Doctoral theses at NTNU, 2022:342

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Energy efficiency renovations and public policies.

Doctoral thesis

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Norwegian University of Science and Technology
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ISBN 978-82-326-5835-0 (printed ver.)
ISBN 978-82-326-5183-2 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

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Printed by NTNU Grafisk senter

1. Abstract

Private household space heating represents 17% of all European final energy consumption. Therefore, it has a large environmental footprint and is a central piece of the puzzle for creating a sustainable world. Energy retrofitting—specifically building envelop measures—is the best way of reducing this energy need. However, behavioural research on energy retrofit policies has been lacking, limiting both effective policymaking and psychological knowledge on the topic.

In this PhD project, I explore what can be done to improve the energy efficiency of private households from a psychological behavioural standpoint. I employ three large-scale Norwegian surveys (n = 2605, 3797, 303) and one agent-based model generated in the project. I summarize psychological decision-making research I theorise should influence energy retrofitting behaviour, but usually investigated under different branches such as heuristics and biases, theory of planned behaviour, and spillover. Based on this, I predict that energy retrofitting is a self-reinforcing process. I replicate existing research on subsidy free-riding and provide the first data regarding the distribution of energy retrofitting subsidies between income classes in Norway. Finally, I generate an agent-based model based on existing psychological decision-making research, and implement and test different policies. Findings from the two first studies on free-riding and consecutive retrofitting are used to validate the model.

My results show that households that have recently energy retrofitted are likely to undergo subsequent energy retrofits. The distribution of subsidies for energy retrofits is skewed towards high-income households. In the agent-based model, the current Norwegian subsidy model reduces household energy use, but lowering the threshold for receiving subsidies will reduce energy use even more. Motivating households to retrofit more also reduces energy use. Marketing a specific energy standard, however, does not reduce household energy use.

Self-efficacy and attitude have a stronger association with energy retrofitting behaviour than age, income, loans, investment capacity, and house size and age. This suggests that psychological variables are more strongly associated with energy retrofitting behaviour than demographic ones. Although more research is needed for causal claims, this could indicate that energy retrofitting behaviour is primarily based on psychological constructs. Further implementing psychological theory and research in policymaking is essential for reducing private households' energy consumption.

2. List of papers

Paper 1: Published.

Egner, L. E., & Klöckner, C. A. (2021). Temporal spillover of private housing energy retrofitting: Distribution of home energy retrofits and implications for subsidy policies. *Energy Policy*, 112451. https://doi.org/10.1016/j.enpol.2021.112451

Paper 2: Published.

Egner, L. E., Klöckner, C. A., & Masini, G. P. (2021). Low free-riding at the cost of subsidizing the rich. Replicating Swiss energy retrofit subsidy findings in Norway. *Energy and Buildings*, 111542. https://doi.org/10.1016/j.enbuild.2021.111542

Paper 3: In review.

Egner, L. E., & Klöckner, C. A. (2021). Effect of policy implementation on energy retrofit behavior and energy consumption in a simulated neighborhood. *Journal of Artificial Societies and Social Simulation.*

Acknowledgments

To my grandpa, who will sadly never see the work he so enthusiastically supported.

29.06.1935 † 27.05.2020

First and foremost, thanks to my supervisor Christian Klöckner, whose continuous support and responsiveness made this work possible and left me embarrassingly privileged when other PhDs complained about their supervisor. Thanks to my co-supervisor Jens, whose academic navigational assistance proved invaluable. Thank you to Giuseppe for the consistent lunches, Dani for the continuous spots, and all other people for keeping me company outside the office. Thanks also go out to my previous supervisor Stefan, whose constant support and cooperation after the previous thesis is no doubt the reason why I got to start this project in the first place.

Finally, a big thank you to the countless researchers whose work lays the foundation for this project, whether through books, articles, courses, Stata-list forum discussions, or responses to my e-mail enquiries. I hope this is a useful, meaningful, and worthy extension to previous work and does its small part to help the currently undergoing environmental crisis.

Table of contents

The recommended reading pattern for this thesis is this abstract, the three journal papers attached, and then the rest of the synthesis.

3. Introduction

Sustainable development is defined as meeting the needs of the present without compromising the ability of future generations to meet their own (UN, 1987). Currently, human land, water, material, and carbon footprints are hampering future generations' ability to meet their own needs and are therefore unsustainable (Allen et al., 2018). Global energy demand represents a major obstacle for sustainable development, as no energy can be produced without significant land, water, material, or carbon footprints. Even though technologies harnessing renewable energy sources have a lower carbon footprint, their power density is orders of magnitude lower, representing a higher land-use footprint (Capellán-Pérez et al., 2017). Land-use change is the leading cause of biodiversity loss (Davison et al., 2021), an issue considered to be of higher risk than climate change (Steffen et al., 2015). Thus, a reduction in energy consumption goes beyond climate change and is vital for several sustainability issues. Alas, this energy demand is set to increase by 4.6% in 2021 (IEA, 2021), and global energy demand will continue to rise (IEA, 2020). In the EU, households represent 26% of final energy consumption (Eurostat, 2019). Of this, space heating represents 63.6% (Eurostat, 2019), making it one of the biggest sources of human energy consumption on the planet. Thus, reducing energy use for household space heating represents a major piece of the puzzle in creating sustainable development.

The best method for reducing existing households' energy use for space heating is upgrading the insulation standard (Verbeeck & Hens, 2005). This is especially true for cold European climates (Felius et al., 2020), with some exceptions for hot climates (AlFaris et al., 2016; Pérez-Andreu et al., 2018). While other measures can also be implemented to reduce the energy need of private households, few measures is as undisputedly good for the energy system and beyond as adding insulation. Lowering the in-house temperature is uncomfortable and can result in health issues (Jevons et al., 2016), and all forms of added energy production have issues. For example, while photovoltaic solar panels installed on the roof reduce household energy needs during the daytime, they do very little during dark winter periods. Heating is the main energy sink for most households. Cooling represents only 0.4% of household energy use and thus does not represent a significant load on the grid (Eurostat, 2019). Therefore, cold dark periods are when households need the most energy. As photovoltaic solar panels do not produce energy in the dark, they do nothing to reduce peak grid demand. As the energy grid needs to handle the peak demand, it has to be further developed regardless of how many households install photovoltaic solar panels. In contrast, a good household insulation standard significantly reduces building energy needs during dark, cold times. This reduces the peak load on the energy grid, thus reducing the need to increase grid capacity. Combined, these factors make improved insulation standards central in achieving the European Green Deal (European Commission, 2019), keeping global warming below 1.5°C (Allen et al., 2019), and achieving sustainable development as a whole.

In this synthesis, I will outline my three years of research on what can be done to improve households' insulation standards through psychology. In the introduction, I first present an overview of the current energy retrofitting situation, including policies, retrofitting rates, and political mandates. This is necessary as any psychological findings must be seen in the context of the existing policy landscape. Next, the synthesis will cover the current state of the energy retrofitting literature. This is done to identify potentially fruitful avenues of research, but also difficulties and challenges in the field that also applied to this thesis. Next, I cover the research topics of these potentially fruitful avenues, psychological science that has yet to be applied in the energy retrofitting literature. Finally, the introduction outlines the specific research gap it intends to fill. First, the current policy landscape of Norwegian private household energy retrofitting.

3.1. **Existing policies**

Because of the importance of achieving several climate-political agreements, most countries have policies aimed towards increasing the energy standards of private households. These policies range from subsidized loans, free advisory services, subsidized training of contractors, and cash subsidies to households that reach specific energy standards. However, the policies tend to be complicated, and between countries, they bear little resemblance to each other. This makes policy research from one country difficult to apply to other countries, and studies rarely investigate policies' effects on more than one country. Additionally, policy documents are usually written in a country's native language, making a comparison of policies difficult (e.g., Enova, 2019; Kessler & Moret, 2009; Kessler et al., 2007; Sigrist & Kessler, 2015). A comparison between the Norwegian and Swiss policies is presented in paper two, but a complete comparison between several countries would elicit a separate research project. However, a quick summary of the Norwegian subsidy system, on which this thesis will focus, is necessary for understanding the framework in which Norwegian houseowners make insulation-related decisions.

3.1.1. The Norwegian subsidy system

In Norway, Enova SF, which was founded in 2011, manages subsidies for energy retrofitting and other energy-related subsidy systems. The Ministry of Climate and

Environment fully state-owns Enova SF and handles most subsidy and incentive schemes related to energy use and production. Four to five categories of subsidies are available for private household energy retrofitting. First, 'Enova answers', a free advisory service that provides information on the retrofitting and subsidy process, is available. Here, homeowners can talk with consultants, who offer a neutral third party input on the retrofitting process that is independent of retailers or contractors. Second, a subsidized loaning scheme organized through 'husbanken' is also available. As mentioned in paper two, though, only 14 private persons on average have utilized the system annually in the period 2008 to 2019 (Husbanken, 2008). This implies issues related to the scheme. Third, many smaller subsidies directed towards specific energy measures exist. For example, households can receive NOK 10 000 for installing a liquid-to-water-heat pump and NOK 5 000 for installing an accumulator tank. At the time of writing, 10 NOK is roughly equivalent to 1 EUR. Several similar and smaller subsidies are also available (Enova, 2021). Finally, 25% of the cost—up to NOK 100 000 to 150 000—is offered for a 'holistic building energy upgrade' (Enova, 2019). Here, households must improve the insulation value of their walls, roof, ceiling, and windows. The heating system must also not be based on direct electrical heating or fossil fuels (Enova, 2019). To be eligible for this subsidy, a contractor must complete the work.

All subsidies are distributed after the relevant measure is completed and documented. The stated overall mandate of the subsidy scheme is to stimulate market change, so that newly established and more climate-friendly solutions are more readily available and no longer dependent on subsidies (Enova, 2020). It could be argued that the mandate conflicts with the realities of energy retrofitting. When asked in an interview whether energy retrofitting involves any new technology, Enova claimed that the subsidies are meant to support 'early movers' (Rørslett, 2021c). I argue that we have long passed what can be considered 'early movers' because households have been insulated since pre-historic times (Bock, 2020; Bozsaky, 2010). Even some animals insulate their homes (Skowron & Kern, 1980). Regardless, Enova's mandate states that new technology and early movers should be the focus, and this mandate must be followed. Additionally, under EU law, the subsidies cannot distort competition (Enova, n.d.)

For the purposes of this thesis, it is important to note that the mandate does not include any social or ethical aspects. Enova has no direct obligation to distribute its funding justly or take into account social aspects. Additionally, a homo economicus paradigm, where users are expected to act rationally according to self-interest, primarily influences the subsidy design (Mill, 1874; Persky, 1995). For example, the subsidies are built around the expectation that as retrofitting becomes cheaper, more households will participate in the process. Motivational factors usually not captured by a utility maximization calculation, such as celebrity endorsement, are seldom to never promoted. Both these elements illustrate that psychological measures seem not to have been employed to improve the insulation standard of Norwegian homes, increasing the relevancy of this thesis.

The Norwegian national media has recently been focusing on the subsidy scheme in a negative light (Ask, 2020; Rørslett, 2021a, 2021b; Rørslett et al., 2021). Homeowners complain that the eligibility rules for subsidies are too rigid (Rørslett, 2021a, 2021b; Rørslett et al., 2021) and unavailable to housing associations (Ask, 2020). In particular, homeowners have repeatedly contested the caveat that an external contractor must complete the retrofitting. It is suggested that only high-income households can afford external contractors to complete the many measures required to reach the threshold for the subsidies. This concern is not unwarranted, as data from Enova show that most of the projects that receive subsidies cost more than NOK 500 000. Projects costing less than NOK 250 000 are virtually non-existent amongst subsidy recipients (see Figure 1). Subsequently, the critique gained political attention prior to the Norwegian parliamentary election on 13 September 2021, as representatives from Sosialistisk Venstreparti, Arbeiderpartiet, and Fremskrittspartiet criticized the scheme (Rørslett et al., 2021).

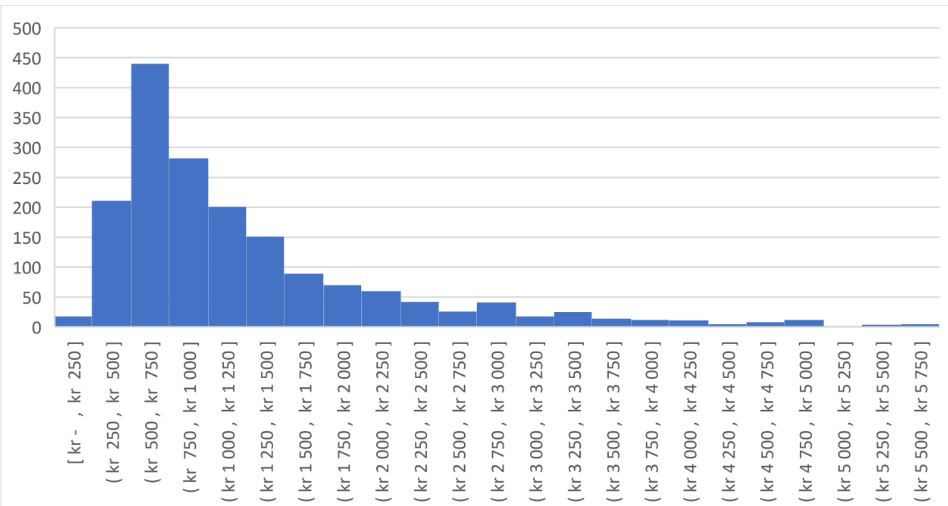

Figure 1: All numbers in 1 000. Histogram of the cost of energy retrofitting projects amongst subsidy recipients for 'oppgradering av boligkroppen' year 2016-2020. Numbers received from Enova through private communication.

Note that the criticism towards Enova does not conflict with its mandate. For example, although people criticize Enova for primarily subsidizing high-income households, this is not contrary to Enova's mandate. Fair distribution of subsides are not part of their mandate. Additionally, by including a caveat that a contractor must do the retrofitting, more capital is transferred to the retrofitting industry than if households were to complete the project themselves. Additionally, the Ministry of Climate and Environment, which signed off on Enova's mandate (Miljødepartementet, 2020), was at the time of the signing, led by a coalition government consisting of the political parties Høyere, Venstre, and Kristelig Folkeparti. Therefore, there is no overlap between the criticizing parties and the government at the time of signing, as one of the parties, Fremskrittspartiet, left the coalition a year prior due to other issues (Krekling et al., 2020).

3.2. **The current state of the energy retrofit literature**

In general, the literature on energy retrofitting policy measures seems to be dominated by two approaches. First, the leading journal in the field, *Energy Policy*, is dominated by a homo economicus approach, where consumers are treated as rational actors. A paper researching energy retrofit incentives exemplifies this, stating in the limitation section, '[…] the decision-making of stakeholders may be affected by irrational factors such as personal emotion' (Xin Liang et al., 2019, p. 189). In this branch of research, models are based on the assumption that consumers make rational choices. For example, when retrofitting becomes cheaper, consumers will retrofit more frequently. Similarly, making consumers change their perception of how important comfort is does not fit this paradigm. Consumers are expected to know how important comfort is to them, and if they choose to retrofit, this is a rational choice. If they choose not to retrofit, this is also a rational choice. Additionally, consumers are often treated as 'all-knowing', where they, for example, know the exact annual return of investment on insulating their roof, walls, ceiling, and windows. The second approach, published in *Energy Research & Social Science,* focuses on more social aspects, such as subsidy framing to homeowners (Fyhn, Søraa, et al., 2019) and energy justice (Pellegrini-Masini et al., 2020). Here, the data sources are often based on interviews and document analysis, where interview statements are usually viewed as accurate. While naturally, there is much overlap between the two and research has been published in other journals, to the best of my knowledge, this bimodal research focus is the general trend.

Consequently, there is limited focus on applying existing psychological behavioural research on energy retrofitting behaviour. For example, the theory of planned behaviour

(Ajzen, 1991) is possibly one of the most applied theories to any intervention study. However, while it has been used on behaviours such as unplugging appliances, decreasing the length of showers (X. Liu et al., 2021), and recycling behaviour (Strydom, 2018), no study can be found on energy retrofitting. Thus, even though energy retrofitting is, in general, a more high-impact behaviour, it seems to garner much less attention. It should be noted that studies on intention to retrofit energy standards exist (e.g., Klöckner, 2014); notably, however, only studies on behaviour are lacking.

Naturally, that I can not locate such a research environment does not prove that it does not exist, as it is challenging to show evidence of something not existing. However, some partial evidence can be presented. For example, according to google scholar, Tversky and Kahneman's (1974) classical article that would be a natural citation if the research touches upon heuristics or biases has only five unique texts citing it containing the words “energy retrofitting”, “energy efficiency retrofitting”, "building envelope measures", "household retrofitting" or "household envelope". Of which only one is an article with empirical data (N = 56; McCarty et al., 2021). Two texts are doctoral thesis’, of which one shares my concerns, stating that “It was surprising to see that limited sustainable HCI [Human Computer Interaction] research was focused on encouraging householders to install energy efficiency measures, and similarly little research looked at helping householders develop sustainable heating patterns.” (Weeks, 2019, p. 172). Suggesting that psychological decision-making research is not the only field where household energy retrofitting seems to receive less attention than what is warranted. Next, I will cover psychological and methodological characteristics of energy retrofitting behaviour that most likely contribute to this.

3.3. **Not like all the other environmental behaviours**

Energy retrofitting differs from other environmental behaviours in ways that make applying general pro-environmental behavioural theories and methods difficult. These differences are a likely reason as to why energy retrofitting behaviour seems under-researched. First, I will cover what makes energy retrofitting differ from other pro-environmental behaviours.

3.3.1. Psychologically different

Firstly, once an energy retrofitting is completed, its results are not clearly visible. This invisibility applies to both extra and intra-household members. Regarding intra-household members, this has been discussed in the literature on the invisibility of energy use (Burgess & Nye, 2008; Fredericks et al., 2020; Hargreaves et al., 2010, 2013). Household members have shown not to be particularly aware of energy consumption within the household (Hargreaves et al., 2010), and making them aware does not seem to have strong effects on energy consumption (Fredericks et al., 2020; Hargreaves et al., 2013).

Regarding extra-household members, while driving an electric car, eating a plant-based diet, recycling, and installing a bug-hotel are visible to other people, virtually none other than the owner can identify the insulation standard of walls, windows, and floors. Attic and floor insulation rarely warrant changes to the façade of the house, and even when work is done to walls and windows, a new façade does not equal improved insulation. The facade can be improved without upgrading the insulation and vice versa. While the retrofitting is highly visible while it is being implemented, this is a relatively short window of time compared to most other pro-environmental behaviours; indeed, for other pro-environmental behaviours, the behaviour is displayed frequently. For example, although a meal is also not visible after it is consumed, eating is a very frequent behaviour that happens in a range of social situations, causing it to be more socially communicated than energy retrofitting. Compared to other pro-environmental behaviours, this could considerably weaken the social aspect of energy retrofitting. It should be noted that knowledge on this is limited, as no direct research on people's awareness regarding other households' energy standards or retrofitting norms can be located. Only suggestive evidence in that qualitative studies on household energy retrofitting does *not* mention social factors can be located (Risholt & Berker, 2013).

Secondly, energy retrofitting adds comfort to a person's life through more stable inhouse temperatures. Most other pro-environmental behaviours add a slight inconvenience. Recycling, for example, requires sorting through waste, travelling by bike requires pedalling, purchasing local goods requires identifying local goods, electric cars' batteries require charging, and switching off the lights requires hitting the light switch. Even household electricity monitors have been reported to cause intra-household conflicts (Hargreaves et al., 2010). In contrast, once energy retrofitting has been completed, a heavily insulated household passively reduces energy bills and increases thermal comfort (with some exceptions, see McGill et al., 2017; Mlecnik et al., 2012). Finally, energy retrofitting is difficult on a technical level. While other pro-environmental behaviours such as adopting a vegetarian diet, separating plastic waste from paper waste, or buying an electric car are technically simple, installing insulation is difficult. In many cases, specialized contractors are hired to do the job.

Energy retrofitting, on the other hand, is not visible to other people, adds comfort, and is technically difficult. While some pro-environmental behaviours exhibit one or two of these traits, I argue that none has *all* of these traits to the same degree as energy retrofitting.

Therefore, it is reasonable to assume that frameworks that rely heavily on descriptive norms, sacrificing comfort, and do not include skill, will have difficulties predicting energy retrofitting, even if these same frameworks have been shown to predict other pro-environmental behaviours. For example, social-altruistic approaches to promoting pro-environmental behaviour are primary approaches to behaviour interventions (Schultz & Kaiser, 2012). Notably, the descriptive norm of insulation standards is only clearly communicated when the retrofit is undergoing. After this, no one but the most skilled artisan can for certain determine the descriptive norm of insulation standards. Thus, a central aspect of the approach is considerably altered compared to other behaviours.

3.3.2. Methodologically difficult

Additionally, energy retrofitting is a problematic behaviour to operationalize and sample. Furthermore, it is a complex behaviour for which to implement interventions. Firstly, there seems to be no commonly accepted definition of what constitutes an energy retrofit and what does not. Some research simply asks respondents if they have implemented building envelop measures (e.g., additional insulation) to reduce heat demand in the last two years (Nair et al., 2010a). In Norwegian reports on energy retrofitting rates, precise requirements were listed, such as the windows that were triple glazed or had a U-value of 1.0 or lower (Fyhn, Berntsen, et al., 2019). U-value is a metric for the insulation standard. The lower the score, the more insulative the properties are. Consequently, households that installed windows with a U-value of 1.01 would not count as having retrofitted their windows, despite their insulative properties being virtually identical to a window with a U-value of 0.99. This way of applying cutoff points results in the data's poor representation of reality. The European Commission has presented four classifications of renovations: below threshold, light, medium, or deep. Here, a below threshold renovation saves less than 3%, a light renovation saves 3-30%, a medium renovation saves 30-60%, and a deep renovation saves more than 60% of final energy use (Felius et al., 2020). Nevertheless, problems can arise with this calculation. Assume a 100 m^2 household installs photovoltaic solar panels that produce 3MWh annually. This will lower their kWh/(m^2a) by 30. This counts as a deep renovation measure if the energy use is reduced from 50 to 20 kWh/(m^2a), but not if the energy use is reduced from 200 to 170 kWh/(m^2a). The same amount of energy saved through the same measure is classified differently. This operationalization must also collect pre-retrofit energy use data, which further complicates researching the topic. I would argue that moving towards more continuous scales, such as units of kWh/(m^2a) or U-value improvements, would be a step in the right direction. Even though such a scale could be problematic regarding subsidies, subsidy thresholds and research do not need to rely on the same metric. Regardless, there seems to be no simple definition regarding what constitutes an energy retrofit and what does not. This lack of agreed-upon definition makes researching the behaviour especially difficult for fields without much technical knowledge of the process, such as psychology.

Secondly, energy retrofitting is more difficult to sample than most other environmental behaviours. In the EU28, the annual amount of medium and deep renovations is around 1.3% (Esser et al., 2019). If the researcher aims to design an intervention study to increase the retrofit rate from 1.3% to 1.75%, a reasonable increase in retrofits, a power analysis with an alpha of 5%, and a power of 80% suggests the group must consist of 5 455 participants.[1] This very high number quickly leaves intervention studies on retrofitting out of the picture for all but the most ambitious research projects. Retrospective studies researching factors associated with energy retrofitting are more accessible but still difficult. For a population sample to reach a sufficient number of participants who have retrofitted in the last year for the most basic of analyses (say 50), the sample must then be 3 847 or more. This makes cheap methods, such as snowball sampling or convenience sampling, impractical. Although these methods are not preferable from a methodological standpoint, the research project must have access to extensive population samples or perform focused samples of households currently undergoing energy retrofitting. Focused sampling methods often require external survey companies and represent an additional barrier to the research project—especially those without sufficient financial resources. Many economic studies rely on publicly available data and do not directly involve participants, and qualitative research generally needs fewer participants. Therefore, this is an obstacle that is mostly relevant for quantitative psychological research. As a solution, many studies ask participants if they have conducted retrofits in the last two to five years (Fyhn, Berntsen, et al., 2019; Nair et al., 2010a, 2010b). While this reduces the need for participants, relying on participants to accurately recall memories from years ago can be optimistic (e.g., T. J. Barry et al., 2019; Winkielman & Schwarz, 2001). Psychologists, which are likely more exposed to research on the limits of human memory than other researchers, could be more sceptical of this method. Here, it is worth mentioning that I have a post-positivistic epistemological position on behavioural research. An objectively true model of the brain and human behaviour exists, but it can be known only imperfectly. We cannot hope to create a system based on the 86 billion neurons (Azevedo et al., 2009) in the average brain and

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[1] Calculated using this freely availiable sample size calculator: https://clincalc.com/stats/samplesize.aspx.

must rely on simplified models such as system 1 and 2 (Kahneman, 2012). But even though I do not believe these models represent reality, some are useful and represent reality ‘enough’. Similarly, an objectively true energy retrofitting rate exists, but we do not have access to it. Although the true retrofitting rate could potentially be acquired by dispatching household inspectors, this is unrealistic. Therefore, we must rely on surveyed rates, which, if done correctly, is a close approximation. Although the participants' memory will for sure be a barrier to reading the true retrofitting rate, it is a ‘necessary evil’ in energy retrofitting research.

Thirdly, interventions, which are a central part of many psychological experiments, are challenging to perform in energy retrofitting contexts. Energy retrofitting is expensive. In 2006, retrofitting 100 m^2 to an energy standard of 70 kWh/(m^2a) was estimated to cost EUR 19 700 (Galvin, 2010). Subsidizing any meaningful share of this cost as an intervention will blow the budget of most research projects. Even seemingly cheap interventions, such as energy consultant visits, become difficult considering the sample size needed, as mentioned in the previous paragraph. That is not to say large studies cannot be conducted. As an example of such a large scale intervention study in household energy retrofitting, one study solicited homes with different letters for energy retrofitting offers (Miller and Ford, 1985, as cited in Stern, 1986). One letter had the company’s letterhead with no mention of the county, another letter had the company’s letterhead with a mention of the county’s involvement in text, and another letter had the county’s letterhead and the signature of the county chair. The study was conducted in collaboration with a county government initiating a retrofitting programme. Even though the manipulation was simple, this required cooperation with companies that could complete the retrofitting. Hypothetical letter invitations would not have the same effect, and fake invitations would have been ethically questionable; thus, large-scale energy retrofitting experimental studies remain difficult to perform.

The combination of loosely defined operationalizations, a need for large samples, and expensive interventions often make these studies unavailable to all but the most well-funded research projects. In addition, a cross-disciplinary understanding of behavioural sciences and building and electrical engineering is crucial for creating a successful research project, further raising the bar. As a result, it is easy to understand why researchers instead change their research topic to similar issues, such as electrical appliances or water conservation. Consequently, because energy retrofitting differs substantially from other pro-environmental behaviours and is difficult to research from a quantitatively psychological standpoint, the approach could be said to have received less attention than it deserves. Other researchers have shared similar concerns, highlighting “…the disparity between researchers’ time and effort, and the potential energy savings the interventions could generate […] caused by the focus on behaviour change, especially with regards to electrical appliances and lighting that have limited impact compared to space heating" (Weeks, 2019, p. 172). To fully clarify what is potentially lost due to this approach's under-utilization, it is useful to first explore the benefits and limitations of other approaches. First, I will examine the limitations of the dominant approach: the economic models.

3.4. **The dominance of economic models**

Economic models have many persuasive elements. First and foremost, they reach precise conclusions that can often be applied directly to policymaking. In general, psychological behavioural models do not achieve the same level of precision as economic models. A central reason for this is that, for the most part, in a closed system with rational actors, financial aspects can be fully understood, but psychological models have to account for human decision-making, where the same level of understanding cannot be reached. For example, given a retrofitting cost and how much a household saves on energy by completing the retrofit, it is relatively simple to model return on investment. However, modelling whether a household will complete the retrofit invites greater uncertainty, as the full extent of factors predicting retrofit behaviour is unknown. While many psychological behavioural models can predict impressive portions of variance in behaviour (Ajzen, 1991; Klöckner & Blöbaum, 2010; Schwartz, 1977), none can claim to describe the complete basis for human behaviour.

It is worth mentioning that a failure to include a valid representation of human behaviour does not represent a critical limitation in some economic research on energy. For example, accurate behavioural models should not be essential when investigating the ideal buildout of the energy grid on a European level, aggregating millions of humans and all industry sectors into a single demand variable (Marañón-Ledesma & Tomasgard, 2019). Of course, researchers could *improve* the model by implementing accurate human behaviour, but it is not critical. However, this is not to say that accurate behavioural models are obsolete in energy system models. On the contrary, companies and governments are subject to the same human limitations as consumers, and any system involving humans would benefit from accounting for these limitations. Nonetheless, when individual households and citizens are a central part of the research, problems definitively start arising in energy studies that do not accurately represent behaviour.

A part of the 'energy efficiency gap' is an excellent example of this problem. Although some variations of its definition exist, the energy efficiency gap is often defined as 'a wedge between the cost-minimizing level of energy efficiency and the level actually realized' (Allcott & Greenstone, 2012, p. 4; Drummond & Ekins, 2016, p. 590; Y. Liu et al., 2019, p. 1). This includes both the gap between the cost-minimizing level of energy efficiency in design and the level actually implemented, and the distance between the projected energy use of the implemented technology and its actual consumption (Abrardi, 2019). Note that the latter overlaps with what environmental psychology defines as the rebound effect, which refers to the degree to which increased consumption offsets a technological improvement (Berkhout et al., 2000). For example, households increasing their indoor temperature after adding insulation is a clear example of a rebound effect. Usually, it is found to offset about 0-30% (Berkhout et al., 2000; Dimitropoulos et al., 2018; Gillingham et al., 2016). For this example, I will only focus on the first 'half' of the energy efficiency gap, the difference between cost-effectiveness and implementation.

This part of the gap is the distance between what a theoretical homo economicus would do, and what is observed in the real world. Usually, researchers propose measures to 'close' this part of the energy gap (e.g. Pelenur & Cruickshank, 2012). Here, 'closing' the gap means making people act according to homo economicus. In other words, the barriers causing humans to act "irrational" should be removed. An underlying assumption to this is that humans both want and can act according to homo economicus. I argue there is strong evidence that humans cannot act according to this, and most attempts to turn humans into "rational" actors are doomed to fail (Also reflected by Kahneman, 2012; Lilienfeld et al., 2009). Scholars have researched the limitations of human cognition for many decades (Norman, 2013; Thaler & Sunstein, 2009; Tversky & Kahneman, 1974), and even today, new limitations are being discovered (Adams et al., 2021). On the contrary, I argue that all measures to increase energy retrofitting must use humans' shortcuts in decision-making as a tool. For me, this part of the household energy gap is not the difference between ideal behaviour and the irrational under-retrofitting of households; it is the difference between economics and the reality of human behaviour. The current average household energy standard is exactly where it should be according to all factors that lead humans to perform energy retrofitting. Thus, economics must come closer to reality to close the energy gap, not the other way around.

One could also argue that even though the economic approach has been the dominant one for many years, the energy efficiency of Norwegian households has not substantially improved. For example, since 1995, only a 12% improvement has occurred (SSB, 2014) (see Figure 2). However, much of this improvement may be attributed to the continuously developed legal energy requirements for new buildings (Kommunal- og Regionaldepartementet, 1984, 1997, 1999, 2001, 2003, 2007).

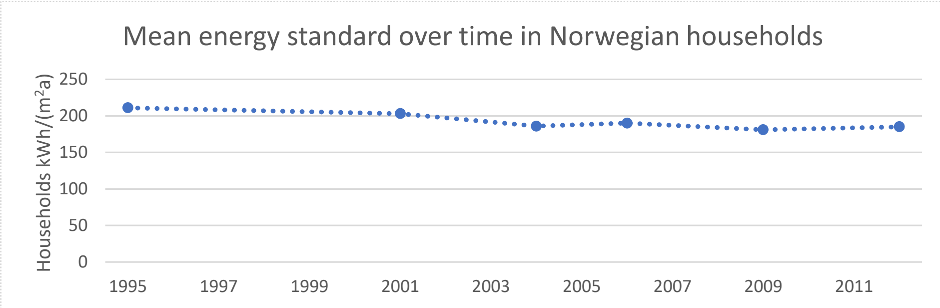

Figure 2: Development of the mean Norwegian household energy standard, measured as kWh/(m^2a), from 1995-2012. Numbers adapted from SSB (2014). Note that kWh/(m^2a) are actual consumption, not the technical standard of the building.

In short, the current approach does not seem to have the desired effect of developing the household building stock. Therefore, other approaches that could improve households' energy efficiency should be explored. Specifically, behavioural psychology is an especially promising and possibly underexplored area of research for reducing the energy footprint of the household building stock, thus solidifying the relevancy of this thesis. With a clear understanding of the current status of the building stock, policies and mandates of official institutions, and methodological difficulties researching the topic, we can move on to the primary topic of this thesis.

3.5. **Behavioural psychology and energy retrofitting**

As outlined above, the existing research on energy retrofitting draws its data primarily from interviews or homo economicus assumptions. As a result, there seems to be an underutilization of existing psychological concepts usually not revealed through these methods. Here, I am referring to concepts that generally have an 'unconscious origin' or are seated in what is usually referred to as 'system 1'. This includes, but is not limited to, concepts such as heuristics and biases, conditioning, attitudes, self-efficacy, and social influence.

For the most part, research regarding these factors is mainly done in scientific fields that research such mental mechanisms for their own sake or reasons unrelated to energy retrofitting. Often, they require elaborate novel experiments to reveal (e.g. Asch, 1955; Loftus & Palmer, 1974), and unless the researcher has training, or a particular interest, in the field, they would not be aware of such mechanisms. For example, interviews would probably not reveal that a legal professional's sentencing is affected by throwing a dice, but it does (Englich et al., 2006). Similarly, participants in an interview would likely not answer "because I'm good at it" as to why they started a retrofitting project, even though existing research shows that self-efficacy greatly influences behaviour.

For the purpose of this thesis, I will name this field psychological decision-making research. This definition could encompass a bit more than intended, but it is the closest I can get. As far as I know, no overview of decision-making research relevant to energy retrofitting exists. Additionally, most decision-making research has not been applied to energy retrofitting. Therefore, it is up to this thesis to attempt to make the connections. Next, I will give an overview of the relevant psychological decision-making research located. This will include mechanisms that seem to act as both drivers and barriers. For structure, I will organize this literature under the paradigms they are mostly used, but often base the literature on research from outside that paradigm.

Finally, it is important to note that the purpose of this thesis is not to test if the presented cognitive mechanisms occur in energy retrofitting behaviour. Instead, the thesis assumes they apply and then looks for outcomes this should create. I am especially interested in situations where psychological decision-making predictions contradict the existing research based on interviews and homo economicus assumptions and where this has policy implications. Therefore, the following section will focus on the implication for household energy retrofitting behaviour if the discussed research applies to the behaviour.

3.5.1. Factors related to the Theory of Planned Behaviour

The Theory of Planned Behaviour (Ajzen, 1991) is one of the most well-known theories in pro-environmental behavioural science. Its components, self-efficacy, attitude, subjective norms, and intention are factors with much research dedicated to them. However, as previously discussed, the visibility of energy use and energy retrofitting makes existing research on subjective norms difficult to apply, and intention is mostly a product of other mental concepts. Therefore, for the purpose of this project, I will cover self-efficacy and attitude.

Usually, self-efficacy is conceptualized as the appraisal of one's capability to mobilize motivational, cognitive resources and the behaviour required to cope with an expected situation (Lauren et al., 2016). Self-efficacy has been found to influence job burnout (Shoji et al., 2016), self-regulated learning (Panadero et al., 2017), and academic performance (Talsma et al., 2018). Although self-efficacy has been investigated directly in relation to several household energy factors (N. A. Barry et al., 2016) and indirectly through survey items such as 'I could not undertake EERM [energy efficient refurbishment measures] without professional help because I do not have the skills to do it myself' (Baumhof et al., 2017), the relationship between energy retrofitting and self-efficacy has not been thoroughly explored. I discuss why this could be the case in Section 3.3. Although there is a lack of data on the topic, I nevertheless argue that self-efficacy predicts energy retrofitting measures. Knowing who to contact, how long the retrofit will take, how much disturbance there will be, and what the outcome will feel like are all self-efficacy factors that should affect the likelihood of starting and completing energy retrofit measures. Additionally, self-efficacy is a central part of the most commonly used general theory to predict and change behaviour: the theory of planned behaviour (Ajzen, 1991). Although the theory has recently received criticism (see Sniehotta et al., 2014), it is also difficult to ignore its many successful applications (McEachan et al., 2011).

Attitude towards behaviour is also part of the theory of planned behaviour, and it is one of few variables that has been shown to predict behaviour in general (Glasman & Albarracín, 2006; Kraus, 1995). Nevertheless, its role in predicting energy retrofitting has not been substantially explored. For example, Long et al. (2015) showed that attitude is associated with participation in a local energy retrofitting scheme called the 'Kirklees Warm Zone', where households were offered free energy audits and simple insulation measures. The scheme will be covered in Section 3.6. Unfortunately, attitude was surveyed after the installations were completed, making causality difficult to establish. Additionally, the researcher's data analysis primarily reports descriptive statistics, making statistical significance and possible covariates challenging to interpret. Regardless, there is little reason to believe that attitude towards energy retrofitting does not influence energy retrofitting. If households feel positively about retrofitting, they are more likely to perform retrofits; similarly, if households feel negatively about retrofitting, they are less likely to perform retrofits.

