Agent-Based Modeling in Energetic Refurbishment

Exploring Communication and Stakeholder Cooperation in Energy Transitions

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***Abstract*— Energetic refurbishment is essential for achieving European climate and energy targets, yet renovation rates remain below expectations. This paper presents an exploratory agent-based model of German homeowners' refurbishment decisions, structured by the Hierarchy of Effects model and grounded in survey data. The model distinguishes between mass communication (e.g., campaigns) and personal communication (e.g., consultancy) and analyzes their combined effects. Results show that mass communication alone increases awareness but has limited impact on intentions, whereas even moderate levels of personal communication strongly accelerate adoption, with diminishing returns at higher cost levels. More importantly, the findings demonstrate that communication effectiveness is regime-dependent: the impact of mass communication, personal communication, and social influence varies systematically with the overall level of communication intensity, giving rise to distinct diffusion dynamics. The study further shows that communication costs are distributed across multiple stakeholders and that effective acceleration requires coordinated action among governments, municipalities, consultants, and homeowners, concluding that refurbishment strategies must balance communication instruments and stakeholder cooperation, as isolated measures fail to generate efficient and scalable adoption.**

Keywords*— *Agent-Based Modeling (ABM); energetic refurbishment; mass and personal communication; stakeholder cooperation; energy transition.

I. Introduction and Motivation

A preliminary version of this model was presented in an earlier conference paper [1], where the focus was on identifying an "optimal mix" of communication measures. In contrast, the present paper adopts an explicitly exploratory perspective, extends the model with additional assumptions and sensitivity analysis, and provides a more comprehensive discussion of policy implications.

A. Policy and Practical Context

Energetic refurbishment has become a central pillar in international and European energy policy debates. Buildings are responsible for roughly 40% of total energy consumption in the European Union (EU) and approximately 36% of greenhouse gas emissions [2]. Within this context, improving the energy efficiency of residential buildings is considered a prerequisite for reaching the EU's climate-neutrality target by 2050 and for meeting the interim goals of the "Fit for 55" package. In Germany, the challenge is particularly pronounced: more than two thirds of the housing stock was constructed before the existence of energetic building standards, which results in disproportionately high heating demands and a large ecological footprint [3].

The urgency of accelerating refurbishment has grown since the outbreak of the war in Ukraine. The dependence of Germany and other European countries on Russian natural gas exposed significant vulnerabilities in energy security [1]. Sharp increases in energy prices since 2022 have further underscored the need to reduce demand in the heating sector and to promote energy efficiency measures at scale. Policymakers therefore emphasize not only ecological but also geopolitical and economic benefits of refurbishment.

Despite strong policy goals, refurbishment rates remain far below the required levels. Research and practice have documented several persistent barriers such as high upfront costs, long payback periods, behavioral inertia among homeowners, and concerns about consultants or contractors. [4]. These barriers often translate into hesitation, procrastination, or refusal to undertake necessary investments. Governments have traditionally relied on marketing-like instruments such as mass media campaigns to motivate homeowners. However, evidence suggests that such measures alone have achieved little impact in changing long-term refurbishment behavior [5]. In recent years, governments and local authorities have begun experimenting with sales-like measures — such as subsidized visits of energy consultants, on-site audits, or personalized advice. These measures introduce direct interaction with households and therefore hold potential to increase the effectiveness of policy interventions [6].

Understanding how different combinations of marketing and sales measures influence homeowners' decision-making is crucial. More broadly, it is necessary to study not only which measures are effective but also how their costs and responsibilities are distributed among multiple actors: governments, consultants, and homeowners themselves. This multi-actor dimension is central to the present work. However, existing approaches often focus on individual communication measures in isolation, without systematically consid-

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ering how their effectiveness depends on the overall level of communication intensity.

B. *ABM in the Energy Transition*

ABM has emerged as a promising approach to study complex socio-technical transitions. ABM simulates the decisions and interactions of heterogeneous agents — such as households, firms, or policymakers — and allows researchers to observe how individual behaviors aggregate into system-level outcomes. The method is particularly well suited for exploring emergent phenomena, feedback effects, and nonlinear dynamics that are characteristic of the energy transition [7].

Over the past decade, ABM has been widely applied to study the adoption and diffusion of renewable energy technologies. For example, Baranzini et al. [8] analyzed the role of *social contagion* in the adoption of photovoltaic (PV) systems, Rai and Robinson [9] investigated the impact of policy incentives and peer effects on electric vehicle (EV) diffusion, and Derkenbaeva et al. [10] modeled household decisions related to decentralized energy systems in Amsterdam. These studies demonstrate that heterogeneous preferences, social influence, and local contexts can significantly shape technology adoption pathways.

However, the application of ABM to energetic refurbishment remains comparatively scarce. Most existing models focus on investment in new technologies (e.g., solar PV), while the more mundane but equally impactful decision to insulate a home, replace a heating system, or upgrade windows has received less attention [3]. Refurbishment decisions differ fundamentally from renewable adoption: they involve higher complexity, more intrusive interventions in existing buildings, and multiple technical and financial uncertainties. This gap in ABM research motivates the present study.

C. *Distinguishing Marketing and Sales in Decision-Making*

From a marketing science perspective, communication is not a monolithic concept but can be differentiated into *mass communication* (e.g., advertising campaigns, information brochures, social media outreach) and *personal communication* (e.g., face-to-face advice, consultancy visits, or sales talks). Classical theories such as the Hierarchy of Effects (HOE) model [11] emphasize that these different communication modes affect different stages of the decision-making process. Mass communication is effective in creating awareness and knowledge, whereas personal communication is crucial in later stages such as conviction and intention formation [12].

Research has repeatedly demonstrated that homeowners require different types of information at different stages of the refurbishment journey. Early phases are characterized by information gathering and the reduction of uncertainty. Later phases demand personalized guidance on financial, technical, and constructional aspects [13]. Mass communication alone cannot satisfy these needs, while personal communication is often too costly or resource-intensive to be scaled to entire populations.

Although ABM has been successfully used to simulate consumer behavior in marketing contexts [14], most existing models do not differentiate between marketing and sales. They treat communication as a generic process rather than a layered, staged phenomenon. This constitutes another gap addressed by the present paper: the integration of marketing and sales distinctions into an ABM of refurbishment decisions. In addition, the effectiveness of these communication mechanisms may depend not only on their functional role within the decision process, but also on their combined intensity within the system. This raises the question of how different levels of mass and personal communication jointly shape diffusion dynamics.

D. *Stakeholder Cooperation in Refurbishment*

A further underexplored dimension is the role of stakeholder cooperation. Energetic refurbishment requires the alignment of efforts across multiple actors:

- **Governments and municipalities** fund and design communication campaigns, create subsidy schemes, and regulate standards.
- **Energy consultants and contractors** provide personalized advice and execute technical measures.
- **Homeowners** make final investment decisions and bear substantial portions of the costs.

