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Subsidy free-riding is positively correlated to the development of energy efficiency in the housing stock

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Abstract

Incentivizing energy-efficient retrofits in residential sectors often involves subsidies, which are aimed at lowering a building's environmental impact. However, the effectiveness of these subsidies has been debated, particularly concerning an unintended consequence known as free-riding. Free-riders are investors who would have made energy-efficient retrofits even without the subsidy. Typically, a high prevalence of free-riding is perceived negatively from an economic perspective in terms of the impact and efficiency of a policy. However, apart from economic efficiency, it is unclear what the relation between free-riding and the progression of the buildings' energy standards is. We employed an agent-based model to mimic a neighborhood and discovered an intriguing pattern: Areas with more free-riders actually showed advanced energy standards in their building infrastructure now and 7 years into the future. These insights enhance our comprehension of free-riding and can help policymakers take this relation into account when designing subsidy schemes.

Keywords Agent-based modeling · Energy retrofitting · Intentions · Retrofit subsidies · Subsidy free-riding

1 Introduction

The heating of private households accounts for 70% of the total energy used in an average EU household (Eurostat, 2019). While new buildings must often conform to statutory energy efficiency rules, older buildings were often not constructed with respect to the efficiency requirements of the 21st century. One estimate suggests that 75% of the housing stock in the EU needs energy retrofitting (Economidou et al., 2011). While this represents

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a major challenge for countries on the way to achieving Paris' 1.5°–2 °C goal (Revi et al., 2022), it is at the same time a suitable starting point for targeted policy measures (Economidou et al., 2019). Estimates suggest that comprehensive thermal retrofits can cut energy consumption down between 30 and 60% (IEA, 2023b). However, given the current yearly global retrofit rate of less than 1%, reaching an energy-sustainable building stock is a difficult endeavor, as a rate of 2.5% would be necessary (IEA, 2023a).

From a purely economic standpoint, individuals should be inclined to retrofit their homes because, over the long term, such investments can yield a positive net value, due to reduced energy costs (Hondeborg et al., 2023; Mayer et al., 2022). However, in practice, the relation is considerably more intricate, and the lack of retrofitting uptake despite potential benefits has been labeled the "energy-efficiency gap" (Jaffe & Stavins, 1994). The literature has offered various explanations for this discrepancy. Examples include the misalignment of incentives between property owners and users (i.e., tenants), substantial costs, uncertainties surrounding energy savings, and a general aversion to risk (Du et al., 2022; Hondeborg et al., 2023). In countries with a large proportion of rented housing, the issue of split incentives is especially salient. For instance, an analysis from Germany demonstrated that the marginal costs for homeowners significantly surpass the marginal benefits (Groh et al., 2022). Thus, policy makers are looking at potential measures that can be applied to overcome these hurdles.

Subsidies or grants are among the most favored political strategies designed to assist individuals in surmounting the mentioned barriers to thereby foster a sustainable transformation (Bertoldi et al., 2021). Within the scope of the current study, a retrofitting subsidy refers to a fiscal, financial incentive program designed by a government, local authority, or other organization that aims to encourage private property owners to improve the energy efficiency and thus the sustainability of existing buildings. Moreover, retrofits may have a secondary effect on a building's safety, value, and comfort, and enhance the overall energy security in a given area (Gillingham et al., 2021). When correctly implemented and tailored toward local circumstances, subsidy schemes are said to be among the most effective and efficient political instruments (Bertoldi et al., 2021). However, a common point of criticism of subsidy schemes is the problem of free-riding (e.g., Collins & Curtis, 2018; Egner et al., 2021). Free-riders are investors who take advantage of the subsidy but would have invested even in the absence of the incentive (Haugland, 1996). From an economic perspective, free-riders can significantly undermine the efficiency of subsidies, depending on their proportion (Labandeira et al., 2020). From the standpoint of energy justice (Hernández et al., 2022), a substantial prevalence of free-riders implies that a considerable segment of the subsidy's beneficiaries might not need such financial support, thereby channeling funds toward often affluent households and rendering the subsidy socially inefficient. Simultaneously, a minimal incidence of free-riders might also suggest that subsidies are predominantly allocated to extensive and, consequently, potentially costly retrofitting measures, an issue that poses its own set of challenges from both social and ethical viewpoints (Egner et al., 2021).

While the debate on economic and social efficiency is indeed important, there appears to be a lack of research that has examined the direct impact of the free-riding rate on the development of energy efficiency in the housing stock. Against this background, with our research, we aim to adopt a novel and distinct approach. Instead of concentrating on the potential economic and justice-related drawbacks associated with subsidy free-riding, our objective is to investigate the genuine association between the rate of free-riding and the true energy standard (in kWh/m^2a) of the building stock and whether it is constant over time. We thereby aim to frame the free-riding rate as an indicator for the housing stock development, specifically, by investigating the following research question (RQ). **RQ**: What indication does the rate of free-riding have for the overall energy transition in the building stock?