3.5.2. Factors related to heuristics and biases

Research on heuristics and their resulting biases was pioneered by Amos Tversky and Daniel Kahneman (Kahneman & Tversky, 1972; Tversky & Kahneman, 1974) and has since grown into a solid research discipline. In this line of research, researchers take especially interest in uncovering mental 'shortcuts' and their effect on behaviour, showing that in some instances, human behaviour systematically deviates from both rational behaviour and what others and the person themself predict. Many of these mechanisms centre around cognitive shortcuts, occur subconsciously, and require creative experiments to discover. Naturally, all mechanisms cannot be covered in this synthesis. Therefore, I will only cover those that I, through an initial assessment, judged to be relevant for energy retrofitting. These include subtractive blindness, loss aversion, mere exposure, cognitive inconsistencies, habits, and availability heuristics.

A recent line of research shows that people are likely to overlook subtractive solutions to problems (Adams et al., 2021). The researchers have not named this phenomenon; therefore, I will for now dub it subtractive blindness. I argue that subtractive blindness could be relevant for energy retrofitting. For example, one of the most efficient ways to save energy on heating would be to downsize the house. When there is less volume to heat, less energy is needed to reach a comfortable temperature. This also goes for secondary homes or cabins. No cabin is as energy-efficient or has as low a carbon footprint as a cabin that does not exist. Regardless, subtractive solutions such as downsizing remain a small niche area compared to additive solutions such as adding more insulation. Subtractive blindness is also reflected in the policy documents. Only additive solutions such as installing more insulation, creating more complex heating systems, or establishing or expanding free advice services are discussed. Throughout the PhD programme, I have not come across one policy that subsidizes or generally promotes energy efficiency by removing parts of the house, simplifying official routine or procedures, or installing smaller hot water tanks. Note that this thesis is also subject to subtractive blindness, as I discuss very few, if any, subtractive solutions to energy retrofitting behaviour. To policymakers' and my own defence, this line of research is very new. Here, I should mention that subtractive blindness is not the only factor causing subtractive policies not to be proposed. They are also most likely unpopular, and loss aversion should, in theory, play a major role in making them unpopular.

Loss aversion refers to a disproportionate dislike for potential losses compared to equal-sized gains (Kahneman & Tversky, 1979). In general, losses are experienced twice as impactful as gains (Brown et al., 2020). For example, most humans would not accept a 50:50 bet for gaining or losing EUR 1 000. When increasing the bet to winning EUR 1 300 and losing EUR 1 000, most people would still not accept this bet. Instead, most people would only start accepting the bet when there is a 50:50 chance of winning EUR 2 000 and losing EUR 1 000 (Brown et al., 2020). Loss aversion could come into play when households consider the investment costs and potential payback of insulating. The fixed cost of performing the retrofit is guaranteed, but the payback is not. Even though the company trying to sell you the retrofit promises your money back in reduced energy bills, and it seems like this is true when researching online, this is not enough to make this a guaranteed net gain. Thus, in the view of the household, energy retrofitting is *guaranteed* to lose some money, but after retrofitting, it is only *likely* that the household will gain more than it lost over time. Therefore, I argue it is likely that loss aversion makes this feel like a bad deal.

Loss aversion is also highly relevant to the previously discussed topic of subtractive retrofit solutions. Most likely, households would be very hesitant to reduce their hot water tank's capacity, sell their car and only bike everywhere, or section off parts of their house to tenants to increase the number of people per heated m^2. Assuming the theory applies to energy retrofitting, households would see these losses as extra impactful because of loss aversion. Therefore, even though subtractive solutions to household energy use are systematically overlooked, it is reasonable to believe such solutions would be unfruitful.

The mere exposure effect postulates that individuals will start liking something by merely being repeatedly exposed to it (Montoya et al., 2017; Zajonc, 1968). For example, seeing your neighbour every day will cause you to start liking that neighbour more than you would if you did not see him. This is likely also relevant for energy retrofit measures, as one should not expect people to start liking new solutions as soon as they are introduced. For example, suppose wood-fired ovens heat a household, and that household can replace the ovens with air-to-air heat pumps. If the household has been heating with wood-fired ovens for some time, they will likely grow an attachment to this method. Indeed, if they have no previous exposure to air-to-air heat pumps, they will not like that method as much and will feel sceptical about upgrading. Therefore, it could be argued that the more friends, neighbours, and advertisements they see for air-to-air heat pumps, the more likely the household will like it, and thus upgrade to one. This highlights the importance of marketing, giving consumers time to accept new policies, and not judging policies as failures when they are inevitably not as well-received as the previous policy. Additionally, the mere exposure effect could also be said to predict that the more a person performs retrofits, the more the person will start to like retrofitting. This indicates that energy retrofitting could be a self-reinforcing behaviour.

Another cognitive mechanism likely affecting households' energy retrofitting stance after project completion is the apparent need for consistent behaviour and cognition. Cognitive dissonance theory (Festinger, 1957) is the most well-known explanation of this phenomenon. Cognitive dissonance theory (Festinger, 1957) claims that people desire a balance in thoughts, values, and behaviours. For example, a set of conflicting thoughts, such as 'I like Arsenal', 'I don't like Peter', and 'Peter likes Arsenal', creates a mental inconsistency that causes a minor stressor. Often, these stressors can be resolved by changing one of the values, such as starting to believe that you do not think Peter really likes Arsenal that much, and he is not a true Arsenal fan. While the research supports that cognitive and behavioural inconsistencies lead to changes

(Osbaldiston & Schott, 2012), it is unclear whether or not the mental process cognitive dissonance theory describes is the cause for these changes (Vaidis & Bran, 2019). Several other approaches can also account for why inconsistencies lead to changes (Gosling et al., 2006; Randles et al., 2015; Simon et al., 1995; Steele & Liu, 1983). It is out of the scope of this thesis to assess why inconsistencies work. For the purposes of this project, we only need to establish that, generally, detecting inconsistencies cause changes in pro-environmental behaviour (Osbaldiston & Schott, 2012). To avoid confusion with cognitive dissonance theory (Festinger, 1957), I will address the phenomenon as 'cognitive inconsistencies' throughout the synthesis.

I argue that cognitive inconsistencies can lead households to view retrofitting positively retroactively. Energy retrofitting requires substantial time and money. To maintain the idea that this time and money were well utilized, as you are a person with good decision-making capabilities, positive outcomes must be located. The cognitions "I decided to use 50 000 EUR on energy retrofitting", "I make good decisions", and "I didn't like the energy retrofitting process" is inconsistent. Consequently, starting to believe that one liked the process could be a simple way to justify the resources spent. This is especially true when other reasons, such as environmental concerns, are not present. Thus, to maintain the idea that the time and money were well spent, one can begin to believe that you liked the process. What little research can be found on the topic suggests this to be the case. Owner-occupied renovations are reported to be '[…] a memorable emotive user experience, whereby satisfaction may be gained from learning new skills, completing a task or gaining a better home' (Haines & Mitchell, 2014, p. 467). Here, it should be noted that this is the only piece of research I can find that explores how private households perceive renovations. While I do agree that the direct evidence (Haines & Mitchell, 2014) for energy retrofitting being a positive experience is meagre, it is indirectly supported by research on mere exposure and cognitive inconsistencies. Therefore, I judge retrofitting to most likely be a positive experience—at least in retrospect—but more research should confirm this.

The availability heuristic also seems to be relevant for energy retrofitting. This heuristic outlines a phenomenon where people 'evaluates the frequency of classes or the probability of events by availability, i.e., by the ease with which relevant instances come to mind' (Tversky & Kahneman, 1973, p. 207). The effect has also been shown to extend to self-assessment, where individuals judge themselves to be more assertive after recalling instances where one was assertive (Schwarz et al., 1991); notably, this effect was proportionate to the time spent recalling the assertive moments. Availability heuristics should be relevant in two aspects. Firstly, the more energy retrofitting to which a homeowner is exposed, the more the homeowner should believe energy retrofitting to be a normal behaviour, thus influencing the descriptive norm. This will occur regardless of whether the homeowner witnesses retrofitting through their neighbours, movies, news reports, or elsewhere. Secondly, when homeowners first start considering to which energy standard to retrofit, they most likely consider an energy standard that they have freely available in their memory. For example, if friends and neighbours upgrade to a very high energy standard, the homeowner will most likely also consider upgrading to this standard. From and to which energy standard homeowners retrofit has been researched significantly less than whether homeowners retrofit at all. I have not seen any research linking the issue to availability heuristics, and the connection seems ripe for future research.

While habits are usually not categorized as a heuristic or bias, they have many similarities as both are unconscious rational-free phenomena often employed as decision-making shortcuts. Habits are behaviours done frequently and automatically, and they are often cued by something in the environment (Swim et al., 2012). Naturally, homeowners do not come home from work and mindlessly start calling up their local tradesmen or adding insulation to their attic by habit. Yet when a homeowner has been undergoing retrofitting projects for some time, some behaviours, such as throwing away building materials or walking into the living room to continue working on the project you have been working on for the last 2 months, can become habits. When these behaviours can no longer be completed, new habits must be formed, which could in itself be a minor stressor. This is strongly related to the seemingly under-researched phenomenon of ‘post-project depression’, where a certain gloom and meaninglessness can be felt after completing an engaging project, such as a video game, fiction novel, doctoral thesis, or possibly retrofitting. The enjoyment experienced during the project is no longer available, and nothing else seems to fill the void left behind. In a way, this could be said to be a smaller version of the ‘empty nest syndrome’, where some parents self-report experiences of depression and emotional distress when children leave home (Mitchell & Lovegreen, 2009). Similarly, energy retrofitting projects likely give some homeowners a feeling of meaningfulness and purpose, leaving a small void behind when completed. This void could potentially be filled by starting a new project. Alas, the scientific literature on the topic seems close to nonexistent. Only one scientific article can be found, which focuses on using the phenomenon to promote selling memorabilia such as clothing, books, and film studio visits (Kottasz et al., 2019). Thus, no certain claims can be made regarding retrofitting and post-project depression. The topic seems ripe for further research.

3.5.3. Predictions from spillover effect research

Most behavioural outcomes rely on several cognitive mechanisms, not just one. Where these fields are sufficiently developed, frameworks exist. One such very relevant behavioural outcome with a framework is the spillover effect. Definitions of the effect vary. Some define it as 'the extent to which engaging in one behavior influences the probability of conducting a subsequent behavior' (Nilsson et al., 2017), while others define it as 'an effect of an intervention on subsequent behaviors not targeted by the intervention' (Truelove et al., 2014). A short discussion between the two definitions is available in paper one in Section 1.1. In short, I will use the first definition (from Nilsson et al., 2017), as it does not require an intervention. For example, if a household receives subsidies for energy retrofitting and then uses those subsidies to invest in an electric vehicle, this is a spillover effect from energy retrofitting to mobility. This is often called a positive spillover effect, as something 'good' is happening. If the household instead uses the subsidies to book a flight, or any other anti-environmental behaviour, this is called a negative spillover (Thøgersen, 1999). Furthermore, some research defines temporal, contextual, or behavioural spillover (Nilsson et al., 2017). Here, temporal spillover refers to the person doing more of the same behaviour later; for example, exercising leads to more exercise in the future. Contextual spillover refers to the same behaviour in a different context, such as running on a treadmill leading to running outdoors. Behavioural spillover refers to one behaviour affecting another behaviour, such as exercising resulting in a healthier diet.

Decision mode theory (Truelove et al., 2014) provides a framework for predicting pro-environmental behavioural spillover's presence, direction, and strength. In general, the theory suggests that spillover results from people deciding how to behave in three different 'modes'. These modes are calculation-based decisions, affect-based decisions, and rule- and role-based decisions. Calculation-based decisions are rational decisions free of bias and emotional influence. Because the behaviour is rational, spillover can be both positive and negative, depending on the behaviour. Affect-based decisions are emotionally based and serve to either remove a negative mood or act on a positive one. For example, going for a run after weighing yourself and feeling shameful after seeing your weight increase is an affect-based decision. Here, the spillover is usually negative, as the motivation for doing something, such as feeling shameful about increased weight, is reduced when the action is complete. Rule- and role-based decisions are based on social roles and expectations. For example, if a person sees themselves as a fit individual, they are more likely to exercise, thus reinforcing their 'fit image' and resulting in positive spillover.

As readers could predict, I cannot entirely agree that humans are capable of making completely rational decisions—especially when the topic is complex, such as whether or not to retrofit. However, I agree that some decisions are more rational than others, and this distinction is useful. Concerning retrofitting, one could argue that the decision to retrofit is probably more rational than most other behaviours and could thus be labelled calculation-based. As a calculation-based behaviour, choice model theory predicts both positive and negative spillover in energy retrofitting. First, the theory predicts positive spillover because the initial behaviour is difficult; second, the theory predicts negative spillover because the subsequent behaviour is also difficult and can be attributed to external factors, such as comfort and financial gain. On the one hand, one could argue that because the theory has two factors predicting negative spillover and one factor predicting positive spillover, it predicts a weak negative spillover. But on the other hand, the strengths of these factors are uncertain, and the one positive could be stronger than the two negative. In total, decision mode theory prediction for the direction of energy retrofit spillover is unclear.

3.5.4. Shame and poverty associations

The research on shame is relevant for the distribution of energy retrofitting subsidies. Most likely, subsidies will always be one of the most popular policies, and thus, they will always be part of energy retrofitting policies. One of the more discussed facets of such subsidies is free-riding. Free-riding refers to the phenomenon of conservation programmes financing investments that would have taken place even in the absence of the programme (Haugland, 1996). One of the most commonly discussed solutions for free-riding is making subsidies only accessible to low-income households. While seemingly a good idea, this could potentially lead to the under-utilization of the subsidies. In a study from the United States, 4% of responders who were eligible for childcare subsidies but did not receive them stated that they did not apply because they would not feel good about themselves if they took a form of public assistance (Shlay et al., 2004). The under-utilization of income maintenance programmes has long been theorized to result from stigma (Friedrichsen et al., 2017; Wyers, 1976; Yaniv, 1997). Receiving subsidies because of one's weak financial situation should, according to self-perception theory, give rise to a feeling of being in a weak financial situation (Bem, 1972; Costa et al., 2018; Woosnam et al., 2018). Although this is true, negatively viewing one's financial abilities and acknowledging that one's life is not going according to plan is difficult. In Norway, receiving financial social assistance aimed at covering basic necessities such as food, shelter, and clothing has long been stigmatized (Bråthen et al., 2016). Convincing oneself and others that you are of medium or high socioeconomic status while accepting subsidies specifically tailored to people with low socioeconomic status could be a mental inconsistency. One possible solution to resolve this inconsistency is not to utilize the subsidies and possibly not conduct the retrofitting. Suppose the association between energy retrofitting and low income becomes strong enough. In that case, there is a genuine possibility that energy retrofitting will be seen as something associated with low socioeconomic status, and thus, it will become undesirable. This line of research should be at least somewhat explored before subsidies are focused on lower-income households. Currently, the research on Norwegian free-riding is lacking, and no concrete data suggest that the distribution of subsidies according to income level is skewed. This would be the first step in establishing whether shame related to households' energy retrofitting subsidies is a potential issue.

Related to energy retrofit subsidy free-riding, many economic models estimate the share of free-riders in different countries (Alberini et al., 2014; Collins & Curtis, 2018; Grösche et al., 2009; Nauleau, 2014; Rivers & Shiell, 2016). Additionally, some employ survey methods to estimate the same share (Studer & Rieder, 2019). This literature is covered in paper two, and I will not repeat it here. However, the critical point is that the literature rarely employs identical methods of estimating free-riding, thus making their findings difficult to compare. Replicating the methods from one of the studies would benefit the free-rider literature and be the first of its kind to estimate the share of free-riders in Norway.

The topic of distributing subsidies for energy retrofitting also has ethical applications. All Norwegian retrofit subsidies are based on 'the Enova fee', which is an electricity fee. Assuming that low-income households live in less insulated households than high-income households, low-income households contribute more to this subsidy scheme. If subsidies are primarily distributed to higher-income households, this creates a 'reverse Robinhood' scenario, where money is taken from the poor and given to the rich. In addition to being ethically problematic, this increases wealth inequality, which has again been associated with increasing per capita emissions (Knight et al., 2017). Therefore, the subsidies intended to decrease carbon emissions could, as an unintended side effect, actually increase them, thus counteracting the very problem they intended to solve in the first place. As such, even though Enova's mandate does not involve social issues such as wealth distribution, this issue is closely tied with emissions, making the distribution of subsidies relevant to Enova's work. Therefore, researching the distribution of subsidies becomes an essential precursor to several psychological topics.

3.6. **Psychological research on energy retrofitting**

As mentioned above, the direct behavioural research on energy retrofitting measures, especially building envelop measures, is somewhat scant. The possible reasons for this are discussed in Section 3.3. Next, I will cover the relevant existing research regarding factors associated with performing energy retrofitting. Note that literature already covered in the articles will be discussed concisely.

The 'Kirklees Warm Zone' was a UK-based scheme offering free loft and cavity wall insulation to all suitable properties (Butterworth et al., 2011; Long et al., 2015). The scheme is estimated to have saved 105.9 GWh across 51,155 households, assuming half of the energy savings are lost to thermal comfort improvement (Long et al., 2015). Half of all the households that were offered the scheme participated in the formal assessment, where inspectors looked inside the house, and 32% of those households went on and had measures installed. Note that a 32% participation rate for any building envelop measure policy is exceptionally high. In comparison, Norway has an annual retrofitting rate of 3.37% (Fyhn, Berntsen, et al., 2019). A survey was distributed to households afterward to understand the differences between households that had the measures installed and households that did not, as well as the reasons why households either accepted or rejected the measures. The results are mainly presented as descriptive statistics, and it could be argued that very few of the measurements qualify as psychological items. Interestingly, even though the scheme was widely marketed, free of charge, and distributed in a forced-choice method, 'only' 32% of households attended. Indeed, 40% of non-participants stated home disruption as a primary reason why they turned down the scheme, followed by a lack of time (25%), loft inaccessibility (25%), and the inability to clear the loft (10%). From a psychological standpoint, it could be interesting to investigate if retrofitting rates in Kirklees are currently above or below comparable cities.

Analysis of the psychological items of the Kirklees Warm Zone survey (Long et al., 2015) shows some differences between people that installed measures and those that did not. Participants of the scheme indicated that they agreed more with the statements "I enjoy saving energy", "I feel obliged to do my bit for the environment", and "If energy can be saved in the household, it should be". The authors do not present the numbers from their statistical analysis, so quantifying the effect size is difficult. They only present the share of responses visually. Data from nonsignificant items, or what those items were, are also not presented. Although the lack of established methods of presenting the data blurs the interpretation, one could say that participants in the scheme had higher attitudes towards environmental and energy-saving variables. As this is a cross-sectional study done after the scheme was complete, we cannot say whether participation caused the increased attitude, vice versa, or a third variable affected attitude and participation.

Occasionally, some research for planned retrofits also includes what could be considered psychological items. The researchers showed that 16%, 11%, and 4% of Swedish homeowners plan to replace or improve the windows, attic insulation, or wall insulation, respectively, in the next three years (Nair et al., 2010b). They also surveyed households that improved building envelope component(s) over the last two years. Although they do not conduct statistical tests between households that had completed envelope measures and not, it is possible to do this manually by using the reported standard errors, means, and *n*'s in t-tests. By doing this, we see that households that had improved building envelope component(s) during the last two years do no not rank installation-related factors statistically significantly different from the general population. These factors include comfort, environmental benefits, ease of installation, greenhouse gas emission reduction, aesthetics, and status. As covered in the theory section, assuming cognitive inconsistencies apply to energy retrofitting similarly to other topics it has been researched under, it predicts that people that had undergone energy retrofitting would rate factors such as greenhouse gas emission reduction and comfort higher. The reasons for performing building envelope measures seem similar between the two groups. This indicates that energy retrofitting is not a self-reinforcing behaviour.

The research also looks into factors associated with planning retrofits (Nair et al., 2010b). However, I cannot entirely agree with the author's choice to aggregate response categories for planning to upgrade over the next zero to three years with planning to upgrade over the next three to ten years. I argue that the latter response option more represents 'I should [retrofit], but I won't'. Planning to do something more than three years into the future probably does not correlate strongly with actual retrofitting measures. Possibly, this choice was made due to low power, with the study having only 1,101 respondents. A reasonable number for any other fields, but not for energy retrofitting, as covered in Section 3.3.2.

A recent line of research investigating private Norwegian households' energy retrofitting measures is highly relevant to this project (Klöckner, 2014; Klöckner & Nayum, 2016, 2017; Klöckner et al., 2013). Through a process from group interviews to surveys, the researchers formulate stages of energy retrofitting decision-making and a list of drivers and barriers that affect these stages. The stages of the model build on existing decision-making research (Bamberg, 2007, 2013a, 2013b), where the individuals transition from a more general feeling that something should be done to more specific plans for implementations to actual action. In the latest model, these stages are (1) 'not being in a decision mode', (2) 'deciding what to do’, (3) ‘deciding how to do it’, and (4) ‘planning implementation’. The specific drivers and barriers that were found to affect the transition from each stage is listed in Table 1.

Table 1

An overview of which factors influence transition in the specific stages, adapted from Klöckner & Nayum (2016). *Only statistically significant factors are listed.*

Barriers	Stage 1 -> Stage 2	Stage 2 -> Stage 3	Stage 3 -> Stage 4
Unsure about the saving potential for energy costs after an upgrade	0.085	-0.040	
Plans to move soon	-0.040		
I do not manage to make a decision for what to do		-0.062	-0.031
I do not own the dwelling	-0.083	0.030	
The right point in time has just not come to upgrade	-0.077	-0.070	-0.041
Building protection regulations prevent me from upgrading	-0.042		
Not enough economic resources		-0.038	-0.031
Difficult to know if information about energy upgrades can be trusted		-0.033	
Demands much time to supervise the contractors			-0.042
Drivers			
Reduction of energy costs expected after upgrade	0.128	0.083	
Increased market value of the dwelling expected after upgrade	0.096		
Payoff of the investment within a reasonable time frame	0.117	0.066	0.051
Positive health effects expected after upgrade	0.082	0.055	
The building standard of the dwelling is perceived as a waste of energy	0.106		
Better living conditions in the dwelling expected after upgrade	0.138	0.060	
Higher comfort levels expected after upgrade	0.141	0.040	0.041
Information about energy upgrade is easily accessible		0.098	
There are subsidy schemes in place supporting the upgrade	0.063	0.060	

The factors listed in table 1 influence the transition from one decision-making stage to the next. For example, a household expecting higher comfort levels after energy retrofitting will affect the transition between all decision making stages. On the other hand, worrying about time to supervise the contractors will only affect the transition from stage 3. The relevance of each variable to transitioning through the stages is determined by its moderating effect size between two stages. Therefore, each of the variables impacts for each stage is quantified. The research has arguably developed the most complete, specialized decision-making model for household energy retrofitting that exist at the time of writing. The model is also highly quantified, making it suitable for simulated models. Still, even though the research is very well-suited for it, it has not been employed in simulation work.

3.7. **Agent-based modelling**

Agent-based modelling is a method that 'allows one to simulate the individual actions of diverse agents, and to measure the resulting system behaviour and outcomes over time' (Crooks & Heppenstall, 2012, p. 86). Usually, this is done through computer simulations, where hundreds or thousands of independent agents are given instructions through code and act on these. One classic example is flock movement in birds, where agent-based models have shown that the seemingly complex movement patterns observed in large flocks can be replicated by telling each simulated bird to fly in roughly the same direction as nearby birds. Agent-based models can also be used to integrate findings from different research fields into the same framework. For example, findings regarding the non-linear relationship between price and quality in energy retrofitting (Galvin, 2010) do not easily integrate with findings that descriptive norms affect energy retrofitting behaviour (Helms, 2012). What exactly is the combined interactive result of these two findings? Once researchers begin to discuss this, they are creating implicit mental models of this interaction. Writing this mental model down into code to make it explicit has been argued to be a principal advantage of agent-based modelling (Epstein, 2008).

So far, all agent-based models on private household energy retrofitting could be argued to be somewhat limited in including research, as they base their behavioural mechanisms on generalized and maybe not so central theories of behaviour (Boria, 2020a, 2020b; Friege et al., 2016; Xin Liang et al., 2019). For example, in the 'Neighbor Influenced Energy Retrofit' model (Boria, 2020a, 2020b), households are divided into leaders, conformists, and stigma-avoiders. In the model, leaders try to maximize their energy efficiency, conformists aim for the mean, and stigma-avoiders avoid having the worst energy standard. However, during this project, I have not come across any research that indicates this division is an accurate representation of building retrofit behaviour. Furthermore, even though it has some rough resemblance to the diffusion of innovation theory (Rogers, 2003) it is difficult to argue it is strongly rooted in mainstream psychological behavioural theory. Generally, I argue that a nominal classification of psychological traits (e.g., introvert or extrovert) is generally not in line with the psychological literature. Most psychological traits are continuous (e.g., extroversion score from 1-5).

As mentioned above, a behavioural framework for private household energy retrofitting exists (Klöckner, 2014; Klöckner & Nayum, 2016, 2017; Klöckner et al., 2013). Although this framework is more complex than previously applied frameworks, it should be compatible with agent-based modelling. Thus, generating a simulation based on research that focuses on private household energy retrofit decision-making seems like a promising yet unexplored avenue of research. Such a model should integrate research from other disciplines, making the model compatible with other energy system models, including but not limited to energy retrofitting costs (Galvin, 2010) and more commonly used energy rating measurements such as kWh/(m^2a) (as used in Xinxin Liang et al., 2017).

3.8. **The research gap to be filled**

Many impactful and interesting aspects of energy retrofitting behaviour are unexplored from a psychological decision-making research perspective. For example, I find it reasonable that attitude and self-efficacy will predict energy retrofitting. Therefore, the theory of planned behaviour (Ajzen, 1991) could have been utilized as a core framework in this thesis. Yet, I argue that it is more interesting to go one step further and look at factors that cause changes in attitude and self-efficacy. Additionally, assuming these predictions are true, what impact do these changes have on policymaking. Therefore, I argue that this project will find more interesting and impactful results by basing the research on the literature covered in Section 3.5.

Some preliminary observations can be noted. Firstly, the psychological decision-making barriers seem more permanent than the drivers. The mere exposure effect only comes into play when exposed to retrofitting; cognitive inconsistencies as a driver occur only when having to justify a retrofitting project, and for positive spillover to potentially occur, the original behaviour must be completed. Additionally, retrofitting should be one of the best ways to increase retrofit-specific self-efficacy. In contrast, the barriers seem permanent. The loss aversion in relation to investment behaviour should be constant, and subtractive blindness to downsizing is most likely stable. Justifying why you are *not* retrofitting could reduce attitudes toward energy retrofitting projects. This could explain that the retrofitting rates are lower than economic theory suggests. Here, it is again important to note that the above theory has not been applied to and tested in energy retrofitting behaviour. It is only my prediction, assuming the psychological decision-making research applies to energy retrofitting similarly to the behaviour it has been researched under. Next, I will outline the research questions addressed in this thesis using the literature covered.

3.8.1. Distribution of energy retrofits

The biggest discrepancy between assumptions of the established energy retrofitting literature and predictions of psychological behavioural theory concerns ‘who retrofits?’. The economic literature generally assumes that whoever needs it the most, retrofits. This has resulted in several studies researching 'lock-in' (Dubois & Allacker, 2015; Risholt & Berker, 2013; Urge-Vorsatz et al., 2013; Weiss et al., 2012). Here, if households retrofit to a medium energy standard, they will not retrofit again for some time, locking in the energy standard for some time.

Lock-in contrasts most of the theory covered in section 3.5, which predicts that energy retrofitting is self-reinforcing, assuming the research extends to energy retrofitting behaviour. Firstly, research on self-efficacy and attitude indicates that energy retrofitting could be self-reinforcing. The more experience a person has with energy retrofitting, the more self-efficacy they should also have. Both mere exposure and detecting cognitive inconsistencies should lead to a better attitude towards retrofitting and energy efficiency after a person has undergone energy retrofitting projects. Subtractive blindness and loss aversion should cause the household to ignore other solutions to reducing energy consumption. Habits could also lead households to continue energy retrofitting projects. However, not all the psychological literature predicts that energy retrofitting leads to more energy retrofitting. Decision mode theory predicts that because energy retrofitting is a calculation based decision, there could also be some negative spillover.

To the best of my knowledge, no research has investigated if households undergo consecutive energy retrofits. The results should have implications for both the spillover and lock-in literature and the reliability of building development metrics. If some households are constantly undergoing energy retrofitting, the annual rate of buildings retrofitted will not be a reliable indicator of the development of the building stock. Whether or not consecutive retrofitting occurs or not will be the focus of the first paper.

3.8.2. Distribution of retrofit subsidies and free-riding

Media reports (Rørslett et al., 2021) are insufficient to claim that subsidies are distributed to the rich, and no research on Norwegian free-riding exists. If consecutive energy retrofitting is a phenomenon, such a distribution will be extra problematic, as low-income households will be left further behind. Although this research will not investigate it, it is an important first step in establishing whether or not shame in receiving subsidies aimed at low-income households is a worthwhile research topic.

Recent Swiss free-riding research presents a simple way of measuring free-riding through surveys (Studer & Rieder, 2019). Replicating this research will help determine the item's validity and measure energy retrofit subsidy free-riding in Norway. Because whether or not subsidy recipients are free-riding is closely associated with the income of the same subsidy recipients, I fit both research questions into one paper. These are the topics of the second paper.

3.8.3. Psychological agent-based energy retrofit modelling

Finally, there is potential for employing decision-making research specific for households' energy retrofitting measures in agent-based modelling. Existing models are either not based on psychology or apply very general frameworks. Moreover, such a psychological modelling project would fit seamlessly with the research mentioned above. Concepts such as continuous retrofitting and free-riding on subsidies could validate the model if replicated inside the model. The model will base itself on the research conducted by Klöckner and Nayum (2016), and supplement with more general psychology where the model does not specify. For example, the model does not specify what makes a person choose a high or low ambition on their project. Here, people likely start considering energy efficiency levels they have been exposed to, in line with availability heuristics (Tversky & Kahneman, 1973).

This forms the basis for the research. First, research energy retrofitting outcomes that, from a psychological decision-making research standpoint, could exist. Second, create an agent-based model based on this assumption, as well as existing energy retrofitting behaviours. Studies on existing behavioural patterns will have their own value, but they will also validate the model. See Figure 3 for a visualization.

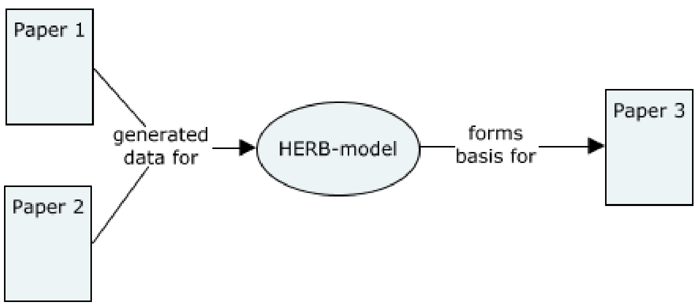

Figure 3: A visualization of the interconnectivity between the papers in the thesis.

All papers will utilise knowledge gained in the psychological decision-making field and apply it to energy retrofitting, bridging the gap between the two. The two first papers will investigate inferred predictions from psychological decision-making research and check if the predicted behaviour can be observed in energy retrofitting. Both papers will investigate the role of attitude and income in energy retrofitting phenomena. Additionally, the first paper will investigate the role of self-efficacy. Paper three will use the results of the first two papers to generate an agent-based model where policies can be tested. Without the two first papers, options for validating the model would be limited.

4. Methods

This method section is organized as follows. First, I introduce aspects that are shared between all articles. This includes data gathering, data availability, and multiple imputation methods. Next, I sequentially present aspects that are specific to each individual paper.

4.1. Common aspect - Data collection

Three different surveys form the data foundation for the doctoral thesis. None of the surveys was collected with the sole intention of being used in the thesis. This way, by cooperating with other projects that enjoyed a larger budget for data collection, I ended up with a much larger dataset than I would have been able to collect on my own, overcoming the issues related to sample size discussed in Section 3.3.2. See Table 2 for a summary of the data used in the thesis.

Table 2

Overview of surveys applied in the thesis.

	Time Distributed	N	Summary
Survey 1	2014 January-March	2605	Norwegian representative sample. Sponsored by Enova. Distributed to investigate energy retrofitting rates in Norway.
Survey 2	2019 March-April	3797	Norwegian representative sample. Sponsored by Enova. Considerable overlap with survey 1 in terms of both items and purpose.
Survey 3	2019 May	303	Recipients of subsidies for housing insulation or energy counselling subsidies. Sponsored by Enova.

The first survey used in this thesis was distributed five years before the start of the project. This survey was part of a project that Enova sponsored, which investigated energy retrofitting in Norway. The survey has been applied in energy retrofit research (Klöckner & Nayum, 2016) and other reports (Klöckner & Nayum, 2015). This survey also collected a focused sample that either recently conducted a deep rehabilitation or planned to do so within three years. I do not list the survey because it is not used in the statistical analysis of the papers. The survey measures current, recent, and planned retrofit measures in private households. Additionally, it measures several demographics, such as age, education, income, and loans. Moreover, the survey collects information about the house, such as size, ownership status, and the year it was built. It also includes several psychological measurements, including an innovation index and drivers and barriers to energy retrofitting. It is worth noting that large parts of the survey were not presented to respondents if they stated they were tenants. This made the inclusion of tenants in the following analysis impossible, and they were functionally omitted from the project years before the project even began.

The second survey used was, in large parts, a replication of the first survey. On behalf of Enova, NTNU Samfunsforskning and the Institute of Psychology at NTNU investigated the subsidies effect in Norway. Initially, the organization approached my supervisor Christian Klöckner about collecting the survey data. Professor Klöckner suggested me instead, and I accepted on the condition that I could also use the data for this thesis. All parties agreed the thesis strengthened the project. From there, I spent a total of six weeks designing and analyzing three surveys, which can be seen in the final report for the Enova contract (Fyhn, Berntsen, et al., 2019). That report is not a part of this PhD thesis.

The third survey was part of the Enova contract, but it was distributed to households that had received subsidies for upgrading the building body (Enova, 2019) or energy counselling. Most of the recipients for the former subsidy had also received subsidies for the latter. The survey asked households about their type of house, income, effects of the retrofitting, and the subsidy process in general. Additionally, we included a subsidy free-rider index that was used previously in Swiss research (Studer & Rieder, 2019).

4.2. **Common aspect - Data availability**

An effort was made to make all data and data processing as openly available as possible. All statistical syntaxes were uploaded to reviewers and then later to a publicly available data repository. An effort was also made to upload the original survey data files, but this had some issues. Although the collector of the first two surveys (Kantar/Norsk Gallup) judged the datafiles not to contain identifiable data, there was reason to argue otherwise. For example, the surveys asked for the age, gender, county, income, loans, size of the house, and currently undergoing retrofit measures of the households and their members. I argue that a combination of these can be used to identify some participants. Therefore, the full datasets were not uploaded. Instead, a dataset containing only variables applied in the analysis and scrambled county data were uploaded. Additionally, the county variable was scrambled by converting the locations to places in the *Lord of the Rings* fantasy universe. See Table 3 for a list of all current and planned publicly available materials from the research project.

Table 3

A list of all non-article publicly available scientific outputs of the project.

Research Output	Availability	Description
Anonymized dataset for paper one	Public: https://data.mendeley.com/datasets/vmyn94prrr/1	Dataset of all variables used in the data processing for the article.
*Statistical syntax for paper one	Public: https://data.mendeley.com/datasets/vmyn94prrr/1	The full statistical treatment of the data, from dataset to article.
Anonymized dataset for paper two	Public: Found under 'supplementary data' in article	Dataset of all variables used in the data processing for one of the analyses.
*Statistical syntaxes for paper two	Public: Found under 'supplementary data' in article	The full statistical treatment of the data, from dataset to article.
HERB-model	Public: https://www.comses.net/codebase-release/51d9ca5a-9057-4ade-8500-3a34486646e7/	The full agent-based model used to generate data for paper three.
*ODD protocol for HERB	Public: https://www.comses.net/codebase-release/51d9ca5a-9057-4ade-8500-3a34486646e7/	Technical description of the HERB model, featuring a more in-depth discussion on specific modelling choices than in paper three.
Experiment data for paper three	Public: https://doi.org/10.18710/XOSAMD	The full dataset for all experiments conducted in the HERB model.
*Statistical syntaxes for paper three	Public: https://www.comses.net/codebase-release/51d9ca5a-9057-4ade-8500-3a34486646e7/	The full statistical treatment of the data, from dataset to article.

* Also available in the appendix of this thesis.

Making one's research publicly available has several advantages. When the entire statistical syntax, from dataset to output, is available, reviewers and other researchers can investigate the statistical methods of the papers in far greater detail than what is possible from paragraphs in a method section. This enhances the reviewing process and makes replication of the results simpler. For example, when this study replicated the free-rider items, the original authors had to be contacted because they did not specify if responding 1 or 2 on a 4-point Likert scale counted as 'no'. Additionally, real examples are great sources for learning for other researchers and students. Finally, when a researcher knows that the code will be open for scrutiny for decades to come, the threshold for implementing 'quick fixes' or unjustified solutions becomes very high. Indeed, it becomes natural to include more comments to explain what is going on in a particular block of code. This has the added benefit of explaining your own code 1, 5, and 30 years into the future, where the researcher will inevitably have forgotten why specific solutions were chosen in the first place. From personal experience, explaining the code also improves the researcher's own understanding of the code. Thus, I made all statistical syntax and agent-based model codes available to reviewers, and after the articles were accepted, I made the codes available to the public.

