system dynamics (SD) modelling is the process of adjusting model parameters and testing structural assumptions to ensure that simulated behaviour aligns with observed patterns and trends in real-world data. Unlike purely statistical approaches, calibration in SD models balances empirical fit with theoretical plausibility and expert judgment. Validation complements this process by testing the model's robustness, internal consistency, and sensitivity to parameter changes, ensuring that its responses to known conditions are realistic.

D-5.3.7.1 Data Sources and Scope

This model draws upon a comprehensive set of data sources to calibrate and validate its behaviour:

- Building stock: Time series from Statistik Austria (2000–2022) on the number of residential units by construction period and building type (single-family, multi-family, apartment block).
- Floor area: Derived from residential unit counts combined with average dwelling size data, also from Statistik Austria.
- Energy performance: Heating energy demand (HWB) values by building type and construction period from the TABULA building typology and Austrian Energy Agency estimates, differentiated between renovated and unrenovated states.
- Heating systems: National statistics on primary heating systems by energy carrier and heating type; government subsidy program data on heating system replacements (2021–2023) used to infer plausible base switching rates.
- GHG emissions: National emissions inventory and energy statistics for residential buildings, covering 2000–2022.
- Energy prices: Carrier-specific energy prices and carbon price time series.
- EU-SILC microdata: Household-level data on income, dwelling characteristics, and energy expenditure for calculating energy burden and identifying energy-poor households.

D-5.3.7.2 EU-SILC Data Processing

A substantial part of the calibration effort involved processing the European Union Statistics on Income and Living Conditions (EU-SILC) dataset to derive housing characteristics that are not directly reported. This entailed:

- Extracting variables on tenure status, household income, dwelling size and type, and total energy expenditures.
- Computing energy burden (share of household income spent on heating) and applying the 10% threshold criterion to estimate energy poverty.
- Mapping households into twelve groups reflecting tenure type (owner/renter), income level, and building type to match model array structures.
- Using clarification variables (e.g., inclusion of heating costs in rent reporting) to refine housing cost estimates while acknowledging reporting inconsistencies.
- Combining EU-SILC self-reports with national statistics to estimate heating system distributions across household groups (gas, oil, wood, district heating, heat pump/electricity).
- Aligning processed data with model arrays for calculating group-specific renovation rates, energy costs, emissions contributions, and policy responsiveness.

This detailed processing enabled the model to simulate socio-economic aspects of decarbonisation, particularly energy poverty, with realistic distributional dynamics.

D-5.3.7.3 Calibration Approach

The calibration process involved adjusting model parameters to reproduce observed trends in:

- Building stock and floor area growth by type and construction period.
- Renovation rates and shares of renovated stock (calibrated to available estimates and subsidy data).
- Heating system composition and observed replacement rates for fossil heating.
- Sectoral GHG emissions and cumulative emissions trajectory.
- Energy use for residential heating (final energy consumption).
- Trends in energy burden and energy poverty incidence.

To achieve this, the model's elasticities and sensitivity parameters—such as the responsiveness of renovation rates to subsidies and policy pressure or switching rates between heating systems—were systematically tuned. Where data were insufficient, proxy variables were used (e.g., subsidy program statistics as indicators for fuel switching dynamics). Elasticities were estimated within plausible ranges and iteratively refined until model outputs closely matched historical data for key indicators. These parameters also serve as levers in sensitivity analysis to test robustness under uncertainty and explore policy impacts.

D-5.3.7.4 Validation and Robustness Checks

Validation consisted of:

- Comparing simulated time series (2000–2022) for building stock, energy use, emissions, heating system shares, and energy poverty with historical data.
- Testing model stability under extreme values for policy levers and elasticities to ensure that dynamics remain realistic.

- Checking internal consistency between modules (e.g., alignment of building stock, floor area, and energy demand).