The interplay between these actors determines both the effectiveness of refurbishment programs and the distribution of costs and responsibilities. For example, governments may pay for mass media campaigns, while households finance consultancy services either directly or indirectly via subsidies. Understanding these distributions is critical for evaluating the fairness and feasibility of different policy approaches [5; 6; 13; 15].

In practice, lack of cooperation can lead to suboptimal outcomes: governments over-investing in mass campaigns with little impact, consultants facing limited demand, and homeowners feeling unsupported or overwhelmed. Conversely, cooperative approaches that align incentives and responsibilities can accelerate refurbishment. The present study takes this cooperation as a central lens, highlighting how different mixes of marketing and sales measures not only affect decision outcomes but also shape the cooperative dynamics between stakeholders.

E. *Contribution of this Paper*

This paper builds on a previous conference contribution by the author [1], which presented a first agent-based simulation of refurbishment decisions under different mixes of marketing and sales measures. While the conference paper introduced the basic model and preliminary results, the present journal article expands the analysis substantially in four directions:

- Exploratory framing – The model is presented not as a tool for strict optimization but as an exploration of plausible pathways. This framing allows for a more nuanced discussion of the directions the results may suggest, rather than prescribing single “optimal” solutions.

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- Transparency of assumptions and process – The modeling approach is clarified as a visual exploration of simulation outcomes rather than an algorithmic optimization. An explicit table of assumptions is introduced to enhance transparency.
- Stakeholder cooperation focus – The paper emphasizes that refurbishment acceleration depends on cooperation between governments, consultants, and homeowners, and that costs are ultimately shared among these stakeholders.
- Expanded content – The paper provides an enriched literature review, more detailed results, and enhanced figures and tables compared to the conference version.
- Interaction perspective – The analysis goes beyond isolated parameter effects by examining how different levels of communication intensity jointly shape diffusion dynamics and lead to distinct patterns of adoption.

Taken together, these extensions shift the contribution of the paper from identifying isolated parameter effects toward demonstrating that communication effectiveness is *regime*-dependent. The interaction between mass communication, personal communication, and social influence produces systematically different diffusion dynamics depending on the overall level of intervention intensity. This highlights that communication effects cannot be meaningfully assessed in isolation, but must be understood as part of an interacting system of mechanisms.

The remainder of this article is structured as follows. Section II presents the expanded literature review on ABM, refurbishment decision-making, and stakeholder cooperation. Section III introduces the conceptual model, the assumptions, and the data used for the simulation. Section IV presents the results of the exploratory analysis, with special attention to stakeholder cost distribution. Section V discusses implications for research, practice, and policy. Section VI concludes by summarizing the contributions and outlining future work.

II. LITERATURE REVIEW

This section reviews the state of the art, outlines relevant research streams, and identifies gaps that motivate the present study.

A. *Energetic Refurbishment and Policy Context*

Energetic refurbishment has become a cornerstone of European climate and energy policy. The European Commission's Renovation Wave strategy explicitly calls for doubling annual renovation rates by 2030 to meet climate neutrality targets [2]. In Germany, more than two thirds of the housing stock predates energetic building standards, contributing to high heating demand and carbon emissions [3].

Multiple barriers explain the sluggish pace of refurbishment. These include high upfront costs, long payback times, and behavioral inertia among homeowners [4]. Financing mechanisms are increasingly seen as a way to overcome these obstacles. Bertoldi et al. [16] provide a comprehensive overview of emerging instruments in the EU, while Nykamp [17] emphasizes the importance of policy mixes to align incentives.

Recent research highlights the role of local governance. Ebrahimigharehbaghi et al. [18] show how municipal approaches in the Netherlands can accelerate retrofitting of owner-occupied homes. Jowkar et al. [19] stress that social factors shape barriers and motivations in Norwegian refurbishment projects. Together, these studies suggest that refurbishment must be understood not only as a technical or economic decision but as a socio-political process requiring cooperation across multiple levels of governance.

B. *ABM in Energy Transitions*

ABM is increasingly recognized as a powerful tool for studying socio-technical transitions. ABM simulates the interactions of heterogeneous agents and captures emergent dynamics that traditional equilibrium models cannot represent [7].

A large body of ABM research has focused on renewable energy adoption. Du et al. [8] reviewed applications in solar PV and other domains, highlighting the importance of sociodemographic factors and peer effects. More recently, Derkenbaeva et al. [10] developed an ABM of household transitions in Amsterdam, incorporating spatial and social dynamics. Van der Kam et al. [20] constructed an empirical ABM of consumer co-adoption of low-carbon technologies, providing insights into policy mixes.

When it comes to refurbishment, the literature is still limited. Du, Han & de Vries [3] provide a review of renovation adoption and diffusion models, calling for more empirical applications. Chen, Fan & Yao [21] modeled evolutionary dynamics of homeowners' retrofit decisions in complex networks, offering methodological advances that are directly relevant to the present study. Shen et al. [22] combined ABM with performance-based modeling to design integrated retrofit frameworks. These examples illustrate the growing but still fragmented use of ABM in the refurbishment domain.

An emerging strand of work explores methodological innovation. Tian et al. [23] integrate ABM with deep learning to simulate household energy consumption, while Khalil & Fatmi [24] use ABM to examine behavioral changes during the COVID-19 pandemic. Such studies suggest that ABM can be used not only predictively but also exploratorily, to probe the potential outcomes of different interventions under uncertainty. This exploratory use is the perspective adopted in the present paper.

C. *Marketing and Sales in Consumer Decision-Making*

In marketing science, the HOE model has long been used to describe how communication influences consumer decision-making [11]. Early stages such as awareness and knowledge are typically influenced by mass communication, while later stages such as conviction and intention depend more on personal communication [12; 25; 26].

Simulation studies have begun to operationalize these ideas. Jager [14] suggested how the 4 P's of marketing could be incorporated into social simulations, and Delre et al. [27] developed an ABM of promotional activities. However, most

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ABM applications in consumer behavior still treat communication as a homogeneous influence, without distinguishing between marketing and sales.

Recent empirical work on sustainable consumption underscores the relevance of this distinction. Chen [28] analyzed how integrated communication tools affect green product purchase intentions. Correia et al. [29] demonstrated the influence of green marketing communication on actual purchase behavior. Krsnik and Erjavec [30] incorporated lifestyle and psychological factors to explain differences in consumer responses - an approach conceptually similar to the Sinus lifestyle segmentation used in the present model. Iliopoulou et al. [31] highlight the role of social media engagement in translating knowledge into sustainable action, underscoring the evolving nature of mass communication channels.