4.3. **Common aspect - Multiple imputations**

Most of the time, surveys have respondents who, for various reasons, do not respond to items. Additionally, very rarely do surveys reach anywhere near a 100% response rate. Both these phenomena will leave the resulting data with 'holes', with the final dataset usually having far less data than it could have had if all respondents had answered all questions. This was the case for all the surveys employed in the project, as listed in Table 3. If the missing data had been randomly distributed, this would not have been a major problem. Then, the complete dataset would merely be a random representative sample of the full sample. This is also known as 'missing completely at random'. However, this should rarely be assumed to be the case. Which respondents reply to surveys and which items are left unanswered is seldom random. Thus, the data the researchers analyze are not a representative sample of the sample they initially set out to collect. For example, respondents with very high and very low incomes often leave items on income unanswered (Rubin, 1987). Not addressing this issue will give the impression of lower variability in income data than in reality. Therefore, measures to ensure that the dataset is as close to the sample the researcher initially set out to collect should be implemented in any survey with missing data. I strongly argue that ignoring the problem by employing pairwise or listwise deletion of respondents with missing items is bad scientific practice (as also argued by Graham, 2009; Schafer & Graham, 2002).

Multiple imputation techniques are one of the best ways to address partial responses and non-responses (Rubin, 1987; Schafer & Graham, 2002). Multiple imputation methods apply statistical methods to predict the missing data based on the existing data. The mean and distribution for all missing values are predicted, and from this distribution, the desired number of complete datasets is created. With this, the researcher will have several slightly different datasets varying around what the 'true' dataset is. After this, the researcher's analysis is run on all of the datasets. Finally, the results are combined by pooling all estimates after 'Rubin's rules' (Rubin, 1987), a way of calculating combined parameter estimates such as regression coefficients, standard errors, and p-values into one value (Heymans & Eekhout, 2019).

The best-case use of multiple imputation methods is when the researchers have some data on all participants before they distribute the surveys. This can include variables like municipality, age, number of employees at a company, country GINI-indexes, data from previous surveys, income, or amount of subsidies received from a subsidy programme. Then, after surveys are distributed and non-responses inevitably show up, the researchers can use the existing data to impute the missing data. Similarly, individually missing items can be imputed based on responses to other items. Here, the only difference is that answers with responses are used to impute answers with no responses. Readers will note that survey number three was the perfect candidate for applying multiple imputation techniques. Enova had extensive data on all subsidies distributed, including but not limited to the project's cost, the subsidies received, the speed of the application, the gender of the applicant, and the size of the house. These data could have been used to impute all non-responders, resulting in a perfectly imputed dataset. Unfortunately, I did not learn about multiple imputation techniques until after the survey was distributed.

As a sidenote, it should also be mentioned that during the treatment of the data from Kantar, I noted that Kantar already has some data on all participants to whom they distribute their surveys. These data include factors such as age, gender, income, education, and more. While the 'default' method Kantar employs to make their sample representative is to weight these factors, an arguably better solution would be to distribute the survey to a representative sample (without weighting), then provide the researcher with the full dataset, including the participants who did not respond. Then, the researchers can use multiple imputation methods to impute the missing data using the data that Kantar has for all participants. While there might be some ethical considerations regarding using data from participants who did not choose to answer the survey, I argue these should not be too much of a challenge. The data would be highly anonymized and would not be very different from current practices. Currently, Kantar reports the share of respondents who did not respond for each age, income, and education group. The only difference would be to report this as a share of respondents with a certain age, income, *and* education who did not respond. The researcher can then put these 'fake' respondents into the dataset and impute. This method was not attempted in this thesis because I learned about multiple imputation methods after collecting the data. Survey number one was collected even before the project started. As the surveys that form the data basis for this project all had missing data, some version of multiple imputation methods was employed in all three papers. Next, I will cover the specific methods of these papers.

4.4. **Paper 1 - Methods**

For the first paper, an inconsistency in the energy retrofit research and the psychological literature was noticed. The energy retrofit literature often mentioned a 'lock-in' effect (Dubois & Allacker, 2015; Risholt & Berker, 2013; Weiss et al., 2012). This effect assumes that after households retrofit once, they will stop retrofitting because consecutive retrofits are not economically viable. Therefore, energy retrofits are generally assumed to be equally distributed amongst the population or primarily to households with a greater need for retrofits. This is in sharp contrast to the psychological literature covered in the introduction that, though not applied to the field of energy retrofitting, clearly predicts that consecutive retrofitting would be a widespread phenomenon. Additionally, no research directly documenting consecutive retrofitting could be found. Therefore, I decided to investigate if previous retrofits were a predictor of currently undergoing retrofits.

For data material, I used surveys one and two, described in Section 4.1. Both surveys contained items that identified whether or not participants had conducted an energy retrofit measure in the form of adding insulation in the last three years, as well as whether they were currently performing any. Additionally, the surveys contained items regarding age, gender, income, loans, investment potential, house size and age, attitude towards retrofitting, and retrofitting self-efficacy. As with all social surveys, these surveys also had missing data. I employed multiple imputations to fill the missing data. As there was a strong over-inflation of zero-counts (as in no retrofits conducted), negative binomial regression modelling (Lawless, 1987; Lindén & Mäntyniemi, 2011) was employed to analyze the data. I created three models to estimate (1) the direct effect of previous energy retrofit measures; (2) the effect of previous energy retrofit measures when controlling for demographic factors; and (3) the effect of previous energy retrofit measures when controlling for demographic factors, attitude, and self-efficacy. For full details concerning the data treatment, please see the statistical syntax with comments. If the effect of previous energy retrofit measures had both a significant and meaningful effect size in all three models, one should be able to conclude that consecutive retrofitting is a phenomenon while motivational 'lock-in' is not.

4.5. **Paper 2 - Methods**

For the second paper, I noted a significant lack of comparable studies on energy retrofit free-riding subsidies. Most studies only investigated one country and did not employ identical methods to other studies. As different methods were employed, the results could not be compared with any meaningful degree of confidence. Additionally, most studies applied an econometric approach to identifying free-riders. The potential for an arguably more valid method of directly asking the subsidy recipients through surveys was largely unexplored. I could only identify one study that measured energy retrofit free-riding subsidies through surveys (Studer & Rieder, 2019). Such a method also had the advantage of prompting for other variables that could be associated with free-riding.

Additionally, I noted a lack of data on the hypothesis that Norwegian retrofit subsidies were primarily distributed to rich households (as theorized by Rørslett et al., 2021). This distribution had to be established before discussing potential policy changes and relevant psychological mechanisms. A survey to subsidy recipients was the only practical method of obtaining these income data. Therefore, I wanted to replicate some data from the energy retrofit subsidy literature and investigate the relationship between Norwegian energy retrofit subsidies and household income.

To measure free-riding amongst Norwegian subsidy recipients, I copied and translated the items employed to measure free-riding in a recent Swiss study (Studer & Rieder, 2019) into survey number three. To the best of my ability, the article uses the exact same statistical methods employed in the original study to identify and predict free-riders. I contacted the original authors and clarified who was considered a free-rider. The only difference in our statistical methods was that in my analysis, missing answers were imputed using multiple imputation methods and not reported as missing. Additionally, because the study identified far fewer free-riders, the number of variables in the logistic regression had to be reduced (as suggested by Tabachnick & Fidell, 2014). Because problems have been shown to arise around five to nine events per variable in logistic regressions (Vittinghoff & McCulloch, 2007), I allowed seven outcome events per variable, which in this case was the number of free-riders. Therefore, the number of variables in our logistic regression was reduced to two. Luckily, this was also the number of statistically significant variables the original study found. As such, we included only the statistically significant variables from the original research (Studer & Rieder, 2019).

To compare income distributions, I pulled the income data from households that had undergone retrofitting in surveys one and two and households that had received subsidies for retrofitting from survey three. Additionally, I received the national average data from SSB. Next, I imputed all missing answers by using multiple imputations, and I estimated the mean and 95% confidence interval for each group. Finally, I graphed all numbers on a figure. The areas where the confidence intervals do not overlap indicate statistically significant differences. To the best of my knowledge, this article is the first to use this method. Again, for full details concerning the data treatment, see the commented statistical syntax.

4.6. **Paper 3 - Methods**

I noted that no existing agent-based model had fully utilized the research on private household energy retrofitting behaviour. Additionally, the degree of inclusion of other research, such as the cost of energy retrofitting (Galvin, 2010) or standardized output metrics such as kWh, was minimal. Finally, the research conducted in the first and second papers was a suitable method of validating such a model. If a model of individual decision-making could be generated based on the literature and transformed into a simulation, different policy scenarios could be tested in the model. Such a model could give feedback on specific policies to a much larger extent than existing research.

The Household Energy Retrofit Behaviour (HERB) model was created. The model, generated in NetLogo, populates a 1 square kilometre area with households with a density equal to Tanem, Trønderlag. Each household is parameterized with one random participant from surveys 1 and 2. After this, a friend-finding algorithm based on the small world approach (Watts & Strogatz, 1998) connects households. Then, the simulation starts. Each iteration, or 'step', represents one week of real-time. For every step, a household can suffer some degradation to its energy standard, regain a small amount of money to be invested in energy retrofitting, and potentially move out of the simulated area. Another household will instantly move in when someone moves out.

To decide to retrofit, each household must transition between the four decision-making stages presented by Klöckner & Nayum (2016), discussed in Section 3.6. The likelihood of transitioning between these stages is based on perceived comfort gain, worry about financing, self-efficacy, normative influence, availability of subsidies, economic gain, and perceived wastefulness of the current energy standard. These variables formulae were determined through a short workshop in the Citizens, Environment and Safety group. Please see the ODD-protocol Section 7.4 'Calculate psychological variables' for a description of each variable. Next, the households normalize each variable, multiply it with its relevance for their stage and themselves, and combine these scores to form an intention to move score. Households then have a chance to transition in stage based on this score. If households transition to stage 4, energy retrofitting begins, the energy standard is upgraded and the household transitions back to stage 1.

Different policies can be placed in the model, and the effect on energy consumption can be observed. A more detailed but still commonplace explanation of the model is found in paper three. A more extensive description is found in the ODD protocol. The model and the statistical syntaxes used to analyze the data can be downloaded from CoMSES at https://www.comses.net/codebase-release/51d9ca5a-9057-4ade-8500-3a34486646e7/. Alternatively, search for “Household Energy Retrofit Behavior CoMSES” in any search engine.

To validate the model, results from the model were compared to findings in the published report (Fyhn, Berntsen, et al., 2019) and papers one and two. Firstly, the annual retrofitting rate was pulled from the model. Like the survey, the model continually retrieved the share of households that had retrofitted in the last three years, divided by three. Secondly, the consecutive retrofitting rate was retrieved by testing the share of households that had retrofitted the last three years when they started retrofitting. Finally, free-riding was pulled from the model by testing if the households that received subsidies would have transitioned through all stages without the subsidies.

In the model, I implemented and tested four different policy scenarios. Firstly, I implemented and tested a replica of the Norwegian primary household energy retrofitting subsidy system. Secondly, I tested whether marketing a specific energy standard and making households consider retrofitting to this standard instead of the one acquired through availability heuristics was effective. For this purpose, I tested all energy standards, from very high to very low. Thirdly, a share of households in the final decision-making stage before retrofitting received a boost to intention, representing a directed motivational campaign. Finally, I tested adjustments to the threshold for subsidy qualification. In this policy scenario, households had to retrofit to a higher or lower energy standard to be eligible for subsidies. If the policy had a reductive influence on energy consumption, this was interpreted as a successful policy.

5. Results

In this section, I will only cover the main findings of the three papers. For full details concerning the findings, please see the respective paper.

5.1. **Paper 1**

The number of currently undergoing energy retrofit measures is strongly associated with the number of retrofit measures completed in the last three years. This association still holds when controlling for demographic variables, and demographical, attitude, and self-efficacy. Thus, households that have previously undergone energy retrofitting are substantially more likely to currently be undergoing more energy retrofits. Therefore, the annual share of homes retrofitted each year as a measurement for the development of the building stock is questionable.

Although the data do not allow for testing this directly, based on the available theory and a lack of other explanations, it is possible that undergoing energy retrofitting could lead to more energy retrofitting. This suggests that energy retrofitting could be a self-reinforcing behaviour and is unequally distributed among households. Therefore, motivating households to undergo small retrofit measures could be a viable policy measure that leads to more retrofitting activities in the future, thus improving the building stock. However, more research is needed to confidently claim such a causal connection.

Finally, higher self-efficacy and a more positive attitude towards retrofitting are positively associated with the number of currently undergoing retrofits. For attitude, there is also a positive interaction effect with the number of previously completed energy retrofits.

5.2. **Paper 2**

Our findings estimate that the Norwegian free-rider rate on energy retrofit subsidies is 10%. Compared to the Swiss rate of 50%, this is very low. Similarly to Switzerland, utilization of advisory services and perception of the implementer are associated with free-riding. Households with a favourable view of Enova and reports that utilize the 'Enova svarer' service report less free-riding. These results suggest that free-riding in Norway could be very low compared to other countries. More research relying on the same operationalization of free-riding is needed to confidently claim Norway's free-riding rate is lower than other countries. I theorize that this low number could be caused by both a high threshold for receiving subsidies and some response bias.

Households that undergo energy retrofits have a higher income than the population mean. Additionally, households that receive subsidies for retrofitting have a higher income than households that undergo retrofits without subsidies. An estimated 50% of all retrofit subsidies are distributed to the 20% of highest-income households. The bottom 50% of households in terms of income receive 12% of the distributed subsidies. Because an electricity fee, which everyone pays, finances the subsidies, this amplifies wealth inequality. Furthermore, because wealth inequality is associated with higher carbon emissions, this could lead to even higher carbon emissions, which the subsidies are meant to reduce.

5.3. **Paper 3**

Validation data from the HERB model show that the model replicates some but not all the findings of previous papers. The annual retrofitting rate is accurate and closely resembles that of earlier findings (Fyhn, Berntsen, et al., 2019). The continuous retrofitting rate is substantially lower than the rate found in paper one, suggesting the HERB model does not simulate the processes resulting in continuous retrofitting. The free-rider rate is higher than the rate found in paper two, but as agents in the model are not subject to response bias, it could be said to be reasonably accurate. With two out of the three validation measures met, some precautions have to be taken when interpreting the results of policy scenarios.

According to HERB model policy simulations, policy one (the current Norwegian energy system) and policy three (motivating households close to retrofitting) reduce household energy use. Policy two (the effects of marketing specific energy standards) does not affect cumulative energy use. Finally, policy four indicates that energy use increases if the threshold for receiving subsidies for energy retrofitting is raised. Similarly, if the threshold is reduced, energy consumption also decreases. The results show that various policies can be tested in the model, providing feedback on their impact. Although the model cannot guarantee whether a policy will work, I argue that it is more likely that a model that works in the HERB model should also work in the real world.

6. Discussion

The discussion section is organized as follows. First, the relevant aspects regarding psychological methods and theory will be covered. Then, drawing on these psychological aspects, I will focus on the policy implications. Finally, I will touch on the need for further research and conclude. This thesis will not fully cover the individual findings of each paper but instead focus on topics where two or more papers can be utilized in the discussion.

6.1. Implications for psychology

6.1.1. Consistency effects

Rarely does anything predict future behaviour as well as previous behaviour. This is true for criminal behaviour (Yukhnenko et al., 2019), as well as children's injuries (Jaquess & Finney, 1994). My research suggests that this phenomenon could also extend to household energy retrofitting behaviour, that households that have retrofitted in the past are more likely to retrofit in the future. Importantly, our first paper showed that this effect extends beyond age, gender, income, loans, investment potential, house age, and house size. Although the nature of our data does not allow for testing this assumption directly, it indirectly supports the notion that attitude and self-efficacy could maintain this consistency effect. That being said, other unknown factors not controlled for could be the cause of the association between previous and current energy retrofits. Assessing the impact of these unknown factors compared to the consistency effect can only truly be done by experiements. Alas, as covered in section 3.3, experiements are difficult to conduct in the field of energy retrofitting. Quite possibly, cross-sectional data, such as this thesis has collected, could be the only data on this question we will have in the forseeable future. Therefore, even though the data is not scientifically suited for claiming causality, I argue there is a case to be made for discussing what is the most likely causal connection.

This is especially true because the question has policy implications, possibly impacting the lives of millions of people. One could argue that researchers should be extra careful in their claims when the field has policy implications, but I argue that this logic is flawed regarding policy fields that will have policies regardless of scientific progress. Energy retrofitting is such a field and will have policies irrespective of the progress of the behavioural research surrounding these. It is better that these policies be based on uncertain research rather than no research. Therefore, I will discuss the likelihood of recent energy retrofits causing future retrofits based on the existing psychological literature and the findings in this thesis in the following section.

As covered in the introduction, the mere exposure effect and detecting cognitive inconsistencies could make people like the retrofitting project more than they 'should'. Indeed, prolonged exposure to the process should make the person like it. Additionally, to avoid cognitive inconsistencies, the person needs to justify the disturbance and spending, which can be done by starting to like the process itself. Both processes should result in positive attitudes towards the process and a higher likelihood of, in this instance, undergoing a retrofit. As the regression model in paper one shows, attitude is positively associated with the number of currently undergoing retrofits for households with two or fewer recently completed retrofits. As this accounts for 99.23% of all participants, it could be said to be generally true. My data can not confidently claim the directionality of this relationship. Either (1) energy retrofitting leads to higher attitude, (2) higher attitude leads to more energy retrofitting, or (3) some unknown variable leads to an increase in both. I argue that, most likely, a combination of all three is in play. Firstly, based on how well researched mere exposure and cognitive inconsistencies are (Montoya et al., 2017; Osbaldiston & Schott, 2012), I argue that at least some of the association should be attributed to energy retrofitting leading to a higher attitude. Again, other scenarios could explain the data, but I argue that with the solid theoretical and empirical work on mere exposure and cognitive inconsistencies, as well as the data that support this as one of the options, it is a likely connection.

Secondly, attitude has been shown to be a predictor of almost all behaviour (Kraus, 1995), and I would argue that this is such a broadly applicable finding that it is more likely that attitude leads to energy retrofitting than not. Therefore, *if* energy retrofitting both leads to a higher attitude, and a higher attitude leads to energy retrofitting, it is a self-reinforcing behaviour. Readers should note that although I find this a highly *likely* phenomenon, the data does not prove this. Finally, it is worth noting that even if one assumes such a self-reinforcing mechanism is in place, this does not eliminate the possibility that one or more external factors influence both previous and current retrofits. Again, experiments are needed to prove causality.

The HERB model decision-making system does not include attitude towards behaviour, which could limit its ability to replicate continuous retrofitting. However, including attitude in the model will require restructuring the factors influencing decision-making, as it is not in the original research that lays the foundation for these factors (Klöckner & Nayum, 2016). That being said, it should be noted that attitude towards energy retrofitting is included in the datasets on which the research is based. Therefore, future projects could conduct further analyses where attitude is included as a variable in the decision-making algorithm. In addition, decisions regarding how to operationalize attitude in code would also have to be made.

Similarly, self-efficacy should possibly also contribute to energy retrofitting as a self-reinforcing behaviour. Again experimental data is needed to confirm this, it is not a finding of the thesis, but I argue it is a possible connection. The more a person retrofits, the more they will learn about the process, and their self-efficacy should improve. The more self-efficacy improves, the more the behaviour should be performed (Ajzen, 1991; Armitage & Conner, 2001). This effect is represented in the HERB model in paper three, where households have more self-efficacy towards energy retrofitting when they have previously completed a retrofit. Unfortunately, this was not enough to replicate the same continuous retrofitting behaviour observed in paper one, most likely because the HERB model does not allow for piecemeal retrofitting in the same manner as real-life retrofitting. Also, attitude is not included in the HERB model, which could also explain this phenomenon.

The strong impact of previous retrofits can act as a problem for overcoming the uneven distribution of subsidies and energy retrofits between income deciles reported in paper two. If high-income households are already retrofitting more than low-income households, and the subsidies primarily support very high-income households, then the process is self-reinforcing. Hence, this trend will continue. Low-income households will not be exposed to the same mere exposure or cognitive inconsistencies creating a positive association to energy retrofitting. Moreover, low-income households will not receive increased self-efficacy from conducting their own energy retrofits. Assuming low-income households mostly socialize with other low-income households (as somewhat indicated by Bianchi & Vohs, 2016), they will not build self-efficacy through other people's projects either.

One could argue, however, that there are some benefits to this system. Importantly, the system likely should lead to an association between high socioeconomic status and energy retrofitting. If mostly high-income households perform the behaviour, it will be associated with this class. If energy retrofitting becomes associated with high income, it could become trendy and spread to the general population. Still, I am aware of no data supporting or opposing this argument, and relying on trendsetting literature from other fields such as fashion (e.g., Goldsmith et al., 1996), is questionable. As mentioned in Section 3.3, 'Not like all the other environmental behaviours', energy retrofitting is different from other pro-environmental behaviours and most certainly from fashion. Additionally, in-group out-group effects could contradict the positive effect, where energy retrofitting could be seen as something for "those rich people". In short, there is not enough research to determine the direction or even existence of this effect.

Based on the existing literature and the research in this thesis, I argue it is possible that psychological mechanisms maintain or worsen the status quo of a skewed distribution of subsidies and energy retrofitting between income deciles. My research shows that attitude and self-efficacy towards energy retrofitting are associated with more energy retrofitting. As discussed above, I argue it is likely that some of this should be attributed to consistency effects, that retrofitting leads to more retrofitting. Assuming this is true, rich households that retrofit will continue to retrofit, and non-rich households will continue not retrofitting. This research finds no indication of psychological mechanisms that will cease the uneven energy retrofit distribution. Simulation research employing retrofit-specific behavioural research is a promising avenue for exploring policies to counteract this imbalance. Regardless, a change in political systems utilizing psychological mechanisms is likely needed to fully utilize private households' vast potential in energy savings.

6.1.2. Attitude

The effect of attitudes is different in the first and second papers. In paper one, a positive attitude is associated with a higher chance of retrofitting. Yet in paper two, a positive attitude towards Enova also predicts non-free-riding. Curiously, households that made changes to their energy retrofitting project to receive subsides (i.e., non-free-riders) have a more positive perception of the organization that made them change their project than the households whose projects were subsidized without changes. Similarly, it makes little sense that households undergoing energy retrofitting projects that Enova considered to be good enough should dislike Enova. Anecdotally, this is similar to academics favouring reviewers who suggest revisions more than reviewers who recommend acceptance. While it could be that households appreciate external organizations encouraging them to increase the ambition of their energy retrofitting projects, I argue that a more likely connection exists.

This more likely connection is, in my opinion, that the free-riding measurement in paper two is heavily affected by overall satisfaction with the retrofitting and subsidy process. If the household liked the process as a whole, then the household will also positively view the effectiveness of the subsidies. On the other hand, if the household disliked the process due to, for example, extended case processing time or not saving as much energy as the contractor indicated, the household could be more inclined towards stating that the subsidies were not as effective. Here, households that enjoyed the subsidy process will positively score the subsidies' effectiveness and their overall perception of Enova.

Kahneman (2012) describes this concept as attribute substitution, where a difficult question is unconsciously replaced with a simple one. For example, the question "How happy are you with your life?" is exchanged by "How do I feel in this moment?". Similarly, the somewhat difficult question "The subsidies increased the scale of the retrofit" could have been replaced by "Did I enjoy the subsidy process?". Ironically, this substitution could have made an item meant to assess free-riding assess the opposite. Participants that did not have to make any changes to their project (free-riders) enjoyed the subsidy process more, and gave the item a higher score. It is again important to remember that this is one possible interpretation of the data. My research shows that substitution of difficult items is a possibility, but more targeted research must be performed to answer this confidently.

Unfortunately, this reduces the validity of the free-riding estimates using the methods of Studer and Rieder (2019) and this project. While I do think it is a more valid measurement than calculating the willingness to pay or treating households as rational economic actors (as done by Alberini et al., 2014; Collins & Curtis, 2018; Nauleau, 2014), the method employed is likely heavily influenced by attitude towards retrofitting. This research in itself cannot make any certain claims about the validity of this operationalization; it can only point out some minor inconsistencies. Further research is needed to determine to what extent attitude affects the free-riding items used in this and other research.

6.1.3. Codification of behaviour theory

This project has shown that it is possible to transform single-behaviour research into simulations that can again give broader policy suggestions than the original research initially could. Although previous research has shown that more generalized models can be used for simulating individual behaviours (Antosz et al., 2021; Boria, 2020a, 2020b; Friege et al., 2016), there is a strong case to be made for utilizing behaviour-specific research. I argue this is especially true when investigating unique behaviours such as household energy retrofitting.

In addition, the codification of behavioural theory effectively points out theoretical limitations, as every detail must be covered before it can be translated into code. In the HERB model, for example, there was no research on which factors are associated with households going backward in stages. The HERB model assumes the same factors apply, but there was no existing research on this. Similarly, while research exists on what causes a household to retrofit, no research could be located regarding *to* which energy standard households retrofit. As shown in policy experiment two, this could matter. Possibly, different factors cause households to upgrade to different energy standards. This, however, is not covered in the literature. Most likely, the lacklustre operationalization of energy retrofitting mentioned in Section 3.3.2 partly caused this phenomenon. Perhaps households high in self-efficacy retrofit more but choose less ambitious projects because they want to do it themselves. Perhaps households with a strong positive attitude towards retrofitting undergo several projects that do virtually nothing to improve the household's energy standard? To this day, nobody knows.

Finally, it is worth noting that, as far as I can tell, the HERB model is designed after somewhat different principles than most other agent-based models. When I designed the model, I designed the agents as objective-less. They simply do what the research has shown them to do. When there was little or no research to indicate what they did in the situation, I applied more general theory. Nevertheless, the households, in my mind, never had any goals.

I have come to understand that this is an unusual approach. For example, all households have an explicit 'goal' variable in the NIER model (Boria, 2020a, 2020b). The ODD protocol (Grimm et al., 2020), prompts modellers to write about the 'objective' of the agents. Macal and North state (2009) that a well-defined objective is part of a useful starting point for some models. The most common question I receive about the model when talking about it with other modellers is 'what is the goal of the agent?'. As far as I can tell, modelling agents with an explicit goal is the consensus in modelling.

Interestingly, although I designed the agents as objective-less, this has little practical impact on the model code. Modelling a drop of water to fall because it *wants* to fall, or because gravity exists, both result in the pseudo-code "if below = air [accelerate down]. The modeller's assumptions of the agent's capability to choose do not impact the code itself. Therefore, it could be argued that agents "objectiveness" does not exist because it does not manifest in code. Indeed, researchers could interpret the HERB model as if the households had goals. If read like this, each household tries to maximize its psychological values, such as having a comfortable house. Then, they choose to retrofit when the combined score of the psychological values for retrofitting exceed those of not retrofitting. This is functionally similar to a utility maximization score where all agents weigh different factors differently, and the factors change according to which decision-making stage they are currently in.

Because much behaviour research formulates its findings after an "if these conditions are in place, humans do this" formula, without explicit goals or objectives, it may have been somewhat under-utilized in agent-based modelling. The HERB model shows that this "objective-less" quantitative behavioural research can, and in my opinion should, be directly implemented in models. Agents do not need explicit goals to fit a model; they can just do whatever the research shows they are doing. Research with larger regression tables predicting a behaviour should be especially suitable for this purpose. This has the potential for creating more valid models and is, as far as I can tell, a largely unexplored avenue in agent-based modelling. This work could also help implement behavioural research in existing energy models that do not sufficiently implement human behaviour. This is done by providing a method of "codifying" the existing behavioural research in a way that, as far as I can tell, has not been done before.

6.1.4. Retrofitting and income

At first glance, there is an inconsistency regarding the effect of income on energy retrofitting between papers one and two. In paper two, a central point of the paper is that high-income households report more energy retrofitting activity than low-income households. This aligns with the literature (e.g., Schleich, 2019). However, in paper one, income has a *negative* effect on the amount of currently undergoing retrofit measures. This is because the regression in paper one includes investment potential and loans, which creates a suppression effect (Tabachnick & Fidell, 2014). Income is strongly correlated to investment potential and loans, which is again correlated with retrofitting behaviour. This creates a positive correlation between income and retrofitting behaviour. When nothing else is controlled for in the model, income positively affects retrofitting, but when the model adjusts for investment potential and loans, the effect is negative. This means that as long as households have the same amount of capital available for investment, low-income households retrofit more. I argue a likely explanation of this is that households experience monetary savings proportionately to their existing income. For example, a household with an combined income of NOK 1 000 000 could possibly not care about saving NOK 10 000 on electricity each year as much as a household with a combined income of NOK 300 000 does. The fact that high-income households have a somewhat lower environmental concern could also contribute to this finding (Bruderer Enzler & Diekmann, 2015). Again, cross-sectional data like this thesis is based on can not establish causal connections, and the proposed mechanisms are a possible interpretation of the data, not what the data shows. That being said, experimental manipulation of income is probably even more difficult than experimental energy retrofitting studies. This makes investigating this topic very difficult. A 'most likely' interpretation could be as close to an answer as we will get in some time.

The HERB model accounts for this suppression effect. Households start worrying about having sufficient capital for investing when the retrofit price approaches their current funds. Therefore, more available capital has a direct, positive effect on energy retrofitting. In terms of economic gain, however, households consider this in relation to their existing income. For example, households with a low income perceive saving 100 EUR in energy each month as more impactful than high-income households. Thus, a low income has a direct, positive effect on retrofitting. Yet this correlation is 'overruled' by income's strong association with available capital for investing. This creates an effect where the correlation between income and energy retrofitting is positive, even though the direct effect is negative.

Seemingly, making capital available to households through subsidized loans could be a good solution. Still, loaning schemes have been shown to have a low impact on retrofitting rates (Walls, 2014). It is reasonable to assume that low-income households could be hesitant towards accumulating debt to increase the energy standard of their households. Several psychological mechanisms support this. For example, research on present bias (Wang & Sloan, 2018) shows that humans prefer smaller, more immediate rewards over larger rewards in the future. Therefore, the energy saved in the future has a smaller impact than it 'objectively' has. Similarly, loss aversion (Kahneman & Tversky, 1979) should mean that the money invested or 'lost' in insulation is not emotionally proportional to the money gained from the energy saved in the future. Understandably, low-income households could be hesitant about spending money they do not have on projects that someone says should pay off in the long-term.

6.1.5. High accuracy of psychological predictions

A general yet important point to note is the high accuracy and strength of psychological predictors. For example, in the first article, psychological theory predicted a high correlation between previous and current energy retrofitting projects. Economic theory—and to some degree, logic—predicted a negative correlation. The correlation was shown to be positive and stronger than all other predictors, except for attitude. Additionally, the second and third strongest predictors of energy retrofitting were attitude and self-efficacy[2], respectively, not any demographic or economic variables.

Concerning the second paper, I could not include any demographic variables in the regression because I identified too few free-riders. The number of free-riders was so low that I could only include two variables, and I chose to include variables based on statistically significant variables in the original study (Studer & Rieder, 2019). Here, the only two statistically significant variables were psychological. Therefore, demographic variables were not included in the analysis and remain untested. One could argue that based on the Swiss study (Studer & Rieder, 2019), which tested several demographical variables and found none of them statistically significant, it is likely the same is true for Norway. But based on the huge differences in freeriding, 10% and 50%, this is a very uncertain assumption I would be hesitant

[2] It should be noted that attitude had a significant interaction effect, and the strength of a predictor variable in a regression with a significant interaction effect depends on the other variable in the interaction. For example, if there is a significant interaction between A and B, the effect of A is A+(AB). Therefore, this ranking of variables with a significant interaction is a simplification.

to communicate even to policymakers. Demographic variable's impact on Swiss retrofitting is low, in Norway they are untested.

Taken together, the research currently available suggests that psychological variables are more relevant for energy retrofitting behaviour than energy retrofitting than demographical ones. In Norway, psychological variables outperform demographics in predicting energy retrofitting behaviour, and in Switzerland, psychological variables outperform demographics when predicting free-riding. Therefore, psychological behavioural theory and research are highly relevant for energy retrofitting in general and should be utilized to a greater extent. Based on this, I argue that policies that aim to utilize psychological mechanisms rather than economic ones will likely have a higher impact. This will be the focus of the next section.

6.2. **Implications for policymaking**

Policymaking is a complex task, where several factors must be predicted and considered. It is important to note that this project does not claim it has the answer to what is considered the best policy. That being said, effective households energy retrofitting policymaking is about changing behaviour. When policies aim to change behaviour through soft measures such as incentives, information, and fees, they rely on voluntary behaviour. In other words, they are attempting to change human behaviour. Obviously, policies that rely on behavioural change will be more successful if they base themselves on research regarding what leads humans to change their behaviour. Concerning energy retrofitting, this could be said to have been somewhat overlooked. This project mainly investigates aspects such as continuous retrofitting, free-riding, and simulated policy settings, and the paper makes suggestions based on these aspects. When designing policies, other factors that this thesis will not cover must also be considered.

6.2.1. Inequality

This research project has shown that high-income households are retrofitting more than low-income households. Additionally, high-income households receive more subsidies than low-income households, even when accounting for the number of retrofits. This creates a situation where low-income households are not retrofitting, nor are they being subsidized to do so. As covered in Section 6.1.1, there also seems to be a lack of psychological mechanisms motivating low-income households to retrofit. This leads to a situation where the energy standard of low-income households is falling behind. This is both an issue for ethical and environmental reasons. Ethically, it results in increased economic inequality and hinders a fair and just energy transition (Heffron & McCauley, 2018; McCauley & Heffron, 2018; Pellegrini-

Masini et al., 2020). Environmentally, the subsidy system does not utilize the energy-saving potential of low-income households.

Although I show that the current subsidy system is not well-suited for low-income households, it is worth remembering that they do not aim to do this. As covered in Section 3.1.1, Enova's mandate does not include social or ethical aspects. Enova's current strategy is to support early movers so that energy retrofitting becomes cheaper, more competitive, and thus more accessible for everyone. Yet research shows that wealth inequality increases per capita emissions (Knight et al., 2017). Therefore, any policy deepening the wealth gap also increases carbon emissions. Naturally, the ultimate goal for the existence of Enova is not to increase the energy standard of households but to reduce carbon emissions. If Enova increases wealth inequality, it is effectively taking emissions from the household sector and giving them to wealth inequality. Therefore, any policy aiming to reduce carbon emissions must take into account its impact on wealth inequality. Otherwise, it is just moving emissions from one cause to another. It could be said that the current system does not account for this social phenomenon.

To avoid potentially moving emissions from one source to another, the subsidy system could benefit from being redesigned to focus more on low-income households. Several options are available. Similar to Swiss subsidies (Sigrist & Kessler, 2015), a minimum share of funding can be implemented. Here, the household is not eligible for subsidies if the project's cost exceeds a certain share of the subsidies. In Switzerland, this number is 20% (Sigrist & Kessler, 2015). For example, if the household is eligible for EUR 10 000, the project cost cannot exceed EUR 50 000. While this policy is intended to reduce free-riding, it could also restrict access to high-income households investing in exceptionally costly projects. Note that such a policy will most likely cut off funding for highly ambitious projects, where costs are comparatively high. The threshold for receiving subsidies will most likely remain unchanged.

Similar restrictions could be implemented concerning income. One could argue that Norway's top 20% wealthiest households can most likely afford to retrofit without subsidies. Excluding these households could reduce both free-riding and better distribute the subsidies to lower-income households, utilizing their potentially large energy savings. Some research should first be done on potential issues related to shame. For example, whether energy retrofitting could become associated with lower social status if subsidies were to be directed towards lower-income households remains a serious yet unexplored possibility. See Section 3.5.4, 'Shame', for an in-depth discussion on this. Additionally, removing the requirement that external contractors must perform the retrofit would most likely help low-income households more efficiently utilize the subsidies. Here, one must also consider that highly ambitious solutions would not be as commonplace, as homeowners do not have the same capacity to perform large-scale projects as a contractor.

Finally, one could argue that subsidies in themselves are not well-suited for low-income households. This is a problem because as long as only high-income households are subsidized, this increases wealth inequality, and low-income households' energy saving potential is not utilized. As long as subsidies cover less than 100% of the investment cost, households living 'hand-to-mouth' cannot participate without loaning money. See the section 'Retrofitting and income' for a discussion on why loaning money seems to be ineffective. Additionally, subsidies could be said not to utilize behavioural psychology to any meaningful extent. As a result, subsidies seem to have a smaller impact on energy efficiency than other methods (e.g., Butterworth et al., 2011; Stern, 1999). These methods will be discussed further in Section 6.2.3, 'Beyond subsidies'.

6.2.2. The representativeness of retrofit ratios

All of the papers in this thesis suggest that the annual share of retrofitted buildings is an inaccurate metric concerning building sector energy-consumption development. Firstly, a large share of the retrofits is performed on recently retrofitted households, inflating this number. Secondly, the retrofits are focused on high-income households, which could be already reasonably energy-efficient. This fits well with other research that criticizes the calculations behind other energy-saving projects, where the final project can be compared to a theoretical one that never came to fruition (Johansen et al., 2021). When Enova calculates energy savings, it relies on estimated savings from the project description, not actual measurements (Riksrevisjonen, 2015). When the Office of the Auditor General (Riksrevisjonen, 2015) estimated the subsidies' effect on work and industry buildings, they reached 0.68 TWh. Enova estimated the same effect at 3.6 TWh. For private households, Enova claims that it struggles to collect real data on more than half of completed projects due to non-responses to follow-up surveys. As far as I can tell, this has not changed. Thus, there is a clear disagreement on how to measure the actual effect of subsidies.