We begin by examining the risk that free-riding poses to subsidy schemes, and then we discuss its determinants. Afterward, we synthesize these two elements and deduce our hypotheses that free-riding could be indicative of positive energy developments. To evaluate our hypotheses, we present an agent-based model.

1.1 Literature review

1.1.1 Free-riding a subsidy scheme

From an economic viewpoint, an efficient retrofitting subsidy scheme is one that maximizes the environmental and energy efficiency benefits relative to the cost, effectively leveraging limited public funds to stimulate private investments in building upgrades that yield the highest return in terms of energy savings, emission reductions, and long-term sustainability (Bertoldi et al., 2021; Economidou et al., 2019). This means that an efficient subsidy must stimulate new projects or enhance current projects. Thus, by definition, free-riders are a problem to an efficient retrofitting subsidy scheme because they represent economic inefficiency, where funds are claimed for upgrades that would have been undertaken anyway, thus diminishing the intended incentivizing effect and misspend public resources that could have been allocated toward driving improvements somewhere else. Hence, a large proportion of free-riders is often seen as evidence of an inefficient program (Alberini et al., 2014; Rosenow & Galvin, 2013). For example, Rivers and Shiell (2016) noted in their study of a Canadian subsidy scheme that a larger proportion of free-riding limited the energy savings that should theoretically have resulted from the program.

However, the actual proportion of free-riding is difficult to estimate, but current research has identified free-riding rates between 10 and 96% in the residential sector (Alberini et al., 2014; Egner et al., 2021; Grosche & Vance, 2009; Nauleau, 2014; Olsthoorn et al., 2017). In a meta-study of the environmental impact of energy efficiency policies, Labandeira et al. (2020) found that free-riders were responsible for 15–40% of the energy reduction that was achieved through a subsidy scheme (i.e., significantly reducing the efficiency of the policy; Hondeborg et al., 2023). To gain deeper insight into the causes of free-riding, it is essential to understand its determinants.

1.1.2 Determinants of free-riding

One of the pivotal factors that influences the incidence of free-riding in energy efficiency programs is the subsidy threshold. The threshold is defined as the minimum standard of retrofitting that a building must undergo to be eligible to receive the financial incentive. The minimum retrofit requirement in turn is a specified level of energy efficiency improvement that a property must achieve. For example, such improvement may be quantified in terms of energy savings or the installation of certain technologies that meet established energy performance criteria. In the present case, the threshold is defined as a general increase in energy efficiency and is not tied to specific technologies (see Sect. 2.2). It is generally presumed that lower thresholds are likely to increase the probability of free-riding (Egner et al., 2021).

Since free-riding, by definition, requires a household's intention to retrofit independently of a present subsidy scheme, the general population's intentions to retrofit also influence the amount of free-riding that occurs. Nevertheless, the prevalence of free-riding might not be determined by either the threshold or intentions alone but essentially by the distance between these two variables. The higher the intentions to retrofit compared with the threshold, the more free-riding occurs. Conversely, the more difficult it is to receive subsidies compared with the general population's intentions, the lower the amount of free-riding that occurs. For reasons of cost-efficiency, it may therefore seem sensible to set a higher threshold to keep the free-riding rate low. Note, however, that even a subsidy program that achieves economic success may fall short in terms of social and ecological efficiency (Pellegrini-Masini et al., 2020). According to energy justice scholars, subsidies attain full efficiency only if they deliver the intended economic and ecological benefits and concurrently extend to socioeconomically disadvantaged groups (Hernández et al., 2022; McCauley & Heffron, 2018), which are more sensitive to energy costs (Belaïd, 2022; Bohr & McCreery, 2020). Indeed, an analysis of the Norwegian subsidy program revealed that a low free-riding rate of around 10% indicated that it was predominantly affluent households that benefited from the subsidies (Egner et al., 2021). However, there are reasons why free-riding does not necessarily have to be viewed negatively if the emphasis shifts from purely economic and social efficiency to ecological effectiveness.