Together, these studies suggest that communication strategies must be tailored not only to different stages of the decision process but also to different consumer segments. This reinforces the rationale for incorporating both mass and personal communication in the ABM presented here.

D. Stakeholder Cooperation in Energy Efficiency

The acceleration of energetic refurbishment depends on the coordinated actions of multiple stakeholders. The governance literature identifies several dimensions of cooperation that are particularly relevant in this context.

One important perspective is multilevel governance. Björklund et al. [32] synthesize more than two decades of EU experience with energy-efficient and zero-carbon buildings and emphasize that successful policy implementation requires alignment across multiple governance levels — European, national, regional, and municipal. Isolated initiatives at one level often remain ineffective without such vertical coordination.

A second dimension concerns the role of municipal governance. Local authorities are often the actors closest to homeowners and can provide tailored support. Ebrahimigharehbaghi et al. [18] demonstrate that municipal programs in the Netherlands have been central to encouraging retrofits of owner-occupied homes, for instance by facilitating personal advice and acting as trusted intermediaries.

Cooperation is not limited to public authorities. Research also points to the role of private actors and hybrid governance arrangements. Galvin [15] shows that private housing companies in Germany increasingly integrate energy efficiency into their strategic agendas, thereby assuming functions traditionally associated with public governance. Such hybrid approaches indicate that responsibilities and resources can be distributed across state and non-state actors.

Finally, cooperation is also shaped by social contexts. Jowkar et al. [19], for example, identifies how social values influence barriers and motivations for renovation in Norway. This suggests that governance models must be sensitive to context rather than assuming uniform homeowner behavior.

Taken together, the literature highlights that energetic refurbishment requires multi-actor alignment, with complementary roles for governments at different levels, municipalities, private stakeholders, and socially embedded motivations. While each of these strands of research has provided valuable insights, there is still limited integration across them, particularly in combination with quantitative modeling approaches.

III. ABM FOR REFURBISHMENT

This section introduces the ABM, including its conceptual structure, empirical basis, assumptions, and simulation design.

A. Model Overview

The study builds on an ABM designed to investigate how different combinations of mass communication and personal communication influence homeowners' decision-making regarding energetic refurbishment. A preliminary version of this model was presented in an earlier conference paper [1], where the focus was on identifying an "optimal mix" of measures. While such a framing provided a concise entry point for the conference format, it implied a degree of precision that does not fully reflect the exploratory character of the model.

In the present journal article, the same model is taken further and deliberately reframed as an exploratory tool. Rather than prescribing an optimal solution, the simulations are used to compare plausible scenarios and to reason about their implications for policy and stakeholder cooperation. This shift reflects both the limitations of the assumptions (which are numerous and simplifying) and the opportunities to use ABM as a way of probing into the dynamics of decision-making under uncertainty.

The model represents 17,000 simulated households, segmented according to the German Sinus lifestyle typology. Within the model, mass communication (MC) and personal communication (PC) denote the corresponding communication variables and their intensity levels, while the terms mass communication and personal communication are also used in the broader conceptual sense to describe the two communication forms. Each agent interacts with its environment and is exposed to varying levels of communication efforts. Their decision-making follows the HOE framework, which distinguishes between stages such as awareness, knowledge, attitude, conviction, and intention. This allows the model to capture not only whether households decide to refurbish, but also how communication influences different stages of the process.

In addition to communication, the model incorporates neighborhood-level social influence, reflecting evidence that refurbishment decisions can be accelerated when neighboring households have already taken positive action. The combined setup thus enables the exploration of how marketing-like and sales-like measures, together with social contagion, may interact to shape refurbishment pathways.

B. Decision-Making Framework

The decision-making logic of the model builds on the HOE model, which conceptualizes consumer behavior as a sequence of stages leading from awareness to final purchase intention. In the context of energetic refurbishment, this framework is adapted to represent how homeowners move

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through the following stages: awareness, knowledge, attitude, conviction, and intention. Each agent in the simulation progresses through these stages over time, influenced by exposure to communication measures and by social interaction with neighboring agents.

Figure 1 illustrates the adapted HOE model for energetic refurbishment. In this representation, mass communication is assumed to exert its strongest influence in the early stages of awareness and knowledge, but its effect diminishes sharply in the later stages. By contrast, personal communication is relatively weak in the initial stages but becomes decisive in the conviction and intention phases, when households require reassurance, tailored advice, and concrete guidance for action.

To formalize this mechanism, each agent is equipped with a *threshold* variable that accumulates influence from different touchpoints. Once the threshold reaches a defined value, the agent progresses to the next stage of the HOE model. This stepwise updating process is applied iteratively in each simulation period, allowing agents to accumulate communication effects and social influence over time. The strength of each communication touchpoint depends on both its type (mass or personal) and the stage of the decision process. Correction factors are applied to represent the decreasing impact of mass communication and the increasing impact of personal communication across successive stages.

In addition to communication, the model integrates social contagion effects. When one household in a neighborhood decides positively on refurbishment, its neighbors' threshold variables are temporarily increased. This mechanism captures localized peer influence, which has been documented in related energy adoption studies. The resulting setup reflects a multi-channel decision environment, in which homeowners' trajectories are shaped by both institutional communication and social dynamics.

C. Data and Sample

The ABM is empirically grounded in data from the Sinus lifestyle typology, a widely used segmentation of German society that combines sociocultural orientation with social status. The typology distinguishes ten distinct lifestyles, ranging from traditional to progressive orientations and from lower to upper socioeconomic status. Previous research has shown that these lifestyles differ substantially in their attitudes and behaviors toward energetic refurbishment [6].

The empirical basis of the model is a representative survey of n = 4,471 German homeowners, which provides information on the status quo of the refurbishment decision-making process for each lifestyle group. The data capture the proportion of homeowners at different stages of the HOE model (awareness, knowledge, attitude, conviction, and intention). For example, adaptive pragmatics show a relatively high likelihood of forming refurbishment intentions (22.4%), while precarious households demonstrate much lower intention levels (9.3%). These differences highlight the importance of sociocultural segmentation for understanding heterogeneous responses to communication measures.

Figure 1. Hierarchy of effect model for energetic refurbishment [33]

Based on these survey results, the model initializes a population of 17,000 simulated homeowners. The distribution across Sinus lifestyles is scaled to reflect their prevalence in German society. Each agent is assigned an initial position in the decision-making process according to the empirical distributions reported in Table I. This approach ensures that the simulation starts from a realistic baseline, with heterogeneous agents reflecting actual sociocultural patterns in Germany.