Agent-based models can address such impact assessments with multiple 'avenues of effect'. All dependent variables for the HERB model are energy use, not retrofitting rate. One of the future research goals of the HERB model is to estimate to which extent the retrofitting rate is correlated with energy development. If the 'wrong' households are undergoing retrofitting, it is fully possible to have a very high annual retrofit rate with minimal improvements to the actual energy use of the building stock. What matters to the world is the actual decrease in energy consumption, to which the annual retrofit rate is only partly associated. Additionally, several psychological mechanisms seem to be in place to ensure that the wrong households continue to retrofit continues. Prominent researchers in the field (Kahneman, 2012; Lilienfeld et al., 2009), and I, believe attempting to inform humans about these mechanisms so that they can become rational actors is futile. Other measurements must be adapted to ensure a valid metric concerning building energy standard development.

This project strongly argues that other metrics can and should be adopted. Extremely detailed information on households' energy use is stored in 'ElHub', a data hub that handles all measurement data and market processes in the Norwegian power market, including individual households' energy use. These data are stored on an hourly detail level for three years. Additionally, local cadastral maps with information on the building type, number of floors, and floor area are available to municipalities. With these two measures, researchers will have a very detailed kWh/(m^2a) measurement, which, coupled with surveys prompting for the last retrofit, should be able to pinpoint the actual development of the building stock with more validity than the annual retrofit rate.

As far as I can tell, the primary obstacle to retrieving these data seems to be data privacy and the non-existence of established routines. Currently, data can be requested from individual users from the ElHub servers from third parties, which the user must approve within 15 days (ElHub, 2018). Most likely, this method, where survey respondents must log into ElHub some days after the survey is complete, would lead to very high dropout rates. Therefore, alternative solutions such as consenting to share ElHub-data in the survey would have to be implemented to avoid severe dropout. In Norway, access to the cadastral maps, where information about residents, area, floors, and more are stored, is regulated by matrikkellova § 30, which Kartverket enforces. Whether or not these data are available for research purposes seems unclear. Kartverket has yet to respond to my enquiries concerning this.

6.2.3. Beyond subsidies

It could be argued whether distributing subsidies is the most effective use of public money to save energy through energy retrofitting. For example, the annual retrofitting rate in Norway is 3.37% (Fyhn, Berntsen, et al., 2019). For a European context, this could be considered high (Esser et al., 2019). The participation rate in the Scottish project 'Kirklees Warm Zone', where free energy audits and low-cost building envelopes were offered to inhabitants, was 32% (Long et al., 2015). A 32% participation is at least 10 years of Norwegian subsidized retrofitting, assuming households equally perform retrofits. This number increase to 20 years if one assumes that half of all retrofits are conducted by households that have retrofitted in the last three years, as paper one suggests. Naturally, Kirklees Warm Zone was done on a much smaller scale than national retrofitting policies, with only 133 714 households, (Butterworth et al., 2011). But in terms of costs, upscaling does not seem unreasonable. The Kirklees project cost £ 20.9 million (Butterworth et al., 2011). Upscaling the project to the entirety of Norway will cost 0.3% of the Norwegian national budget[3]. A hefty cost, but not unrealistic. Note that only upscaling the cost probably oversimplify several aspects of the project. Additionally, little is known about the retrofitting time after the project. I only want to want to point out that the impact of the project was large, and the costs were not unreasonably high.

Similarly, requests for energy audits jumped from 6% to 31% when the soliciting letter had a letterhead from the county and a signature from the chair of the county board of commissions (Miller and Ford, 1985, as cited in Stern, 1986). Although this only represented requested audits, a 31% participation rate is still far beyond any subsidy participation rate I have come across during this project.

Some arguments can be raised against the use of non-subsidy energy retrofit policies. Firstly, as mentioned above, the retrofitting rate is only one part of what leads to energy-efficient households. Which houses are retrofitted, and to which energy standards these houses are retrofitted, are equally important queries. These questions need to be addressed before confident claims about non-subsidy policies can be made. Secondly, subsidies are probably more politically popular than most other policies. This creates multi-partisan support for the policy, which would be simple to pass, even with parties that do not prioritize climate issues. Finally, a higher participation rate in the current subsidy model would not allow for expensive retrofitting measures, thus increasing demand for such measures and reducing the price of high-tech, not market-ready, energy retrofit measures. This, in turn, makes these measures more accessible. This is the primary stated purpose of the current Norwegian subsidy system (Enova, 2020).

Still, when looking at participation rates and their impact on energy savings, it is difficult to make a solid case for subsidies as a central policy measure to increase households' energy savings. Given the enormous potential for energy savings in private households, as well as the urgency of reducing energy consumption, it can be argued that applying methods that have been proven to work should take precedence over methods that have had their chance,

[3] Kirklee cost 20 900 000 £ = NOK 249 585 217. Number of households equal to 5.3% of Norway. Norwegian 2022 national state budget 1 553 000 000 000. (249 585 217 / 0.053) / 1 553 000 000 000 = 0.3%

regardless of how well the latter may fit the current paradigm. In general, such methods are under-researched, but some observations can be made.

First, both the Kirklees project and the letter study had state involvement. In the letter study, participation rates rose sharply only when state involvement was made clear. In Kirklees, the municipality was the organizer. Both schemes had very high participation rates. Although two studies are far from sufficient data to claim something with certainty, it is reasonable to believe that communicating state involvement in a scheme is beneficial. I believe it is reasonable to assume this effect is limited to areas where public trust is high.

Similarly, it seems that both projects had a limited timed offer. In Kirkless, the project was only going on for some time. In the letter study, participants likely thought the states' involvement was only for this project, not future projects. Private companies would always be available to offer energy retrofits, but state involvement was something new, and therefore most likely time-limited. This coincides with research findings suggesting that the feeling that 'the right time has not yet come', is a major barrier in household energy retrofitting (Klöckner & Nayum, 2016).

6.3. **Further research**

The largest identified research gap in this project could be the lack of research concerning policies and demographic or psychological variables predicting from or to which energy standards households retrofit. Firstly, this is of psychological interest, as it offers a rare instance of studying what factors lead households to choose one out of several (seemingly similar) options. For example, does the household decide to insulate the walls but not the roof because the neighbours did it, commercials promoted it, or the builder suggested it? Secondly, it is also highly relevant for policymaking. For example, upgrading from 200 to 80 kWh/(m^2a) has a far higher impact on energy consumption than upgrading from 100 to 30 kWh/(m^2a). Only looking at the annual retrofitting rate, however, offers only a partial picture. Such a project would require accurate energy use data and could include moderating factors on the rebound effect.

Furthermore, it seems like many psychological aspects are not fully explored in the literature. For example, different heating systems could have substantially different usage patterns. Traditional firewood heating is a perpetual opt-in system, where users must actively light and maintain the fire to create heat. This should, in theory, make households that employ firewood as their primary source of heating spend considerably less energy than households with heating systems with an on/off switch. In these systems, users much opt-in to turn them on, and more importantly, off. Despite this, during this project, I have seen no research or official document treating wood-fired heating different from other heat sources.

Similarly, psychological research could investigate ways to make people less hesitant towards using loans to finance their household's energy retrofitting projects. Which policy implementations could be relevant to make households better utilize loans? Possibly, households want assurance that their investment will pay off. This could be done by showcasing successful energy retrofits or governmental backing of certain measures. Since public trust in Norway is particularly high (OECD, 2021), this could be fruitful. As far as I am aware, no research on this topic exists. Regardless, increasing the use of loans for financing private households' retrofitting projects seems like a promising research avenue.

Another indirect way of using behavioural knowledge to reduce households' energy use through energy retrofitting is to reduce subsidies' central role in the policy landscape. Although the research is limited, other measures covered in Section 6.2.3 have shown more promising results, indicating that this could be a more fruitful approach. For example, free opt-out energy counselling and state-sponsored specific building envelop measures have shown far greater success than any subsidy system. While this could be because the only metric for measuring policy success has been retrofitting rates, it is more likely than not that a high retrofitting rate is indeed better than a low retrofitting rate. Regardless, even though the existing research is limited, it shows high potential and, in my opinion, should receive more attention from both researchers and policymakers.

Finally, there is a case to be made for the continued development of agent-based models on energy retrofitting. Agent-based models, where individual behaviour is modelled, are ideal gathering points for much decision-making and policy design research. These models can be continuously developed as new knowledge is being generated. Each new addition to the model adds to the model's ability to make specific policy suggestions. Thus, these models can provide policymakers with valuable information on what kind of policy should decrease households' energy use the most.

7. Concluding remarks

Comprising 17% of European final energy use, heating in private households is an essential factor that must be mitigated to create a more sustainable world. Private household energy retrofitting measures are almost completely dependent on individual behaviour. While regulations that set a minimum energy standard for new buildings can be introduced, it is very difficult to force households to undergo energy retrofitting. Therefore, behavioural research is vital in achieving meaningful reductions in households' energy use.

This thesis summarizes the research done throughout the project to help bridge the behavioural gap between energy retrofitting and political climate goals. Using existing psychological decision-making research, this work has (1) shown that attitude, self-efficacy, and recent energy retrofitting projects is associated with current energy retrofitting; (2) estimated Norwegian subsidy free-riding behaviour and explored ethical aspects of subsidy distribution; and (3) created a behavioural simulation of energy retrofitting, where policies can be tested.

I argue that a likely interpretation of my findings is that, similarly to most other behaviours, energy retrofitting is self-reinforcing, but more research is needed to confirm this. The thesis finds that an improved attitude and self-efficacy towards retrofitting is associated with more currently undergoing energy retrofitting measures. Based on the existing literature, I argue that a likely interpretation of this is because a positive attitude and self-efficacy lead to more energy retrofitting, and vice versa. Attitude towards Enova could also be a covariate in measuring free-riding through survey items, negatively affecting the measure's validity. Even though the validity is reduced, I argue that one can still claim significantly less free-riding on retrofitting subsidies in Norway than in Switzerland. This reduced free-riding does not, however, come freely, as the research also showed that high-income households receive most of the distributed subsidies. This leads to higher wealth inequality between households, which other research has shown is associated with higher carbon emissions.

The unequal distribution of households' subsidies could be addressed by either adjusting or completely redesigning energy retrofitting policies. Firstly, an income or project cost threshold could be implemented, reducing access to high-income households or excessively costly projects. Secondly, the policies could be redesigned to focus on affordable solutions where subsidies cover a larger share of the cost. This would make the subsidies more appealing to low-income households. Such a policy has been shown to be very effective (Butterworth et al., 2011). However, some questions on the correlation between retrofitting rates and the improvement of the building stock remain to be answered.

Agent-based modelling based on behavioural research, can help locate the most effective energy retrofit policy. If sufficiently developed, such models can assist in assessing how the suggested policy will affect energy use, retrofitting rates, inequality, continuous retrofitting, public spending, and more. I argue that if a policy shows a trait in the model, it is more likely than not to show this same trait in the real world. As long as the model is well-constructed and sufficient precautions are considered in its interpretation, models could be a helpful tool in developing energy retrofitting policies.

No matter what policies are developed, I argue they must account for human decision-making. All energy retrofit policies that do not account for this will be far less efficient than policies that do. Human decision-making is complex, and designing policies that account for this is difficult. I hope this thesis makes the task of generating such policies easier.

8. References

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9. Appendix

9.1. Paper 1

9.2. Paper 2

9.3. Paper 3

9.4. ODD Protocol

9.5. Statistical scripts

Paper I

Energy Policy 157 (2021) 112451

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Temporal spillover of private housing energy retrofitting: Distribution of home energy retrofits and implications for subsidy policies☆

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ARTICLE INFO

Keywords:
Energy efficient renovations
Energy retrofitting
Spillover
Decision mode theory
Sustainability
Subsidies

ABSTRACT

Energy retrofitting of private housing is fundamental to reducing the environmental footprint of the building stock, and energy efficiency policies are based on assumptions of the effects of retrofitting, including those on further retrofitting, also called temporal spillover. No study has directly investigated the impact of energy retrofitting on future energy retrofits.

Our results (N = 6402) show that respondents who completed energy retrofits in the past three years are significantly more likely to undertake new energy retrofits (IRR = 3.449). This is also true when controlling for demographic variables (IRR = 2.752), attitude and self-efficacy. Younger age, lower income, higher investment capacity, a more positive attitude, and higher self-efficacy toward retrofitting are associated with more energy retrofits.

Since a strong temporal spillover effect is present in energy retrofitting, we suggest that locking in the energy building standard to a suboptimal level after partial retrofitting is not as great a challenge as previously thought. Moreover, due to the distribution of retrofits, the average number of retrofits undertaken is a misleading indicator of the trends in a nation's building stock, and subsidizing small scale-retrofits may provide major benefits for households' overall environmental footprint.

1. Introduction

In 2017, households represented 27.2% of the final energy consumption in the EU. On average, 64.1% of a household's energy consumption is used for space heating (Eurostat, 2019). Reducing residential energy need for heating is therefore crucial to reducing energy use and lowering greenhouse gas (GHG) emissions in the EU and beyond. Apart from increasing the energy standard for new buildings, upgrading the insulation of existing homes is the most important strategy for energy conservation in buildings (Verbeeck and Hens, 2005) because they account for a substantial amount of the building stock for decades to come. To encourage building energy conservation, governmental bodies often offer substantial subsidies for insulating private homes. How these subsidies are distributed is based on several premises, often making predictions about "post-retrofitting" effects. These include topics such as how much energy will be saved as a result of retrofitting, but also how a retrofit will affect future implementations of other energy-saving measures. To fully understand the benefits and challenges, both technical and behavioral sciences are central to studying the effect of private household energy retrofits.

Within technical research, the "lock-in" effect has been prominently discussed (Dubois and Allacker, 2015; Risholt and Berker, 2013; Weiss et al., 2012). This effect refers to the idea that once a retrofit is completed, further projects are less likely to start, thus "locking in" the current energy standard for a longer period of time (Urge-Vorsatz et al., 2013). For example, if a household invests EUR 20,000 on improving wall insulation, it cannot later decide to remove the insulation and get the money back; the capital is locked in and cannot be spent on other, potentially more energy-saving, measures. Issues related to lock-in can quickly add up. For example, if a household invests in an energy-efficient boiler then later invests in insulating the roof, the boiler may become too large for the household, as it was originally intended for a house with greater heat loss. Regarding policy design, most research discussing technical lock-in suggests subsidizing large-scale energy retrofits – ideally combining different types of measures in one large retrofit project – that aim for a high energy standard to avoid this problem (eg. Risholt and Berker, 2013; Weiss et al., 2012). This is especially important in colder climates, where high energy standards

☆ 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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https://doi.org/10.1016/j.enpol.2021.112451
Received 20 July 2020; Received in revised form 4 June 2021; Accepted 28 June 2021
Available online 6 August 2021

usually save more energy than in warmer climates (Al-Sallal, 2003). However, technical arguments can be made against the focus on large-scale retrofits. In energy retrofitting, an exponentially growing cost per saved kWh/(m^2a) ratio exists (Galvin, 2010). Investing a given amount of capital on upgrading as many houses as possible to an energy standard of 150 kWh/(m^2a) will save significantly more kWh and GHG emissions than investing the same amount of capital in upgrading only some houses to 15 kWh/(m^2a). In Norway, where the average energy consumption in buildings is 210–220 kWh/(m^2a) (Economidou et al., 2011), energy retrofits must achieve an energy use of less than 120+(1600/m^2) kWh/(m^2a) to be eligible for government subsidies[1] (ENOVA, 2019). Households that achieve energy ratings of 80+(1600/m^2) kWh/(m^2a) are eligible for higher subsidies, which suggests that highly ambitious energy retrofits are prioritized. However, the Norwegian energy retrofit rate is at a standstill compared to four years ago, with a yearly energy retrofitting rate of about 3.4% (Fyhn et al., 2019). While technical arguments regarding energy retrofitting are important, we argue that the literature often overlooks potential behavioral outcomes of completing an energy retrofit.

1.1. Spillover effect

The most relevant branch of behavioral research concerning energy retrofitting could be said to be the field of pro-environmental behavioral spillover. A classic pro-environmental spillover effect shows that participants incentivized to purchase "green" products also show changes in other, non-incentivized pro-environmental behaviors (Lanzini and Thøgersen, 2014). The definition of the effect varies; some define it as "an effect of an intervention on subsequent behaviors not targeted by the intervention" (Truelove et al., 2014). Others define it as "the extent to which engaging in one behavior influences the probability of conducting a subsequent behavior" (Nilsson et al., 2017). Note that the former definition requires an intervention to be in place, while the latter does not. We argue that even though it is methodologically advantageous to limit the effect to comparing pre- and post-intervention spillover to detect causality, excluding all non-intervention studies makes research into capital-intensive pro-environmental behavior difficult. Naturally, the resources required to produce sufficient intervention subsidies to incentivize participants to buy organic food are much smaller than those required to sufficiently incentivize participants to undertake energy retrofitting. All but the most exceptionally well-funded research on energy retrofitting spillover must therefore be conducted with no intervention. For the purpose of this paper, we thus define the spillover effect as the extent to which engaging in one behavior influences the probability of engaging in a subsequent behavior (from Nilsson et al., 2017).

The concept of spillover has significant overlap with the rebound effect, which also deals with behavioral responses to energy efficiency (Berkhout et al, 2000; Sorrell et al., 2018). A key difference is that rebound is, per definition, negative, while spillover can be positive. For example, someone who raises the indoor temperature after an energy retrofitting is displaying a rebound effect. A rebound effect can be direct, such as driving more miles in a fuel-efficient vehicle, or indirect, such as using the money saved on gas to buy more clothes. While there is a large overlap in the effects of rebound and spillover (despite some disagreement: Dolan and Galizzi, 2015), it could be said that literature defining the phenomenon as spillover focuses on behavioral psychology, while literature defining it as rebound focuses on economics. This paper will focus on spillover.

[1] 120 plus 1600 divided by square meters of a building, which allows for somewhat higher kWh/(m^2a) in smaller buildings, as they have a higher surface-to-volume ratio. For example, a 50 m^2 house must reach 120+(1600/50) = 152 kWh/(m^2a) to be eligible for subsidies. A 400 m^2 house must reach 120+(1600/400) = 124 kWh/(m^2a).

1.1.1. Direction and mechanisms

The effects of pro-environmental spillover can be classified as either positive or negative, and the three types of relationship to the subsequent behavior as contextual, temporal or behavioral. First, the direction of the spillover concerns how the initial promotion affects subsequent pro-environmental behaviors (Thøgersen, 1999). If the adoption of a second pro-environmental behavior increases, such as increased recycling rates after being incentivized to bike to work, this is defined as a positive environmental spillover. If the adoption of a second pro-environmental behavior decreases, such as increased air travel after donating to a fund supporting local wildlife conservation, this is defined as a negative environmental spillover. Second, the type of spillover describes the relationship between the original behavior and the subsequent behavior (Nilsson et al., 2017). If the subsequent behavior differs from the original behavior, such as recycling and raising indoor temperature settings, this is defined as behavioral spillover. If the behaviors are the same but the effect is shown at different times, such as the number of flights booked from one year to the next, this is defined as temporal spillover. If the behaviors vary in context, such as eating habits at work and home, this is defined as contextual spillover. The direction and type of spillover can be combined in any order; for example, a positive contextual spillover such as recycling at work and at home (shown by Andersson et al., 2012) or a negative behavioral spillover such as reduced altruism after purchasing green products (shown by Mazar and Zhong, 2010). It should be noted that the distinction between types of relationship between behaviors in spillover is not as established as the direction of spillover, but we find the typology well defined, as well as useful for the purpose of this article.

The cognitive mechanisms generating spillover effects are not entirely agreed upon, but some processes are generally believed to be central. There is general agreement that people's need for consistency, mediated through cognitive dissonance or self-perception, is central to positive spillover (Maki et al., 2019; Nilsson et al., 2017; Truelove et al., 2014). Cognitive dissonance theory (Festinger, 1957) states that when a person experiences two or more opposing thoughts or behaviors, such as thinking "I don't care about the environment" and spending EUR 20,000 on an energy retrofit, the person will experience mental discomfort. The person will try to resolve the inconsistency by either starting to care about the environment or rationalize the behavior with a thought that reduces the inconsistency, such as "I think energy retrofitting is a good thing regardless of environment. I do it for my own comfort and financial energy savings." This could lead to individuals viewing their retrofitting process in a more favorable light. It could also lead people to see themselves as more environmentally friendly because they are undertaking an energy retrofit, which can in turn lead to in spillover to other environmental behaviors.

Self-perception theory (Bem, 1972) proposes that individuals look to their own behavior to shape their attitudes, emotions and other internal states. For example, someone who helps a turtle to cross a busy street will come to see themself as more concerned about animal welfare than about people not encountering the turtle in the first place. Similarly, homeowners who are, for whatever reason, energy retrofitting their home, will shape their attitudes, emotions and other internal states to justify that behavior. This may result in more pro-environmental behavior being conducted, and thus produce positive spillover.

Regarding negative spillover, different cognitive mechanisms seem to be in play. A "moral licensing" effect seems to be the most commonly accepted (Maki et al., 2019; Nilsson et al., 2017; Truelove et al., 2014). Moral licensing theory claims that a prior good deed provides a "license" that allows one to perform morally questionable behavior later on (Blanken, van de Ven and Zeelenberg, 2015). The effect occurs regardless of whether a participant actually performed the morally good act, is reminded of a morally good act they once performed, or even just imagined performing a morally good act. For example, if homeowners see their own energy retrofitting as a moral act, they may think they have "done their fair share" and can therefore adopt other, non-sustainable, behaviors.

Some cognitive mechanisms not usually associated with spillover but still relevant to private household energy retrofit spillover are worth mentioning. The "peak-end rule" states that how much people retrospectively enjoyed an experience is based mostly on the peak and the final emotion in that experience (Kahneman et al., 1993). When exposed to a 60-s painful stimulus, and subsequently to the same 60-s painful stimulus followed by a 30-s mildly painful stimulus, participants prefer the latter scenario. The peak-end rule is also supported in pleasurable experiences (Do et al., 2008). It has received less support for longer experiences such as holidays, but the same research also suggests that holidays are consistently remembered as more pleasurable after the experience than during it (Kemp et al., 2008). While one should be careful in applying theory to areas where the theory is not yet investigated, there are grounds to speculate that homeowners remember their energy retrofit as more pleasurable than they actually were during the retrofit if the overall result of the endeavor is to their liking.

Finally, self-efficacy is a likely factor in positive spillover. Self-efficacy is conceptualized as the appraisal of one's capability to mobilize motivational, cognitive resources and of the behavior required to cope with an expected situation (Lauren et al., 2016). It has been found to influence academic performance (Talsma et al., 2018), job burnout (Shoji et al., 2016) and self-regulated learning (Panadero et al., 2017), and is a central part of the much applied theory of planned behavior (Ajzen, 1991). In general, the findings show that if someone believes they are able to do something, the likelihood of their doing it increases. Self-efficacy has been shown to mediate behavioral spillover from easy to hard behavior (Lauren et al., 2016), but we can find no research relating to temporal spillover or spillover from hard to hard behavior.

The difficulty of agreeing on a common set of cognitive mechanisms to explain pro-environmental spillover could be amplified by the fact that spillover is not a mechanism in itself, but rather an outcome. This outcome is likely a result of multiple cognitive mechanisms which vary in their relevance depending on context.

1.1.2. *Decision mode theory*

Although theories exist regarding the different cognitive mechanisms resulting in spillover, they provide little ground for predicting the presence and direction of spillover. For example, the abovementioned theories do not predict whether a pro-environmental behavior leads to positive spillover through a consistency effect, or to negative spillover through moral licensing. Decision mode theory (Truelove et al., 2014) fills this gap by predicting the presence, direction and strength of environmental spillover. The theory suggests that the decision mode in which the initial decision was taken, and subsequent attribution of one's behavior, combined with moderating variables, predicts the direction and strength of subsequent spillover. The theory postulates three modes: calculation-based, affect-based, and rule- and role-based decisions. Calculation-based decisions are based on an analytic cost–benefit processing of available actions, meaning no consistent spillover should be present. By "consistent", the theory suggests that person-specific spillover is present, but it can be both positive or negative depending on the individual, making it difficult to statistically identify any general spillover across populations. Affect-based decisions are made on an emotional basis, such as amending actions in the face of guilt. Action is taken in response to a negative mood, and once that mood is removed, no further action is taken. This suggests that promoting pro-environmental behavior with negative emotions, such as showing chainsaws cutting down habitats of cute koala bears, will likely cause negative spillover as soon as the negative affect is removed. Finally, rule- and role-based decisions are based on rules of conduct derived from a social role of the individual. To act out the behavior associated with a role will then reinforce the role, resulting in positive spillover. For example, an environmentalist advocating for biodiversity at a social event will reinforce their image as an environmentalist, resulting in other pro-environmental behaviors.

As moderating factors, choice model theory suggests difficulty, similarity of behaviors, and attribution (Truelove et al., 2014). Regarding difficulty, the order of difficulty is suggested as important. If someone performs a difficult initial pro-environmental behavior, this is likely to result in positive spillover. A difficult secondary behavior[2] has a higher likelihood of causing negative spillover. Regarding behavioral similarity, when behaviors contribute to the same goal, such as turning off lights and lowering the indoor temperature for the sake of conserving energy, spillover is more likely to occur. The direction depends on the decision mode. In negative affect-based decisions, negative spillover is amplified, and in role-based decisions, positive spillover is amplified. Finally, decision mode theory suggests that post-decision causal attribution to either internal or external causes affects spillover, where external attribution causes negative spillover and internal attribution causes positive spillover.

1.2. *Spillover of energy retrofits*

Based on decision mode theory, it is possible to make some predictions regarding spillover effects of private housing energy retrofitting. We consider energy retrofitting to be a high-difficulty, calculation-based behavior, with little similarity to other environmental behaviors, with some external attribution due to subsidies and financial gain, and which could by some individuals be seen not as environmental behavior at all. First, we judge contextual spillover to be nonexistent in most countries, as the vast majority of individuals only have one home to retrofit. Retrofitting of subsequent homes when moving house could be said to be defined as temporal spillover. That being said, contextual spillover is likely more relevant in countries with prevalent secondary homes, such as cabins in Norway. If strong contextual spillover exists, subsidizing or otherwise motivating cabin retrofitting, familiarizing the owner with the retrofitting process, could be a cheap way of increasing home energy retrofitting rates. Furthermore, contextual spillover could play a role in landlords' decisions to retrofit their own homes as well as their rental properties, and thus lead to temporal spillover in those properties. Although Norway has a high percentage (80%) of owner-occupied households, this ratio is dropping, similar to the trend in the EU (Eurostat, 2020). As this trend continues, non-owner-occupied households' energy retrofitting behavior should receive increased attention. However, due to the lack of research into cabin energy retrofitting and the still developing state of spillover theory, few predictions can be made and more research is needed regarding possible spillover between households, cabins, and rental apartments. Behavioral spillover is most likely more than normally varying, but on average nonexistent to slightly negative. According to choice model theory, spillover will be nonexistent if people undertake energy retrofitting as a primarily pro-environmental behavior. If people see it as an investment in comfort and/or as a financial investment, positive and negative spillover will be present, averaging to net no spillover. If seen as a status gain, positive spillover will be present.

Decision mode theory predicts that incentives for the initial behavior increase negative spillover (Truelove et al., 2014). Many countries offer economical incentives for energy retrofits, which could contribute to negative spillover. However, contrary to decision mode theory, we argue that external economic incentives in the present do not reduce intrinsic motivation for energy retrofitting. Meta analyses show that negative effects of external rewards for intrinsic motivation are only present in very specific, somewhat unrealistic, scenarios, such being rewarded for doing a task, but with no requirement to complete the task in order to receive it (Cameron et al., 2001). When participants are required to complete a task or surpass a set score, as is the case in many

[2] The behavior affected by the spillover, for example raising the indoor thermostat after energy retrofitting. Energy retrofitting is the primary behavior, raising the indoor temperature is the secondary behavior.

energy retrofit subsidy schemes, no effect on behavioral motivation can be found, and self-reported task interest *increases*. Therefore, we argue that the relationship between intrinsic motivation and external rewards is more complicated, and probably weaker than decision mode theory suggests. As pointed out by Cameron et al. (2001), the only consistent finding between external rewards and intrinsic motivation is that it is an enduring myth in the literature. Regarding energy retrofits, we argue that it most likely has no effect.

The most interesting question from our perspective on spillover and retrofitting is whether energy retrofitting has a positive, negative, or no temporal spillover effect. In other words: does energy retrofitting lead to more energy retrofitting? The literature surrounding technical lock-in suggests that energy retrofitting leads to less retrofitting in the future, as it becomes less economically viable and less funds are available. In other words, a negative temporal spillover in energy retrofitting. Choice model theory predicts varying directions of spillover based on three factors. First, it suggests that because the initial behavior is hard, positive spillover occurs. But second, since the subsequent behavior (which is essentially the same behavior) can also be considered hard, negative spillover also occurs. Third, since attributing the retrofit to non-environmental factors such as comfort and monetary gains is likely, negative temporal spillover should also be present. Finally, it predicts that the behavioral similarity and consistency effect do not influence spillover in energy retrofitting, since it is a calculation-based decision.

Two points are important to note. First, choice model theory does not specify the type of spillover, but generally appears to mostly concern behavioral spillover. Temporal spillover could likely rely on somewhat different cognitive mechanics. For difficult calculation-based initial pro-environmental behaviors, retrofit-specific self-efficacy is a likely contributor, since performing the retrofitting should familiarize, and therefore ease, the process during subsequent retrofits. Second, choice model theory specifies that difficult secondary behaviors could increase negative spillover. However, while energy retrofitting is certainly not an easy behavior, the second time someone undertakes an energy retrofit is more likely to be *relatively* easier than the first, since the individual will be more familiar with the retrofitting process. To summarize, decision mode theory could be said to predict a weak negative spillover effect in energy retrofitting based on external motivation and behavioral difficulty. Based on the relative difficulty of the initial and subsequent retrofitting, probably mediated by self-efficacy as well as questioning the effect of external motivation, we predict that a weak positive spillover effect is present.

1.3. Existing research

To the best of our knowledge, no study has directly investigated a temporal spillover effect in private housing energy retrofitting. Other related research findings have nonetheless investigated the issues indirectly. Tenants have described living in retrofits as difficult and disruptive (Sunikka-Blank et al., 2012), and disruption is mentioned as a key barrier to retrofitting both office buildings (Jones, 2013) and railroad stations (Kelsey, 2003). While it seems intuitive that the same should apply to homeowners, what little research can be found on the topic suggests instead that owner-occupied renovation is “a memorable emotive user experience, whereby satisfaction may be gained from learning new skills, completing a task or gaining a better home” (Haines and Mitchell, 2014, p. 467). This could suggest that energy retrofitting is subject to the peak-end rule, as well as to positive temporal spillover. Moreover, Swedish respondents were more likely to prefer household energy-saving strategies that required investment over non-investment strategies when they had replaced building components during the past two to 10 years (Nair et al., 2010). Although Nair et al. do not further discuss this finding in their article, it suggests that some individuals are more inclined to energy retrofit, or points to a likely positive temporal spillover effect in energy retrofits.

1.4. Sustainability

Some points can be made regarding the sustainability of private household energy retrofitting. Household purchasing power, and therefore environmental footprints, should be considered as a potential impact on housing retrofitting. When tracing the origin of products’ carbon, land, material, and water footprint back to households, total household expenditure explains 83, 49, 85, and 54 percent of total footprint variance, respectively (Ivanova et al., 2016), suggesting that these aspects are strongly related to expenditure. Naturally, reducing household income is a politically unpopular approach, but reallocating household spending to smaller, or even negative, footprint activities, such as energy retrofits, could have large impacts. Not only is the energy retrofit reducing the environmental footprint of the building itself, but it is also reducing the environmental footprint of capital which would otherwise most likely be spent elsewhere on larger footprint activities, such as mobility or clothing (Ivanova et al., 2016). Controversially, if temporal spillover in house energy retrofitting is not a phenomenon, this may indicate that economically optimal solutions with short payback times will increase the environmental footprint of the household, as money will be saved in the long term. Furthermore, non-optimal economical approaches, such as successive small-scale retrofitting, which is more costly, might have environmental advantages due to lost household purchasing power. It is possible that the money lost to successive retrofitting would be allocated to retrofitting regardless, and to maximize the energy savings, the most effective retrofitting methods should be chosen. But this depends on whether people first decide how much money to allocate to retrofitting and then decide the method, or whether they first decide on the retrofitting method and then allocate the funds. Behavioral models on retrofitting decisions suggest that decisions on what to do are made before decisions on how to do it, and economic resources are mostly relevant after decisions on what to do have been reached (Klöckner and Nayum, 2016). This suggests that decisions on what to retrofit primarily come before decisions on how much capital is allocated, and not the other way around. Ultimately, successive retrofitting could result in a lower housing energy standard if more plans than capital are available, or in the same energy standard if more capital than plans is available. Nevertheless, a higher cost of retrofitting should not be seen as a purely negative factor, and it is still highly relevant to see whether successive retrofitting, or temporal spillover in energy retrofitting, is a phenomenon.

Finally, temporal spillover in private home energy retrofitting has both local and global policy implications. Private house retrofitting has direct consequences for UN Sustainable Development Goal (SDG) 7: Affordable and clean energy, as well as for SDG 13: Climate action (Sachs et al., 2019). Energy retrofitting will affect energy-related CO_2 emissions per capita, which is a SDG 13 indicator. Additionally, reduced energy demand for heating as a direct effect of energy retrofitting will reduce the overall demand on the energy grid, making it easier to increase the share of renewable energy in total final energy consumption, which is a SDG 7 indicator.

Because energy retrofitting is an important piece in the sustainable development puzzle, we decided to investigate temporal spillover in private housing retrofitting. To do this, we study the relationship between recently completed, planned, and currently ongoing energy retrofits, controlling for demographic and psychological variables. We predict that the number of recently completed retrofits will be significantly related to the number of currently ongoing or completed retrofits. In line with self-perception theory, we predict that the attitude towards retrofitting will be affected by the adoption of retrofitting behavior, and that, regarding behavioral difficulty, self-efficacy from the learning experience will increase. We predict that more positive attitudes will predict more retrofitting, and so will higher self-efficacy.

2. Methods

Data were analyzed from two surveys administered to representative samples of Norwegian households between January and March 2014 and between March and April 2019. The surveys had 2605 and 3797 respondents, respectively, and were pooled for the analyses reported in this paper, forming a total sample of 6402 respondents. The surveys were distributed independent of each other, and we cannot know whether some respondents answered both surveys, but the likelihood is very small. The data were originally collected for and funded by Enova SF to investigate trends in private housing energy retrofitting in Norway. Analyses based on the older dataset were published elsewhere, but temporal spillover in energy retrofitting was not investigated in those papers (Fyhn et al., 2019; Klöckner, 2014; Klöckner and Nayum, 2015). Because the survey design does not allow tenants to answer questions about investment potential, which was a variable we wanted to include in the model, tenants were excluded from the dataset.

Both surveys contained questions about whether respondents were planning, were currently undertaking or had completed significant renovations of their basement/floors, walls, windows or roof in the preceding or coming three years. Respondents who answered yes to any of these questions were asked whether they had increased or were planning to increase the standard of insulation as a part of the renovation. Parts of the house with both renovation and insulation measures were marked to indicate where an energy retrofit measure was currently being undertaken, was planned or was completed. This made it possible to identify up to four types of energy retrofit measures in the house that were planned, were currently ongoing or that were completed. The maximum of four types of measure is a result of that the survey only prompted for these measures. All variables were self-reported. For example, if a respondent stated that they were currently renovating walls and floors but were only adding insulation to the floor, this project counted as one energy retrofit measure. To avoid counting smaller projects, such as installing a single energy-efficient window while installing new roof tiles, only renovations involving insulation being installed in a specific area of the house were counted.

2.1. Statistical analysis

We employed weighted multiple imputations to deal with missing data points (as suggested by Schafer and Graham, 2002) and negative binomial regression modeling to analyze the data. Income and loan data from 2014 were multiplied by the difference in consumer price index to match the 2019 data (SSB, 2020), and converted from NOK to EUR to ease international readability. Data were weighted to adjust the sample to match age, gender, and living arrangement to the population (SSB, 2017). The dataset, complete with a full statistical process featuring comments on smaller methodological choices, is available as a Stata do file at https://data.mendeley.com/ https://doi.org/10.17632/vmyn94prrr.1. To preserve the anonymity of the respondents, location data not employed in the analysis have been removed, and location data employed in the analysis have been replaced with the names of random locations taken from the *Lord of the Rings* fantasy universe. This should help maintain the anonymity of the respondents while maintaining the replicability of the statistical analysis. The studies' attitude and self-efficacy scales were aggregated from individual items in the survey, reaching a Cronbach alpha of .93 and .63, respectively. See the accompanying syntax and dataset files for details.