1.2 Hypothesis development – free-riding and energy efficiency development in the housing stock

The relation between the threshold and intentions has implications for the connection between free-riding and the development of energy efficiency in the housing stock. On the one hand, Klöckner and Nayum (2017) found that high intentions to retrofit in a population are a good sign for the overall rate of retrofitting, regardless of the presence of any subsidy scheme. On the other hand, low thresholds for subsidies may pose an issue that goes beyond just free-riding. Concerns highlighted in the literature suggest that "lock-in" effects might ensue, and further, that initial investments may lead to decreased intentions to make further improvements (Dubois & Allacker, 2015). Lock-ins refer to situations where current decisions or investments limit or constrain future opportunities to improve energy efficiency or reduce greenhouse gas emissions. For example, if a building is retrofitted with a heating system that relies on fossil fuels, transitioning to a more sustainable energy source later may be more difficult and expensive. Against this background, it seems intuitive that low thresholds limit the effectiveness of subsidy schemes, but interestingly, Egner and Klöckner (2022) found that—when all else is held constant—the overall energy efficiency of the building stock decreases as the subsidy threshold increases. The interpretation is that, even though subsidized retrofits are typically ambitious in high threshold environments, the fact that fewer households can afford retrofitting due to high upfront costs has a negative impact on the development of energy efficiency in the housing stock. Additionally, Wiethe (2022) demonstrated that accepting lock-ins as a result of early and consequently less ambitious retrofitting measures can also lead to long-term CO_2 savings. Moreover, Egner and Klöckner (2021) found that a recent investment was indeed positively correlated with the likelihood of undertaking additional retrofits. One of the reasons for this result is that those who have recently retrofitted have a greater understanding of the benefits of retrofitting, and uncertainties and concerns about retrofitting tend to decrease (Collins & Curtis, 2018). Additionally, research has demonstrated a neighborhood effect that serves as a normative influence. When neighboring households undertake retrofitting, it increases the likelihood that other households in the vicinity will do the same (Helms, 2012). If lower subsidy thresholds facilitate more widespread retrofitting, this trend can yield beneficial outcomes for the entire neighborhood (Egner & Klöckner, 2022).

Hence, it is possible to state: A high level of retrofitting intentions in a population is a favorable sign for the development of energy efficiency in the housing stock; low thresholds are also related with positive developments; and recent investments, which are encouraged by low thresholds, may prompt further own and neighborhood investments. Since the free-riding rate can be seen a proxy for the distance between intentions and the threshold and is higher the more the intentions exceed the threshold, the following hypothesis can be formulated.

Hypothesis 1 The higher the free-riding rate, the better the current development of the energy efficiency of the housing stock.

Both early (Wiethe, 2022) and recent retrofits (Egner & Klöckner, 2021) have positive effects on the energy standard over time. In addition, early retrofits and the general number of retrofits are both promoted by low subsidy thresholds, and the latter additionally makes subsequent retrofits more likely to occur (Egner & Klöckner, 2021). Against this background, it can be assumed that if a positive association is found in support of Hypothesis 1, it will also remain stable over time.

Hypothesis 2 The higher the free-riding rate, the better the future development of the energy efficiency of the housing stock.

2 Methods

2.1 Estimating the prevalence of free-riding

Several attempts have been made to estimate the proportions of free-riding associated with different retrofitting subsidy schemes (Alberini et al., 2014; Collins & Curtis, 2018; Egner et al., 2021; Grösche et al., 2009; Rivers & Shiell, 2016; Studer & Rieder, 2019). However, for the present study, the prevalence of free-riding must be experimentally manipulated to generate enough variance to be able to conduct the statistical analysis. Therefore, approaches that survey people in real environments are unsuitable because it would be very difficult to generate a sufficiently large amount of variability, as actual subsidy programs would need to be rolled out with varying thresholds and intention levels in the population. Thus, researchers must rely on other options. One is to use agent-based models (ABMs). An ABM can be explained as a bottom-up, disaggregated simulation approach that focuses on the individual (i.e., the agent) rather than on the system in an interactive environment (An, 2012; Kiesling et al., 2012). An agent is an autonomous decision-making unit. Each of these agents makes decisions on the basis of a set of rules and an evaluation of its own situation. The product of such decisions can be different behaviors that are defined by the system itself. For example, agents may produce, consume, or sell —or make the decision to renovate a house in terms of energy efficiency (Bonabeau, 2002). Several attempts have been made to model the retrofitting behavior of households, thus suggesting that ABMs are an excellent tool that can be used to investigate the link between the prevalence of free-riding and the development of energy efficiency in the housing stock (Egner & Klöckner, 2022). While there are other methods (e.g., discrete event simulations or system dynamics) that could have been applied to the same research questions, we chose ABMs because readily available models were at hand, and we were familiar with the methods. We outline the model we based our study on below.

2.2 Household energy retrofit behavior model

The Household Energy Retrofit Behavior (HERB) model builds on retrofitting-specific behavioral research (Klöckner & Nayum, 2015, 2016, 2017). This line of research investigated Norwegian homeowners' energy retrofitting behavior and suggested that homeowners move through stages, ranging from not really thinking about retrofitting to planning how to implement the retrofits. Afterward, the researchers quantified the extents to which different factors (e.g., expected gains in comfort) influenced the transition between stages. It differentiates itself from other behavioral models, such as the theory of planned behavior (Ajzen, 1991), by focusing on one specific behavior rather than on several.