By grounding the ABM in representative data, the model captures not only aggregate tendencies but also lifestyle-specific differences in responsiveness to communication. This provides a richer foundation for exploring how different mixes of marketing-like and sales-like measures influence the trajectories of diverse homeowner groups.

D. Assumptions

As with any ABM, the present simulation relies on a set of assumptions that specify how agents behave, how communication affects decision-making, and how costs are calculated. To increase transparency, these assumptions are explicitly listed in Table II. While they may not capture all real-world complexities, they provide a consistent framework for comparing alternative communication scenarios. The number and scope of assumptions also underline that the model should be interpreted as exploratory rather than predictive.

E. Simulation Design

The simulation experiments were designed to explore how different levels of mass communication (MC) and personal communication (PC) influence the development of refurbishment intentions among German homeowners. Both communication variables were systematically varied across five levels (0–5), resulting in a matrix of possible combinations.

TABLE I. EMPIRICAL DATA FROM [33]

German's Sinus lifestyle	Status quo in DM				
	Aware-ness [%]	**Know-ledge [%]**	**Atti-tude [%]**	**Con-viction [%]**	**Inten-tion [%]**
Homeowners in general	98.7	77.1	48.5	33.5	14.3
1. Established conservat.	99.0	80.1	51.0	33.7	14.9
2. Liberal-intellectual	99.7	82.9	57.9	40.6	13.3
3. High achiever	98.9	79.5	48.4	32.9	18.4
4. Movers and shakers	98.4	76.9	52.3	34.6	16.6
5. Adaptive pragmatics	99.5	69.0	53.9	42.4	22.4
6. Social-ecological	99.7	80.0	52.3	36.2	17.0
7. New middle class	98.5	76.9	44.1	32.6	11.8
8. Traditional	99.0	78.8	44.5	30.8	10.6
9. Precarious	99.6	64.4	36.1	20.6	9.3
10. Escapists	92.8	59.3	33.7	21.9	12.2

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TABLE II. KEY ASSUMPTIONS FOR MODEL INITIALIZATION AND SIMULATION

Variable	Value / Assumption	Source
Decision model	HOE stages: awareness → knowledge → attitude → conviction → intention	[11; 12; 33]
Threshold for stage change	4	Assumed
Mass comm. impact	Declines by stage (1.0; 0.5; 0.0; 0.0)	[25; 26]
Personal comm. impact	Increases by stage (0.0; 0.0; 0.5; 1.0)	[25; 26]
Social contagion	+30% per neighbor, max. +120%	[8]
Simulation period	2023–2050 or until 95% refurbishment intention	Policy target
Agents	17,000 homeowners (scaled from n = 4,471 survey)	[3; 33]
Mass comm. cost	€ 13.50 CPM	[3]
Personal comm. cost	€ 16.67 per touchpoint	[3]
Consultant capacity	30,000 consultants; max. 3M touchpoints/year	[3]

For each combination, the model was run for a period of 27 years (2023–2050), corresponding to the timeframe of European climate neutrality targets. In addition, a second set of experiments was conducted in which the model was terminated once 95% of households had developed refurbishment intentions. This dual approach makes it possible to compare scenarios with respect to both cumulative outcomes and the speed of diffusion.

To account for stochasticity in agent-based simulation, each scenario was repeated 20 times. The analysis therefore relies on 720 observations (36 combinations × 20 repetitions). For each observation, the model recorded:

- the distribution of homeowners across HOE stages,
- the proportion of agents reaching refurbishment intention,
- the time required to reach 95% refurbishment intention (where applicable), and
- the accumulated economic costs of mass and personal communication.

These costs are calculated at an aggregate (macro) level for each scenario, enabling a direct comparison between effectiveness and cost efficiency. Optimization of outcomes was not conducted algorithmically. Instead, the results were evaluated visually and comparatively across scenarios. This exploratory procedure makes it possible to identify plausible pathways, highlight trade-offs between speed and cost, and reason about how communication measures may be distributed among different stakeholders.

The model was implemented in NetLogo, a widely used platform for ABM. The implementation follows a modular structure, allowing systematic variation of key parameters and reproducible simulation runs. The model implementation is available on GitHub (under https://github.com/mart-verhoog/RefurbishmentModel).

IV. RESULTS

This section presents the simulation results, focusing on the effects of different communication scenarios and key parameter variations.

A. *Overall Development of Refurbishment Intentions*

The first experiments examined the overall development of refurbishment intentions over the simulation period of 27 years (2023–2050). Figure 2 summarizes the proportion of homeowners that reached the intention stage under different combinations of mass communication (MC) and personal communication (PC). This figure focuses on the final level of refurbishment intention reached after the simulation period.

The results show that mass communication alone is insufficient to bring about substantial change. Starting from a baseline of 14.3% refurbishment intention (Table I), sustained exposure to maximum levels of mass communication (MC = 5, PC = 0) increases this share only marginally, reaching 18.6% after 27 years. This finding echoes observations in practice that large-scale campaigns, while important for raising awareness, have limited impact on actual decision-making.

In contrast, the inclusion of personal communication strongly accelerates progression through the decision-making process. Even modest levels of personal communication (PC = 1) combined with high mass communication (MC = 5) lead to near saturation, with over 99% of households reaching refurbishment intention by 2050.

Scenarios with higher levels of personal communication (PC = 2–3) achieve similar results but at higher costs, as will be discussed in Section IV.C.

The results also confirm that personal communication cannot fully substitute for mass communication. Scenarios with high personal communication but low or absent mass communication (e.g., MC = 0, PC = 3) produce higher overall intentions than MC-only cases, but they fail to achieve saturation within the simulated timeframe. This pattern indicates that mass communication plays a necessary role in creating initial awareness and knowledge, which then enables personal communication to be effective in the later stages of decision-making.

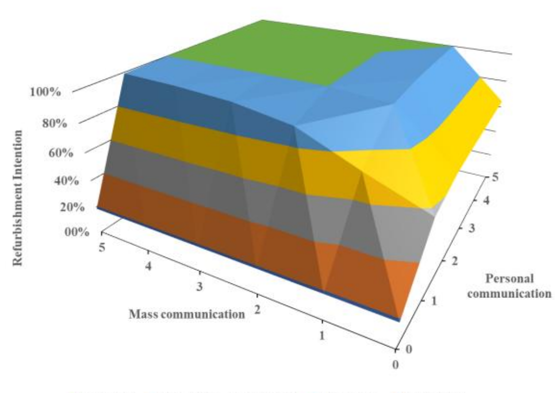

Figure 2. Final refurbishment intention (%) after 27 years across communication scenarios

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Overall, these findings suggest that the interaction of mass and personal communication is critical. Mass communication alone is inefficient, and personal communication alone is insufficient, but the combination of the two produces the strongest outcomes. This dynamic provides the basis for further analysis of the speed and cost trade-offs in subsequent sections.