2.1.1. Multiple imputation

Multiple imputation was employed to impute missing income, loan, and energy retrofit investment capacity values. Multiple imputation is a statistical method developed to handle missing data, primarily in surveys (Rubin, 1987). Usually, one cannot assume that non-responses are random. For example, high-income and low-income groups often do not list their income in surveys, resulting in less variability in reported income than what is actually the case. With multiple imputation, we apply statistical methods, usually regression, on other non-missing data such as age, gender, country, education, and occupation to make an "educated guess" of the respondent's income or, more precisely, of a distribution of likely values for the person. Multiple imputation also accounts for the uncertainty of these educated guesses by creating several datasets where the estimated data vary as several values are drawn from the distribution of likely values (Rubin, 1987). We employed multiple imputations because we wanted to use household income, loan, and investment capacity as predictor variables, which we expected would be important variables to the final analysis. These variables had a lot of missing data points and would represent both a large loss of respondents and a skewed sample if we had applied less elaborate methods to handle missing data, such as listwise deletion. To impute household income, loan, and investment capacity, we used information on how many people in the household contributed to income, the personal gross income category, age, education, ownership status of the residence, county, sex, main source of income, living situation, renovation measures completed in the past three years (regardless of energy-saving implementations), and current energy retrofits completed, planned, and ongoing. This allowed for imputation of 71% of missing cases. We believe this created a good estimate of household income, loans, and loaning capacity. Following the rule of thumb of applying a number of imputations equal to or larger than 100 times the largest fraction of missing information, which in our data was 0.34 (StataCorp, 2019), 50 imputations were applied. In the following regression, all Monte Carlo error estimates were less than 10% of the standard error of imputed variables, and Monte Carlo estimates of p were less than approximately .01 when the true p-value was .05, satisfying literature guidelines concerning sufficient number of imputations (White et al., 2011).

2.1.2. Regression model

We employed a negative binomial regression model to analyze the data. We chose this model because the data had a large number of zeros in the primary outcome variable "currently ongoing energy retrofits". Since our income, loan, realistic investment, and house size and age variables showed little resemblance to a normal distribution, we transformed them using the square and logarithmic functions to achieve a better model fit. Which transformation was applied to which variable is indicated in Table 3. The coefficient (C) in a negative binominal regression is the difference in the logs of expected counts of the response variable for every one unit change in the predictor variable. To receive coefficients that were easier to interpret, we recalculated the coefficients to incidence rate ratios. For each point difference in the variable, the expected outcome variable was multiplied by the incidence rate ratio. For example, a variable with an incidence rate ratio of 2 would mean a doubling of expected energy retrofits for each one-point increase in that variable. For an estimate of the explanatory power of the three models, we also retrieved the mean McFadden's pseudo explained variance from all individual regression models across all 50 imputations. This number gives a solid indication of what share of retrofitting behavior is explained by the three different models. Finally, we ran the analysis with standardized variables (Z) so that the influence of each variable could be compared with the others. A variable with a Z of 2 will have a larger impact on the dependent variable than a variable with a Z of 1.

To show the effect of different sets of variables, we generated three models. In the first model, we only show the connection between previously undertaken energy retrofits and currently ongoing energy retrofits. For the second model, we added demographic variables as covariates, which allows for assumptions of an energy retrofitting spillover effect where demographic variables are controlled for. In the third model, we looked for an interaction effect between attitudes toward energy retrofitting, self-efficacy and previously undertaken energy retrofits. This was done to investigate whether potential variables suggested in the spillover literature could influence the relationship. All models had an alpha value of more than 2.5, suggesting that the numbers of zeros were indeed large and that negative binomial modeling was appropriate. Variables in the interactive terms were centered to avoid artificially inflating the main effects. Centering was performed by subtracting the mean of the variable from each value. Weighted descriptive statistics for the sample are presented in Table 1. When weighted, the gender ratio was 50%.

3. Results

Table 2 shows the percentages of respondents who were currently undertaking or planning an energy retrofit, respondents who had completed an energy retrofit in the past three years, and of respondents who had not.

Three negative binomial regression models predicting currently ongoing energy retrofits are presented in Table 3. Model 1 includes only previous energy retrofits, model 2 adds demographic data, and model 3 adds an interactive term between previously undertaken energy retrofits and attitudes and self-efficacy toward energy retrofitting.

Because interaction effects are difficult to interpret by only looking at the numbers, the predicted incidence rate of the significant attitude and previous energy retrofits interaction effect are plotted in Fig. 1.

4. Discussion

Our results show that the number of previous retrofits is strongly and positively associated with the number of currently ongoing retrofits. Frequencies of energy retrofits presented in Table 2 suggest there is a strong connection between the number of recently completed retrofits and both planned and currently ongoing retrofits. Only 1.7% of respondents who have not undertaken any energy retrofits in the past three years are currently undertaking one or more energy retrofits. By comparison, 11.9% of respondents who have undertaken one or more energy retrofit in the past three years are also currently undertaking a retrofit. Comparing the two groups, a respondent who undertook retrofitting in the past three years is seven times more likely to be currently undertaking one than a respondent who did not undertake a retrofit in the past three years. According to our data, 50% of all currently ongoing energy retrofit measures are being undertaken in households that were retrofitted in the past three years.[3] This implies that retrofits in Norway are generally done piecemeal and that energy retrofitting is in itself a self-reinforcing process.

Table 1
Weighted means and standard deviations of the sample.

Variable	Mean	Standard deviation
Age	50	16
Energy retrofits in the past three years	0.15	0.48
Currently ongoing energy retrofits	0.04	0.25
Size of house m^2, logarithmic	4.8	0.5
Age of house, logarithmic	3.6	0.8
Attitude toward retrofitting	20	6
Self-efficacy toward retrofitting	9	4
Household income, EUR square root	298 (301)[a]	80 (80)[a]
Household loans, EUR square root	375 (398)[a]	168 (165)[a]
Realistic investment, EUR square root	170 (178)[a]	119 (119)[a]

[a] Numbers in brackets represent pre-imputation data. In attitude and self-efficacy numbers, larger means higher.

[3] Calculated from Table 2 by multiplying n with the percentage and number of retrofits, resulting in 103 currently ongoing retrofit measures for the group that did not undertake any energy retrofits in the past three years, and 102 measures for the group that did.

Table 2
Percentages of respondents currently planning or undertaking energy retrofits.

	Has not completed any energy retrofits in the past three years. n = 4908	Has completed one or more energy retrofits in the past three years. n = 578
No planned energy retrofit	90.1%	77.0%
One planned energy retrofit	7.5%	14.9%
Two planned energy retrofits	1.8%	5.5%
Three planned energy retrofits	0.5%	0.7%
Four planned energy retrofits	0.2%	0.6%
No current energy retrofits	98.3%	88.1%
One current energy retrofit	1.4%	8.0%
Two current energy retrofits	0.2%	2.8%
Three current energy retrofits	0.1%	0.7%
Four current energy retrofits	0.0%	0.5%

4.1. Explanation of results

Our regression models show that having undertaken an energy retrofit in the past three years is significantly and positively associated with currently undertaking an energy retrofit. This supports the existence of a temporal spillover effect in private household energy retrofitting, whereby retrofitting could lead to more retrofitting. When no variables are controlled for, a one-point increase in the number of energy retrofits undertaken in the past three years is associated with a 245-percent increase in expected number of currently ongoing energy retrofits. When the demographic variables age, gender, income, current financial loans, size of house, and age of house are accounted for, undertaking one energy retrofitting measure in the past three years is associated with a 175-percent increase in the expected number of currently ongoing energy retrofits. Younger age of the respondent, lower household income, and higher perceived realistic investment potential in energy retrofitting are significantly associated with an increased number of currently ongoing energy retrofitting measures. Owning a larger and older house is also related to an increased number of currently ongoing retrofits, but this relationship is not statistically significant when accounting for the psychological variables in Model 3. The model shows no significant interaction between self-efficacy and previously undertaken energy retrofits, only a direct effect of self-efficacy, where higher self-efficacy predicts more currently ongoing energy retrofits. Regarding the effect of attitude, there is little or no difference in the expected number of retrofits for individuals with low or average attitudes toward retrofitting or for individuals who have not undertaken any energy retrofits in the past three years. Amongst respondents who have not undertaken energy retrofit measures in the past three years, only participants with a very favorable attitude toward retrofitting see a meaningful increase in their expected number of currently ongoing retrofits. When more retrofits have been undertaken, attitude seems to play a larger role. When two retrofit measures have been undertaken, a close linear relationship in attitude toward retrofitting and expected number of energy retrofits can be observed. Interestingly, there is a negative relationship between expected number of energy retrofit measures and attitude when three energy retrofit measures have

Table 3
Three models predicting currently ongoing energy retrofits.

	Model 1		Model 2		Model 2	
McFadden's R2	.082		.135		.196	
Variable	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
Energy retrofits undertaken	**IRR: 3.449** **C: 1.24**** **Z: .584**	.094	**IRR: 2.752** **C: 1.012**** **Z: .477**	.126	**IRR: 3.468** **C: 1.243**** **Z: .586**	.169
Woman			IRR: 0.910 C: −.094 Z: −.094	.239	IRR: 0.951 C: −.050 Z: −.050	.231
Age			**IRR: 0.963** **C: −.038**** **Z: −.579**	.010	**IRR: 0.972** **C: −.028**** **Z: −.433**	.009
Income EUR (sqrt)			**IRR: 0.995** **C: −.005**** **Z: −.387**	.001	**IRR: 0.996** **C: −.004*** **Z: −.307**	.001
Loans EUR (sqrt)			IRR: 1 C: −.000 Z: −.064	.000	IRR: 1 C: −.000 Z: −.029	.000
Realistic investment EUR (sqrt)			**IRR: 1.004** **C: .004**** **Z: .441**	.000	**IRR: 1.004** **C: .004**** **Z: .420**	.000
House m^2 (log)			**IRR: 2.199** **C: .788**** **Z: .383**	.241	IRR: 1.456 C: .376 Z: .182	.235
Age of house (log)			**IRR: 1.695** **C: .528*** **Z: .422**	.216	IRR: 1.143 C: .133 Z: .107	.208
Attitude					**IRR: 1.207** **C: .188**** **Z: 1.090**	.029
Self-efficacy					**IRR: 1.139** **C: .130**** **Z: .486**	.034
Attitude * energy retrofits undertaken					**IRR: 0.922** **C: −.082**** **Z: −.223**	.025
Self-efficacy * energy retrofits undertaken					IRR: .981 C: −.019 Z: −.034	.034
Constant	−3.746		−6.913		−9.900	

Note: All models $p < .0005$. For readability, all significant coefficients at a $p < .05$ level are stated in bold. * = $p < .05$. ** = $p < .01$. IRR: Incidence rate ratios, expected increase per unit increase of variable. C: Coefficient, difference in the logs of expected count. Z: Standardized coefficients.

previously been undertaken. That being said, we stress that the number of energy retrofits previously undertaken has a larger explanatory power than attitude, where more completed previous energy retrofits mostly result in more expected currently ongoing retrofits, regardless of attitude. All households that have completed three energy retrofit measures have a higher number of predicted current retrofits. This could mean that a saturation effect in household energy retrofitting is rare; if a household wants to retrofit, it will find something to retrofit.

Some variables that do not affect the expected count of retrofits should also be noted. First, gender does not influence retrofitting in any of the models. This implies that in Norway, energy retrofitting is a behavior mostly unaffected by gender. Second, the total amount of loans that the household has also seems not to affect the current number of energy retrofits. This indicates that the total amount of loans is also not a variable one should take into consideration when examining energy retrofit behavior in Norway. Additionally, the size and age of the house do not influence the number of expected energy retrofits when self-efficacy and attitude towards energy retrofitting are considered.

4.2. *Causality and limitation*

It is important to note that only a few confident causal claims can be made based on our data. It is reasonable to assume that currently ongoing energy retrofits do not lead to having previously undertaken more energy retrofits in the past, but our data do not show conclusively that having undertaken energy retrofits directly leads to more retrofits, only that they are strongly associated. Factors such as economic resources (Grosche and Vance, 2009), renovation skills (Nair et al., 2010), neighborhood effects (Helms, 2012) and attitudes (Klöckner and Nayum, 2017) are likely to have an impact on both previous and currently ongoing energy retrofits. Our model accounts for economic resources, attitudes, and renovation skills through self-efficacy, but not for neighborhood effects, as we lacked sufficient data in this regard. Further studies should investigate whether homeowners develop plans to retrofit other parts of their homes after completing the first retrofit, or whether the plans were always there but were delayed because of a lack of resources. Furthermore, it is possible that the very act of undertaking smaller retrofits leads to problems such as uneven heating or condensation, which in turn may prompt further retrofitting. Here, successive retrofitting could be an indication of a problem rather than a positive effect. To investigate this, further studies should investigate why households retrofit, and the cumulative effect on actual kWh/(m^2a) of small retrofits versus deep retrofits. Studies without an experimental design can rarely confidently claim causal effects. Other factors which our model does not account for, both known, such as neighborhood effects, and unknown, could represent confounding variables.

The issue of causality is relevant for several of the models' variables. The model alone cannot show causality, but we can nevertheless make educated guesses about which variables are causal and which are not. Age and income have a reasonably strong justification for being causal

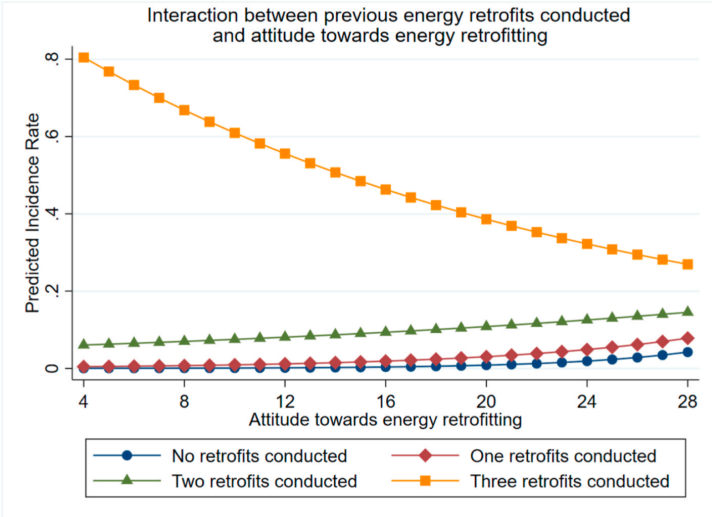

Fig. 1. Plotted expected currently ongoing energy retrofits. Interaction effect of previous energy retrofits completed, and attitude toward energy retrofitting. Higher attitude represents a more positive attitude toward energy retrofitting, and the scale ranges from 4 to 28. The interaction is discussed in sections 4.1 and 4.2.

variables. First, it is impossible that energy retrofitting affects age, so being young either has a causal relationship with undertaking more energy retrofits or it affects some other variable not accounted for in this model, which in turn affects energy retrofitting (e.g., starting a family, moving to a first house which may have a lower energy standard). Nevertheless the direction of the relationship must be that young age and related life situation lead to more energy retrofits, and not the other way around. We also consider it unlikely that energy retrofitting negatively influences household income, and consider it likely that household income influences energy retrofitting. Our finding that income is negatively related to currently ongoing retrofits stands in contrast to the existing literature, which shows that higher-income households are associated with more energy retrofitting (e.g. Schleich, 2019). But it should be noted that this relationship only holds true when loans and realistic investments are included in the model. This indicates a suppression effect; see main analysis syntax file in section 6 for statistical details concerning this. When loans and investment capabilities remain constant, households with lower income tend to undertake more ongoing energy retrofit measures.

Attitude and self-efficacy do not provide a strong theoretical justification for claiming causality. We argue that the negative relationship between attitudes and current energy retrofits in households that have previously undertaken three energy retrofits has a reverse causal direction. Here, we consider it likely that households that have both undertaken and are currently undertaking several energy retrofits have lower attitudes toward retrofitting because they are becoming somewhat tired of it. We do not believe a low attitude leads to a stronger connection between the two. In households that have previously undertaken a lower number of energy retrofits, a two-way causal relationship is likely. First, caused by consistency effects, a strong connection between the number of previously undertaken and currently ongoing retrofits leads to higher attitudes toward retrofitting. Second, a positive attitude toward retrofitting strengthens the relationship between the number of previously undertaken and currently ongoing retrofits. It is important to point out that, based on the non-experimental nature of our data, we cannot confidently claim the directionality of this, only that there is a connection. The same relationship does not exist regarding self-efficacy, as the interactive term is not significant. Self-efficacy does not moderate the relationship between the number of previously undertaken and currently ongoing retrofits. There is only a direct effect of self-efficacy on the current number of ongoing retrofits. Self-efficacy increases the expected number of retrofits, suggesting that measures simplifying the process may have an effect.

As in all research, experimental designs are needed to firmly establish causality. A viable way to test temporal spillover in energy retrofitting could be to conduct an experiment where a random sample of homeowners was significantly motivated to undertake energy retrofits for a given period with subsidies, and then to test whether those households undertake fewer, similar, or more energy retrofits compared with controls after that period. Alternatively, subsidies for small energy retrofits could be given to one group, and for large energy retrofits to another group, and then test whether the energy standard locked in with smaller energy retrofits. As briefly discussed in the introduction, such an experiment would require considerable financial resources.

Another limitation of this study is that it only measures insulating measures. Measures such as boiler and heating system replacements are parts of an energy retrofit, but this study does not capture these aspects. There could be higher spillover from installing insulation than from installing boilers, and future studies should look into this.

4.3. *Theoretical implications*

In general, the analysis does not show support for the prediction of decision mode theory regarding energy retrofitting as a calculation-based decision. Decision mode theory predicts a weak negative spillover effect in energy retrofitting as a calculation-based decision (Truelove et al., 2014). Our findings strongly suggest that a positive temporal spillover exists in household energy retrofitting.

The analysis does not support our prediction that self-efficacy moderates the relationship between previous and currently ongoing retrofits. Nor does it find any interaction effect between self-efficacy and previously undertaken energy retrofits, only a general effect of self-efficacy. As previously discussed in the section discussing causality, we cannot confidently claim that self-efficacy leads to more energy retrofitting, due to the non-experimental nature of our data.

Interestingly, the data shows support for a consistency effect. The number of currently undertaken energy retrofits is positively related to a higher attitude toward energy retrofitting amongst households that have completed 0–2 energy retrofit measures. Although, again, we cannot confidently claim the direction of the relationship, we argue that it is more likely than not that a high attitude toward retrofitting leads to more retrofitting, and vice versa, which implies a consistency effect. Houseowners build better attitudes toward energy retrofits when they undertake them, and undertake more retrofits because of this higher attitude. This constitutes a self-reinforcing cycle, which is the definition of a temporal spillover effect caused by the consistency effect.

Finally, and perhaps most interestingly, our findings match decision mode theory if we assume energy retrofitting to be a role-based decision, as mentioned in section 1.1.2. Decision mode theory predicts positive spillover in role-based decisions when, similar to subsequent behavior, the initial behavior is difficult, and when there is a consistency effect (Truelove et al., 2014). Our data show exactly this: a positive temporal spillover with a difficult initial behavior that is very similar to the subsequent behavior, as well as a consistency effect through attitude. Although decision mode theory suggests that in role-based decisions, a difficult secondary behavior, as well as external attribution, can reduce the positive spillover, we question the effect of external attribution, as discussed in section 1.2. This could imply that energy retrofitting is primarily role-based behavior, and not calculation-based behavior. At the time of writing, decision mode theory is not sufficiently established to confidently suggest that retrofitting is a role-based decision based purely on the predictors found in the analysis matching this kind of decision mode, but this should be considered if the theory is further established.

4.4. Are old buildings being left behind?

Because a temporal spillover effect exists in household energy retrofitting, there is reason to suspect that old houses are being left behind in efforts to make buildings more energy efficient, and that the annual number of energy retrofits is a poor measurement of environmental footprint trends in the building stock. Our results strongly suggest that when buildings have not undergone energy retrofitting for some time, they are far less likely to undergo energy retrofitting in future. Since households that have not undertaken energy retrofits have a higher energy consumption, this also leads to higher running costs, which in turn leads to less available investment capital for the homeowners to undertake energy retrofits. Given that our model shows that investment capacity is a significant predictor of energy retrofitting, this could indicate that medium or high energy-efficient buildings are undergoing more energy retrofits while old buildings are being left behind.

Caution should therefore be exercised when interpreting reported annual energy retrofit rates as a measurement of trends in the building stock (as done in Fyhn et al., 2019). As our model shows, an annual energy retrofit rate of 2% does not mean that a random sample of 2% of all households undertakes energy retrofits. Our analysis suggests that, for the most part, the same buildings are being retrofitted over and over. In 2018 in Norway, energy ratings in residential buildings had the following distribution: A 3%, B 10%, C 13%, D 15%, E 14%, F 18% and G 29% (ENOVA, 2018, august 14). This is problematic if energy retrofit measures focus on buildings with higher energy standards.

Retrofitting 2% of a country's highest energy-using houses compared with retrofitting the lowest or even the 2% medium energy-using houses will have a vastly different impact on the environmental footprint of the overall building stock. We argue that for this reason, "annual energy retrofit activity" is a highly misleading measurement of energy consumption trends in the building stock. What matters more is which houses are being retrofitted, and our data show that half of the reported retrofits are in buildings that have recently undergone an energy retrofit. In the best-case scenario, half of all currently undergoing retrofits have a low impact on energy footprint, as they are being performed on buildings that have recently undergone retrofits. In the worst-case scenario, they contribute nothing and are merely a byproduct of piecemeal retrofitting creating issues in the technical standard that constantly needs to be addressed. Regardless, annual retrofitting rates are a misleading metric concerning the development of the building stock. Researchers and policymakers should focus on measurements such as the trend in distribution of household energy consumption over the years compared with self-reported energy retrofit activity, so that policy support can be applied where it has the strongest effect. Although this data could be complex to obtain and communicate, we argue that it is a much more accurate metric for measuring the actual effect of energy retrofitting, and that it is far from an impossible task given the new electricity smart meters currently being deployed (Gangale et al., 2017).

Finally, it should be clarified that even though our data suggest that negative aspects of shallow retrofits are not as strong as previously thought, deep retrofits are still preferred. First, deep retrofits are technically consistent, where insulation can be fitted to windows, heating unit capacity can be adapted to the heating needs of buildings, and condensation is kept low as consistent insulation standards keep temperatures stable throughout buildings. Second, shallow retrofits are more expensive in the long run and do not achieve the same emission reductions as multiple shallow retrofits (Zhivov and Lohse, 2020). If an actor can choose between deep and shallow retrofitting, a deep retrofit should be encouraged. But since it seems that shallow retrofitting does not impede future upgrades, it should not be discouraged, as it is preferable to undertaking no retrofit at all. One of the primary arguments for only subsidizing large-scale energy retrofits is that the energy standard will be locked in, creating a negative temporal spillover, and that large-scale retrofits are more economically viable than multiple, successive small-scale retrofits. Our data show that households are significantly more likely to retrofit if they have recently retrofitted, questioning the impact of a technical lock-in mechanism. In a broader sense, spending more money on energy retrofits than necessary could lead to reduced purchasing power, which in turn will reduce a household's environmental footprint. Even if the energy retrofit is economically beneficial in the long term, some of the gained capital will be invested in new energy retrofit measures because temporal spillover is strong. While the extra capital could in theory be spent on neutral or negative environmental footprint activities, this is currently not the case for most households (Ivanova et al., 2016). Moreover, we show that perceived realistic investment size is related to retrofitting, a variable that could be directly impacted by subsidies, particularly subsidized loans. The rich ongoing debate regarding the subsidizing of shallow and/or deep energy retrofits encompasses elements that lie outside the scope of this article (see e.g. Galvin, 2014; Naber et al., 2019; Sebi et al., 2019; Zhivov and Lohse, 2020). Identifying the ideal policy is a very difficult, and probably subjective, issue, but we argue that the effectiveness of subsidizing low-to medium-sized energy retrofits could have a stronger impact on households' environmental footprint than has previously been suggested.

5. Conclusion and policy implications

This study suggests that a temporal spillover effect is present in private home energy retrofitting, since once retrofitting activities are first initiated, they lead to new ones. Variance in previous retrofits alone explains 8.2% of the variance in ongoing retrofits, more than any other single variable. This holds true when controlling for several demographic and psychological variables, which suggests that motivating households to undertake small-scale energy retrofits could lead to more energy retrofits in the future. Although deep retrofits are still preferable to shallow retrofits, we find that shallow retrofits lead to more retrofits and are a good second option. Just one recently completed retrofit measure is associated with an expected 247% increase in currently ongoing measures after controlling for demographical and psychological variables. Households' retrofitting behavior is not affected by the total amount of loans or the gender of the houseowner, meaning these are not variables one should take into consideration when examining energy retrofit behavior in Norway. Given that self-efficacy is the second-strongest predictor of currently ongoing retrofits, increasing house-owners' belief that they are capable of undertaking an energy retrofit, either by marketing the process as simple or by actually simplifying the process itself, could be an effective way of promoting energy retrofits. Although we use the best methods available to deal with missing data from our survey, directly assessed findings with no missing data would be even more reliable. Experiments are needed to firmly establish causality. Our findings are not in line with decision mode theory (Truelove et al., 2014) if retrofitting is considered as a calculation-based decision, but they are in line with choice model theory when retrofitting is considered as a role-based decision, which suggests that energy retrofitting is a role-based decision.

Furthermore, our analysis suggests that the average annual retrofitting rate is a misleading measurement of trends in the environmental footprint of the housing stock, because the same houses undergo successive energy retrofits, and half of the houses currently undergoing energy retrofits were retrofitted in the past three years. Instead, we recommend the trend in distribution of household energy consumption over years as a more accurate representation of the housing stocks' environmental footprint development. Both the change in mean and median household energy use, as well as wheater the share of high-energy households is decreasing or not, should be more meaningful indicators. As this paper demonstrates, the annual retrofit rate is only loosely related to this development. Since it seems that undertaking energy retrofitting leads to more retrofitting, this also means that households most likely do not lock in their energy standard when small retrofits are completed, which suggests that a "lock-in effect" could be less of an issue than previously thought. Our research finds that decision-making processes contribute to this, but it should be noted that other reasons that are not covered in this study can also contribute. Completing one or two retrofit measures could lead to a technically messy house where retrofit solutions do not fit each other, and this in itself becomes another driver for continuing the retrofitting. Regardless, getting households staring at one retrofit measure can hook them into an ongoing process that has its own momentum. Finally, our study lends support to the impact of subsidizing small to medium-sized energy retrofits, particularly through subsidized loans.

6. Data availability

Datasets related to this article, as well as the syntax for the analysis, can be found at https://data.mendeley.com/ https://doi.org/10.17632/vmyn94prrr.1, hosted at Mendeley Data (Egner and Klöckner, 2021).

CRediT authorship contribution statement

Lars Even Egner: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Christian A. Klöckner:** Methodology, Supervision, Data curation, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112451.

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Paper II

Energy & Buildings 253 (2021) 111542

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Low free-riding at the cost of subsidizing the rich. Replicating Swiss energy retrofit subsidy findings in Norway

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A R T I C L E I N F O

Article history:
Received 5 May 2021
Revised 30 September 2021
Accepted 1 October 2021
Available online 7 October 2021

Keywords:
Building energy policy
Energy retrofitting
Energy-efficient retrofitting
Subsidies
Free-riding
Norway

A B S T R A C T

Understanding free-riding is central to effective household energy retrofit subsidy policymaking. We replicate a Swiss study on free-riding prevalence in household energy retrofitting in Norway Studer and Rieder (2019). Compared to the original studies free-riding prevalence of 50%, we find only 10%, indicating that Norwegian free-riding is low. Similar to the original study, we find that the use of advisory service and having a good perception of the implementer is associated with not free-riding, but argue these findings should not be interpreted entirely causally, as confounding variables can also explain this association. Finally, we find that Norwegian retrofit subsidies are heavily focused on high-income households, which has ethical implications.

Comparing the subsidy systems of the two countries, our findings indicate that raising the energy standard threshold for receiving retrofit subsidies leads to less free-riding, but could stimulate less retrofitting as a whole and focuses distribution of the subsidies on to rich households.

Contents

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https://doi.org/10.1016/j.enbuild.2021.111542
0378-7788/© 2021 The Author(s). Published by Elsevier B.V.

1. Introduction

In the EU, private household space heating represented 16.5% of final energy consumption in 2018 [16]. Reducing the energy need for private household space heating is therefore of high importance to reducing household energy footprint, reach targets in the Paris climate agreement, and ultimately minimizing the impact of climate change. Several policies are in place to reduce household energy use, and various forms of subsidies are popular in achieving this. Subsidies for private house energy retrofitting is usually one of the bigger subsidies in the private market. However, the cost-efficiency of these subsidies has been criticized for being low, and "free-riding" is a central part of this critique [57,76].

Free-riding refers to the phenomena when conservation programs finance investments that would have taken place even in the absence of the program [29]. For example, a household that already aims to add a significant amount of insulation to their walls because of environmental and comfort reasons, but learns they can also receive subsidies for the implementation, then applies for and receives those subsidies, is free-riding the subsidies. Research generally identifies a free-riding prevalence of around 30–70% in private household energy retrofitting [49,57,76]. However, free-riding percentages as low as 7% [10] and as high as 92% [27]to almost complete [2] free-riding are also reported. The method of operationalizing and measuring free-riding varies, which is most likely one of the main reasons for the varying estimates, together with structural differences in the policies. Methods used include calculation willingness-to-pay [10], revealed preference data [27], comparing post and pre subsidy rates of retrofitting, and simply inquiring about the amount of free-riding in surveys [76]. One might suspect explicitly inquiring participants in surveys should obtain a lower free-riding frequency than other methods. Still, a recent survey in Switzerland found an explicit free-riding prevalence on energy retrofit subsidies of 50% [76], which is completely normal compared to what other methods reveal. This suggests surveying for free-riding could be a valid method of measuring free-riding.

Identifying and combating free-riding on subsidies is central to creating effective public policies [37]. To effectively combat climate change, public money should be spent where it has the most impact [25]. Comparing the share of free-riders between countries can be an important tool to evaluate the effectiveness of a country's policies. While several articles estimate the share of free-riders, we could not identify studies comparing two or more countries using the same methodology for obtaining free-riding prevalence. Comprehensive studies can be identified regarding heating systems [50], but heating systems differ from building envelop measures. Furthermore, we could not identify any study attempting to replicate other studies methodologies for measuring free-rider percentages in other countries. As both the method for obtaining the prevalence and the definition of free-riding will often vary between studies, comparing the results of different studies using different methodologies for estimating free-riding is problematic. For example, regarding Swiss household retrofit free-riding, Rieder [55] finds a free-rider prevalence of about 10% when asking pre-payout, but 30% when asking post-payout. Some years later, when Studer and Rieder [76] find 50% free-riding in the same country, it is difficult to establish how much of the change should be attributed to methodology, cultural changes, or policy changes.

Therefore, replicating subsidy free-riding studies is important. Firstly, it is an important piece of the puzzle in establishing what kind of policies result in low free-riding. Sufficiently scaled experimental research projects on large subsidies, such as buying electric cars or energy retrofitting, are difficult to finance. Subsidizing 50–100 participants' energy retrofitting can quickly require budgets out of reach for all but the most well-funded projects. This means researchers and policymakers must often rely on comparative studies to estimate free-riding prevalence. Different free-rider prevalence in such studies can stem from three sources. Firstly, the policy affects the free-riding rates. It is this free-riding most studies attempts to measure. Second, differences can stem from cultural differences. For example, prosperous countries can have different levels of free-riding even if the policy is identical. Finally, methodological differences can impact the free-rider prevalence. Rieder [55] found both 10% and 30% free-riding with small methodological differences. Other free-riding research states that their free-riding prevalences are not comparable like-for-like with other research [10]. Norway and Switzerland are both small, mountainous, prosperous, European countries that are only partly members of the EU, making them reasonably comparable. If the methods of Swiss free-rider studies are replicated, the methodological impact should also be zero. This would allow for a more direct comparison of free-rider rates where the differences should be based on policies and not other factors. Secondly, replication remains one of the main pillars of science and is extremely important in establishing a cumulative base of knowledge [64]. Nevertheless, replication in the field of social sciences has been, and is too low, which is a problem in the field as a whole [44]. Therefore, producing replicative studies is of great importance to the field of subsidy free-riding, and science as a whole. We aim to replicate research on Swiss free-riding prevalence [76] in Norway. Firstly, however, an overview of both countries' retrofit subsidy policies is given in the next paragraphs to understand the contexts the two studies have been conducted in.

1.1. Subsidy policies

Norwegian and Swiss subsidy policies have several differences and similarities important for subsidy free-riding. Switzerland has a national target to reduce domestic greenhouse gas emissions by 20% from their 1990 levels by 2020 and be climate-neutral by 2050 (Federal [17]. Decarbonization of the heating sector is needed to reach this [19]. This is promoted by subsidy systems, which are divided into national and cantonal programs. The national subsidies focus on the building envelope, while the cantonal subsidies differ significantly between cantons and offer subsidies for local production of renewable energy (e.g., by photovoltaic installations), waste heat utilization, etc. [20]. The annual Swiss energy efficiency refurbishment rate of the total building stock is about 1%, where the large proportion of rental dwellings are believed to be a key barrier [35]. The mean annual Norwegian temperature is 1.0 °C, compared to the Swiss 5.9 °C [87].

The Norwegian system is managed by the national energy efficiency agency Enova SF, which the Ministry of Climate and Environment owns. Subsidies for several implementations are offered, such as installing hydronic heating (which is uncommon in many older Norwegian houses, usually heated by electric resistance heating or air-to-air heat pumps), and local electricity production. The most important subsidies are offered for "holistic building energy upgrade", where 25% of the costs, up to 100 000–150 000 NOK[1], are reimbursed depending on the final energy level. This type of subsidy will be the focus of the present article. The stated overall strategy of the subsidy scheme is to stimulate market change, so that newly established and more climate-friendly solutions are more readily available and will reach a state as soon as possible where they are no longer dependent on subsidies [13]. Norway also has a loaning scheme for upgrading to the same building standard through "Husbanken", but an average of only 14 private persons have utilized

[1] Approx 10.000–15.000 EURO.

the scheme annually in 2008–2019 [34], suggesting issues related to the scheme. Finally, a free advisory service, 'Enova answers', where households can ask questions about energy retrofitting and subsidies. The Norwegian energy retrofit rate is at a standstill compared to 4 years ago, with a yearly energy retrofitting rate of about 3.4% [22], although a small number of households that retrofits often seem to drive up this number [91].

Because Swiss household retrofit subsidies are canton specific, it is difficult to directly compare to the Norwegian system, but trends can be identified from the recommended canton guidelines aimed to harmonize the subsidies [39,40,68]. The most relevant guidelines for this paper are the 2009 guidelines, as they applied in the period up until 2015 where Studer and Rieder [76] collected their data. At that time, Swiss national building envelope funding funded 15% of the investment costs, but in most cantons, additional ''indirect subsidies" of about 20–40% may be deducted from the household taxable income [36]. Notably, the new recommended canton guidelines issued in 2015 increased the minimum funding to 20%. Households are not eligible for funding if the total costs exceed 20% of the funding. The guideline argues that this way, subsidies can sufficiently stimulate demand and not be only for well-informed investors who would have undertaken the measures without funding [68], in other words, free-riders. For the national system, a household is eligible for funding if the retrofitted building was built before 2000, reaches a minimum amount of funding, and can document a minimum level of insulation. The canton recommendations specifically state it does not recommend any specific level of funding, so numbers most likely vary strongly between cantons. The upper limit of the subsidies was set to 50% in the same document, suggesting that subsidies could go above 50% in some cases. Importantly, households are eligible for subsidies when performing the retrofitting both individually or in collaboration with a contractor (Personal communication, Sabine Hirsbrunner, Swiss Federal Office of Energy, September 2020), and subsidies are not only tied to the cost of the retrofitting, but also the outcome [39].

Several aspects of both countries' energy retrofit subsidies are important concerning free-riding prevalence. Subsidies in both Norway and Switzerland can most likely be primarily used by high-income households, which increases free-riding (as suggested by [49]. Norwegian housing energy retrofit subsidies are paid post-retrofit, meaning homeowners must first conduct the retrofitting, then apply for the subsidies. Retrofits that are not completed through a contractor, such as conducting the retrofit yourself, are not eligible for subsidies. This implies that the homeowner must have the financial resources, either through capital or loaning capabilities, to first complete the retrofitting before receiving any subsidies. While high-income households are more likely to have these financial resources, the market does not usually finance energy efficiency measures [31], questioning whether low-income households can finance the investment. This could suggest that subsidies are focused on the high-income portion of the population. Because high-income households are likely more susceptible to free-riding, as they have the financial resources anyway, this could increase free-riding. Similar issues are present in Swiss subsidies. Households cannot benefit from tax deductions if they do not have sufficient income, effectively excluding groups that do not pay enough taxes. They are also paid post-retrofit, meaning households must have the financial means to complete the retrofit before receiving subsidies. This again suggests they could be focused on the high-income households, increasing free-riding. Contrary to Norwegian subsidies, however, households are eligible for receiving subsidies if they complete the retrofitting themselves. This should reduce the barrier regarding available financial resources, making more people eligible for subsidies. The possible income difference related to free-riding is not only an economic

Table 1
Threshold characteristics for energy retrofit subsidies in Norway and Switzerland. Note that numbers are simplified for the sake of comparison.

	Norway	Switzerland
Mean annual temperature	1.0 °C	5.9 °C
Renovation rate	3.4%	1%
Piecemeal retrofits subsidized	No	Yes
Mean energy consumption of households	185 kWh/(m^2a)	112 kWh/(m^2a)
Subsidy eligebility threshold	130 kWh/(m^2a)	90 kWh/(m^2a)

problem regarding efficient financial resource allocation aimed at accelerating the energy transition, but it is also an ethical problem in detriment of a fair and just energy transition, which has recently received increasing attention [30,45]; (Pellegrini-Masini, Pirni, Maran, & Klöckner, 2020).