The model reproduces historical behaviour for building stock and energy use, emissions, and heating systems reasonably well. The calibration of energy poverty is sufficient: while the trends compare well to historic data, absolute values are consistently too low. This indicates that the specification of equations in this module may require further refinements, which are beyond the scope of this project. Since modelled trends are comparable to historic data, we consider the energy poverty module to be sufficiently well calibrated for the purposes of this project.

D-6 Policy Scenarios and Simulation Setup

Scenario analysis is a central tool in SD modelling for exploring possible future developments under varying policy assumptions. Instead of making predictions, scenarios allow us to investigate "what-if" questions: How would different policy interventions—economic incentives, regulatory measures, awareness campaigns, and fossil fuel phase-outs—alter renovation rates, energy use, greenhouse gas (GHG) emissions, and social outcomes such as energy poverty?

Given the long lifetimes of buildings and heating systems, the residential sector exhibits substantial inertia. Policy effects materialize with time lags due to planning and construction delays and the gradual turnover of heating technologies. Scenarios thus help identify which policy mixes can accelerate decarbonisation while avoiding negative social side effects.

D-6.1 Scenario Overview

This project tested eight scenarios compared to a baseline, each targeting different policy levers. Policies were designed to reflect realistic measures debated or partially implemented in Austria, grouped into two main categories: economic/regulatory incentives (ECO scenarios) and greenhouse gas (GHG) reduction policies focusing on heating systems. A comprehensive all-policies package combines the strongest elements of each.

Tab. D-1: Description of policy scenarios tested

Scenario name	Description
Baseline	• Represents continuation of existing policies and trends. • Fossil heating shares decline only slowly, mainly due to natural replacement and efficiency improvements. • Energy prices and median incomes are held constant after 2023.
ECO1 **Higher renovation subsidies**	• Subsidies cover 50% of renovation costs (up from 10%). • Strongest immediate effect on renovation rates without raising energy prices.
ECO2 **Subsidies + carbon pricing**	• Builds on ECO1 by gradually doubling the carbon price from €55/tCO_2 to €110/tCO_2 over 10 years. • Increases financial motivation for energy-saving renovations.
ECO3 **Regulatory improvements**	• ECO2 plus rules allowing landlords to pass more renovation costs to tenants. • Reduces "split incentive" barriers in rental properties.
ECO4 **Full economic package**	• ECO3 plus information campaigns to raise awareness among landlords. • Aims to tackle behavioural barriers alongside financial ones.
GHG1 **Ban on new fossil heating systems**	• Gradual ban by 2040 on installing new gas heating systems (oil already phased out).
GHG2 **Ban including replacements**	• Extends GHG1 to also forbid replacing old fossil systems with new fossil ones. • Accelerates gas phase-out.
GHG3 **Heating bans + renewable electricity**	• Adds full decarbonisation of electricity and district heating supply by 2040. • Strongest direct GHG reduction in the heating sector.
All-policies	Combines the strongest measures from ECO and GHG scenarios: • Increased renovation subsidies

	• Improved cost recovery rules • Awareness campaigns • 100% renewable energy in electricity and heat • Higher carbon price • Ban on new fossil systems and fossil-based replacements.

The policies influence the model through several levers:

- Renovation rate: Adjusted via subsidies, carbon pricing, regulatory changes, and landlord awareness.
- Heating system switching: Governed by bans, subsidies, and carbon price differentials.
- Energy efficiency gains: Driven by renovations and adoption of heat pumps/district heating.
- GHG emissions: Reduced through efficiency and lower fossil fuel shares.
- Energy poverty: Affected by higher energy prices (carbon pricing and electricity costs) and renovation cost recovery mechanisms.