B. *Speed of Reaching 95% Refurbishment Intention*

In addition to analyzing outcomes after a fixed simulation period of 27 years, the model was also used to examine how quickly different communication strategies enable the system to approach saturation. For this purpose, the simulation was terminated once 95% of households had reached the refurbishment intention stage. This indicator captures the speed of diffusion and allows a more direct comparison between alternative mixes of mass and personal communication.

The results reveal a clear trade-off between the level of personal communication and the speed of adoption. Scenarios that rely primarily on mass communication fail to reach the 95% threshold within the simulated timeframe, regardless of intensity. By contrast, the addition of even modest levels of personal communication substantially accelerates diffusion. For example, a combination of MC = 5 and PC = 1 achieves the 95% threshold in less than 20 years, while MC = 5 with PC = 2 shortens this period to around 15 years. Increasing personal communication further reduces the time to saturation, but the marginal gains diminish as PC levels rise beyond 3.

These dynamics are illustrated in Figure 3, which plots the average number of years required to reach 95% refurbishment intention under different communication mixes. In contrast to the previous results, this figure focuses on the speed of diffusion, measured as the number of years required to reach a 95% intention level. The pattern highlights that mass communication alone cannot achieve saturation, whereas the incremental addition of personal communication quickly reduces the time required. At the same time, higher PC levels imply higher costs, raising important questions about efficiency and burden-sharing among stakeholders.

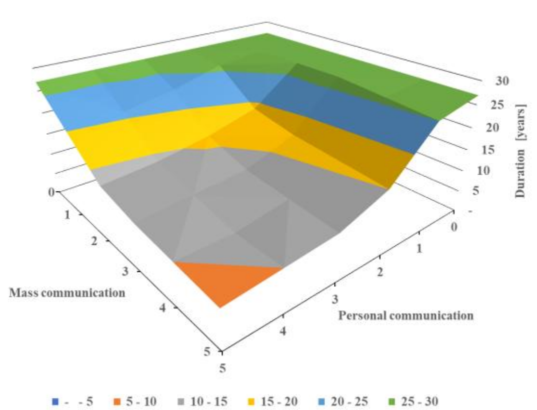

Figure 3. Time required (in years) to reach 95% refurbishment intention across communication scenarios

To quantify these implications, Table III presents the additional communication costs associated with faster adoption pathways. The results suggest that a moderate investment in personal communication offers the most favorable balance between speed and cost, while excessive reliance on personal contact delivers limited time savings at disproportionately higher expense.

C. *Economic Costs of Communication*

The acceleration of refurbishment intentions through communication measures generates additional costs, which differ by type and scale. Their distribution is critical for evaluating the feasibility of alternative strategies.

As shown in Table III (Section IV.B), scenarios with higher levels of personal communication result in disproportionately higher expenditures compared to those relying mainly on mass communication. While the addition of modest levels of PC (e.g., PC = 1) provides a substantial acceleration of adoption, it also raises costs by several hundred million euros over the simulation horizon. Increasing PC further produces strongly diminishing returns, with limited time savings at much higher expense.

Mass communication, by contrast, is relatively inexpensive per exposure but has limited effect on intention formation without personal communication. This implies that mass communication is necessary but not sufficient, whereas personal communication is effective but costly.

An important consideration is that the expenditures are not borne by a single actor. In practice, governments and municipalities typically finance mass campaigns, while homeowners or public subsidy schemes cover parts of the costs of consultancy. Energy consultants themselves also face capacity costs, often supported by professional associations or specific subsidy instruments. To illustrate these responsibilities, Table IV summarizes the typical allocation of cost responsibilities among stakeholders.

TABLE III. ADDITIONAL COSTS FOR FASTER REFURBISHMENT

Combinations of MC and PC		**Characteristics of combination**		
MC	**PC**	**Duration [years]**	**Accumulated costs [mi. €]**	**Additional costs vs. MC = 5 / PC = 1[mi. €]**
5	5	9	460.4	181.7
4	4	10	409.3	130.6
5	4	10	411.6	132.9
4	5	10	509.3	230.6
5	3	11	342.7	64.0
3	5	11	557.4	278.7
4	3	12	371.1	92.4
3	4	12	488.4	209.7
3	3	13	399.0	120.3
2	5	13	656.1	377.4
2	4	14	566.0	287.3
5	2	15	317.3	38.6
4	2	16	334.8	56.1
2	3	16	487.4	208.7
3	2	17	351.8	73.1
2	2	19	388.8	110.1
1	5	20	1,004.8	726.1
1	4	21	845.0	566.3
1	3	23	696.4	417.7
1	2	26	526.7	248.0

It is important to emphasize that Table IV does not assign exact numerical shares. The model calculates only aggregate costs, while the table provides a qualitative illustration of how these costs are typically distributed in practice. This perspective underscores the role of stakeholder cooperation in financing communication strategies for refurbishment acceleration.

D. Segment-Specific Patterns

While aggregate outcomes provide an overall picture of refurbishment dynamics, the segmentation of households according to Sinus lifestyles reveals important differences in responsiveness to communication measures. Table I in Section III showed the heterogeneous baseline distribution of homeowners across the HOE stages. Building on this initialization, the simulation results indicate that communication strategies affect lifestyle groups in uneven ways.

Households from higher-status, future-oriented lifestyles such as adaptive pragmatics and high achievers respond more quickly to both mass and personal communication. In these groups, modest levels of personal communication in combination with high mass communication are sufficient to achieve near saturation well before 2050. Their baseline intention levels are already above average, and communication measures therefore build on an existing disposition to act.

By contrast, groups such as the precarious and traditional lifestyles demonstrate slower progression through the HOE stages. Even with strong personal communication efforts, saturation is not achieved within the simulated period. These households often remain stuck in the conviction stage, reflecting structural barriers such as financial constraints. The results suggest that for these groups, communication alone may not be sufficient; additional policy instruments, e.g., financial support, could be required.

Intermediate groups such as the established conservatives and liberal intellectual fall between these extremes. They reach high intention levels under combinations of mass and personal communication, but the speed of adoption is slower than in more progressive groups. This indicates that while they are not fundamentally resistant, they may require sustained exposure over time.

Taken together, the segment-specific patterns highlight the importance of tailoring communication mixes to different homeowner groups. A uniform strategy may produce strong aggregate outcomes but mask pockets of low responsiveness. Recognizing heterogeneity is crucial for designing efficient and equitable refurbishment policies. A detailed numerical breakdown by lifestyle segments is beyond the scope of this paper.