A subsidy scheme's threshold for giving financial aid should be related to the prevalence of free-riding in the region. A high threshold for receiving subsidies should result in less free-riding, as you need to do more to receive the subsidies. In Norway, the energy retrofit must reduce heat loss by 30% and reach an energy rating of (120 + (1600/A)) kWh/(m2a) with A representing the floor area in m^2, to be eligible for retrofit subsidies[2] [12]. Households that achieve an energy rating of (80 + (1600/A)) kWh/(m^2a) are eligible for larger subsidies, suggesting highly ambitious energy retrofits are prioritized. With the most prevalent Norwegian single household house size being 160–199 m^2 [72] this sets the threshold for receiving subsidies around 130 kWh/(m^2a). The average Norwegian household consumed 185 kWh/(m^2a) in 2012 [70]. The Swiss subsidy threshold for building envelopes differs between cantons, which makes pinpointing a common threshold difficult. However, recommended guidelines for the cantons exist [39], and a reasonable comparison can again be made between the subsidy systems by looking into these guidelines. As a rule of thumb, the MINERGIE standard is followed, where single and multi-family homes have 90 kWh/(m^2a) as a core requirement [47]. However, this kWh/(m^2a) value is weighted according to the energy source and end-use, so it is not directly comparable to the Norwegian value. For example, solar energy and geothermal heat weight 0, meaning they are omitted. For comparison, the mean Swiss household final energy consumption has been measured to be 112 kWh/(m^2a) [75]. Additionally, subsidies are also offered for partial retrofitting, such as windows [39]. While the level of subsidies differs substantially between cantons and is difficult to objectively compare to the Norwegian model, it can generally be said that the overall threshold for receiving subsidies for energy retrofitting is lower in Switzerland, and the subsidy level is higher. See Table 1 for an overview.

The threshold for receiving subsidies is important for establishing the most efficient use of public money. A high threshold for receiving subsidies most likely results in less kWh saved for every euro invested, as an exponential connection between renovation cost and kWh saved exists, where the cost increases exponentially the more energy-efficient the final renovation standard is [23]. At the same time, a high threshold for receiving subsidies may lower free-riding. Whether or not a high threshold for receiving subsidies affects the amount of free-riding is therefore also central in establishing the ideal retrofit threshold for receiving subsidies to maximize the reduction in household energy footprint for the least amount of public money spent.

[2] This formula allows for a higher kWh/(m^2a) in small households, because they have a higher surface-to-valume ratio than large buildings. To excemplify, a large 500m^2 building need to reach 120 + (1600/500) = 123 kWh/(m^2a) to be eligible for the subsidies, while a smaller 70m^2 building must reach 120 + (1600/70) = 143 kWh/(m^2a).

For these reasons, we decide to replicate Studer and Rieder [76] findings on Swiss free-riding in Norway. Studer and Rieder's [76] research involves three studies. Firstly, the estimation of free-riding prevalence, which they estimated to be 50%. Secondly, identifying factors associated with free-riding such as the use of advice services, where they found perception of the implementer (how much they liked the subsidizing body), and the use of advice services to be statistically significant factors. Thirdly, focus group interviews. As quantitative measures arguably afford to minimize variability in replications, we decided to replicate only the two first studies.

Replicating Studer and Rieder's [76] research in Norway, we aim to investigate (1) potential differences in free-riding prevalence between Norway and Switzerland, (2) if similar findings on factors associated with free-riding can be found in Norway, and (3) the income distribution of the Norwegian retrofit subsidy recipients. We hypothesize that because we use close to identical methods, we will get similar results, 50% free-riding, and that the use of advice services and the perception of the implementer will predict free-riding. Finally, we hypothesize that the recipients of retrofit subsidies have a higher income than non-subsidy retrofitters and the average population.

With these hypotheses tested, policymakers will be able to make better-informed decisions regarding implementing household energy retrofitting policies. Firstly, it will shed light on the connection between subsidy threshold level and freeriding, optimizing subsidy schemes for more energy retrofitting, which will reduce energy demand. This helps communities and countries provide affordable and clean energy, and mitigate climate change, which is the core of UN sustainable development goals 7 and 13. Secondly, it will also give actual data to the theorized differences between high and low-income utilization of energy retrofit subsidies, providing direct help to UN sustainable development goal 10, reducing inequalities.

2. Methods

In May 2019, we sent an electronic survey to 2103 recipients who had received Norwegian subsidies for building envelopes or building energy counseling, which counted for the entire population of such subsidy recipients. This is similar to the Swiss sample, which consisted of households that had benefited from subsidies for insulation in the last two years. 2065 received the survey, and 315 clicked the survey link. Some left from the starting page, leaving 303 respondents with actual data and a final response rate of 14.7%. Although some e-mail accounts can be assumed to be inactive, this is a somewhat low response rate for a targeted demographic. Future studies, including incentives for survey responses to increasing response rates [90]), could be advantageous in confirming findings. As we sampled the entire population, we could not increase our sample size to increase confidence. The survey was originally collected for and funded by Enova SF, and some descriptive statistics can be found in a report [22]. There was no further involvement from the funding sources. Free-riding is not investigated in the report. The survey contacted everyone who had received subsidies for energy consultancy and/or energy retrofitting, only 183 stated they had received subsidies for energy retrofitting. Because of the small sample and specificity of some items such as the county, household-type, income, and retrofit activity, combined with the small population of Norway, we do not consider the dataset completely anonymous and can not publish the dataset. A list of all survey items, complete with the full statistical process featuring comments regarding smaller methodological choices, is available as a Stata "do-file" in the supplementary material.

2.1. Missing data treatment

Similarly to the study we replicate, respondents that inconsistently stated the subsidies had an effect on either scope, quality, or startup, but also agreed that the subsidies did not influence the retrofitting ($n = 13$), and vice versa ($n = 6$) were excluded from the dataset.

Because reporting frequencies were important to the study, the number of respondents was somewhat low even though the entire population was sampled, and data was most likely not missing completely at random, we applied multiple imputations [61] to fill missing answers (as suggested by Schafer & Graham [62]). Multiple imputation methods use statistical methods, usually regression, to estimate the most likely value for all missing data. This value, plus an uncertainty based on the confidence of the estimation, is input into the dataset. This process is repeated until several datasets are created. Then, the analysis is completed on all datasets, and the results are combined using Rubin's rules [61]. Although not as unbiased as having a complete dataset with no missing values, it is preferable to ignoring responses with missing data [62]. Because respondents often miss or purposefully ignore some items on a survey, having a complete dataset is impossible for most surveys, and multiple imputations are needed. Missing answers were imputed in a chained equation model in Stata v.16. For a full overview, see attached syntax files. Following the rule of thumb of applying a number of imputations equal to or larger than 100 times the largest fraction of missing information [74], which in our data was 0.26, we applied 50 imputations [82]. All Monte Carlo error estimates were less than 10% of the standard error of imputed variables, satisfying literature guidelines concerning a sufficient number of imputations [82].

2.2. Free-riding data

We applied methods as close as possible to Studer & Rieder [76]. Like the original study, our free-riding items were included in a larger survey distributed to recipients of retrofit subsides. We applied the same 4 point Likert scale (translated to Norwegian), and the same questions regarding the subsidies effectiveness on startup of the retrofitting, scope of the retrofitting, quality of the retrofitting, and a control question on whether subsidies had any influence on the retrofitting. Participants responding "agree" or "completely agree" on the 4 point Likert scale regarding whether the subsidies influence the scope, quality, or startup of the retrofitting were counted as non-free-riders in both studies (personal communication, Sibylle Studer, January 2020).

2.3. Income data

Income data were collected from three different sources. We decided to treat and consequently display these data as income deciles brackets rather than raw income. This allowed for a clearer comparison amongst data sources, especially concerning the population mean in Norway, and improve the anonymity of the respondents. The decile brackets on Norwegian household income according to the whole population, excluding student households or persons under 18 living alone, were retrieved from Statistics Norway [71]). Each bracket represents 239.825 households and is based on census data, which gives absolute numbers [71]. For the sample in our survey, we asked participants for their combined household income, which we later converted to income decile brackets. Finally, we retrieved income data from a representative sample of energy retrofitters in Norway surveyed in the same period [91], also uploaded as supplementary material. Income data from the surveys were self-reported. All sources list household income before tax. Income was adjusted according to the consumer price index to be comparable with each other. Because the three datasets were from different sources, we display them graph-wise with 95% confidence intervals regarding their imputed mean at each point to more clearly indicate where the differences between the samples are. Statistically, where the error bars representing 95% confidence intervals, do not overlap, the difference is $p < 0.05$. Since both datasets had 50 imputations, we also merged the two and tested if the lines as a whole were statistically different using ordered logistic regression. We also retrieved the mean McFadden's pseudo explained variance from all individual regression models across all 50 imputations to estimate the explanatory power. This number gives a solid indication of what share of freeriding behavior is explained by the model.

2.4. Differences in operationalization

Some independent variables differ from their operationalization in Studer and Reider (2019). The variable 'advisory service utilized' can naturally not represent the same advisory system as in Switzerland, as the systems are different. In our study, we measure whether participants used the "Enova answers" service. We judge this measurement to be very close to what the original study measured, described as a "cost-free, publicly funded energy advice services" [76]. As we wanted to keep the survey short and needed to include several items for a summarizing report [22], some compromise had to be made regarding the perception of the implementer index. Instead of basing it on 11 items on whether the implementer was cooperative, efficient, friendly, etc. (as done in the original study), we based our index on five items on the dialogue, information, and whether the subsidies should continue, shown in the appendix. Although they are different, we believe they should represent roughly the same underlying attribute.

2.5. Uneven group-sizes

Even though we expect a 50:50 distribution between free-riders and non-free-riders, there is a possibility that the distribution will be skewed to one side. In the event of uneven distribution, our statistical power will be reduced because one of the groups will be smaller. In the case of uneven distribution, we will eliminate predictor variables (as suggested by Tabachnick & Fidell [77]) allowing one predictor variable for every 7 outcome events per predictor variable, starting with variables that showed significant results in the original study [76]. Problems related to logistic regression are uncommon when it reaches 5–9 outcome events per predictor variables [79].

3. Results

Using similar methods, we find substantially different free-riding prevalence than Studer and Rieder [76]. See Table 2 for details. Results indicate free-riding on energy retrofits subsidies in Norway is low.

Because the frequency of free-riding is low, the free-riding group consists of, on average, 16.7 participants across imputations. Therefore, we reduce the number of regression variables to the utilization of advisor service, and the perception of the implementer.

Regression results, seen in Table 3, suggest that utilizing the advisory service and having a favorable perception of the implementer (Enova) is associate with more effective subsidies, as in no free-riding.

Income data suggest that amongst Norwegian energy retrofitters, households that receive subsidies on average belong to a higher income decile (M = 7.8 SE = 0.27) than households that retrofit without subsidies (M = 6.7 SE = 0.12), which again belong to a higher income decile than the population average (M = 5.5). This is illustrated in Fig. 1. Cumulatively counting the estimated percentile of subsidy recipients according to income decile starting from the top income decile gives 30, 50, 67, 83, 88, 89, 91, 92, 93, 100%. Ordered logistic regression shows income decile distribution is different between subsidized and non-subsidized retrofitters (OR = 2.78 SE = 0.56 $p < 0.0005$).

Table 2
The proportion of reported effectiveness of subsidies between findings.

The subsidies contribute to...	Frequency (SE) N = 164	Studer and Reider (2019) N = 588
Total at least one effect = effectiveness beyond free-riding assured	90%	50%
No effect = no effectiveness assured, free-riding behaviour	10% (0.03)	50%
Decision to renovate (only)	1% (0.01)	3%
Increase in quality of renovation (only)	4% (0.02)	8%
Increase in scope of renovation (only)	4% (0.02)	4%
Decision to renovate and increase in quality	5% (0.02)	9%
Decision to renovate and increasing in scope	1% (0.01)	1%
Increase in quality and scope	37% (0.04)	8%
Decision to renovate and increase in quality and increase in scope	37% (0.04)	14%
Incomplete answers but at least one effect	*	3%

* Not applicable as missing answers were replaced using multiple imputations.

4. Discussion

Our findings show that household energy retrofit subsidy free-riding in Norway is low relative to Switzerland. Where a survey finds 50% free-riding in Switzerland, our replicated survey finds 10% free-riding in Norway. The use of the advisory service and having a favorable perception of the implementer is strongly associated with not free-riding. Additionally, the subsidies are given primarily to high-income households, both relative to the population average and energy retrofitting households in general.

4.1. Free-riding frequencies

Overall, the amount of free-riding on retrofit subsidies in Norway seems to be one-fifth of the Swiss free-riding rate, but some nuances are important to note. Firstly, the proportion of free-riders in the two countries differs regarding the influence on the decision to retrofit, quality, and scale. The smallest difference is found in the decision to retrofit category, where 44% of Norwegian respondents state the subsidies made a difference, versus 27% of Swiss[3]. This is contrasted by the largest difference, found in retrofitting scale, where 79% of Norwegians state the subsidies made a difference, versus 27% of Swiss. For quality, 83% of Norwegians stated the subsidies made a difference versus 39% of Swiss. We believe that the differences regarding quality and scale stem from the higher threshold for receiving Norwegian subsidies, compared to the Swiss. With the high threshold, the original project needs to modify both quality and scale to be eligible for subsidies, and is changed thereafter. If the household realizes that they cannot reach the threshold for receiving subsidies, few or no changes are made. An important factor is probably that the Norwegian subsidy requires all parts of the house to be retrofitted, while the Swiss generally do not.

Regarding the smaller difference concerning the decision to retrofit, it is likely this difference also stems from the threshold difference. Free-riding could be much higher in small-scale retrofits,

[3] Percentages are calculated by adding up categories in table 1.

Table 3
Logistic regression on effects on the effectiveness of subsidies beyond free-riding. Model p = 0.0029. Mean McFadden's R2 = 0.173.

Independent variables	Range	Odds ratio (se)	Significance level
Advisory service utilized	0–1	5.18 (3.50)	0.015
Perception of the implementer index	1–7	2.20 (0.60)	0.004
Constant		0.04 (0.07)	0.049

which are not part of the Norwegian sample. Free-riding in large-scale retrofits could therefore be similar between Norway and Switzerland.

As the high threshold Norwegian subsidies seem to have an especially large effect on the scale and quality of retrofits, they are most likely very effective in preventing technical lock-in. Technical lock-in refers to the idea that further energy retrofitting is less likely to start once a recent building retrofit has been completed, thus "locking in" the current energy standard. Although some researchers stress that small scale retrofits are associated with more retrofitting [91], the established consensus suggests exclusively subsidizing large-scale retrofits that aim for a high energy standard to avoid problems associated with technical lock-in (e.g. [56,81]. This is especially important in colder climates, where high energy standards usually save more energy than in warmer climates [3].

4.2. Predicting free-riding

The use of the advisory service and having a more favorable perception of the implementer is associated with lower free-riding. This is similar to the findings of Studer and Rieder [76], suggesting this association is not restricted to one country. Contrary to the for the most part causal interpretation by Studer and Rieder [76], we believe these findings are heavily influenced by how much the participant "liked" the processes. This is especially true for the perception of the implementer index. According to associative learning mechanisms such as evaluative conditioning [11,32], if a household had an unfavorable experience during the retrofitting and subsidy process, this feeling will be associated with the entire process, including its implementer. For example, a household could experience that the retrofitting process was tiresome, overly bureaucratic, or did not achieve the energy-saving indicated because of the rebound effect [65]. Consequently, unfavorable emotions concerning this will be associated with the implementer *and* the effectiveness of the subsidies [73]. Households that have a unfavorable view of the implementer will therefore also report the subsidies to less effective, resulting in an association between non-free-riding and a favorable perception of the implementer, as the findings show.

The use of the advisory service could lead to less free-riding, but a complete causal relationship is still unlikely. The statistical association between the two could be caused by households that already had concrete plans for projects which surpassed the subsidy threshold did not utilize the advice service. This leads to an association between free-riding and utilization of advice services, where the latter does not lead to the former. Although households with smaller projects could utilize the advice service to increase the scope of their retrofit, which would be a causal relation, this effect is most likely not as strong as the regression effect size suggest. With the current evidence, it could be said that it is more likely than not that advisory services reduce free-riding, but more research is needed to establish this claim.

4.3. Income differences

Our results show that which households are being subsidized when conducting energy retrofitting is heavily dependent on the

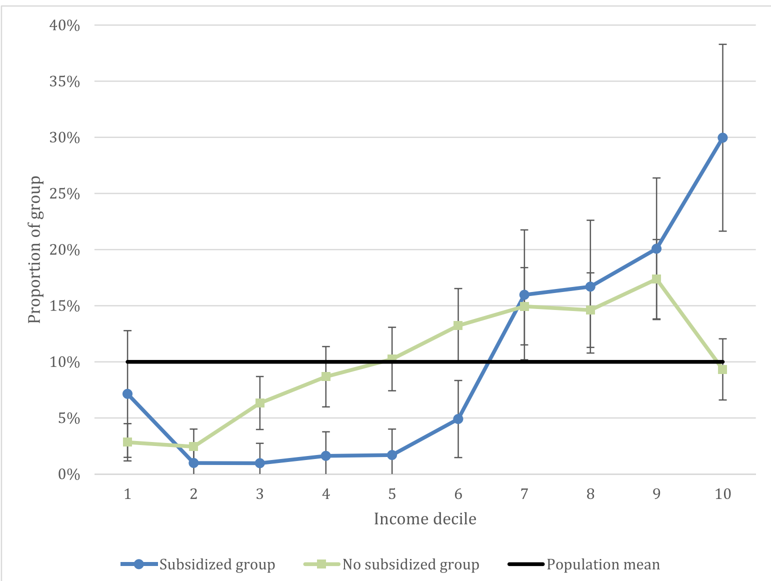

Fig. 1. The figure shows the income distribution within three groups. The population average (in black), people who have conducted energy retrofits without subsidies (in yellow squares), and those who have received energy retrofitting subsidies (in blue circles). Income decile 1 is the 10% poorest households, while income decile 10 is the 10% richest. Error bars represent 95% CI, non-overlapping error bars indicate statistically significant differences. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

decile income bracket of the household. In general, poorer households are receiving fewer subsidies. The thirds, fourth, fifth, and sixth income deciles receive statistically significant fewer subsidies compared to their rate of retrofitting, and the tenth income bracket is receiving significantly more. Additionally, there is a trend for the seventh, eighth, and ninth income brackets to also receive more subsidies relative to their retrofitting rate in the lower brackets. There is a linear relationship regarding the income bracket of the household and their rate of retrofitting, except for the highest income bracket. We hypothesize this is because the richest income bracket buys and lives in houses that are in no need of energy retrofitting, or are financially and environmental-consciously unaffected by high energy bills. There is a negative correlation between income and environmental concern [9], which indicates that richer households to a lesser extent retrofit for environmental reasons.

Several factors related to the subsidy policy design are important for its uneven distribution amongst income deciles. Firstly, Norwegian households must already have the financial resources to raise the scale and quality of the retrofitting, and the energy retrofitting must be completed through an external contractor. Therefore, we judge it as very likely that the 1-6th income deciles to a lesser extent have the financial resources to raise the scale and quality of their retrofits to be eligible for subsidies. As a consequence, the quality and/or scale of non-subsidized retrofits are not affected. Secondly, lower-income households likely implement the retrofitting themselves to a larger extent, with limited or no outside contractors as the households do not have the financial resources to outsource the retrofitting. Nonetheless, performing the retrofitting through other means than through contractors makes the household non-eligible for Norwegian subsidies.

Loans, or subsidized loans, seem like an intuitive way to help the lower six income deciles utilize the subsidies, but the literature suggests both have problems. Traditional means of financing energy retrofitting have issues (summarized by Hill [31]) where investors are hesitant to invest due to factors such as, but not limited to, volatile energy prices, risk aversion, and long payback periods. These issues indicate that unsubsidized large-scale financing of energy retrofitting is still a somewhat unrealistic possibility. Subsidized loans have also been subject to criticism. The most prominent issues are not increasing actual retrofitting rates compared to regular subsidies, and being subject to free-riding [7,38]. Walls [80] summarizes subsidized retrofit financing as very cost-effective, but low impact on actual retrofitting rates.

Finally, implementing subsidy income restrictions to combat the uneven distribution should be done with caution. Currently, household retrofit subsidies are not subject to stigma, such as public welfare [21,88,89]. Introducing a household income cap on receiving subsidies will most likely create an association between the subsidies and low socioeconomic status. Households could choose not to pursue the subsidies, including the minimum standards they include, as they do not wish to associate themselves with the low status of the subsidies and the following energy standard [18]. In a worst-case scenario, high and medium-income households could purposefully avoid retrofitting to a high energy standard because these buildings are associated with a low socioeconomic status. While it is difficult to predict cultural and normative change, the psychological research supporting such an outcome definitively exists [4,5,6,32].

4.4. Ethics of subsidy distribution

Several ethical issues are related to the skewed distribution of retrofit subsidies. It can be said that the success of a subsidy program largely depends on its goals. If the subsidies are meant to increase retrofitting rates in low-income households by making them more affordable, this distribution is negative. If the subsidies are meant to push the quality and scale of the more expensive retrofits, so that these methods become available to everyone, a sort of "trickle-down technology", it could be favorable. As stated in section 1.1, this is similar to the stated strategy of Enova. Therefore, it could be said that concerning their stated goal, the income distribution is not negative. But this could be disputed because if it is true that higher-income households often live in larger houses, it is usually low-income households who inhabit older and less efficient homes, which require more extensive and expensive retrofits as calculations of annual space heating requirements for houses in the UK building stock e.g. show [52]. Additionally, this effectively means Norway, in practice, does not have a subsidy scheme for energy retrofitting for low and medium-income households. More likely than not, this is an unintended side effect. Several aspects concerning energy justice are relevant concerning this.

As pointed in the introduction, scholars are increasingly arguing for the need for a just energy transition [30,45]; (Pellegrini-Masini et al., 2020) which is considered to be resting on the concept of energy justice [46,53,69], defined as "a fair and equitable process of moving towards a post-carbon society" [45]. Energy Justice and the just transition are centred on the three tenets of energy justice: distributional justice, procedural justice, and recognition justice, which mean, respectively, equitable distribution of energy services, inclusive democratic processes of energy policymaking, and the recognition of the rights and need for inclusion of especially disadvantaged social groups [46]. The justice arguments for a fair energy transition are rooted not only in equalitarian ethical arguments, but also in social and environmental considerations [54]. Arguing on empirical grounds, it has been stated that equitable distributions of goods appear to facilitate sustainable societies [83,84] while inequality appears to exacerbate carbon emission pollution [42]. While, with specific regards to energy and the future of energy systems, it has been warned that prosumerism and microgrids will mostly benefit those citizens that can afford new technologies [86], thereby fostering inequality and hindering the transition towards sustainable energy. Scholars [28,63] have shown that German network charges aimed at grid expansion to integrate renewables and the cost of feed-in tariffs supporting renewables have increased economic inequality in Germany. Growing inequality therefore risks becoming a byproduct of regressive policies adopted to facilitate the energy transition. In the specific case that we have presented, it could be argued that low-income households cannot implement retrofits or at very least their retrofits do not match for their entity or type those covered by subsidies, thereby excluding those more in need of energy cost saving actions and preventing them from accomplishing their environmental aspirations. Ultimately this regressive policy could contribute to a problem of energy vulnerability described as "the propensity of an individual to become incapable of securing a materially and socially needed level of energy service in the home" [8]. Although this might appear as an unlikely circumstance in a wealthy country like Norway, research shows otherwise: 2.7% of Norwegians in 2018 were in arrears in paying their utility bills [15], July 30), 15% of Norwegians in 2016 declared to consider themselves vulnerable with regards to the energy sector and of those considering themselves in such condition, 7% attributed the cause to their financial situation and 3% to their employment situation [14].

4.5. Context and further research

That a higher threshold for receiving subsidies most likely leads to lower free-riding must be seen in the context of other research. This is only one finding in a plethora of other factors that should be considered when designing retrofit subsidies (e.g., [1,24,33,48]).

For example, it is likely that a household's self-efficacy regarding using the subsidies to retrofit is significantly affected by the subsidy threshold. Self-efficacy is mostly referred to as "...a personal appraisal of one's capability to mobilise the motivation, cognitive resources, and behaviour required to cope with a prospective situation" [43], and has shown to influence several behaviors [51,66,78]. Because the Swiss system has a lower threshold, the self-efficacy related to receiving subsidies for energy retrofitting is likely higher in Switzerland. This should, in turn, lead to higher absolute rates of retrofitting caused by the subsidies. This is, of course, difficult to test, as other factors than the subsidy program affect the total retrofitting rate, and teasing apart the effect of the retrofitting program is challenging. But as this article argues, a low-threshold subsidy system leads to more free-riding, so the payoff regarding lowering the threshold must be carefully evaluated. To determine ideal thresholds for retrofitting subsidies is outside the scope for this paper but should be a fruitful area for further studies. A modeling approach focused on a behavioral model regarding energy retrofitting (eg. [41]) should prove especially useful. Similarly, excluding higher-income households from access to the subsidies could prove initially beneficial, but the possibility of shame and, therefore, underutilization should be first thoroughly explored.

Finally, the research should be extended to other places with similar cultures. We especially suggest the UK, which has received considerable research on its housing energy retrofitting policies [26,50,59,60,67,85]. Estimating UK free-riding compared to other countries is especially interesting considering its unique Supplier Obligation program (for an overview, see [58]).

4.6. Conclusion

Our findings show that low amounts of energy retrofit subsidy free-riding are present in Norwegian households, which is most likely connected to the high threshold for receiving these subsidies. Although a high threshold leads to larger scale retrofits that are more cost-effective, policymakers aiming for low free-riding by raising the threshold for receiving subsidies to achieve this must take into account that this also most likely both lowers the total amount of retrofitting caused by the subsidies, as well as focus the subsides on high-income households. Subsidizing high-income households raises not only ethical concerns, but as inequality appears to exacerbate carbon emissions, this counteracts the very problem the subsidies were meant to address in the first place. Our findings suggest that the availability of a free advisory service could lower the prevalence of free-riders and increase retrofitting rates. However, more research is needed to claim this confidently. Finally, we argue there is little support for claiming that raising the public perception of the subsidy implementers leads to less free-riding.

Replicating the same inventory measuring subsidy free-riding from Switzerland in Norway, we find the prevalence of free-riders to be much smaller, only 10%. Comparing the policies of both countries, we propose that the threshold for receiving subsidies is key in explaining this difference. Similar to Studer and Rieder [76], we also find that using advisory service and having a better opinion of the implementer is associated with lower free-riding. We argue this association could be caused by confounding variables, making the interpretation of how much of the association can be explained by causality difficult. Additionally, we find that the recipients of Norwegian subsidies are heavily concentrated amongst the higher-earning households. Although this is not in conflict with the overall stated goal of the subsidies, to subsidize new technology that is yet to become market competitive, we argue this widens inequalities in society, which is in itself an indirect source of carbon emissions, as well as impedes energy justice. To either make the subsidies more accessible or restrict the subsidies to low-income households could be an option. Still, careful attention must be directed to freeriding numbers and the possibility of shame associated with the subsidies.

Funding

This work was supported by the European Commission Social innovation Modelling Approaches to Realizing Transition to Energy Efficiency and Sustainability (SMARTEES) project [grant number 763912]; and partly by Enova SF, Trondheim, Norway [Project SID 09/1914 and SID 18/11690]. The financial sponsors played no role in the execution, analysis and interpretation of data, or writing of the study.

CRediT authorship contribution statement

Lars Even Egner: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Christian A Klöckner:** Funding acquisition, Supervision, Writing – review & editing. **Giuseppe Pellegrini Masini:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Amarasinghage Tharindu Dasun Perera for his help regarding the literature search on Swiss Subsidy policy, and Sabine Hirsbrunne from the Swiss Federal Department of the Environment, Transport, Energy and Communications, for help in clarifying some aspects related to the same literature.

Appendix A

Table 3. Perception of the implementer index.

Item	Range
Information regarding the subsidy program has been good.	1–7
Information regarding the subsidy program has been easily accessible	1–7
Information regarding the subsidy program gave an impression that fits my actual experience with the program.	1–7
The dialogue with Enova has been good.	1–7
Enova's subsidy program should continue.	1–7

Principal components analysis load the first component with eigenvalue 3.18 and the second component with eigenvalue 0.848. This strongly suggesting one underlying component. The scale generated from the components has a Cronbachs Alpha of 0.85.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2021.111542.

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Paper III

Effect of policy implementation on energy retrofit behaviour and energy consumption in a simulated neighbourhood.

[Personal data anonymized]

This unpublished version of the article is not included in NTNU Open the final published version is available in JASSS : Journal of Artificial Societies and Social Simulation 2022 ;Volum 25.(4)
https://doi.org/10.18564/jasss.4936

Abstract

As the heating of private households represents 16.5% of all EU final energy consumption, household energy retrofitting is a central part of the solution for the ongoing climate crisis. However, ABM models have not sufficiently been explored as a tool for designing policies for reducing household heating energy consumption through energy retrofitting. This paper presents the Household Energy Retrofit Behavior (HERB) model, which simulated energy retrofitting in a neighbourhood. The HERB model feeds a decision-making process based on existing behavioural household retrofit research with survey data and assesses the impact of different policies on cumulative energy need over 100 years. The model finds that the current Norwegian main retrofit subsidies have a positive effect on energy use. Furthermore, although motivating households to retrofit to a specific standard has no positive impact, motivating households close to retrofitting has a positive effect. Finally, lowering the threshold for receiving subsidies has a positive impact.

Keywords: Energy Efficiency, Thermal Insulation, Policy Assessment, Decision-Making Process

ODD protocol

Overview, Design concepts, and Details protocol for the Housing Energy Retrofit Behavior Model.

[Personal data anonymized]

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al., 2006, 2020)

1. Purpose

The purpose of the Housing Energy Retrofit Behavior (HERB) model is to simulate the energy retrofitting decision-making process of house-owner using recent research on homeowner's movements in decision-making stages. Firstly, it investigates if a model primarily based on psychological decision making, rather than economical, fits real-world data regarding overall retrofitting rate, mean energy standard consecutive retrofitting, and free-riding on subsidies. Secondly, it explores current and proposed energy retrofit policy effect on energy consumed by households. It does this by comparing different policies' effects on cumulative energy usage and final energy standard.

2. Entities, state variables, and scales

The model features one entity, the household. Households exist on a 1 square kilometer simulated area, where 1 grid cell represents $10*10m^2$. One tick in the model equals one 1/52th of a year or about 1 week of simulated time, and the model runs for 100 years. State variables are listed below in table 1.

Table 1

State variables in the HERB model

Entity	Variable	Description	Possible values	Units
Household	M2	Size of the household	Theoretical: 0 - ∞ Realistic: 20-600	m^2
	Technical kWh/(m^2a)	Technical standard of the household.	Theoretical: 0 - ∞ Realistic: 20-1000	kWh/(m^2a)
	Ambition	The current energy standard the household is either thinking about or currently retrofitting to.	Theoretical: 0 - ∞ Realistic: 20-600	kWh/(m^2a)
	Investment potential	How much money the household can potentially invest in energy retrofitting	0 - ∞	EUR
	Ambition timer	Tracks for how long the current ambition has been kept.	0 - 12	weeks
	Income decile	Which income decile the household belongs to	1 - 10	--
	Half max income	Half of the max income of the households income decile	12.889 - 93.143	EUR
	Retrofit stage	Determines wheater the household is (1) not thinking about, (2) considering, (3) planning, or (4) currently retrofitting.	1 - 4	--
	Intention1/ Intention2/ Intention3	The current intent of the household to transition from stage 1 to 2/ 2 to 3/ 3 to 4.	--	--
	Time in stage 1/2/3/4	How much time the household has spent in its current stage	0 - ∞	weeks
	Personal multipliers	Seven different variables moderating the importance of all psychological motivations to retrofit.	0-1	--
	Social friends	A list of all other households the household considers to be its friends.	--	--
Global	Electricity price	Feeds the price of one kWh to the households.	0.18	EUR

3. Process overview and scheduling

Each week, the households perform 8 distinct submodels, with submodels 4-6 being the most central. Where the execution order of the agents is not specified, the order is random. When relevant, a submodel is run through all households before the next submodel is started[1].

1. There is a small chance of the household decreasing its energy standard by some units of kWh/(m^2a). This chance is significantly increased if the household has not been retrofitted in the last 25 years.
2. If the household is in stage 1 “not in decision mode”, and has had the same ambition for some time, it picks a new ambition better than its current energy standard from the pool of its friends and neighbor's energy standards. If the households have the best energy standard of their friends and neighbors, it sets a 20% improvement of its own energy standard as the ambition.
3. The household regenerates a small part of its max investment potential.
4. The households calculate distinct values for each of the psychological motivations to retrofit. These are normative influence, self-efficacy, worry about financial resources, perceiving their energy standard as wasteful, perceived economic gain, comfort gain, and availability of subsidies.
5. All psychological variables are standardized, multiplied with the respective regression weight according to stage transition, the household's multiplier for that psychological value, and summarized into intention scores.
6. Households transition in retrofit stage based on the decision-making algorithm of the model.
7. If the household has spent enough time in stage 4 “currently retrofitting” to complete the energy retrofit, the current energy standard is updated to ambition, the cost of the retrofit is subtracted from the household's investment potential, and the household transitions back to stage 1.
8. The household has a small chance of changing owners.

4. Design concepts

At its core, the HERB-model is feeding real survey data through the proposed behavioral model of Klöckner and Nayum (2016), and with the help of other research (Fyhn et

[1] For example, submodel 1 is run in all households before submodel 4, because the energy standard of *other* households affects perception of wastefulness of own house. But submodel 2 is ran in unison with submodel 3, as no variables in submodel 2 affects variables in submodel 3, and separating them would only increase simulation time of the model without chaninging the outcome.

al., 2019; Galvin, 2010), creates a fully simulated energy retrofit model. The core idea is that households transition through different stages in decision-making before concluding. The transition between "stages", is strongly based on a series of existing research (Klöckner & Nayum, 2016) which is again based on Bambergs stage-based model of self-regulated behavior change (Bamberg, 2007, 2013a, 2013b). Households move through different stages in decision-making to reach a decision, and the importance of different aspects such as comfort and economic gain varies for transition between different stages. Studies (Klöckner & Nayum, 2016) have been performed that quantify the importance of these different aspects. The HERB-model tries to implement these findings in a simulated neighborhood.

4.1. Basic principles

At its core, the HERB-model transforms physical aspects such as energy standards into psychological variables such as perceiving the building as wasteful. These psychological variables then decide households transition through a 4 stage decision-making process, which eventually affects energy retrofitting, changing those original physical aspects. We use the specific regression coefficients (from Klöckner & Nayum, 2016) to determine the impact of each psychological variable on the transition from each specific stage.

A separate process transformed the items in the research from Klöckner and Nayum (2016) to simulated values. Firstly, the lead author transformed some of the items from the survey to overarching aspects. For example "Higher comfort levels expected after upgrade" was transformed to comfort gain. Some items, such as "The right point in time has just not come to upgrade" were deemed impossible to replicate in code and excluded. The outcome is documented in appendix A. After this, all aspects were transformed into formulas that could be replicated in code. For example "comfort gain", was transformed to "movement in kWh/(m^2a) from current to upgraded standard". After this, a short workshop was held within the lab group [anonymized] at the lead author's affiliation, featuring several behavioral researchers, to verify and adjust the fit of the operationalized psychological constructs. This method of transforming survey items to psychological constructs to code is both inherently subjective, reliant on the opinions of experienced researchers, and difficult to replicate, with no "best" way to do it. Nevertheless, we think such a process needs to have such subjective considerations, and by leaving these subjective considerations up to experienced behavioral researchers, we ultimately reached a good end product. We give a visual overview of the entire model in figure 1.