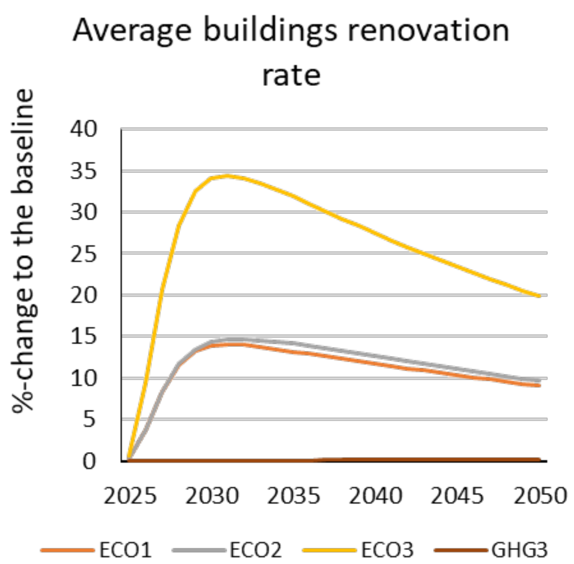
D-7 Results

This section presents the results of the scenario simulations conducted with the SD model. The analysis explores how different policy measures—economic incentives, regulatory changes, and heating system decarbonisation—affect renovation activity, fossil fuel phase-out, GHG emissions, and energy poverty in Austria's residential building sector up to 2050. We focus on relative changes compared to the baseline scenario, which provide meaningful insights into the direction and magnitude of policy effects.

D-7.1 Renovation Activity

Renovation rates are a crucial driver of long-term energy efficiency gains in the building sector. The simulations show that policies directly targeting renovation have a positive but moderate effect. ECO1 and ECO2 appear as the most influential policies regarding renovation activity. They increase the financial incentive by decreasing renovation cost (ECO1) and increasing potential energy savings in renovated buildings through increased energy cost (ECO2). The increase in financial incentives becomes more effective when regulations allow landlords to benefit through the possibility to increase rents to (partially) recover costs from renovation investment. Overall, financial subsidies (ECO1) combined with carbon pricing (ECO2) increase renovation rates by around +9-10% compared to the baseline by 2050. If complemented by regulatory changes (ECO3), renovation activity increases substantially (up to 35% compared to the baseline). The combined economic package (ECO4) achieves similar effects and is therefore omitted from figure D-3.

Abb. D-3: Renovation rates under baseline and policy scenarios



Policies GHG1-GHG3 show no trade-off regarding the renovation rate. Policy scenario GHG3 (fossil heating bans + renewable electricity) has a slight impact on average renovation rates via two distinct effects: first, the weighted average energy prices rise by the switch from fossil to renewable heating systems, which are generally more expensive. Second, in contrast, the energy use decreases for households using heat pumps, due to the superior efficiency of this technology. Both effects influence the expected financial savings from buildings renovation and therefore the average building renovation rate. However, as the figure highlights, the impact is only small and only increases in the second half of the simulation period, as the share of households using heat pumps only expands over time.

In contrast, heating system decarbonisation policies (GHG1–GHG3) and the all-policies scenario do not substantially raise renovation rates (≤ +0.23% change), indicating that emissions reductions in these scenarios stem mainly from heating system transitions and renewable energy supply rather than large-scale deep renovations. This result highlights the structural barriers and long planning horizons that constrain rapid increases in renovation activity.

D-7.2 Building Energy Use

The model shows that total energy use in Austria's residential building sector is influenced by two counteracting dynamics: First, an upward pressure from projected growth in the number of households and, consequently, the building stock. Second, a downward pressure from increased adoption of renewable heating systems—particularly heat pumps—that operate more efficiently than fossil-based systems, combined with incremental renovation activity.