TABLE IV. TYPICAL DISTRIBUTION OF COMMUNICATION COSTS ACROSS STAKEHOLDERS

Communication type	Typical stakeholder(s) bearing costs
Mass communication campaigns	National government, municipalities
Personal communication (consultant visits)	Homeowners (direct payment), subsidy schemes
Consultant capacity and infrastructure	Consultants, professional associations, partly public support

E. Exploratory Insights

The results of the simulation are not intended to deliver precise forecasts or to prescribe an optimal communication strategy. Instead, they provide a structured exploration of plausible pathways, highlighting trade-offs and dependencies that are relevant for both policy and practice.

A first key insight is that mass communication and personal communication are complementary rather than substitutable. Mass campaigns are necessary to create broad awareness and knowledge, but they remain ineffective without the reinforcing role of personal advice in the later stages of decision-making. Conversely, personal communication is powerful in driving conviction and intention but cannot generate sufficient reach on its own.

A second insight is that speed and cost are inherently linked. Faster adoption requires more personal communication, which is costly and resource-intensive. Moderate levels of PC offer the best balance between speed and cost, while very high levels of PC accelerate adoption only marginally but at disproportionately higher expense.

A third insight concerns stakeholder cooperation. The model makes clear that communication costs are substantial and cannot realistically be borne by a single actor. Governments are best positioned to finance mass campaigns, while homeowners and subsidy schemes contribute to the costs of consultancy, and consultants themselves provide the necessary capacity. Effective acceleration therefore depends on shared responsibility and coordination among stakeholders.

Finally, the analysis underscores the exploratory value of ABM. By making assumptions explicit and systematically varying key parameters, the approach allows researchers to reason about possible outcomes, tensions, and leverage points. Rather than predicting an optimal solution, the model highlights the conditions under which refurbishment pathways may accelerate or stall, and it provides a transparent basis for policy reflection.

F. Sensitivity Analysis

To assess the robustness of the results presented above, a targeted sensitivity analysis was conducted. The core research question of this study inherently adopts a sensitivity perspective by examining how varying levels of mass and personal communication influence decision outcomes. Building on this, two key parameters were systematically varied: the decision threshold and the strength of social contagion.

The analysis was performed under three communication scenarios representing different intervention intensities: low (MC = 2, PC = 0), medium (MC = 3, PC = 1), and high (MC = 4, PC = 3). For each scenario, parameters were varied *ceteris paribus*. The threshold parameter was tested at three levels (3, 4, 5) while keeping social contagion constant at 30%, and vice versa (15%, 30%, 45%) while keeping the threshold fixed at 4. Each configuration was simulated 20 times, and mean values were reported for the final share of homeowners reaching refurbishment intention and the number of years required to reach 95% intention. Table V presents the results of the threshold sensitivity analysis, while Table VI summarizes the results for social contagion.

TABLE V. SENSITIVITY OF MODEL OUTCOMES TO VARIATION IN THE THRESHOLD PARAMETER

Scenario	MC	PC	Threshold	Final Intention (%)	Years to 95%
A	2	0	3	100.0	6
A	2	0	4	94.9	10
A	2	0	5	59.8	NA
B	3	1	3	100.0	5
B	3	1	4	100.0	6
B	3	1	5	100.0	8
C	4	3	3	100.0	4
C	4	3	4	100.0	4
C	4	3	5	100.0	5

TABLE VI. SENSITIVITY OF MODEL OUTCOMES TO VARIATION IN SOCIAL CONTAGION STRENGTH

Scenario	MC	PC	Contagion	Final Intention (%)	Years to 95%
A	2	0	0.15	65.2	NA
A	2	0	0.30	60.8	NA
A	2	0	0.45	57.8	NA
B	3	1	0.15	100.0	7
B	3	1	0.30	100.0	6
B	3	1	0.45	100.0	6
C	4	3	0.15	100.0	5
C	4	3	0.30	100.0	4
C	4	3	0.45	100.0	4

Note: "NA" indicates that 95% adoption was not reached by the end of the simulation period.

The results show that the effect of parameter variation depends strongly on the level of communication intensity. Under low communication intensity (MC = 2, PC = 0), the threshold parameter has a substantial impact on model outcomes, determining whether diffusion occurs at all. Under moderate intensity (MC = 3, PC = 1), all configurations reach full adoption, but the threshold influences the speed of diffusion. Under high communication intensity (MC = 4, PC = 3), the model becomes largely insensitive to threshold variation, with rapid convergence in all cases.

In contrast, variation in social contagion shows only minor effects across all scenarios. While small differences can be observed under low communication intensity, the overall influence of this parameter remains limited compared to the threshold.

Overall, the results indicate that the model exhibits context-dependent robustness. While outcomes are sensitive to parameter variation under low communication intensity, the main patterns remain stable under moderate and high intensity. This suggests that the observed dynamics reflect structural properties of the model rather than being driven solely by specific parameter choices. At the same time, the analysis highlights that sensitivity is not uniformly distributed across parameters and regimes, but follows a consistent and interpretable pattern. In particular, individual resistance—captured by the threshold parameter—becomes critical under low-intensity conditions, while diminishing in relevance as communication pressure increases. Taken together, this combination of structured sensitivity and stability supports the validity of the model in exploring communication-driven diffusion processes.

V. DISCUSSION

This section discusses the findings in relation to existing literature, derives implications for policy and practice, and reflects on the limitations of the model.

A. Integration with Existing Literature

The simulation findings resonate with and extend several strands of existing research in marketing, energy transitions, and ABM.

First, the model's differentiation between mass communication and personal communication aligns closely with classical marketing theory. The HOE model [11; 12] and subsequent marketing research emphasize that mass communication is primarily effective in the early stages of awareness and knowledge, while personal communication is crucial in the conviction and intention stages [25; 26]. The results of this study empirically support these theoretical expectations in the specific domain of energetic refurbishment.

Second, the findings connect to the growing body of research on the role of energy consultancy and advice. Studies such as [5; 6; 13] have shown that personalized advice is often decisive for overcoming barriers to renovation. Our model results mirror this insight, demonstrating that even modest levels of personal communication trigger sharp increases in refurbishment intentions, whereas mass campaigns alone achieve only marginal effects.

Third, the results contribute to the literature on ABM in energy transitions. Previous applications have largely focused on technology adoption, such as photovoltaic systems [8]. Renovation has been underexplored, despite its equal or greater importance for climate targets. By applying ABM to energetic refurbishment and explicitly modeling communication dynamics, this study extends the methodological repertoire of ABM applications in the energy domain.

Finally, the exploratory framing of the model reflects a broader methodological trend. As noted by [24], ABM is increasingly recognized not only as a predictive tool but also as a means to support exploratory analysis and policy learning under uncertainty. The present study adopts this perspective explicitly, using the model to reason about plausible pathways, trade-offs, and stakeholder responsibilities rather than to prescribe a single optimal solution.