The suggested stages were "not in decision mode" (Stage 1), "deciding what to do" (Stage 2), "deciding how to do it" (Stage 3), and "planning implementations" (Stage 4). In the first stage, households are affected by normative influence, financial gains, comfort gains, wastefulness of their current energy standard, retrofit efficacy, and availability of subsidies. These factors impact their likelihood of transitioning to Stage 2 and are impacted by different weights, which are again based on existing research on energy households' retrofitting behavior (Klöckner & Nayum, 2016). See Table 1 for an overview. If these factors are strong enough, households move to Stage 2. Here, households are again affected by different factors, and move on to Stage 3. In Stage 3, only financial and comfort factors are considered. If these factors are sufficient, households start retrofitting if they can afford to.

The psychological factors that influence household energy retrofits are underpinned by a variety of physical bases. Normative influence is shaped by how recently friends and neighbors have undertaken retrofits, with more recent actions having a stronger effect and those over 5 years old are disregarded. Friends are based on a small worlds network (Watts & Strogatz, 1998). Worries about finances are quantified on a scale ranging from 0 to 1,

Table 1 Overview of the weight of each factor in determining whether a household moves from one stage to another

Factor	Stage 1	Stage 2	Stage 3
Normative influence	0.5	0.1	0
Worry enough finances	0	0.038	0.031
Financial gain	0.245	0.149	0.051
Comfort gain	1.099	0.155	0.041
Wastefulness	0.106	0	0
Retrofit efficacy	-0.085	0.171	0
Subsidies	0.063	0.06	0

where the cost of a project below half the available capital eliminates worry, whereas higher costs increase concern proportionally. The financial gain from retrofits is evaluated by the time required to recoup costs through energy savings, considering subsidies, and the relative monthly savings on energy bills. Comfort gain is gauged by the expected increase in thermal comfort, represented by a reduction in energy consumption per square meter per year. A household considers its energy standard to be wasteful if the energy standard falls more than 10% below the mean standard of their social group, with the measure being the disparity between these standards. Retrofit efficacy reflects a household's and its social group's recent retrofitting activities, with the individual's actions having four times the impact of others and only considering actions within the past two decades. Finally, the potential subsidies a household could receive for planned retrofits are also considered.

When all variables have been calculated, they are standardized and summarized. Then, the household's chance of transitioning to the next stage is based on this number. Because households' energy retrofitting behavior is also affected by factors that are unknown to research, as well as by potentially truly random effects, there is also a random element to the transitioning from stage to stage. If a household transitions to Stage 3 and decides to retrofit, it needs to check whether it can afford the retrofit. If it cannot, the household goes back to Stage 1. If the household can pay for the retrofit, it starts retrofitting and is marked as "currently energy retrofitting" for a period of 1 week per 5 kWh/(m2a), considerably impacting other households' willingness to retrofit. When the energy retrofitting has been completed, its energy standard is updated, and the household moves back to Stage 1 "not in decision mode" and begins the process anew.

The model was previously used to provide input regarding Norwegian energy retrofitting policies (Egner & Klöckner, 2022). In this previous study, the model was validated by matching its outcomes regarding overall retrofitting rates, free-riding rates, and consecutive retrofitting rates with the same data gathered from empirical surveys from the same households. The model achieved valid results on the first two measures but had somewhat inaccurate results for consecutive retrofitting behavior. For our study, we adapted the HERB model (see Fig. 1) to detect free-riding, providing us with the opportunity to examine the relation between measured free-riding and the development of the energy efficiency of the housing stock.

To have a subsidy scheme to measure free-riding, the current Norwegian energy retrofitting subsidies were added to the model (Enova, 2019). Here, households are eligible to receive 100,000, 125,000, and 150,000 NOK (ca. 8500€, 10500€, and 12500€, respectively, as of November 2023) for retrofitting to an energy standard of about 130, 110, and 90 kWh/(m2a), respectively. This scheme makes households eligible for different sums of subsidies depending on the energy standard of their planned retrofitting. The model assesses whether these extra monetary incentives were needed to get a household to retrofit. If the household would have retrofitted without the subsidies, it is marked as a free-rider. If the subsidies were responsible for making the household retrofit, it is marked as a non-free-rider. Households that did not receive subsidies are not included in the free-riding statistics but are included in the energy data. This way, if a subsidized retrofit has a cascading effect, it will affect the energy data.