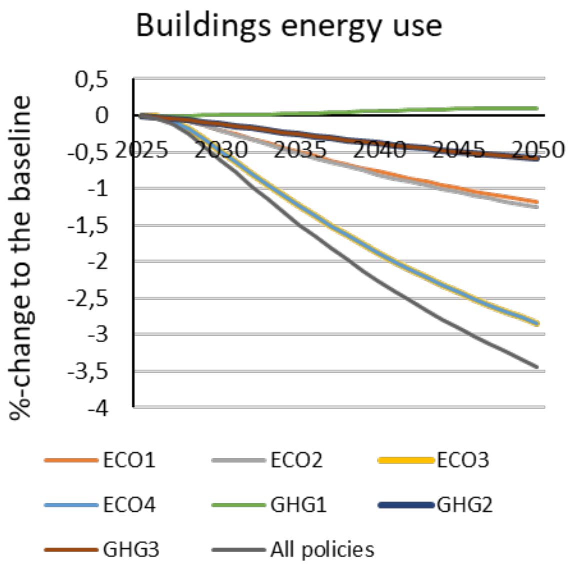
In the baseline scenario, these forces largely offset each other, resulting in only a modest long-term reduction in total energy use. By 2050, residential sector energy use remains close to 8 million MWh, a level comparable to the "With Existing Measures" scenario published by Austria's Environmental Agency.

Policy interventions alter this trajectory only moderately:

- Subsidy-focused scenarios (ECO1, ECO2) deliver small energy use reductions of around –1.2% compared to baseline by 2050.
- When combined with regulatory measures that improve landlords' ability to benefit from energy savings in rental properties (ECO3, ECO4), reductions are more pronounced, reaching –2.85%. These policies effectively raise renovation activity and increase the overall energy efficiency of the housing stock.
- Raising awareness through information campaigns (as part of ECO4) does not create a noticeable additional effect beyond financial and regulatory measures.
- Scenarios focused on phasing out fossil heating (GHG2, GHG3) also lead to efficiency gains, reducing energy use by approximately –0.6%, while GHG1 shows virtually no change.
- The all-policies scenario, which combines all economic, regulatory, and heating system measures, achieves the largest reduction in building energy use—around –3.4% relative to baseline by 2050.

These findings suggest that significant reductions in energy demand require bundled measures that simultaneously incentivize renovations and promote transitions to more energy-efficient heating systems. However, even in the most ambitious scenario, energy demand does not decline sharply, reflecting the sector's inherent inertia and the limited pace of deep renovations.

Abb. D-4: Building energy use under baseline and policy scenarios



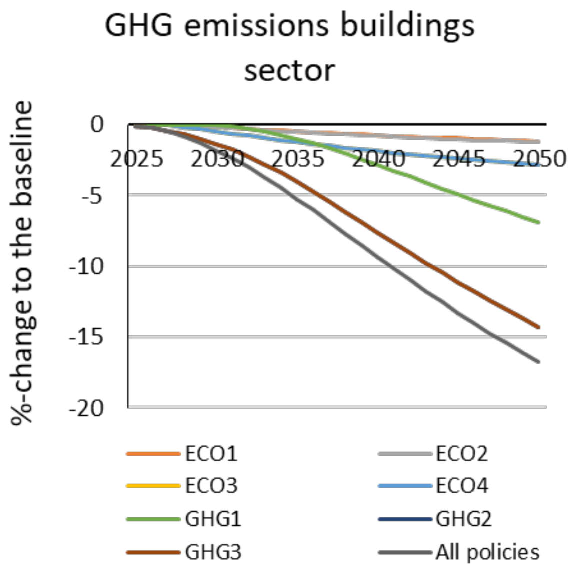
D-7.3 Greenhouse Gas Emissions

GHG emissions in the building sector only considers emissions from operating fossil fuel heating systems. Emissions that are caused by electricity or heat generation are accounted for in the energy sector but are considered in the GHG emissions gap below. GHG are reduced in all scenarios (including baseline) either by the switch from fossil fuel heating systems to electricity or district heating (GHG1-GHG3), or by reductions in energy use (ECO1-ECO4).