Taken together, the results extend existing literature on communication-driven diffusion processes by suggesting that the effects of communication mechanisms are not uniform, but depend on the overall level of intervention intensity. While prior research emphasizes the role of mass communication, interpersonal influence, and social contagion, the present findings indicate that their relative importance varies systematically across different regimes. In particular, the results suggest that parameter effects should not be interpreted in isolation, but in relation to the broader communication context in which they operate.

B. Implications for Policy and Practice

The simulation results provide several implications for policy design and practical implementation. They show that communication measures are necessary for accelerating refurbishment but that their effectiveness depends critically on cooperation among stakeholders and coordination across governance levels.

First, the findings highlight the importance of multilevel governance. Björklund et al. [32] emphasize that energy renovation policies in the EU succeed only when European, national, and local actions are aligned. In the simulation, national-level mass communication raises awareness but fails to generate substantial refurbishment intentions on its own. Only when combined with personal communication—often facilitated at the municipal level—does the system accelerate toward saturation. This indicates that higher-level campaigns must be complemented by localized, trusted interventions.

Second, the results underscore the leverage of municipal governance. Ebrahimigharehbaghi et al. [18] demonstrate how municipalities in the Netherlands mobilize homeowners by offering targeted programs and advice. The simulation confirms this mechanism: even modest amounts of personal communication (PC = 1) are sufficient to dramatically speed up adoption. This suggests that small-scale municipal initiatives, such as subsidized consultation visits or neighborhood information events, may provide high returns relative to their cost.

Third, the model points to the role of private actors and hybrid governance. Galvin [15] argues that private housing companies increasingly integrate energy efficiency goals into their corporate strategies, taking on responsibilities traditionally reserved for public authorities. The cost structures in the simulation reflect this: while governments typically finance mass campaigns, the expenses of consultancy are partly borne by homeowners and subsidy schemes. Consultants themselves face capacity costs. These findings indicate that hybrid arrangements—where public and private actors share the financial and organizational burden—are not only realistic but necessary for large-scale acceleration.

Finally, the results suggest the importance of social contexts. Jowkar et al. [19] find that social values influence barriers and motivations for renovation in Norway. In the model, lifestyle groups such as precarious households lag behind others despite strong communication measures, reflecting deeper structural and social barriers. This implies that communication alone cannot reach all groups equally and must be embedded in broader strategies that also address financial constraints and trust.

Taken together, these insights point to a policy approach that avoids reliance on a single "optimal" communication instrument. Instead, policymakers should pursue policy mixes that combine broad awareness-building through mass campaigns with personalized, trust-based interactions at the local level, and that mobilize both public and private actors in financing and implementation. The simulation shows that such cooperation is not optional but essential for achieving large-scale acceleration in a cost-effective and socially inclusive manner.

The results further suggest that policy interventions should be aligned with the prevailing communication intensity within the system. Under low-intensity conditions, efforts to reduce individual barriers to adoption—such as financial constraints or informational deficits—are particularly critical, as these factors can determine whether diffusion occurs at all. In contrast, under moderate communication intensity, increasing the level or coordination of communication activities can significantly accelerate diffusion processes. Finally, under high-intensity conditions, additional communication efforts may yield diminishing returns, as adoption levels are already close to saturation. This highlights the importance of tailoring policy strategies to the specific diffusion regime rather than applying uniform intervention approaches.

C. *Limitations of the Model*

While the simulation provides valuable exploratory insights, several limitations must be acknowledged. These limitations relate to the scope of the assumptions, the operationalization of decision-making, and the boundaries of the model.

First, the model is based on a substantial number of simplifying assumptions. Table II made these explicit, covering thresholds, communication impacts, social contagion, and cost structures. Such assumptions are necessary to make the model tractable but inevitably reduce its realism. For example, the influence of communication measures is represented by fixed correction factors, which may not fully capture the diversity of responses across households. Similarly, the cost parameters are treated as stable averages, whereas in reality they vary across regions, time, and communication channels. In addition, the threshold parameter represents a stylized proxy for individual resistance to behavioral change and is not directly calibrated to empirical data, which limits its interpretability in real-world terms.

More fundamentally, the model deliberately abstracts from structural barriers such as high renovation costs (typically €50,000–€150,000) and demographic constraints, e.g., older homeowners facing long payback periods. These factors are not explicitly modeled, as the analytical focus is on isolating communication-driven decision dynamics. Holding such constraints constant allows for a clearer interpretation of how mass and personal communication influence the formation of refurbishment intentions. At the same time, this abstraction limits the model's ability to assess real-world feasibility and financial constraints, and should be considered when interpreting the results.

The empirical basis of the model builds on earlier data and conceptual assumptions that predate the recent energy market disruptions triggered by the war in Ukraine. However, the model is designed to capture structural behavioral mechanisms rather than short-term market conditions. Its purpose is therefore not to reproduce a specific market situation, but to explore general patterns of decision-making under different communication regimes. While this limits direct empirical applicability to current market conditions, the conceptual insights into communication effects and decision dynamics remain valid.

The model is partially calibrated to empirical data, as the 17,000 simulated agents reflect both the distribution of Sinus lifestyles and the empirically observed status quo across the stages of the HOE model. However, not all parameters are calibrated in the same way. In particular, the threshold parameter is modeled in a stylized manner and represents a

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proxy for individual resistance to behavioral change. Similarly, the social contagion mechanism is not empirically calibrated but implemented as a simplified representation of neighborhood-level peer effects. Accordingly, the model combines empirically grounded initialization with exploratory behavioral assumptions. Its value lies less in exact prediction than in examining how different communication regimes interact with heterogeneous starting conditions and decision dynamics. To account for this, a targeted sensitivity analysis was conducted for these non-empirically calibrated parameters, allowing the robustness of the model results to be assessed under systematic ceteris paribus variation.

Second, the decision-making process is modeled using a static adaptation of the HOE framework. While this provides a clear and structured logic, it assumes that all households progress sequentially through awareness, knowledge, attitude, conviction, and intention. In practice, decision-making may be more iterative, with households skipping or revisiting stages, or being influenced by external shocks such as sudden policy changes or energy price fluctuations. These dynamics are not fully captured in the current model.

Third, beyond structural constraints, the model focuses exclusively on communication measures. Other policy instruments, such as financial incentives, regulatory standards, or market mechanisms, are not included. This narrow focus is deliberate, as it isolates the specific role of communication, but it limits the model's capacity to assess the combined effect of policy mixes. Given the importance of subsidies and regulations in real-world renovation programs, this omission must be borne in mind when interpreting the results.