A mix of various other policies were used to trigger variability in free-riding. These policies consisted of providing subsidized loans, raising the energy standard threshold for eligibility for subsidies, giving extra motivation to some households in Stage 3, making

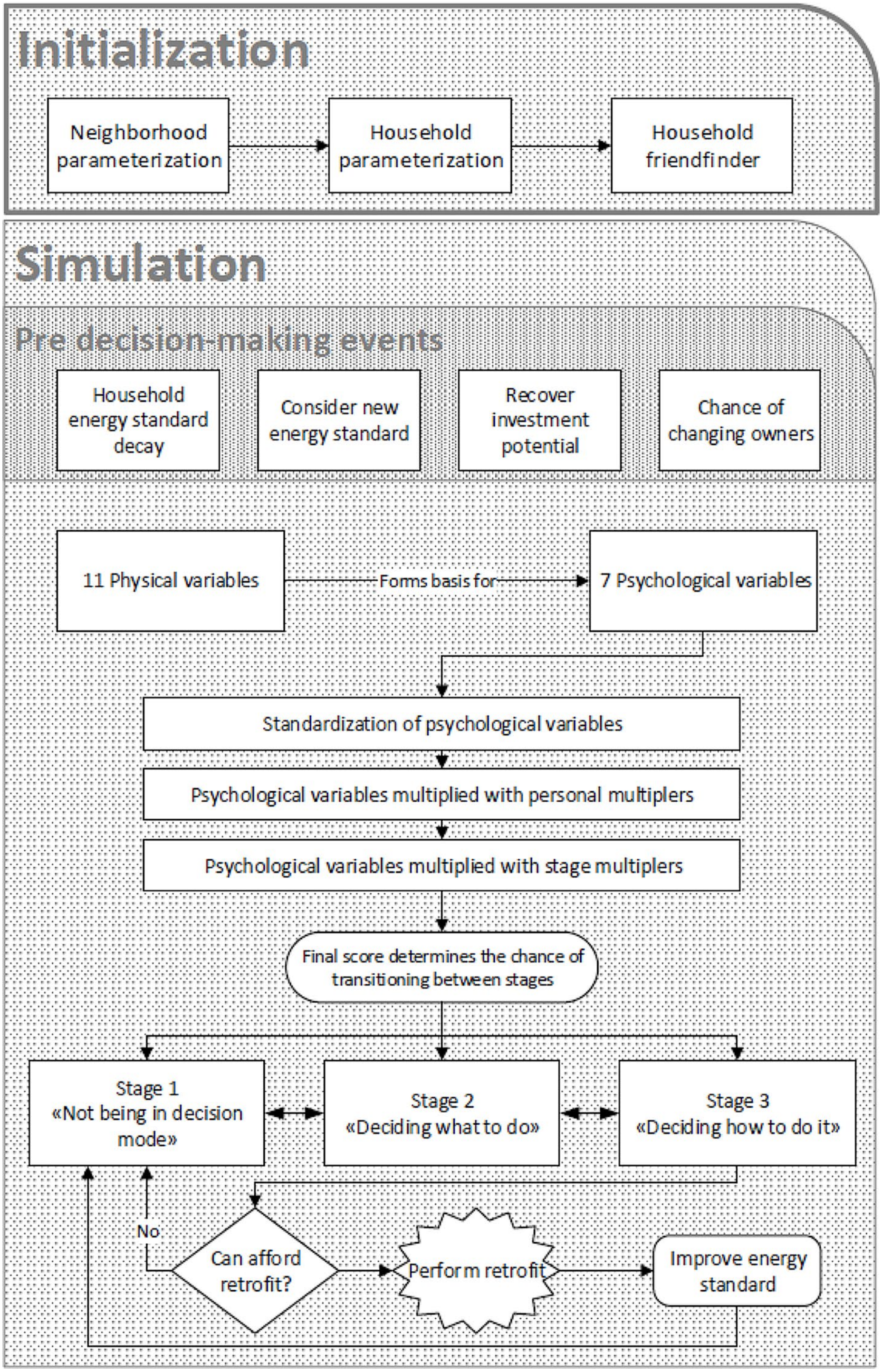

Fig. 1 A simplified overview of the HERB model

households consider a specific advertised energy standard, and adjusting energy costs. We chose these policies on the basis of what seemed like a realistic policy approach and could be integrated into the model. We excluded policies that made subsidies entirely unavailable for all households, since free-riding can occur only when subsidies are available. The combination of policies is listed in Table 2. The final data output includes all possible variations in the policies, resulting in 648 different combinations. For a full overview, design concepts, and a detailed protocol (Grimm et al., 2006, 2020), see Online Resource 1 (Link 1).

Five regression models were fit to the data to estimate the effect each policy had on the proportion of free-riding (after 3 years) in the HERB model. This procedure was followed to assess whether the mixture of policies produced sufficient variability in the free-riding ratio to proceed with the analysis of the relation between free-riding and the energy standard. From the five different policies included in the policy mix to trigger variability in free-riding, the subsidy threshold adjustment and ambition marketing significantly positively influenced the proportion of free-riders. This finding is in line with current research (Egner et al., 2021; Klöckner & Nayum, 2017). The amount of the subsidy loan, the energy costs, and the final push policy had no significant impact on the proportion of free-riding, although they were included in the ABM with the expectation that they would have an impact (Egner & Klöckner, 2022). The full results can be found as supplementary material in Online Resource 1 (Table 1). Although a higher functionality of policy adjustments, in terms of their impact on free-riding, would have been desirable, the lack of impact did not pose a problem for the research question under investigation because the purpose of the policy mix was only to generate variability in free-riding. Note that free-riding was measured on the basis of the previous subsidy policy, not the policies introduced in Table 2.