Under baseline conditions, GHG emissions from the residential building sector decline only slightly over time, reflecting the slow natural replacement of heating systems and moderate renovation activity. Introducing isolated economic incentives or regulatory measures has limited additional impact:

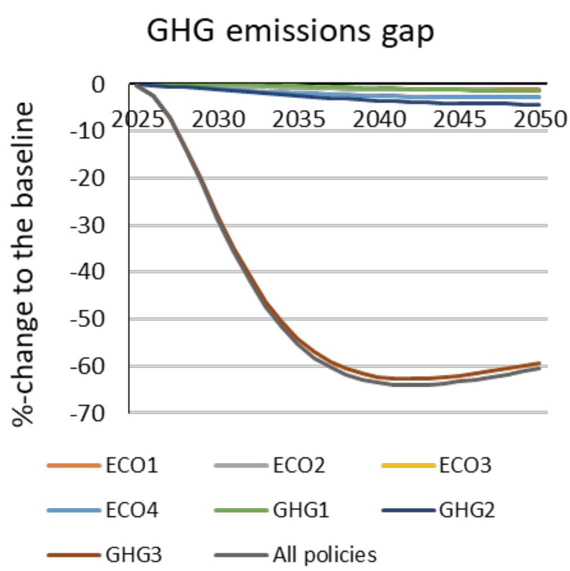
- ECO2 and ECO3 reduce emissions by about 1.2–1.25% relative to the baseline by 2050.
- ECO4, which combines multiple economic measures, achieves a slightly larger reduction of –2.8%.
- Heating-focused measures show stronger effects: GHG3, which includes comprehensive fossil fuel bans and renewable electricity and heat, reduces emissions by –4.2%.

Abb. D-5: GHG emissions under baseline and policy scenarios)



The most substantial reduction is achieved with the all-policies package, combining economic incentives, regulatory improvements, heating system bans, and renewable energy supply. This integrated approach reduces emissions by approximately –59% relative to baseline levels by 2050. Despite this improvement, full climate neutrality remains out of reach within the simulated time horizon. The GHG emission gap compares the actual emissions in the buildings and energy sector that are caused by household energy use with the target emissions reflecting a linear decrease to zero emissions until 2040[3]. No scenario that is considered here achieves the target. Several factors may explain this: In 2040 there remains a significant stock of gas heating systems, as replacement is only induced when heating systems are obsolete (i.e., reach the end of their lifespan). In addition, the the reductions in energy use are small and therefore also the impact on GHG emissions gap in ECO1-4 scenarios.

Abb. D-6: GHG emissions gap under baseline and policy scenarios



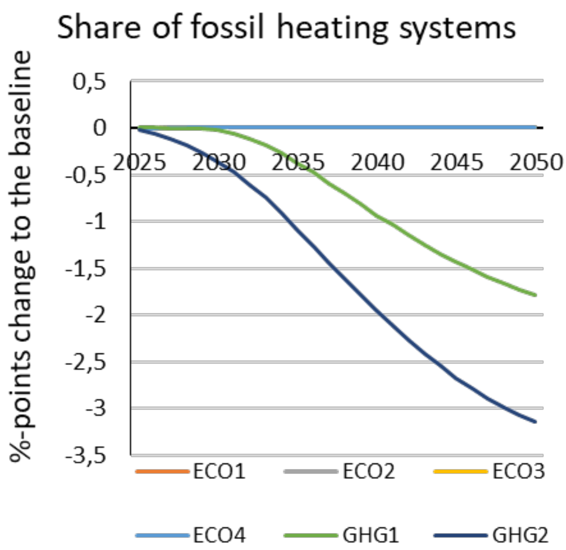
[3] Here, also the GHG emissions that would be accounted for the energy sector are considered.

D-7.4 Fossil Heating System Phase-Out

The share of fossil-based heating systems (gas and oil) declines gradually in the baseline scenario, but policy interventions accelerate this trend unevenly. Economic measures alone (ECO1–ECO4) barely change fossil heating shares (≤ +0.9 percentage points difference from baseline). Regulatory measures targeting heating systems show stronger effects:

- GHG2 and GHG3, which include bans on new and replacement fossil installations, reduce the fossil heating share by about –3.15 percentage points by 2050.
- The all-policies package achieves a similar reduction (–3.15 percentage points), showing that comprehensive approaches mainly drive emissions reductions via fuel switching rather than renovation.