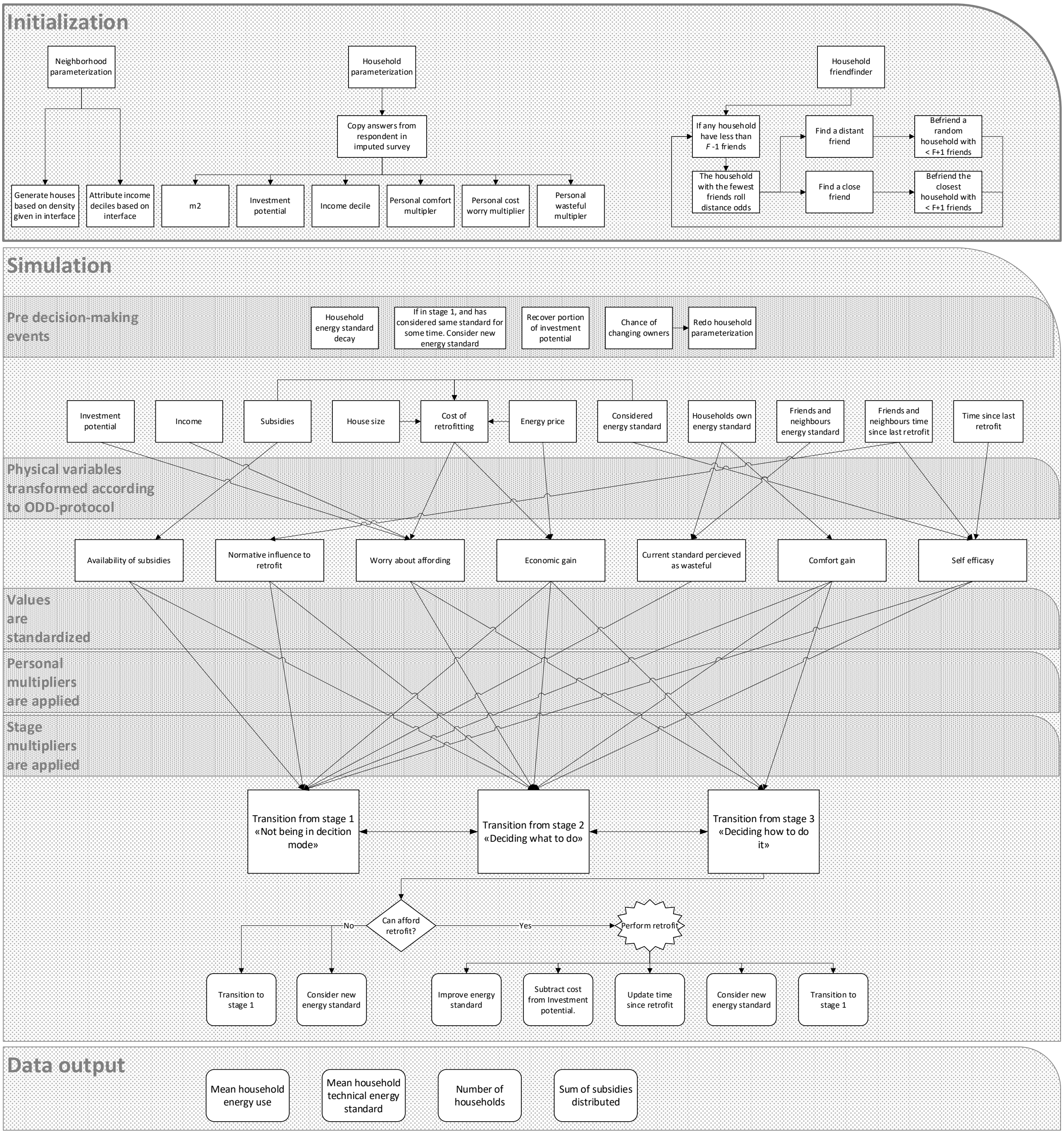

Figure 1: A visual overview of the HERB model

4.2. Emergence

The key emergent behavior, that all aspects of the model affect, is energy retrofitting. To which energy standard, when, how often, and the impact of subsidies are key characteristics of the retrofitting. All these aspects emerge from the decision-making process mentioned above. For example, by lowering the threshold for energy retrofit subsidies, we expect an overall increase in retrofit rate as households will have more money to spend, and thus worry less about money available. But we also expect a higher retrofit rate towards lower energy standards as they gain access to subsides, and a lowering of energy retrofitting towards high standards as these subsidies become less exclusive. We would also expect an increase in directly measured free-riding, but cannot say for sure to which extent it would affect total cumulative energy usage.

4.3. Adaption

Households are influenced and adapt to the behavior of other households in three ways. Firstly, several of the raw unstandardized psychological values determining movement in a stage is relying on variables outside of its entity. Normative influence is a direct result of the retrofit rate of households in its vicinity. Retrofit self-efficacy is a result of the household's own, but also other households' retrofit activity. Perceiving your energy standard as wasteful is a direct effect of the energy standard of other households. Secondly, all psychological values undergo standardization before they are summarized as an intention score, and standardization relies on the values of all other households. For example, having a high self-efficacy counts for more if other households have low self-efficacy.

Thirdly, households mostly consider upgrading to energy standards that other households currently have. Unfortunately, we could not locate any research regarding what ambition level households consider. Therefore, we based this function on a broader psychological mechanism, the availability heuristic (Tversky & Kahneman, 1973, 1974). Broadly speaking, this research shows that humans greatly emphasise the ease with which relevant instances come to mind in their conclusions. We generalize this to mean that the energy standard of friend's and neighbour's households are easily available to the household and will be empathized when making a decision. Thus, households only consider upgrading to energy standards they are exposed to through neighbours and friends. This part of the model should be updated as soon as more research on what energy standards households consider is available.

4.4. Objectives

The households' code can be read as if their objective is to maximize their psychological variables through retrofitting and not retrofitting. The optimal psychological values vary between households due to personal scores and change according to which decision-making stage the household is in. That being said, the model is built on the idea that agents simply do what the research has shown them to do and do not attribute any reasoning for *why* they do this. Most of the behavioural research the model is based on does not speculate on objectives for the observed behaviour, and therefore we also try to avoid this.

4.5. Learning

Households do not change their behaviour as a consequence of learning.

4.6. Prediction

The most evident case of prediction in the HERB-model is households calculating a naïve return on investment in submodel 4. This is done by calculating the retrofit cost by how much the household saves on electricity yearly. The household does not include degradation of energy standard, investment opportunity cost (capital lost as a consequence of not being able to invest the money elsewhere), or inflation in this calculation, as we believe most households are not aware of these factors. The household always perfectly predicts whether it is eligible for subsidies, and how much. Additionally, the household predicts its comfort level of the energy standard it imagines upgrading to. Finally, the household could be said to predict the loss of social stigma of a low energy household, when considering its energy standard as wasteful.

4.7. Sensing

Households sense the energy standard and time since retrofitting of other households. This is sensed through what households consider neighbors and friends. Neighbors are all households in a certain range, adjustable in the interface but preset to 250 meters. This represents that members of a household can usually observe, and therefore understand the average energy standard and renovation activity in their neighborhood.

Friends are other households in the environment that the household has 'bonded' with during the initialization. Here, a 'friend finder' is run so that every household has F amount of friends +- 1. Technically, the household with the fewest friends forms a friendship with either the closest household or a random household in the simulated area with no more than F+1 friends. The odds of picking a close or distant friend can be changed. This process repeats until all households have F-1 or more friends. The model can then calculate average path length and clustering coefficients (from Wilensky, 2015). The function is based on small-world networks (Watts & Strogatz, 1998), and can be calibrated to specific average path lengths and clustering coefficients by changing the F and the odds of choosing a close or distant friend. To get a social model better representing the one being researched, researchers should calibrate to the social network they are studying. The simplest way to do this is to run the model with all variations, remove the model runs with undesirable path lengths and clustering coefficients, and check which initial settings produce the remaining runs.

4.8. Interaction

There are no direct interactions in the model, but agents interact indirectly through the standardization procedure, as mentioned in submodel 5. This is a central step in keeping the "weights" of the original research. If the model had introduced parameterization weights onto the different psychological variables, the weights from the original research could be said to no longer apply. By doing this, we take a "hands-off approach" in deciding which variable is most important, and their mean strength in determining the final intention score is only relying on the original research regression coefficients. As the strength of one psychological variable is the z-score of that variable, the strength of one psychological variable is always dependent on other households. For example, if a household is eligible for 1000 € in subsidies to retrofit, this is in itself not enough to know how much this will affect the motivation of the households to transition between stages, and ultimately retrofit. If the mean of available subsidies to all households is more than 1000 €, this will lead to the household being less likely to retrofit. If it is less than 1000 €, it will lead to increased chances of retrofitting. Intuitively, it could feel "off", that if all households are offered 1 million EURO for retrofitting will be as motivating as no subsidies, but we argue this system has some merits. For example, we see it as likely that a household will be more motivated by receiving 1000 EUR in subsidies if all other households are only eligible for 100 EUR. Contrarily, the same 1000 EUR will be a lot less motivating if all other households were eligible for 10000 EUR.

As one tick in the model represents one week, agents interact on a weekly time scale.[2] We decided on a weekly time scale based on what we considered the shortest realistic time to go from not considering retrofitting to starting a retrofit project. We estimated this to be somewhere around one month. As agents have to transition between 4 stages to retrofit, the fastest time to start a retrofit, with a weekly time-scale, is three weeks. Note that agents transitioning from stage 1 to stage 4 in three ticks is rare.

4.9. Stochasticity

Several aspects of the model have elements of stochasticity. Firstly, the behavioral choice model described in submodel 6 relies on random chance. For practical purposes, no combination of psychological motivation and financial capability is guaranteed to make the household retrofit as fast as possible, it can only shorten the likely time it takes for the households to decide to retrofit. Theoretically, a household that is extremely motivated to retrofit could never decide to retrofit, and a household that is not particularly motivated can

[2] To be precise, one tick in the model is not one week, but 1/52th of a year, or 7.02 days. However, we write 'week' for simplification.

retrofit. We believe this stochasticity is a vital part of the model that represents the field's non-complete understanding of households' decision to retrofit. The parameters for the stochasticity of this submodel are the primary way of balancing the retrofitting rate of households to fit real-world data. It could be argued that real decision-making is influenced by randomness and that therefore, introducing a random variable is accurate. But we find this more of a philosophical debate and argue that for practical purposes, random and unknown are either way still best represented by random.

4.10. Collectives

Households do not gather in collectives.

4.11. Observation

Several types of data are pulled from the model. To parameterize the model, we used yearly retrofit rate. This is reported in annual statistics by ENOVA (Fyhn et al., 2019). Originally, we planned to parameterise the model with free-riding and consecutive retrofit rates but ultimately decided against it. Firstly, the only way to directly adjust these rates was by changing the psychological values' weights, which we did not want to do as the existing research already set them. Secondly, when not adjusting them, we can better use them as validation criteria. To parameterise, we graphed the numbers in the model, where users can observe the ideal real-world data graphed in blue. After this, we adjusted the values in the decision-making algorithm until we had a reasonable number of households in each stage, and observed that the retrofitting rate had a reasonably stable oscillation over time around the desired number. The final numbers for this state can be seen in table 5.

Different data was observed when running experiments. Here, we were primarily concerned with the cumulative power use of an average household, the final energy standard of the households, and the various policy scenarios. The first was collected each step, while the two latter were collected only in the end. All collection of energy use data in the model dubbed is "actual_kWh/(m2a)". This represents the households' technical energy standard multiplied by the values in table 2, which are pulled from research showing that low-income households spend less energy than their energy standard implies, and rich households spend more (Arthur, 2019). This value is only used when pulling data from the model. For example, households do not use this value when calculating financial gain in terms of energy usage, as we see it as unlikely that households are aware of this.

Table 2

Transformation of technical building standard to actual energy use.

Income decile	Technical to actual kWh/(m^2a) multiplier
1	0.834
2	0.834
3	0.851
4	0.870
5	0.884
6	0.890
7	0.895
8	0.923
9	0.956
10	1.024

4.12. Additional concept; subsidy system

An additional central concept of the model is its subsidy system. The subsidy system is made up of several global variables mirroring most aspects of the current main Norwegian subsidy system (Enova, 2019). These include the maximum amount of subsidies received for each retrofit, the minimum technical energy standard the building must reach to be eligible for the subsidies, the percentage increase of building standard that must be conducted in order to be eligible for the subsidies, and the maximum percentage of the cost of the retrofit the subsidies can cover. Although three subsidies are available, they are exclusive and only one is available at any time. Details about the subsidy system are listed in table 3.

Table 3

Description of the subsidy system implemented in the HERB model.

	Subsidy 1	Subsidy 2	Subsidy 3
Maximum EUR paid in subsidies	14779	12316	9853
Minimum kWh/(m^2a) value that must be achieved to qualify for subsidies	80 + 1600 / m^2	100 + 1600 / m^2	120 + 1600 / m^2
Minimum improvement in kWh/(m^2a) standard to qualify for subsidies	30%	30%	30%
How much of the total retrofit cost the subsidies can cover	25%	25%	25%

Due to limitations in the model, this implementation does not capture the full extent of the Norwegian subsidy system. Firstly, the real subsidies require that the building is heated from efficient sources such as ground-to-air heat pump, that some of the heat is "recycled" through heat retention systems, and that most of the building is touched upon when performing the retrofit. These are aspects that the current HERB-model did not simulate, and was thus not included as a requirement. As a consequence, being eligible for subsidies could be easier in the HERB model than in real life.

5. Initialization

To initialize the model, households received an income decile, personal comfort, worry and wastefulness multipliers, building size, and investment potential from a random respondent in the survey mentioned in subheading 6 input data. If investment potential is less than the median for that income decile, the maximum potential was changed to the median investment potential of the same income decile, but with unchanged current investment potential. As we had no data basis for the personal normative multiplier, we applied a random value between 0 and 1. To not let psychological variables with a modifier have less influence, the mean of all other modifiers was applied to psychological variables with no modifier. The time since the last retrofit was set a random time in the last 60 years, and the time remaining for the household to pick a new ambition a random value up to the maximum time the household uses to pick a new value. Finally, households were distributed on a square kilometer of the simulated area according to a real small town in Norway (SSB, 2021d).

Similar to other household retrofit models (Friege, Holtz, & Chappin, 2016), we had difficulties reaching a stable state on initialization. Although the model could reach a steady state of energy standards on its own, initializing in this same stable state was difficult. We identified the initial kWh/(m^2a) standard as the main reason for this. First, we distributed energy standards based on income deciles from official sources (SSB, 2014). Although this statistic was far too general to apply to individuals, having the true mean was useful. After letting this model reach a steady state, we pulled all input agent data and predicted building energy standards using negative binomial regression. See the accompanying document "Description of negative binomial regression for ODD" for details on this process. We then calculated the energy standard on initialization using the results of the regression and multiplied it to reach the "true" mean (SSB, 2014). At this point, the model was reasonably stable in the beginning, but not completely. As a final method of initialization, we let the model reach a steady state, pulled all agent data except for position, friendships, and neighbors. Then we multiplied kWh/(m^2a) values to reach the true mean and initialized using that data. In the model, this method of initialization is dubbed the "photograph method". Users are free to choose the initialization method they prefer, but we recommend using the photograph method as it gives the most stable system from the get-go.

The model stops after 100 years. This extended simulation period has pros and cons. On the negative side, it is reasonable to assume that many model assumptions will not hold for 100 years. It is very likely that retrofit prices, building laws, and the financial situation of most households will change. It is also reasonable that what motivates people to retrofit will change, and the rate of changing households will go up or down. The authors do not believe that the model accurately replicates how energy retrofitting is in 100 years. The model only tries to capture policies effect in 100 years, which will be obscured by other changes that are impossible to predict. Therefore, the model results will only cover the effect of policies assuming all other factors remain constant, not predict how the building stock actually is.

A long simulation time allows the simulation results to cover the long term effects of subsidies adequately. For example, suppose some policies only motivate high-income households to retrofit, and demotivate low and medium-income households. In that case, it could show a positive effect over 20 years, as some households retrofit. But over time, low and medium-income households will start falling behind, increasing the neighbourhood's energy consumption. Therefore, implementing a short or long time period has pros and cons. For the original research article, we have chosen a long time period to cover the long term effect of policies. Still, researchers much estimate the most appropriate time period for their own research project.

6. Input data

The model use data from both empirical, theoretical, and free parameter sources. We go into detail on these in other sections, but will provide an overview here.

Table 4

Epistemological overview of model variables and functions.

Variable/ Function	Short description	Origin
Household size	Size of the household in meters squared	Empirical; individual - From the survey
Household investment potential	How much money the household can potentially invest in energy retrofitting.	Empirical; individual - From the survey
Savings regeneration	How many years it takes households income to regenerate their investment potential	Free parameter - Parameterized.
Household income decile	Which income decile the household belongs to	Empirical; individual - Raw income taken from the survey and transformed to income decile through publicly available data (SSB, 2018).
Household half max income	Half the top income of an income decile.	Empirical; collective - From publicly available data (SSB, 2018).
Personal comfort/ cost worry/ wasteful multipliers	How much the household cares about the specific psychological variable.	Empirical; individual - From the survey.
Personal normative multiplier	How much the household cares about normative influence.	Free variable - Randomly varies from 0 to 1.
Electricity price	The price of one kWh.	Empirical; collective - From publicly available data (Eurostat, 2019).
Household location	Where the household is on the simulated map.	Empirical; collective - From publicly available data (SSB, 2021d).
Social friends	Which other households the household consider friends.	Theoretical - Small world (Watts & Strogatz, 1998)
Neighbours	Which other households the household considers a neighbour.	Theoretical - Deduced from neighbourhood effects (Helms, 2012).
Energy standard awareness	How much better energy standard other household has before it is noticeable.	Free parameter - Discussed in workshop.
Retrofit brevity	How long an energy retrofit takes.	Free parameter - Discussed with building engineer.
Retrofit durability	How long a retrofit last before deterioration ramps up.	Theoretical - Mentioned in existing research (Galvin, 2010).
Energy standard deterioration	How fast and how the energy standard of a house deteriorates.	Free parameter - Discussed with building engineer.
Retrofit cost	How much it costs to retrofit.	Empirical; collective. From existing research (Galvin, 2010).
Stage mechanism	How households change between stages of retrofitting intention and the factors moderating these transitions.	Theoretical - Based on existing research (Klöckner, 2014; Klöckner & Nayum, 2016, 2017; Klöckner, Sopha, Matthies, & Bjørnstad, 2013).

Stage transition random effects	How much and in which direction the random effect affect stage transition.	Free parameter - Parameterized.
Ambition mechanism	How household pick their ambition.	Free parameter - Based on the availability heuristic (Tversky & Kahneman, 1973).

Note: Empirical: Data source is real-world collected data, either through surveys collected by researchers, public data, or elsewhere. Individual: The values can be traced to individual real-world entities where this value is used in the model. Collective: The values stem from summarized data, such as mean income from a group, and can not be traced back to individual entities. Theoretical: The data or function is based on theoretical frameworks. Free variable: The variable or mechanism is based on a non-scientific source, such as a discussion with experts, parameterization, or a broader theoretical framework.

6.1. Survey

The model uses input data from two surveys distributed to representative samples of Norwegian households between January and March 2014 and between March and April 2019. The surveys had 2,605 and 3,797 respondents, respectively, and were pooled, forming a total sample of 6,402 respondents. The data were originally collected for and funded by Enova SF to investigate trends in private housing energy retrofitting in Norway. The input data can be seen together with the model, and the model cannot be run without the original input data.

As with all survey data, our data also had missing data. To deal with this missing data, we used predictive mean matching multiple imputations with 10 neighbors and 5 imputations. The syntax for this imputation can be found in appendix B. Consequently, the dataset in the model is not the raw dataset, but a combination of all 5 imputations. Therefore, it contains 5 times as many respondents as the original dataset. Although this method of using imputed datasets ignores Rubin's rules for combining the final effect size (Rubin, 1987), we consider it to be a better option compared to case-wise deletion ignoring respondents that left some items unanswered. By combining 5 imputations, the data input consists of mostly real data, but includes various estimated points where items have been left unanswered.

An alternative approach would be to run the same simulation on all imputed datasets, perform analysis on the result of all output data, and then combine this data using the Rubin's Rules. As the Rubin Rules were not created with ABM's in mind, which introduces several steps between imputation and statistical analysis, we are not sure if this approach is valid. Firstly, the ABM's introduce other random parameters into the analysis that the imputations do not account for. Secondly, this severely breaks the rule of thumb that one should not alter the data between imputation and analysis. One could argue the ABM is itself part of the analysis, but as it produces a different dataset, it is also just an intermittent step. Finally, it should be noted that this significantly increases simulation time, with 5 imputations taking 5 times as long to simulate. All in all, no material on ABM's and multiple imputations exist and it is outside the scope of this protocol and project to best determine the best approach. Further research should investigate how to best combine the two approaches.

Input data underwent varying levels of treatment from the survey to the model. Translated items and transformations where applicable are listed in table 4. All personal multipliers were normalized. Translation serves only to give an impression of the items and should not be used as professional translations for the originally Norwegian survey items.

Table 4

Overview of survey items transformation to HERB variables.

HERB item	Survey item	Transformation
m^2	"How big is your home / apartment? Please state the living area of the home / apartment in square meters:"	--
Investment potential	How many kroner do you think it is realistic that your household could have invested in the rehabilitation of your home (either from savings or through borrowing), if it had been relevant to rehabilitate it today?	NOK -> EUR * 0.098527
Income decile	What is the household's total gross income (before tax) per. year?	Transformed to 1-10 based on income decile brachets
Personal comfort multiplier	A "Re-insulation makes my house generally better to live in" B "Re-insulation provides better comfort" C "It is important for me to feel good. I like to "pamper myself" sometimes"	(((A + B) / 2) * C)
Personal cost worry multiplier	It is important for me to have good money. I want to afford things and be able to buy expensive things	--
Personal wasteful multiplier	A "Due to my values / principles, I feel obligated to re-insulate my home" B ""I personally feel obligated to re-insulate my home»	(A + B) / 2

7. Submodels

Below, we specify the submodels ran in the simulation.

7.1. Decay of building standard

As a general rule, buildings have a 10% chance of suffering a technical failure each year, reducing the energy standard by a random number between 1 and 40. If the building has not been retrofitted for 25 years, this chance is three times as high. However, as the simulation works on a weekly time-scale, the building degradation calculation is slightly different. Every week, this will reduce a buildings energy standard by an average of (0.1/ 52) * 20 = 0.038. Yearly, this is (0.1/ 52) * 20 * 52 = 2. This represents some kind of error occurring with the building, leading to a loss of energy standard. The greater chance of an error happening after 25 years represents that this is usually the listed amount of years building insulation parts are expected to last (Galvin, 2010).

7.2. Pick new ambition

If the household is in stage 1, it picks a new ambition every 12 weeks. If it is time to pick a new ambition, the households make an agent list of all friends and neighbors with better energy standards than themselves, then sets their ambition to one of these. If the household has no friends and neighbors with better energy standards, they pick a 20% upgrade as their ambition. The household also calculates the retrofit cost when picking a new ambition. This cost was based on previous energy retrofitting cost research (Galvin, 2010), adjusted for inflation to 2019 numbers (SSB, 2021c), and multiplied by 1.2, as the cost data was gathered in Germany, which is somewhat warmer than Norway, implying retrofitting to the same energy standard would have a different cost. Future research could improve this simplified retrofit cost formula. For example, rurality, pre-retrofitting kWh/(m^2a) standard, and how much of the retrofitting the household completes on its own are most likely relevant factors concerning the final price of the retrofit. We nonetheless believe that the fitted line covers the most important aspect of energy retrofitting cost in relation to the purpose of the simulation.

While it could seem unintuitive that a household in stage 1, defined as “not in decision mode” picks a new energy standard to “think about” every 12 weeks, it is a necessary addition for both the HERB model and existing theoretical models. For example, research (Klöckner & Nayum, 2016) shows that an increase in comfort is important for the transition from stage 1 to 2. Logically, the household needs to have some sort of energy standard in mind if they think the comfort can be improved. Therefore, households regularly pick an energy standard to think about upgrading to, even though they are not in decision mode.

7.3. Investment regeneration

Each tick, if the household has less current investment potential than their maximum potential, the household regains a small portion of their investment potential. The amount regained is scaled so that household on average takes 10 years to regain 100% of their investment potential with no subsidized loans. To add some variation, the household randomly regenerates between 0 and 200% of this amount each tick.

7.4. Calculate psychological variables

Next, all psychological variables are calculated. Some elements apply to several psychological variables. When "friends and neighbors" is mentioned, first the score for neighbors is calculated, then for friends. Then the neighbors' score is multiplied by 0.4365, and the friend's score by 0.5635. This ratio corresponds to the number of people stating that friends influenced their retrofitting behavior versus the number of people stating neighbors influenced the survey discussed in point 6. After this, the scores are combined. This represents that friends have a somewhat larger influence on retrofitting behavior than neighbors. Households can be both a friend and a neighbor to another household.

Normative influence is based on friends' and neighbors' retrofit activities in the last 5 years. Retrofits in the last year count 5 times as much as a retrofit in the last 4-5 years. For example, a friend that has retrofitted 4 years ago and a friend that has retrofitted 1 year ago, this gives a total of 2+5 "units" of normative influence. This score is divided by the number of friends or neighbors and combined using the method described above.

Self-efficacy follows the same rules as a normative influence, but the household's own retrofit behavior represents 80% of the score, while friends and neighbor's retrofit experience represents 20% of the score. Additionally, the last 20 years are counted, and not only the last 5 years.

Worry about financial resources is zero if the cost of retrofitting is less than half of the household's available money. If it is between half and max, it is two times the retrofit cost divided by investment potential minus one[3]. If it is more than max, it is 1. Finally, the value is multiplied by -1, as a higher number must mean a higher willingness to retrofit for the standardization to work.

Perceiving the household energy standard as wasteful has a somewhat straightforward calculation. If the mean energy standard of friends and neighbors is 10 % better than the household's own energy standard, this mean difference is how wasteful the household thinks their standard is. This "10% rule" is implemented because we believe households would not notice that other households' standards differ when they are this close. Households cannot be demotivated to retrofit as a consequence of perceiving their household as non-wasteful.

[3] 2 * (retrofit cost / investment potential) - 1.

Perceived economic gain is a result of both naïve return on investment, and the relative increased disposable income. Naïve return on investment is how many years it takes to earn back the retrofit cost including subsidies excluding degradation, investment opportunity cost, and inflation. These are not included because we do not think households take this into account when or even if doing this calculation. This number is multiplied by -1, as more years before the investment pays of implies less economic gain. Relative increased disposable income is how much money the households save on energy each year in relation to the half max income of their income decile (SSB, 2018). Poor households care about saving EUR 1000 on energy more than rich households. As this last number is much larger than the first, it is divided by 3, which makes the two numbers roughly comparable. Finally, they are combined into one number representing perceived economic gain.

Comfort gain is the flat increase in kWh(m^2a) standard from the household's current energy standard, to the energy standard it considers retrofitting to.

Availability of subsidies is how many EUR of subsidies the household is eligible for with the current ambition standard in mind. Take note that fees, implemented as negative subsidies can easily be implemented in the model if further research wants to try this out.

7.5. Intention scores

Next, the model calculates the mean and standard deviation of all psychological variables. If the standard deviation is 0, which can happen if, for example, no subsidies are available to households, it is set to the arbitrary value 1, this does not impact the simulation, as the resulting z-score will be 0 regardless. Next, households calculate the z-score of all their psychological variables by subtracting the mean and dividing by the standard deviation.

Then, to create weighted z-scores, households multiply the z-score with personal the relevant multiplier, and its importance for that stage, shown in table 4. This is also done for psychological variables that have no impact on that specific stage, so this can later be changed if new research indicates they are relevant. Finally, all weighted z-scores are added up to one score representing the household's intention to transition stage.

Note that in addition to the factors listed by Klöckner and Nayum (2016), normative influence was added. This was done as the resulting list ended up with no normative influence in it, even though this has been shown to strongly influence behavior in general (Ajzen, 1991; Clayton, 2012). Although far less attention has been paid to the role of social influence in the adoption of energy-efficient appliances or whole-home insulation and retrofits (Wolske, Gillingham, & Schultz, 2020), and a whole individual research study could be launched to determine this, some research does exist (Helms, 2012) making it more likely than not social influence plays a significant part. Therefore, a medium effect of normative influence was added to the psychological factors influencing stage transition. It does not affect the transition from stage 3 to 4, as this seems like a more "slow thinking" stage, where normative influence is weaker.

Table 4

Psychological variables weights for movement from different intention stages.

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

7.6. Decision-making

A decision-making algorithm was constructed to let the households move through stages of retrofitting. In short, a random number C, was generated between point A and B. If value C was smaller than the households intention score minus an uncertainty score D, the household moved up in stage. If C was within the uncertainty range, the household remained in the same stage. If C was larger, the household moved down in stage. If the household is in stage 2 or 3 and does not move stage, a small negative value E, is applied to D, reducing it, which eventually forces the household to transfer stage. Each household generated its own number C independently from others. The decision-making algorithm is demonstrated in figure 2.

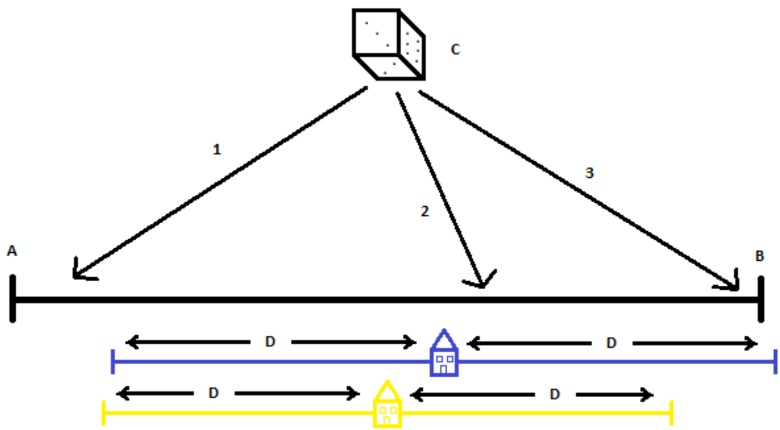

Figure 2: A visual representation of the decision-making algorithm.

Alternatively, the formula can be described in pseudo-code like this:

```
ask households [
     let C random A → B
     let I household_intention_score
     let E weekly_uncertainty_decay
     let D cumulative_uncertainty_decay
     if C < I - D [move_up_in_stage]
     if C > I + D [move_down_in_stage]
     else set D (D - E)
     ]
```

In the example in figure 2, if the number C produces the number indicated by arrow 1, both the blue and yellow household advances 1 stage. If the number is 2, no household transfers in stage. If the number is 3, the blue household remains in the same stage, but as the yellow household has a shorter D due to having remained in that stage for a long time, it transfers 1 stage down. Note that the blue household cannot move down in stage, regardless of chance, as its intention score is too high and uncertainty score is too low. Actual numbers for A-E in every stage used in policy experiments and suggested to use as a baseline without major changes to the model is listed in table 5.

Table 5

Numbers for the decision making model used.

	A	B	D	E
Stage 1	-10	5	10	0
Stage 2	-2.07	2.15	2	0.001
Stage 3	0.62	0.6	0.6	0.001

With this decision-making algorithm, we believe to capture all influence of the psychological variables on stage transition, while leaving the "rest" of the real-life variance up to random chance. This includes both factors that are currently unknown to the research on energy retrofit behavior, as well as truly random effects on decision-making.

Additionally, if the household tries/ want to go from stage 3 to 4, but the total retrofit costs are higher than what the household can currently afford, the household instead moves back to stage 1 and picks a new intention. This retrofit cost does not include subsidies, as Norwegian subsides for retrofitting are paid after the retrofit is complete. This sometimes happens, as the worry about the cost of retrofit can be overruled by other factors such as perceived gain in comfort.

This 'investment capability check' could have been integrated before, between, or after the stages. We did not want to integrate it between the stages, as we wanted the existing research to be the only thing modulation stage transitioning. We could have implemented the check at the beginning in the ambition picking model, where households could never consider energy standards they cannot afford. But, to assume households never think about things they cannot afford is probably unrealistic. Additionally, the retrofit cost is probably not something households are completely aware of early in the decision-making process. At this stage, households likely have a general feeling of they can afford and not, but this should be already covered by the 'Worry enough finance' psychological variable. Because of this psychological variable, households will be hesitant in transitioning stages when considering energy standards they cannot afford. Thus, the only viable choice to implement this check was the end of the decision-making process.

Although not a central part of the model, free-riding is also registered in this submodel. If the household transitions in stage and is eligible for subsidies, a new intention score for that same stage is calculated as if the household did not have access to subsidies. This includes recalculation of the perceived economic gain and the motivational gain from access to subsidies. It's important to note that concerning motivation from subsidies, it is not calculated as if the household had access to 0 subsidies. This would create a non-logical situation where if all households had access to 1000 EUR subsidies, the households would be severely demotivated by receiving 0 subsidies because of standardization. It is only the motivation that comes from the subsides that is set to 0. Theoretically, if the household has access to subsidies, but this is less than the mean amount of subsidies available to other households, this would increase motivation. This is however extremely unlikely unless subsidies are set to be distributed in a somewhat complicated manner and is not a problem for the current build of the model. If the household would have advanced in stage without the subsidies, they are free-riding the subsidies in that stage.

7.7. Retrofitting

When the household is in stage 4, it is currently undergoing retrofitting. The time it takes to complete the retrofit is 1 week/tick pr. 5 kWh/(m^2a) improvement, with a minimum of 2 weeks and a maximum of 26 weeks. When the retrofit is complete, the household sets its technical energy standards to its ambition, sets its retrofit stage to 1, adjusts its time since retrofit to 0, subtracts the retrofit cost minus the subsidies from its investment potential, and looks for a new ambition. It's necessary to immediately look for a new ambition, as having the same ambition as the standard breaks several of the psychological value calculations. In this step, we also store a list of the freerider status of all retrofits performed, retrofits performed across income deciles, and the cost of all subsidized retrofits.

7.8. Moving

Finally, the households have a small chance of changing owners. This moving submodel simulates households moving in and out of the area. In its essence, every tick, every household in stage 1 has a 13.09% / 52 chance of replacing its personal multipliers, investment potential, ambition timer, and current ambition. All other variables are kept constant, including income decile. This represents households of a certain standard that is usually inhabited by the same people.

We arrived at the yearly moving chance of 13.09%, as 697,684 people moving within Norway in the year 2019 (SSB, 2021b)[4], while Norway had a population of 5,328,212 (SSB, 2021a). This leads to a total of 13.09% of the population moving. As our simulation only accounts for homeowners, and tenants probably move more 13.09% is probably somewhat too high. But this is offset by that only households in stage 1 "not in decision mode" can move.

[4] In the SSB statistic, moving between municipalities, counties, and parts of the country are non-exclusive. To get the total numbers of moves, combine within and between municipality moving (Personal communication Magnus Haug, SSB, e-mail 27.04.2021).

Although we do not believe the amount of moving is equally distributed in the population, implementing a calculation for which household was likely to move was outside the scope of this simulation.

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Appendix A.

Transformation of survey items to psychological constructs.