2.3 Data

To gather data on free-riding and the energy standard, we simulated 10 years of energy retrofitting using the NetLogo (version 6.1.0) software (Wilensky, 1999). The simulated neighborhood consisted of 710 households and mirrored real respondents from a survey distributed in Norway. Only residential households were simulated, not commercial buildings. At the start of the model, an initial policy mix was chosen. After 3 years, the model assessed which households free-rode or were affected by their last subsidy grant. Here, a neighborhood's total energy standard for residential heating was also assessed. To investigate the

Table 2 Policy mix in the HERB model

Policy	Setting	Explanation
Subsidized loans (in €)	0; 10,000; 50,000	*Households have access to this much more capital.*
Subsidy threshold	80; 130; 180	*The kWh/(m^{2}a) threshold for receiving subsidies is either raised or lowered.*
Final push	0%; 10%; 30%	*Some households in Stage 3 receive an increase in their intention to retrofit.*
Outreach (a)	0.5; 1	
SD affected (b)		
Ambition marketing	0%; 10%; 30%	*Some households start considering upgrading to a certain energy standard instead of the one they are currently considering.*
Yearly push rate	50; 100	
Energy standard marketed		
Energy price change (in €)	0.18; 0.36	*The price of one kWh changes.*

long-term effects of free-riding, the model ran for another 7 years, collecting energy data. See Fig. 2 for a model overview.

The data set initially consisted of 2,592 model runs. Through scatter diagrams, we found model variations with 0% or 100% free-riding. In investigating the data, we found that these were caused by cases where very few subsidies had been distributed during the program. We found that removing all cases with fewer than eight subsidized retrofits after 3 years removed all these outliers, resulting in $N=2{,}438$ model runs in the final data set.

2.4 Analysis approach

To test our hypotheses, we analyzed whether the proportion of free-riding predicted the development of the energy standard amongst households 3 and 10 years after the model started, by calculating two linear regressions (Field et al., 2014). It is important to recognize that even when a regression analysis is computed, the rate of free-riding should not be considered a direct causative factor in the development of an energy standard for houses, since it essentially serves as a proxy for the distance between intentions and threshold. Because we aimed only to test the relation between free-riding and the energy standard, we did not include confounders in our model.

We checked for the assumptions of linear regression. Specifically, we graphically checked for a linear relation, no heteroscedasticity, and approximately normally distributed residuals for both models. Furthermore, we conducted an examination using Cook's distance, a diagnostic tool that is crucial for identifying influential data points in regression analyses. Cook's distance measures the effect of deleting a given observation (Cook, 1977). We found that all points were within the cut-off of $D_i < 1$ (Maximum Year 3: $D_i = 0.023$, maximum Year 10: $D_i = 0.017$) suggested for large N (Cook & Weisberg, 1982). We then ran the two regression models with the proportion of free-riding in % as the predictor and the mean household energy consumption in kWh/(m2a) as the outcome. The proportion of free-riding after 3 years was calculated by dividing the number of subsidies that had no effect (the free-riding count) by the total number of subsidized energy retrofits up to that date. The mean proportion of free-riding in the final sample after 3 years was $M=53\%$, $SD=12\%$.

The analysis was carried out in RStudio (version 1.4.1106). We used the R packages base, stats, utils (R Core Team, 2021), broom (Robinson et al., 2021), olsrr (Hebbali, 2020), psych (Revelle, 2021), and tidyverse (Wickham et al., 2019).