Abb. D-7: Fossil heating share across scenarios



Despite these changes, gas heating remains widespread by 2050, underscoring the challenge of phasing out fossil technologies without aggressive early intervention

D-7.5 Energy Poverty

Energy poverty rates are strongly influenced by changes in energy prices. The sharp increase observed after 2019 are mostly a result of the energy price following the outbreak of the COVID-19 pandemic and the Russian invasion of Ukraine. This implies that the assumption that energy prices will return to pre-crisis levels would also bring down energy poverty rates substantially. In the baseline, decreases in energy poverty are caused by assumptions regarding energy efficiency improvements alongside reduced shares of fossil fuel heating systems.

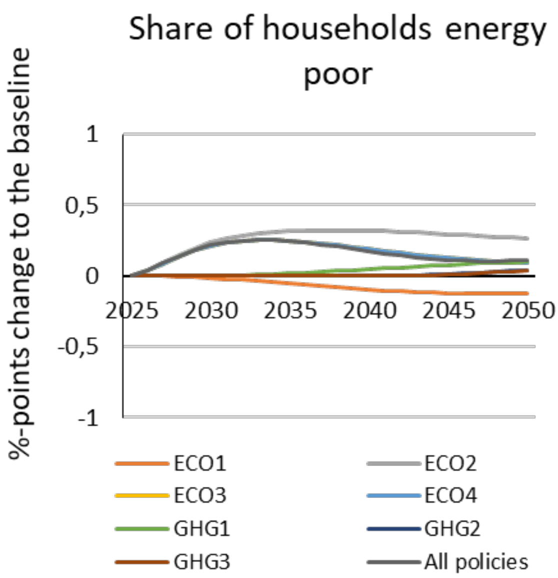
Decarbonisation policies have nuanced effects on household energy affordability.

- Purely subsidy-based measures (ECO1) slightly reduce energy poverty (–0.12%), reflecting lower net energy costs for households.
- However, scenarios introducing carbon pricing or heating system bans (ECO2–ECO4, GHG1–GHG3) slightly increase energy poverty (+0.04–0.26%) due to higher energy costs from carbon levies or shifts to more expensive low-carbon heating.

- The all-policies scenario leads to an overall +0.11% increase in energy poverty by 2050, even as emissions fall significantly.

The switch to electricity and district heating tends to increase energy poverty as prices for operating these heating technologies are higher compared to fossil fuel heating systems. Similarly, carbon pricing (ECO2-ECO4) tends to increase energy poverty in the short run and in the absence of compensation measures. However, in the long run the effect may be mitigated by increased renovation rates which lower energy use and thus energy costs and poverty.

Abb. D-8: Changes in energy poverty share under different scenarios



Several caveats must be noted here. First, energy poverty levels (in absolute terms) could not be calibrated well to historic data. While the overall trends align well with historic data (and follow mainly changes in energy prices), the share of energy poor households is too low in absolute terms. Therefore, our results should be interpreted with caution and mostly consider changes relative to the baseline. Second, energy poverty rates in the simulation runs are likely overestimated since the model does currently not yet include compensation mechanisms such as heating cost allowances (*Heizkostenzuschuss*) or other targeted compensation payments to households.

Overall, however, these findings highlight a key trade-off: ambitious climate policies can exacerbate affordability issues unless accompanied by targeted compensation or income support for vulnerable households.

D-7.6 Summary

The integrated all-policies scenario delivers the largest overall climate benefit, with a 59% emissions reduction, moderate fossil heating phase-out, and minor renovation rate increases relative to the baseline. However, even with this ambitious package, full decarbonisation is not achieved by 2050, and energy poverty worsens slightly. This outcome illustrates:

- The long lifetimes of buildings and heating systems, which delay the impact of policies.
- The need for earlier and stronger measures to phase out fossil heating technologies.
- The importance of deep renovation programs that go beyond current incremental improvements.
- The necessity of socially balanced policies to mitigate adverse distributional effects.