Fourth, the simulation treats stakeholder cooperation qualitatively rather than quantitatively. While Table IV outlined typical cost responsibilities across actors, the model does not calculate exact financial allocations to governments, consultants, or homeowners. This makes the stakeholder dimension illustrative rather than predictive. Future work could strengthen this aspect by coupling ABM results with economic or institutional modeling to better represent the distribution of costs and responsibilities.

In addition, the sensitivity analysis indicates that the role of social contagion within the current model structure is comparatively limited. Variations in contagion strength lead to only minor changes in diffusion outcomes across most scenarios. This may be a result of the specific model design and parameterization, and suggests that indirect social influence is dominated by direct communication effects under the given assumptions.

Finally, the model is designed as an exploratory tool rather than a predictive engine. The results should therefore not be interpreted as forecasts of refurbishment adoption in Germany, but as illustrations of plausible trajectories under different communication mixes. At the same time, the sensitivity analysis shows that model behavior is not uniformly stable, but depends on the overall communication context, which further supports its use as a tool for exploring conditional dynamics rather than generating precise predictions. This limitation is also a strength: it highlights the value of ABM for reasoning under uncertainty, while avoiding the false impression of precision.

D. Future Research Directions

The limitations of the present study also open up several promising directions for future research. These concern methodological refinements, integration with additional policy instruments, and deeper consideration of social factors.

A first avenue lies in broadening the policy scope. The current model isolates communication measures to make their effects explicit. However, real-world renovation programs combine communication with financial incentives, regulatory standards, and technical support. Extending the model to simulate policy mixes would make it possible to analyze synergies and trade-offs between different instruments. For example, combining subsidies with communication could test whether financial incentives amplify the effectiveness of personal advice among households with financial constraints.

A second direction involves enhancing the temporal dynamics of the simulation. In this study, outcomes were evaluated after a fixed period of 27 years or at the 95% threshold of adoption. While informative, this design could be enriched with continuous time series analyses that show how different communication mixes shape trajectories year by year. A new figure comparing diffusion curves across selected scenarios (e.g., MC = 5/PC = 0 vs. MC = 5/PC = 1 vs. MC = 0/PC = 3) would illustrate dynamic differences more vividly. This type of visual enrichment would strengthen the exploratory potential of the model and facilitate policy dialogue.

A third research direction concerns heterogeneity and social diversity. The present model integrates lifestyle segmentation through Sinus milieus, but it treats social factors only indirectly. Empirical studies [19] show that social values strongly influence renovation decisions. Future models could incorporate social or regional variations in responsiveness, willingness to cooperate, thus improving the model's ability to represent diverse contexts. In addition, such extensions could help to better capture indirect social influence mechanisms, which appear only in a limited form in the current model.

A fourth opportunity lies in refining agent behavior. The current HOE-based decision logic assumes sequential progression through stages. Future models could include more adaptive or iterative pathways, allowing agents to skip, revisit, or regress between stages. They could also simulate learning effects, where repeated exposure to communication or peer influence gradually lowers thresholds. This would bring the model closer to real-world decision-making dynamics. It would also allow for a more realistic representation and empirical calibration of behavioral thresholds, which are currently modeled in a stylized manner.

Finally, further work could focus on quantifying stakeholder cooperation. The present study illustrates typical distributions of costs qualitatively. Future research could couple the ABM with economic models or institutional analyses to assign financial burdens more precisely to governments, consultants, and homeowners. Such an approach would support more detailed assessments of cost-sharing fairness and efficiency.

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Taken together, these directions point to a rich research agenda. By expanding scope, improving temporal dynamics, integrating social diversity, refining agent behavior, and quantifying stakeholder roles, future work can strengthen the ability of ABM to inform effective and equitable refurbishment policies. In particular, further research could build on the regime-dependent dynamics observed in this study to better understand how different intervention intensities shape diffusion processes under varying conditions.

VI. CONCLUSION

This paper has presented an exploratory agent-based simulation of communication-driven energetic refurbishment decisions among German homeowners. Building on earlier work, the analysis expanded the model with explicit assumptions, lifestyle segmentation, and a stakeholder perspective. The results demonstrate that communication is a necessary but not sufficient driver of refurbishment acceleration: its effectiveness depends on the interplay of mass communication and personal communication, the balance between speed and cost, and the cooperation of multiple actors in financing and delivering these measures. In addition, the results indicate that these effects depend strongly on the overall level of communication intensity, rather than on individual parameters in isolation.

Three key contributions emerge from this study. First, the model confirms and operationalizes a central insight from marketing theory: mass communication is essential for generating awareness and knowledge but weak in creating conviction and intention, whereas personal communication is decisive in later decision stages. Their combination, rather than either instrument alone, produces the strongest effects.

Second, the results indicate that diffusion dynamics can be characterized by distinct regimes, depending on the overall level of communication intensity. Under low-intensity conditions, adoption is highly sensitive to individual resistance, while under moderate intensity, diffusion outcomes become stable but vary in speed. Under high-intensity conditions, diffusion approaches saturation, and parameter variations have only limited effects. This regime-dependent behavior highlights that the effectiveness of communication strategies cannot be assessed in isolation, but must be understood in relation to the broader communication context.

Third, the paper situates refurbishment acceleration within a governance perspective. By aligning the simulation results with insights from the literature on multilevel governance, municipal engagement, hybrid public–private arrangements, and social influences, the study highlights that effective communication strategies require coordination across actors and contexts. Acceleration is unlikely to be achieved through isolated measures; it depends on cooperation among governments, municipalities, consultants, homeowners, and, in some cases, private housing companies. This perspective is consistent with the regime-dependent dynamics observed in the model, which emphasize the need for coordinated interventions across different actors and intensity levels.

The study also underscores the value of ABM as an exploratory tool. By making assumptions explicit and systematically varying key parameters, including targeted sensitivity analyses, the model provides a structured way to reason about plausible pathways, tensions, and leverage points in refurbishment policy. While not predictive, the approach supports policy learning under uncertainty and offers a transparent platform for dialogue among policymakers, practitioners, and researchers.

Future work should extend the model to include policy mixes beyond communication, explore time series dynamics, incorporate social diversity more explicitly, and quantify stakeholder cost allocations. These extensions would further strengthen the relevance of ABM for the design of effective and equitable renovation strategies.

In conclusion, the findings highlight that communication-driven refurbishment processes are governed not only by the presence of communication measures, but by their interaction within different levels of communication intensity. In particular, the results suggest that the relevance of individual resistance, communication strategies, and social influence varies systematically across different diffusion contexts. While the model is exploratory in nature, it provides a structured perspective on how communication strategies shape adoption dynamics and supports a more differentiated understanding of policy interventions. Rather than offering precise predictions, the study contributes to identifying the conditions under which communication measures are most likely to be effective.

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