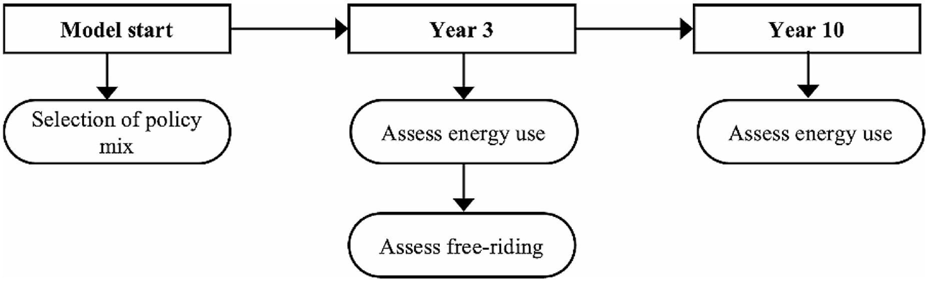

Fig. 2 Schematic representation of data collection in the HERB model

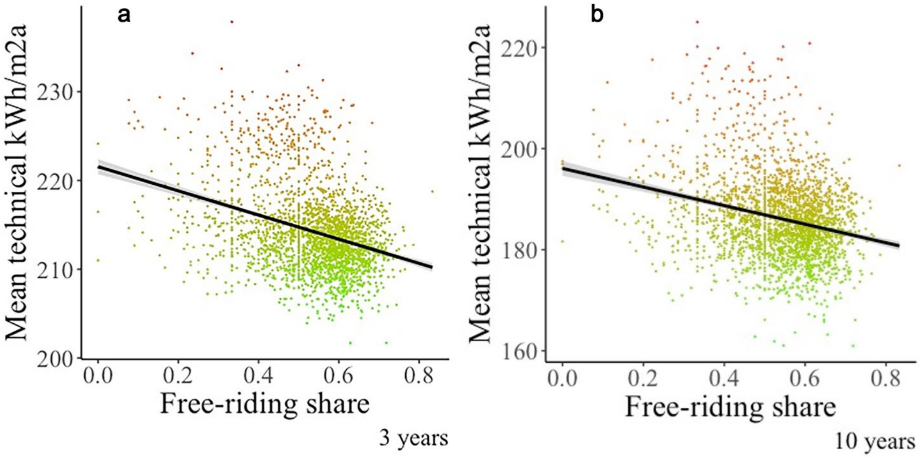

Fig. 3 Scatterplots with fitted lines between the proportion of free-riding and the energy standard of households after years 3 (a) and 10 (b)

Table 3 Regression results after years 3 and 10

	Model 1: After 3 years			
Predictor	*b*	*b* 95% CI [LL, UL]	*p*	Fit
(Intercept)	221.56	[220.70, 222.41]	<0.001	
Proportion of free-riders	-13.62	[-15.18, -12.05]	<0.001	
				$F(1, 2436) = 291.9, p < .001, R^2 = 0.107$
	Model 2: After 10 years			
(Intercept)	196.07	[194.60, 197.54]	<0.001	
Proportion of free-riders	-18.38	[-21.08, -15.68]	<0.001	
				$F(1, 2436) = 178.4, p < .001, R^2 = 0.068$

Note. LL and UL indicate the lower and upper limits of the 95% confidence interval

3 Results

Linear regression analyses showed that free-riding measured after Year 3 could, to a certain extent, predict the mean energy standard of households after both Year 3 and Year 10 (see Fig. 3). For Year 3 (Model 1 in Table 3), a 1% increase in free-riding corresponded to a 0.14 decrease in the mean household's current kWh/(m^2a), $SE = 0.008$, $p < .001$. For Year 10 (Model 2 in Table 3), a 1% increase in free-riding in the third year corresponded to a 0.18 decrease in the mean household kWh/(m^2a), $SE = 0.014$, $p < .001$. These results support Hypotheses 1 and 2. However, for a better interpretation of the results, the size of the effects should be considered (Cohen, 1988). When only one predictor is present in a linear regression model, the R^2 is simply the square of the correlation coefficient (r) between the predictor and the response variable. Hence, to estimate the effect sizes, we can simply take the square root of the R^2 of both models to retrieve r, which can then be interpreted on the basis of Cohen's (1988) recommendation. For Model 1, $r = -.33$ constitutes a moderate-sized effect, and for Model 2, $r = -.26$ constitutes a small effect. As robustness checks we have further conducted quantile regression analysis to reveal how the relation between the variables changes across different points in the distribution (25th, 50th and 75th percentile; Huang et al., 2017). Results indicate a stable, significant relation between the free-rider share and the mean energy standard of households in Year 3 and Year 10. For details, please refer to the supplementary files in Online Resource 1 (Tables 2 and 3).

4 Discussion

In this study, we adapted the HERB model (Egner & Klöckner, 2022) so that it could be used to investigate the relation between the prevalence of free-riding and the development of energy efficiency in the housing stock. As anticipated, the current occurrence of free-riding positively indicated both the present energy efficiency standards of buildings (Hypothesis 1) and their potential future advancements (Hypothesis 2). The actual direction of the effects was negative, as a lower kWh/(m^2a) constitutes a higher energy efficiency standard. In addition, the effect sizes in the models were medium in magnitude for Hypothesis 1 and small for Hypothesis 2. Thus, we were able to find empirical support for the hypotheses, but we cannot assert that the connection is strong. However, the primary objective of this study was only to establish a previously unexamined connection (i.e., free-riding and energy efficiency development in the building stock). Hence, also no additional variables were included in the analyses.