Overall, the scenario results suggest that:

- Single-policy interventions are insufficient for transformative change.
- A comprehensive policy mix combining renovation incentives, heating system bans, and renewable energy support is essential to approach climate targets.
- Even with ambitious packages, achieving full climate neutrality requires faster fuel switching and much higher renovation rates than current trends or policies deliver.
- Policies must be designed to balance climate mitigation and social equity, ensuring that vulnerable households are supported throughout the transition.

D-8 Discussion, Limitations and Outlook

D-8.1 Interpretation of Simulation Outputs

The scenario results underscore the complexity and inertia of the residential building sector. Even with ambitious policy packages combining subsidies, regulatory improvements, fossil heating bans, and renewable energy expansion, emissions in the sector remain substantially above climate neutrality targets by 2050. This reflects several structural factors captured by the model:

- Slow stock turnover: Buildings and heating systems have long lifetimes, meaning that even aggressive replacement and renovation policies take decades to transform the overall stock.
- Limited renovation dynamics: While subsidies and cost recovery regulations modestly increase renovation rates, they do not induce a step-change large enough to significantly alter sector-wide heating energy demand.
- Fuel switching inertia: Heating system bans and incentives gradually reduce fossil fuel shares, but without strong early action, a substantial proportion of gas boilers persists well into 2050.
- Trade-offs with social equity: Policies that reduce emissions often raise energy costs, slightly increasing energy poverty unless compensated through subsidies or targeted support.

The model highlights that single-policy interventions (e.g., subsidies alone or heating bans alone) have limited standalone effects. Emission reductions in isolated economic or regulatory scenarios are mostly below 5%, while a comprehensive all-policies package achieves a 59% reduction. This suggests that bundled measures are essential to overcome behavioural and technical barriers and to accelerate both renovation and heating system decarbonisation.

D-8.2 Calibration Caveats and Model Limitations

It is important to interpret these findings with caution due to several limitations of the current model version:

- Incomplete calibration: Due to time constraints, a full-scale calibration against historical data for all variables (building stock evolution, energy use, heating system dynamics) was not completed. Absolute simulation outputs (e.g., GHG emissions in $MtCO_2e$) may therefore diverge from observed values.
- Use of relative indicators: To mitigate this, results are presented as relative changes compared to a baseline scenario. This approach is robust for identifying policy effects but does not produce precise forecasts.
- Simplified social dynamics: Household group shares are static and do not dynamically adjust to demographic or economic changes over time. Deep renovations and differentiated low-carbon heating technologies (e.g., various heat pump types) are not yet fully modelled.
- Behavioural elasticities: Parameters for how landlords and households respond to subsidies, carbon pricing, and regulatory pressures are partly based on literature and expert judgment rather than Austrian-specific empirical data. Future work should refine these elasticities using available program evaluation data.
- Limited feedback loops: While the model captures climate and social policy pressures, other feedback mechanisms (e.g., energy market dynamics, interactions with EU-wide policies) remain outside the system boundary.

Despite these caveats, the model is structurally sound, data-informed, and capable of revealing the direction and magnitude of policy impacts. The simulation framework provides a robust foundation for future refinements, including improved calibration, scenario expansion, and sensitivity analysis.

D-8.3 Policy Implications

The modelling insights lead to several important implications for policy design:

1. Comprehensive policy packages are essential: A mix of economic incentives, regulatory measures, heating system bans, and renewable energy expansion is necessary to achieve substantial emission reductions. Relying on a single instrument will not deliver transformative change.
2. Earlier intervention is critical: Delays in phasing out fossil heating systems lock in emissions for decades. Early and decisive bans on new and replacement fossil boilers, combined with generous heat pump subsidies, are needed to accelerate decarbonisation.
3. Boosting deep renovation rates: Achieving climate neutrality requires moving beyond incremental improvements toward mass deep renovations. This calls for stronger incentives, streamlined permitting, technical support, and possibly mandatory renovation standards for worst-performing buildings.
4. Addressing social impacts: Carbon pricing and heating system transitions can raise household energy costs, disproportionately affecting low-income tenants. Future policy scenarios must integrate redistributive measures (e.g., targeted subsidies, “warm rent” systems) to ensure affordability and maintain public support for climate action.
5. Leveraging feedbacks: Policies should be designed to harness reinforcing feedback loops, such as increasing public awareness, strengthening landlord motivation, and sustaining political pressure to close the emissions gap.

D-8.4 Path Forward for Model Development

The current model provides a proof-of-concept tool for understanding long-term dynamics of building sector decarbonisation in Austria. To enhance its policy relevance, future efforts should:

- Complete model calibration against historical data for building stock, heating systems, and emissions.
- Refine social dynamics, including dynamic household group shares and detailed distributional analysis.
- Differentiate renovation types (shallow vs. deep) and heating technologies for more granular transition pathways.
- Expand the policy module to include income-based compensation mechanisms and financing schemes.
- Conduct sensitivity analyses on key elasticities and delays to improve robustness of results.
- Explore interactions with EU-level climate policies and external energy market shocks.

These improvements will support evidence-based policymaking by providing a more detailed and calibrated simulation platform to test ambitious, socially fair pathways toward Austria’s 2040 climate neutrality target.

D-9 Conclusion

This project set out to develop a SD model to explore pathways for decarbonising Austria's residential building sector in a way that is both effective and socially just. Buildings play a critical role in Austria's climate mitigation strategy, accounting for roughly a third of final energy use and around 10% of total GHG. At the same time, housing is a social necessity, and policies to decarbonise the sector must avoid exacerbating energy poverty or disproportionately burdening tenants.

Using a SD approach allowed us to capture the complex feedback loops, delays, and interdependencies that characterise building sector transitions. The model integrates building stock evolution, renovation dynamics, heating system choices, energy use, emissions, and distributional impacts across household groups. The current model version is structurally sound and able to simulate baseline and policy scenarios, providing valuable insights into long-term transition dynamics.

The scenario results highlight both opportunities and challenges for building sector decarbonisation. Individual policies—such as subsidies or heating system bans—have limited standalone effects on emissions and renovation rates. Even when combined into more ambitious packages, current policy instruments fall short of delivering full climate neutrality by 2050. The model shows that most emissions reductions are driven by fuel switching and renewable energy supply, with relatively modest gains from renovation activity. This reflects long lifetimes of buildings and heating systems, as well as persistent barriers to deep renovation.

At the same time, ambitious climate policies can have unintended social consequences. Scenarios with higher carbon prices and fossil heating bans tend to slightly increase energy poverty, as low-income households face higher heating costs during the transition. Without targeted support, these effects risk undermining public acceptance and fairness of climate policy.

These findings underscore three main implications. First, decarbonising the building sector requires comprehensive policy packages that combine economic incentives, regulatory measures, and rapid deployment of renewable heating technologies. Second, earlier and stronger interventions are needed to accelerate the phase-out of fossil heating systems and scale up deep renovations, avoiding lock-in of inefficient buildings and emissions. Third, social equity must be central to climate policy, with mechanisms like income-based subsidies or warm rent systems ensuring that vulnerable households benefit from, rather than bear the costs of, the transition.

The project also contributes methodologically by delivering the first SD model tailored to Austria's residential building sector with a focus on justice and energy poverty. While time constraints limited calibration and scenario exploration, the groundwork is laid for a fully validated and refined simulation tool. Future work will enhance calibration, differentiate renovation depths and heating technologies, incorporate compensation measures, and run sensitivity analyses to test policy robustness.

In sum, the project demonstrates the value of a dynamic, system-level perspective for understanding building sector decarbonisation. It provides both conceptual insights and a practical modelling framework that policymakers and stakeholders can use to design fair and effective strategies for achieving Austria's 2040 climate neutrality goal. The findings call for urgent, ambitious, and socially balanced action to transform the residential building stock in line with both environmental sustainability and social justice.

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