An important point to acknowledge is that the relation between free-riding and the development of an energy standard for houses is not causal. Instead, it probably stems from the connection between intentions to retrofit and the subsidy threshold, which is indirectly embedded in the HERB model, as explained in Sect. 2.2. These indirect embeddings invite criticism, as it suggests that the relation between intention and subsidy threshold, determining the propensity for free-riding are predictable outcomes of the model's design. However, these associations are integrated not only in a subtle manner, but also rest on a robust theoretical foundation that was derived from prior research (Egner & Klöckner, 2022; Klöckner & Nayum, 2015, 2016, 2017). Beyond the abovementioned studies, the theoretical link connecting free-riding, intention, and threshold is further supported by more general theoretical considerations regarding behavior from a psychological perspective. According to Kaiser et al. (2010; see also Kaiser & Wilson, 2019), the probability of any given behavior depends on an individual's behavioral intentions and an objective measure of behavioral difficulty. When the intention to retrofit surpasses the objective costs that are involved (e.g., financial expenditure), the likelihood that a person will engage in this behavior increases. Subsidies play a crucial role in this dynamic by lowering the costs, thereby making retrofitting a more feasible option. Further, the fact that households that undertake retrofitting increase the likelihood that other households in the vicinity will do the same, might likewise indicate lowered behavioral costs by these households functioning as an example and setting social norms (Egner & Klöckner, 2022; Helms, 2012). Simultaneously, a stronger intention to retrofit also heightens the likelihood of utilizing existing subsidy programs, especially when there is a low threshold for obtaining them.

Therefore, we are confident that we have accurately represented the factors that influence free-riding. Furthermore, it could be argued that the strength of the HERB model lies precisely in its ability to make theoretically justified assumptions about the psychological determinants of free-riding and thereby demonstrating understudied links between free-riding and energy efficiency.

As such, although the effects are small-medium, the data still permit some conclusions. If achieving the maximum ecological benefit is the goal of a subsidy program, tolerating a higher rate of free-riding (and thus a lower level of economic efficiency) might be considered acceptable. However, it is important to recognize that improving building energy standards by taking them to a higher level does not automatically lead to a decrease in overall energy consumption. In fact, improvements in energy efficiency come with the potential risk that consumption will increase as well. This phenomenon is referred to as the rebound effect, which has been observed to negate about 10–15% of the efficiency gains in a retrofitted building through increased consumption (Galvin, 2015). Further, our analysis focused solely on the relation between free-riding and the development of an energy standard for houses in scenarios where subsidies are granted without considering other factors, such as place of residence, income, or additional socioeconomic variables. However, for subsidy schemes that focus more on a just distribution of public funds, as requested by energy justice scholars (McCauley & Heffron, 2018; Pellegrini-Masini et al., 2020), the relation between free-riding and the development of an energy standard for houses might differ. In other words, if measures are implemented to reduce the free-riding rate, such as requiring every household to demonstrate social entitlement (i.e., financial needs) in addition to the need for energy improvements in order to qualify for a subsidy, the dynamics of this relation could change. Future studies could start here to gain further insights.

Finally, this study comes with methodological limitations that are inherent to the use of an ABM. First, no current model of behavior is a perfect representation of human behavior. All models are a more or less close representation of reality, and the psychological basis for energy retrofitting in the HERB model is no exception. Although the outcome of the model has been validated to some extent (Egner & Klöckner, 2022), readers should keep in mind that the underlying model is only an educated approximation. For example, financial feasibility is the only "hard" barrier to energy retrofitting included in the model. Realistically, other factors, such as the availability of contractors and local zoning laws, will also have an effect. Although the model has some random variability that may account for such variables, the model could be improved by expanding the number of factors affecting energy retrofitting behavior.

5 Research conclusions

In this study we investigated whether the free-riding rate can be seen as an indicator of a positively developing energy standard of the housing stock through an ABM-approach. To conclude, whereas it is certainly true that retrofit subsidy schemes that are susceptible to free-riding should be re-evaluated in terms of their economic and social efficiency, the present study indicates that stand-alone free-riding can also be seen as a positive sign for the current and future energy standards of the building stock – although the effect was found to be only moderate in size.

In terms of practical implications, it could thus be favorable accepting a higher free-riding rate to effectively fulfil a retrofitting subsidy's actual energy saving target. However, it might come at the expense of economic and social efficiency, rendering this a somewhat paradoxical situation (Egner et al., 2021). Thus, policy makers should be cautious, when designing a subsidy scheme and carefully balance potential economic, societal and ecological effects. However, more research is still needed to help determining whether this broader picture of the proportion of free-riding could be a useful way to find a policy that resembles an equilibrium between the economic, social and ecological efficiency of a retrofit subsidy scheme. As such, this study is merely intended to show that there is a positive correlation between free-riding and energy standards in the building sector and this connection is yet another consideration that should be included in policy considerations.

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Data availability The data sets (including the R-script) generated during or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. This work was supported by the European Commission [grant number 763912]; and Enova SF, Trondheim, Norway [Project SID 09/1914 and SID 18/11690].

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