Survey item	**Psychological construct**
Not enough economic resources	Worry enough finance
Depending on agreement with neighbors	Normative influence
Contractors which could do the job lack the necessary competencies	Self-efficacy
Information about upgrading is difficult to find	Self-efficacy
Negative experience from previous projects	Self-efficacy
Information about energy upgrade is easily accessible	Self-efficacy
Information about energy upgrade is trustworthy	Self-efficacy
Unsure about the saving potential for energy costs after an upgrade	Self-efficacy reversed.
Difficult to know if information about energy upgrades can be trusted	Self-efficacy reversed.
Reduction of energy costs expected after upgrade	Perceived economic gain
Payoff of the investment within a reasonable time frame	Perceived economic gain
Positive health effects expected after upgrade	Comfort gain
Better living conditions in the dwelling expected after upgrade	Comfort gain
Higher comfort levels expected after upgrade	Comfort gain
There are subsidy schemes in place supporting the upgrade	Subsidies
Plans to move soon	Excluded
I do not manage to make a decision for what to do	Excluded
I do not own the dwelling	Excluded
The right point in time has just not come to upgrade	Excluded
Building protection regulations prevent me from upgrading	Excluded
Too much disturbance of the everyday life through such a project	Excluded
Demands much time to supervise the contractors	Excluded
Increased market value of the dwelling expected after upgrade	Excluded

Appendix B - Statistical syntax for imputations.

```
     version 16
     clear
     cd "[File path]"
     use "[File path]"

     drop filter_

     svyset [pweight = Vekt]


     recode persincome houseinc (98 = .)
     recode perswinc EIER Age_house ISO_walls ISO_roof HSTYPE
(9999 = .) (9996 = .)
     recode posloan (. = .a) if EIER == 3 //Respondentes not
presented with option to answer posloan if stated they rent in
survey design. This was possibly a poor choice in survey
design. We have three options (1) drop all renters from
analysis. (2) Impute values on all renters. (3) Not impute and
stay away from varables they are excluded from. Imputing
renters with non-renters data not a good solution. Staying
away from posloan could be even worse, at it seems important.
Functionally 1 and 3 is very similar. For now we pick option
1.
     drop if EIER == 3

     // Adjusting income, loan and loaning capabilities between
feb 2014 to mar 2019, according to norwegian consumer price
index (https://www.ssb.no/priser-og-
prisindekser/statistikker/kpi/maaned/2014-09-10)
     // We adjust the income before imputations, as variables
such as ownership status, work and location should be
unchanged and have the same effect on income in 2014 and 2019.
     replace income = income*1.37 if DATASET == 1
     replace loan = loan*1.37 if DATASET == 1
     replace posloan = posloan*1.37 if DATASET == 1
     replace persincome = persincome*1.37 if DATASET == 1

     drop if income > 5000000 & income <
9999999999999999999999999999
     gen incomesqrt = sqrt(income)
     label variable incomesqrt "Household income, squareroot"

     drop if loan > 12000000 & loan <
9999999999999999999999999999999
     recode loan (0 = .)
     gen loansqrt = sqrt(loan)
     label variable loansqrt "Household total residental loan,
squareroot"

     drop if valhs > 30000000 & valhs <
9999999999999999999999999999999
```

```
gen valhssqrt = sqrt(valhs)

drop if posloan > 14000000 & posloan < 
99999999999999999999999999 //Drops excessive posloans

//--- Generate EURO values and not NOK
replace posloan = posloan / 9.8527

gen posloansqrt = sqrt(posloan)
label variable posloansqrt "Household realisticly largest 
capital+loan spent on renovation, squareroot"

// NOTE - Drops total 66 participants, or 66/5484= 1.2%, 
which is pretty reasonable when dropping based on economic 
variables.

gen sizelog = log(SIZE)

gen houseage = 2020 - Age_house
gen houseagelog = log(houseage)

rename EER_plan_do eer_do
rename EER_plan_plan eer_plan
rename ENE4_done_code_sum eer_done

// --- Rename and recode missing into missing.
rename VALUE8 personal_cost_worry_multiplier
recode VALUE7 FAC7 FAC8 PN1 PN2 
personal_cost_worry_multiplier (9996 = .) (9999 = .)

// --- Generating personal caring about comfort multiplier
sumscale, f1(FAC7 FAC8)
generate personal_comfort_multiplier = Factor1_average * 
VALUE7 / 49

// --- Generating worry about costs multiplier
generate personal_worry_multiplier = 
personal_cost_worry_multiplier / 7
drop Factor1_average

// --- Generating wasteful personal multiplier
sumscale, f1(PN1 PN2)
generate personal_wasteful_multiplier = Factor1_average / 
7

// Only keeping the variables we are actually using.
keep sizelog houseinc incomesqrt posloansqrt Vekt 
personal_comfort_multiplier personal_worry_multiplier 
personal_wasteful_multiplier

// --- IMPUTATION
```

```
     // We use 10 neighbors as suggested by Morris, T. P., I.
R. White, and P. Royston. 2014. Tuning multiple imputation by
predictive mean matching and local residual draws. BMC Medical
Research Methodology 14: 75.
     cd "C:\stata local"
     save ABMdataset2, replace
     use ABMdataset2
     mi set wide
     mi register impute incomesqrt posloansqrt sizelog houseinc
personal_comfort_multiplier personal_worry_multiplier
personal_wasteful_multiplier
     mi impute chained (pmm, knn(10)) income posloansqrt
sizelog houseinc personal_comfort_multiplier
personal_worry_multiplier personal_wasteful_multiplier
[pweight = Vekt], add(5) rseed(1775)
     save ABMdataset2, replace
     use ABMdataset2, clear

     //--- Generate income deciles and others
     mi passive: generate INT_KR_kpi = incomesqrt*incomesqrt *
0.9783
     mi passive: generate INT_KR_decile_imputed = .
     mi passive: replace INT_KR_decile_imputed = 10  if
INT_KR_kpi < 1000000000000000000
     mi passive: replace INT_KR_decile_imputed = 9 if
INT_KR_kpi < 1526000
     mi passive: replace INT_KR_decile_imputed = 8 if
INT_KR_kpi < 1194000
     mi passive: replace INT_KR_decile_imputed = 7 if
INT_KR_kpi < 986000
     mi passive: replace INT_KR_decile_imputed = 6 if
INT_KR_kpi < 813000
     mi passive: replace INT_KR_decile_imputed = 5 if
INT_KR_kpi < 666000
     mi passive: replace INT_KR_decile_imputed = 4 if
INT_KR_kpi < 551000
     mi passive: replace INT_KR_decile_imputed = 3 if
INT_KR_kpi < 452000
     mi passive: replace INT_KR_decile_imputed = 2 if
INT_KR_kpi < 351000
     mi passive: replace INT_KR_decile_imputed = 1 if
INT_KR_kpi < 256000

     mi passive: generate size = exp(sizelog)
     mi passive: generate posloan = posloansqrt*posloansqrt


     drop houseinc Vekt incomesqrt posloansqrt sizelog
personal_comfort_multiplier personal_worry_multiplier
personal_wasteful_multiplier INT_KR_kpi INT_KR_decile_imputed
size posloan _1_houseinc _2_houseinc _3_houseinc _4_houseinc
_5_houseinc _1_sizelog _2_sizelog _3_sizelog _4_sizelog
```

```
_5_sizelog _1_incomesqrt _2_incomesqrt _3_incomesqrt
_4_incomesqrt _5_incomesqrt _1_posloansqrt _2_posloansqrt
_3_posloansqrt _4_posloansqrt _5_posloansqrt _1_INT_KR_kpi
_2_INT_KR_kpi _3_INT_KR_kpi _4_INT_KR_kpi _5_INT_KR_kpi,
```

Statistical scripts

1. Paper 1

1.1. Main analysis

```
version 16
clear
// Please insert directory here.
cd "[Please insert the path correct datafile here]"
use "[Please insert the path correct datafile here]"

drop filter_
svyset [pweight = Vekt]


// First we construct the indexes from the original survey.
Although many are not used in the final alalysis, we leave
time in, as other reaearchers might want to use them for their
own projects.
recode ATT1 ATT2 ATT3 ATT4 (9999 = .) (9996 = .)
sumscale, f1(ATT1 ATT2 ATT3 ATT4) fsum
rename Factor1_sum att_sum
label variable att_sum "Sum of 4 attitute towards insulation"
//Very good reliability. CBA = .93

recode DN1 DN2 DN3 (9999 = .) (9996 = .)
sumscale, f1(DN1 DN2 DN3) fsum
rename Factor1_sum social_renovation
label variable social_renovation "Normality of insulation.
Sumscale of 3"
//Too low internal reliability. Do not use.

recode SN1 SN2 (9999 = .) (9996 = .)
sumscale, f1(SN1 SN2) fsum
rename Factor1_sum subjective_norm
label variable subjective_norm "Subjective norm towards
insulation. Subscale of 2"
// Zero inflated, consider cutoffpoint into dictonimous var.

recode PA1 PA2 (9999 = .) (9996 = .)
sumscale, f1(PA1 PA2) fsum
rename Factor1_sum climate_worry
label variable climate_worry "Insulation affect climate.
Subscale of 2"
//Too low internal reliability. Do not use.

recode PN1 PN2 (9999 = .) (9996 = .)
sumscale, f1(PN1 PN2) fsum
rename Factor1_sum personal_norm
label variable personal_norm "Personal norm towards i should
insulate. Subscale of 2"
// Zero inflated, consider cutoffpoint into dictonimous var.
```

```
recode CONEF1 CONEF2 (9999 = .) (9996 = .)
sumscale, f1(CONEF1 CONEF2) fsum
rename Factor1_sum helplessness
label variable helplessness "Helplessness in relation to
climate worry. Subscale of 2"
//Too low internal reliability. Do not use.

recode SELEFF1 SELEFF2 (9999 = .) (9996 = .)
sumscale, f1(SELEFF1 SELEFF2) fsum
rename Factor1_sum selfeff
label variable selfeff "Selv efficacy in relation to
insulation. Subscale of 2"
//OK but borderline reliability. CBA = .63

recode persincome houseinc (98 = .)
recode perswinc EIER Age_house ISO_walls ISO_roof HSTYPE (9999
= .) (9996 = .)
recode posloan (. = .a) if EIER == 3 //Respondentes not
presented with option to answer posloan if stated they rent in
survey design. This was possibly a poor choice in survey
design. We have three options (1) drop all renters from
analysis. (2) Impute values on all renters. (3) Not impute and
stay away from varables they are excluded from. Imputing
renters with non-renters data not a good solution. Staying
away from posloan could be even worse, at investment
possibility is important. Functionally 1 and 3 is very
similar. We opt for option 1.
drop if EIER == 3

// Adjusting income, loan and loaning capabilities between feb
2014 to mar 2019, according to norwegian consumer price index
(https://www.ssb.no/priser-og-
prisindekser/statistikker/kpi/maaned/2014-09-10)
// We adjust the income before imputations, as variables such
as ownership status, work and location should be unchanged and
have the same effect on income in 2014 and 2019.
replace income = income*1.37 if DATASET == 1
replace loan = loan*1.37 if DATASET == 1
replace posloan = posloan*1.37 if DATASET == 1
replace persincome = persincome*1.37 if DATASET == 1

// We drop outliers from the analysis that has outlier-high
income, and recalulate to squared varibales to fit the model
better.
// Additionally, we convert from NOK to EURO, as this makes
the regression more understandable for international readers.
// We use the exchange rate of 1EUR:0.10332553NOK from
https://www.exchange-rates.org/Rate/NOK/EUR/3-19-2019
drop if income > 5000000 & income <
9999999999999999999999999999
replace income = income*0.10332553
```

```
gen incomesqrt = sqrt(income)
label variable incomesqrt "Household income EUR, squareroot"

// We drop outliers from the analysis that has outlier-high
loans, and recalulate to squared varibales to fit the model
better.
drop if loan > 12000000 & loan <
9999999999999999999999999999999
recode loan (0 = .)
replace loan = loan*0.10332553
gen loansqrt = sqrt(loan)
label variable loansqrt "Household total residental loan EUR,
squareroot"

// We drop outliers from the analysis that has outlier-high
value of their household, and recalulate to squared varibales
to fit the model better.
drop if valhs > 30000000 & valhs <
9999999999999999999999999999999
replace valhs = valhs*0.10332553
gen valhssqrt = sqrt(valhs)

// We drop outliers from the analysis that has outlier-high
loans, and recalulate to squared varibales to fit the model
better.
drop if posloan > 14000000 & posloan <
99999999999999999999999999
replace posloan = posloan*0.10332553
gen posloansqrt = sqrt(posloan)
label variable posloansqrt "Household realisticly largest
capital+loan spent on renovation EUR, squareroot"

// NOTE - In total this outlier deletion drops total 66
participants, or 66/6550= 1.01%, which is pretty reasonable
when dropping based on economic variables. Analysis does not
include the 1% richest Norwegians.

// Squaring some more terms to fit the regression.
gen sizelog = log(SIZE)

gen houseage = 2020 - Age_house
gen houseagelog = log(houseage)

//Renaming some varibales for readability.
rename EER_plan_do eer_do
rename EER_plan_plan eer_plan
rename ENE4_done_code_sum eer_done

//Centralize interaction terms
foreach a of varlist eer_done att_sum selfeff {
summarize `a', meanonly
```

```
gen c_`a' = `a' - r(mean)
}

// Displaying means and SD for testing MI.
foreach a of varlist eer_do eer_done sex age incomesqrt
loansqrt posloansqrt sizelog houseagelog att_sum selfeff{
quietly mean `a' [pweight = Vekt]
estat sd
}

/*For calulating M and SD of imputed values after imputations.
Note that imputations needs to be done again after this as it
converts to long format.
mi convert flong
misum incomesqrt, m(1(1)50)
misum loansqrt, m(1(1)50)
misum posloansqrt, m(1(1)50)

/* Table featuring frequencies. Manually converted to
percentages.
gen eer_done_dict = eer_done
recode eer_done_dict (2=1) (3=1) (4=1)
tab eer_plan eer_done_dict
tab eer_do eer_done_dict
*/

/*
Testing proportional odds assumption, which we expect to fail.
Should be different factors influencing 0-1 renovations than
1-2, 2-3, and so on.
svy: ologit eer_do eer_done subjective_norm personal_norm
selfeff
omodel logit eer_do eer_done subjective_norm personal_norm
selfeff
P=0.0017, meaning assumption is violated.
 */

/*
tabstat eer_done, stat(mean var)
Shows variance is meaningfully higher than mean. Theoretical
justification for two processes is weak, and not really what
we are looking for, so no ZIP. Go for NBR with MI.
*/

// Imputing the income and potential loan values. R-seed
retrieved from random.org
// Initial income variables: HSTYPE perswinc income persincome
houseinc EIER REH_done_tot_score ENE_done_tot_score eer_done
eer_do eer_plan sizelog loan valhs posloan age dinFylke sex
work edu boligstatus
```

```
// Reduced list due to missing patterns. Allow for imputation
of 70% of cases, which should be an ok compromise between
scope and accuracy in imputations: perswinc persincome age edu
EIER sizelog dinFylke sex work i.boligstatus
REH_done_tot_score eer_done eer_do eer_plan



/* The rest of the code is commented out, as it is branced.
Run the code from here to the dotted ------ line to for all
estimations not including the standardized scores. For
standardized scores, run the code under the dotted ------
line.

// --- IMPUTATION
// Setting local directory as it is faster, and faster is
needed for imputations.
cd "C:\stata local"
save mispilloverdataset, replace
use mispilloverdataset
mi set wide
mi register impute posloansqrt incomesqrt loansqrt
mi register regular perswinc persincome age edu EIER sizelog
dinFylke sex work boligstatus REH_done_tot_score eer_done
eer_do eer_plan
mi impute chained (regress) posloansqrt incomesqrt loansqrt =
perswinc persincome age i.edu i.EIER sizelog i.dinFylke i.sex
i.work i.boligstatus REH_done_tot_score eer_done eer_do
eer_plan [pweight = Vekt], force add(50) rseed(1775)
save mitestingdataset, replace
use mitestingdataset, clear

// Technically no point in doing MI estimates for model 1
which has no imputed values, but it allows for somewhat
simpler presentation of the models in exthange for some use of
unnessecary data processing and god knows my brain has less
spare processing power than Stata.

// --- REGRESSION MODELS
mi estimate, dots: nbreg eer_do eer_done [pweight = Vekt]
mi estimate, dots: nbreg eer_do eer_done i.sex age incomesqrt
loansqrt posloansqrt sizelog houseagelog [pweight = Vekt]
mi estimate, dots: nbreg eer_do eer_done i.sex age incomesqrt
loansqrt posloansqrt sizelog houseagelog att_sum selfeff
c.c_att_sum#c.c_eer_done c.c_selfeff#c.c_eer_done [pweight =
Vekt]

//Manual calculation of IRR because Stata we could not make
the option work with MI. We used exp(coefficient) in google
sheets. For future reference, it works if you insert the "irr"
option before the ":", where the dots option also is.
```

```
// --- GRAPHING THE INTERACTIONS
//Need separate nbreg because Stata dont understand that
centralized terms are the same as uncentralized. Graphically
they represent the exact same thing uncentralized, just not
with weird legends at the YX-axis.
mi estimate, dots: nbreg eer_do eer_done i.sex age incomesqrt
loansqrt posloansqrt sizelog houseagelog att_sum selfeff
c.att_sum#c.eer_done c.selfeff#c.eer_done [pweight = Vekt]
mimrgns, at(att_sum=(4(1)28) eer_done=(0(1)3)) atmeans
cmdmargins predict(ir)
marginsplot, xdimension(att_sum) noci title(Interaction
between previous energy retrofits conducted and attitude
towards energy retrofitting)


// --- MCERRORS
mi estimate, dots mcerror: nbreg eer_do eer_done [pweight =
Vekt] //OK
mi estimate, dots mcerror: nbreg eer_do eer_done i.sex age
incomesqrt loansqrt posloansqrt sizelog houseagelog [pweight =
Vekt] //OK
mi estimate, dots mcerror: nbreg eer_do eer_done i.sex age
incomesqrt loansqrt posloansqrt sizelog houseagelog att_sum
selfeff c.c_att_sum#c.c_eer_done c.c_selfeff#c.c_eer_done
[pweight = Vekt] //OK


// --- MEAN PSEUDO R2 CALCULATIONS
//--- Testing Fisher's z over imputed data for the Pseudo R2.
This pseudo R2 is used in the article. Tecnically no point in
doing this for model 1 since it has no imputed values, but
better to be consistent at the cost of some extra useless data
processing.
local M = 50
scalar r2_p = 0
qui mi xeq 1/`M': nbreg eer_do eer_done [pweight = Vekt];
scalar r2_p = r2_p + atanh(sqrt(e(r2_p)))
scalar r2_p = tanh(r2_p/`M')^2
display as text "r2_p using Fisher's z over imputed data = = "
as res r2_p

local M = 50
scalar r2_p = 0
qui mi xeq 1/`M': nbreg eer_do eer_done i.sex age incomesqrt
loansqrt posloansqrt sizelog houseagelog [pweight = Vekt];
scalar r2_p = r2_p + atanh(sqrt(e(r2_p)))
scalar r2_p = tanh(r2_p/`M')^2
display as text "r2_p using Fisher's z over imputed data = = "
as res r2_p
```

```
local M = 50
scalar r2_p = 0
qui mi xeq 1/`M': nbreg eer_do eer_done i.sex age incomesqrt
loansqrt posloansqrt sizelog houseagelog att_sum selfeff
c.c_att_sum#c.c_eer_done c.c_selfeff#c.c_eer_done [pweight =
Vekt]; scalar r2_p = r2_p + atanh(sqrt(e(r2_p)))
scalar r2_p = tanh(r2_p/`M')^2
display as text "r2_p using Fisher's z over imputed data = = "
as res r2_p



---------------------------------------------------------------
-------------------------
//For readability of regression coefficient, we do the entire
thing again, just with normalized scores. This produce the
same numbers as we use the same random seed.

foreach a of varlist posloansqrt incomesqrt loansqrt perswinc
persincome age sizelog REH_done_tot_score eer_done houseagelog
att_sum selfeff innovation c_att_sum c_eer_done c_selfeff{
egen z_`a' = std(`a')
}

cd "C:\stata local"
save mispilloverdataset, replace
use mispilloverdataset
mi set wide
mi register impute z_posloansqrt z_incomesqrt z_loansqrt
mi register regular z_perswinc z_persincome z_age edu EIER
z_sizelog dinFylke sex work boligstatus z_REH_done_tot_score
z_eer_done eer_do eer_plan
mi impute chained (regress) z_posloansqrt z_incomesqrt
z_loansqrt = z_perswinc z_persincome z_age i.edu i.EIER
z_sizelog i.dinFylke i.sex i.work i.boligstatus
z_REH_done_tot_score z_eer_done eer_do eer_plan [pweight =
Vekt], force add(50) rseed(1775)
save mitestingdataset, replace
use mitestingdataset

// --- REGRESSION MODELS
mi estimate: nbreg eer_do z_eer_done [pweight = Vekt]
mi estimate: nbreg eer_do z_eer_done i.sex z_age z_incomesqrt
z_loansqrt z_posloansqrt z_sizelog z_houseagelog [pweight =
Vekt]
mi estimate: nbreg eer_do z_eer_done i.sex z_age z_incomesqrt
z_loansqrt z_posloansqrt z_sizelog z_houseagelog z_att_sum
z_selfeff c.z_c_att_sum#c.z_c_eer_done
c.z_c_selfeff#c.z_c_eer_done [pweight = Vekt]
```

```
// --- EFFECT OF INCOME.
// Because income has a somewhat unintuitive effect on the regression, with a negative coefficient, we test it's direct effect too.
mi estimate: nbreg eer_do z_incomesqrt [pweight = Vekt]
// As it has a positive, but non-significant effect, we locate the smallest number of relevant variables that enable the relation. We find this to be loans and realistic investment potential. As income needs these two to be statistically significant. This is shown by these two models:
mi estimate: nbreg eer_do z_incomesqrt z_posloansqrt z_loansqrt  [pweight = Vekt]
mi estimate: nbreg eer_do z_eer_done i.sex z_age z_incomesqrt z_sizelog z_houseagelog z_att_sum z_selfeff c.z_c_att_sum#c.z_c_eer_done c.z_c_selfeff#c.z_c_eer_done [pweight = Vekt]
// This indicates a supression effect. We investigate this by looking at the correlations.
correlate eer_do z_incomesqrt z_posloansqrt z_loansqrt
// We see that income is indeed reasonably strongly related to both, which indicates a supression effect.
// In conclusion, we see that income is negatively related to currently conducted  retrofits energy, but only when loans and investment potential is accounted for. When these are not accounted for, it has no statistically significant effect on the model. This indicate a supression effect. When loan and ivestment capabilities are kept at a constant, households with lower income have more undergoing energy retrofits. Between two houses with identical investment capabilities, but different income, the lower income household conduct more energy retrofit measures.
```

2. Paper 2

2.1. Main analysis.

```
version 15
clear
// Insert local file path
use "[Please insert the path correct datafile here]"


// labeling and dropping nonimportant values.
drop Test1 test2 test3 filter__
label drop Test1 test2 test3 filter__
label define Avkrysset 1 "Avkrysset" 0 "Ikke avkrysset" .a "Vet ikke" .b "Ignorert" .c "Ingen svarmulighet"
label values STØ_01 STØ_02 STØ_03 STØ_04 STØ_05 STØ_06 STØ_07 STØ_08 STØ_09 STØ_10 STØ_11 STØ_12 STØ_13 STØ_14 STØ_15 STØ_16 STØ_17 Avkrysset
```

```
label drop STØ_01 STØ_02 STØ_03 STØ_04 STØ_05 STØ_06 STØ_07
STØ_08 STØ_09 STØ_10 STØ_11 STØ_12 STØ_13 STØ_14 STØ_15 STØ_16
STØ_17
label values Husdel_01 Husdel_02 Husdel_03 Husdel_04 Husdel_05
Husdel_06 Husdel_07 Husdel_08 Avkrysset
label drop Husdel_01 Husdel_02 Husdel_03 Husdel_04 Husdel_05
Husdel_06 Husdel_07 Husdel_08
label define likert_4 1 "Helt uenig" 2 "Uenig" 3 "Enig" 4
"Helt enig" .a "Vet ikke" .b "Ignorert" .c "Ingen
svarmulighet"
label values FREE_bygg_01 FREE_bygg_02 FREE_bygg_03
FREE_bygg_04 likert_4
label drop FREE_bygg_01 FREE_bygg_02 FREE_bygg_03 FREE_bygg_04
label define likert_7_viktig 1 "Veldig uviktig" 2 "Ganske
uviktig" 3 "Litt uviktig" 4 "Verken eller" 5 "Litt viktig" 6
"Ganske viktig" 7 "Veldig viktig" .a "Vet ikke" .b "Ignorert"
.c "Ingen svarmulighet"
label define likert_7_enig 1 "Veldig uenig" 2 "Ganske uenig" 3
"Litt uenig" 4 "Verken eller" 5 "Litt enig" 6 "Ganske enig" 7
"Veldig enig" .a "Vet ikke" .b "Ignorert" .c "Ingen
svarmulighet"
label values Grunn_upg01 Grunn_upg02 Grunn_upg03 Grunn_upg04
Grunn_upg05 Grunn_upg06 Grunn_upg07 Grunn_upg08
likert_7_viktig
label drop Grunn_upg01 Grunn_upg02 Grunn_upg03 Grunn_upg04
Grunn_upg05 Grunn_upg06 Grunn_upg07 Grunn_upg08
label values v13_001 v13_002 v13_003 v13_004 v13_005 v13_006
v13_007 likert_7_enig
label drop v13_001 v13_002 v13_003 v13_004 v13_005 v13_006
v13_007
label values v14_001 v14_002 v14_003 v14_004 v14_005 v14_006
likert_7_enig
label drop v14_001 v14_002 v14_003 v14_004 v14_005 v14_006
label values v16_001 v16_002 v16_003 v16_004 v16_005 v16_006
likert_7_enig
label drop v16_001 v16_002 v16_003 v16_004 v16_005 v16_006
label value v17_001 v17_002 v17_003 v17_004 v17_005 v17_006
v17_007 Avkrysset
label drop v17_001 v17_002 v17_003 v17_004 v17_005 v17_006
v17_007
label value v18_001 v18_002 v18_003 v18_004 Avkrysset
label drop v18_001 v18_002 v18_003 v18_004
label values v19_001 v19_002 v19_003 v19_004 v19_005
likert_7_enig
label drop v19_001 v19_002 v19_003 v19_004 v19_005
label values v21_001 v21_002 v21_003 v21_004 v22_001 v22_002
v22_003 v22_004 likert_4
label drop v21_001 v21_002 v21_003 v21_004 v22_001 v22_002
v22_003 v22_004
label values v24_001 v24_002 v24_003 v24_004 likert_7_enig
label drop v24_001 v24_002 v24_003 v24_004
```

```
label define Boaar_stotte 1 "0 år" 2 "1 år" 3 "2 år" 4 "3 år"
5 "4 år" 6 "5 år" 7 "6 år" 8 "7 år" 9 "8 år" 10 "9 år" 11 "10
år" 12 "11 år" 13 "12 år" 14 "13 år" 15 "14 år" 16 "15 år" 17
"16 år" 18 "17 år" 19 "18 år" 20 "19 år" 21 "20 eller flere
år" .a "Vet ikke" .b "Ignorert" .c "Ikke svarmulighet"
label values Bo_til_stotte Bo_fra_stotte Boaar_stotte
label drop Bo_til_stotte Bo_fra_stotte
label values Ambisjon likert_7_viktig
label drop Ambisjon
label drop v15
label define ja_nei 1 "Ja" 2 "Nei" .a "Vet ikke" .b "Ignorert"
.c "Ingen svarmulighet"
label values v15 ja_nei
label define v23 .a "Vet ikke", add
label define v23 .b "Ignorert", add
label define v23 .c "Ingen svarmulighet", add


// Recoding variables into missing.
// .a = Explicitly stating he/she do not know;
// .b = Ignored answering even though had the possibility to
answer question
// .c = Did not get the possibility to answer question because
of branching
recode INT_KR (-9999 = .b)
label define only_missing .a "Vet ikke" .b "Ignorert" .c "Ikke
svarmulighet"
label values INT_KR only_missing
recode Fylke (19 = .a)
label define Fylke 1 "Østfold" 2 "Akershus" 3 "Oslo" 4
"Hedmark" 5 "Oppland" 6 "Buskerud" 7 "Vestfolk" 8 "Telemark" 9
"Aust-Agder" 10 "Vest-Agder" 11 "Rogaland" 12 "Hordaland" 13
"Sogn og Fjordane" 14 "Møre og Romsdal" 15 "Nordland" 16
"Troms" 17 "Finnmark" 18 "Trøndelag" .a "Vet ikke", replace
recode STØ_01 STØ_02 STØ_03 STØ_04 STØ_05 STØ_06 STØ_07 STØ_08
STØ_09 STØ_10 STØ_11 STØ_12 STØ_13 STØ_14 STØ_15 STØ_16 STØ_17
(0 = .b) if STØ_01 == 0 & STØ_02 == 0 & STØ_03 == 0 & STØ_04
== 0 & STØ_05 == 0 & STØ_06 == 0 & STØ_07 == 0 & STØ_08 == 0 &
STØ_09 == 0 & STØ_10 == 0 & STØ_11 == 0 & STØ_12 == 0 & STØ_13
== 0 & STØ_14 == 0 & STØ_15 == 0 & STØ_16 == 0 & STØ_17 == 0
//Does nothing, but good to know I checked.
recode IINT_pers (7 = .a)
label define IINT_pers 1 "Ingen" 2 "1 person" 3 "2 personer" 4
"3 personer" 5 "4 personer" 6 "5 personer eller flere" .a "Vet
ikke", replace
recode Bo_til_stotte Bo_fra_stotte (miss = .b) if STØ_02 == 1
recode Bo_til_stotte Bo_fra_stotte (miss = .c) if STØ_02 == 0
recode Bo_til_stotte Bo_fra_stotte (22 = .a)
recode Husdel_01 Husdel_02 Husdel_03 Husdel_04 Husdel_05
Husdel_06 Husdel_07 Husdel_08 (miss = .b) if STØ_02 == 1
```

```
recode Husdel_01 Husdel_02 Husdel_03 Husdel_04 Husdel_05
Husdel_06 Husdel_07 Husdel_08 (miss = .c) if STØ_02 == 0
recode FREE_bygg_01 FREE_bygg_02 FREE_bygg_03 FREE_bygg_04
(miss = .b) if STØ_02 == 1
recode FREE_bygg_01 FREE_bygg_02 FREE_bygg_03 FREE_bygg_04
(miss = .c) if STØ_02 == 0
recode Grunn_upg01 Grunn_upg02 Grunn_upg03 Grunn_upg04
Grunn_upg05 Grunn_upg06 Grunn_upg07 Grunn_upg08 (miss = .b) if
STØ_02 == 1
recode Grunn_upg01 Grunn_upg02 Grunn_upg03 Grunn_upg04
Grunn_upg05 Grunn_upg06 Grunn_upg07 Grunn_upg08 (miss = .c) if
STØ_02 == 0
recode Grunn_upg01 Grunn_upg02 Grunn_upg03 Grunn_upg04
Grunn_upg05 Grunn_upg06 Grunn_upg07 Grunn_upg08 (8 = .a)
recode Ambisjon (miss = .b) if STØ_02 == 1
recode Ambisjon (miss = .c) if STØ_02 == 0
recode Ambisjon (8 = .a)
recode v13_001 v13_002 v13_003 v13_004 v13_005 v13_006 v13_007
v14_001 v14_002 v14_003 v14_004 v14_005 v14_006 (miss = .b) if
STØ_02 == 1
recode v13_001 v13_002 v13_003 v13_004 v13_005 v13_006 v13_007
v14_001 v14_002 v14_003 v14_004 v14_005 v14_006 (miss = .c) if
STØ_02 == 0
recode v13_001 v13_002 v13_003 v13_004 v13_005 v13_006 v13_007
v14_001 v14_002 v14_003 v14_004 v14_005 v14_006 (8 = .a)
recode v15 (miss = .b)
recode v16_001 v16_002 v16_003 v16_004 v16_005 v16_006 (miss =
.b) if v15 == 1
recode v16_001 v16_002 v16_003 v16_004 v16_005 v16_006 (miss =
.c) if v15 == 2
recode v16_001 v16_002 v16_003 v16_004 v16_005 v16_006 (8 =
.a)
recode v16_001 v16_002 v16_003 v16_004 v16_005 v16_006 (miss =
.c) if v15 == .b //If ignoring entry question to these, define
missing as "cant answer".
recode v17_001 v17_002 v17_003 v17_004 v17_005 v17_006 v17_007
(miss = .b) if v17_001 == . & v17_002 == . & v17_003 == . &
v17_004 == . & v17_005 == . & v17_006 == . & v17_007 == .
recode v18_001 v18_002 v18_003 v18_004 (miss = .b)
recode v19_001 v19_002 v19_003 v19_004 v19_005 (miss = .b)
recode v19_001 v19_002 v19_003 v19_004 v19_005 (8 = .a)
recode v21_001 v21_002 v21_003 v21_004 (miss = .c) if STØ_01 +
STØ_02 < 2
recode v21_001 v21_002 v21_003 v21_004 (miss = .b) if STØ_01 +
STØ_02 == 2
recode v22_001 v22_002 v22_003 v22_004 (miss = .c) if STØ_01
== 0
recode v22_001 v22_002 v22_003 v22_004 (miss = .b) if STØ_01
== 1
recode v23 (miss = .c) if STØ_01 == 0
recode v23 (miss = .b) if STØ_01 == 1
```

```
recode v24_001 v24_002 v24_003 v24_004 (miss = .c) if STØ_01
== 0
recode v24_001 v24_002 v24_003 v24_004 (miss = .b) if STØ_01
== 1
recode v24_001 v24_002 v24_003 v24_004 (8 = .a)


//Removing innattentive responders according to Studer
original survey.
generate inattentive = 1 if (FREE_bygg_01 >= 3 | FREE_bygg_02
>= 3 | FREE_bygg_03 >= 3) & (FREE_bygg_04 >= 3) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03,
FREE_bygg_04)
recode inattentive (miss= 2) if (FREE_bygg_01 <= 2 &
FREE_bygg_02 <= 2 & FREE_bygg_03 <= 2) & (FREE_bygg_04 <= 2) &
! missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03,
FREE_bygg_04)
drop if inattentive == 1 | inattentive == 2


// Generating freeriding categories without imputations.
generate FREE_bygg_sum = .
recode FREE_bygg_sum (. = 1) if (FREE_bygg_01 > 2.5 &
FREE_bygg_02 < 2.5 & FREE_bygg_03 < 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
recode FREE_bygg_sum (. = 2) if (FREE_bygg_01 < 2.5 &
FREE_bygg_02 > 2.5 & FREE_bygg_03 < 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
recode FREE_bygg_sum (. = 3) if (FREE_bygg_01 < 2.5 &
FREE_bygg_02 < 2.5 & FREE_bygg_03 > 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
recode FREE_bygg_sum (. = 4) if (FREE_bygg_01 > 2.5 &
FREE_bygg_02 > 2.5 & FREE_bygg_03 < 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
recode FREE_bygg_sum (. = 5) if (FREE_bygg_01 > 2.5 &
FREE_bygg_02 < 2.5 & FREE_bygg_03 > 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
recode FREE_bygg_sum (. = 6) if (FREE_bygg_01 < 2.5 &
FREE_bygg_02 > 2.5 & FREE_bygg_03 > 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
recode FREE_bygg_sum (. = 7) if (FREE_bygg_01 > 2.5 &
FREE_bygg_02 > 2.5 & FREE_bygg_03 > 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
recode FREE_bygg_sum (. = 8) if (FREE_bygg_01 < 2.5 &
FREE_bygg_02 < 2.5 & FREE_bygg_03 < 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
label define freeriding_bygg 1 "Decision to renovate (only)" 2
"Increase in quality of renovation (only)" 3 "Increase in
scope of renovation (only)" 4 "Decision to renovate and
increasin in quality" 5 "Decidition to renovate and increase
in scope" 6 "Increase in quality and in scope" 7 "Decision to
```

```
renovate and increase in quality and increase in scope" 8 "No
effect" .a "Vet ikke" .b "Ignorert" .c "Ingen svarmulighet"
label values FREE_bygg_sum freeriding_bygg
recode FREE_bygg_sum (. = .c) if STØ_02 == 0 //.a and .b will
not be coded because they will be transformed back to .
anyways before imputation.
generate FREE_bygg_cat = 0 // Generating categorical yes/no
variabel.
recode FREE_bygg_cat (0 = 1) if FREE_bygg_sum == 8
recode FREE_bygg_cat (0 = .c) if FREE_bygg_sum == .c
recode FREE_bygg_cat (0 = .) if FREE_bygg_sum == .

// Recoding of the income var because its many outliers to fit
MI and later regression. deciles retrived from SSB stat 12558
14/01/2020.
// First multiply the income of 2018-2019 of 97.83% on the
income. As income categories are for 2018 and the income
numbers are from 2019. No deciles from 2018 availiable.
generate INT_KR_kpi = INT_KR * 0.9783
generate INT_KR_decile = .
recode INT_KR_decile (. = 10) if INT_KR_kpi <
1000000000000000000
recode INT_KR_decile (10 = 9) if INT_KR_kpi < 1526000
recode INT_KR_decile (9 = 8) if INT_KR_kpi < 1194000
recode INT_KR_decile (8 = 7) if INT_KR_kpi < 986000
recode INT_KR_decile (7 = 6) if INT_KR_kpi < 813000
recode INT_KR_decile (6 = 5) if INT_KR_kpi < 666000
recode INT_KR_decile (5 = 4) if INT_KR_kpi < 551000
recode INT_KR_decile (4 = 3) if INT_KR_kpi < 452000
recode INT_KR_decile (3 = 2) if INT_KR_kpi < 351000
recode INT_KR_decile (2 = 1) if INT_KR_kpi < 256000
drop INT_KR_kpi


// ---------- Creating indexes and other variables.
// Very few of these variables ended up being used, as
freerider group ended up way to small, but we create them if
other researchers want to use them in the future.
// Contact with Enova
generate v18_sum = v18_001 + v18_002 + v18_003 if v18_001 == 1
| v18_001 == 0 //Cronbach Alpha 0.13, too low too use.
recode v18_sum (miss = .b)
rename v18_sum contact_sum

// Perception implementer index
sumscale, f1 (v19_001 v19_002 v19_003 v19_004 v19_005)
//Cronbach Alpha 0.85
recode Factor1_average (miss = .b)
rename Factor1_average perception_implementer

// Appreciation of energy counceling
```

```
egen float v24_mean = rowmean(v24_001 v24_002 v24_004) if !
missing(v24_001, v24_002, v24_004) //Cronbach Alpha 0.78
label variable v24_mean "Appreciation of energy counceling"
recode v24_mean (miss = .c) if STØ_01 == 0
recode v24_mean (miss = .b) if STØ_01 == 1
rename v24_mean consult_sat

//Type of building living in
generate enebolig = 0
recode enebolig ( 0 = 1 ) if Boligtype == 2 | Boligtype == 3 |
Boligtype == 4

// Median splitting variable
egen mean=mean(Bo_til_stotte)
gen bo_til_stotte_mediansplit = 0 if ! missing(Bo_til_stotte)
recode bo_til_stotte_mediansplit (0 = 1) if Bo_til_stotte <
mean
recode bo_til_stotte_mediansplit (. = .c) if STØ_02 == 0
drop mean

//Size of retrofitting
egen float husdel_sum = rowmean(Husdel_01-Husdel_08) if !
missing(Husdel_01-Husdel_08)
recode husdel_sum (. = .c) if STØ_02 == 0

//Percieved effect of retrofitting
egen float experienced_effect = rowmean(v14_001-v14_006) if !
missing(v14_001-v14_006)
recode experienced_effect (. = .c) if STØ_02 == 0 // Cronbach
Alpha 0.63

//Reasons to retrofit
egen float grunn_sum = rowmean(Grunn_upg01-Grunn_upg08) if !
missing(Grunn_upg01-Grunn_upg08) // Cronbach Alpha 0.77
recode grunn_sum (. = .c) if STØ_02 == 0

label variable husdel_sum "2Size of renovation"
label variable experienced_effect "2Experienced positive
outcomes of the renovation"
label variable grunn_sum "2Reasons for doing the renovation"
label variable contact_sum "3How much contact with ENOVA
during the process. LOW CBA"
label variable perception_implementer "3Perception about
implementer and information"
label variable consult_sat "4Satisfaction with the energy
councelor"

// Some preparatory commands for the MI
destring, replace
drop completed //Not going to be used, cleaner to remove
rather than work around.
```

```
drop inattentive // No longer in use
recode * (.b = .) // recoding ignored answers into soft
missing.
recode * (.a = .) // recoding "i dont know" answers into soft
missing.


/* Testing for predictors of missingness.
NOTE:Can comment out later to speed up code as the only real
putput is inclusion in the mi register commands.
Test againt var list: FREE_bygg_01 FREE_bygg_02 FREE_bygg_03
FREE_bygg_cat INT_KR_decile i.enebolig
i.bo_til_stotte_mediansplit husdel_sum experienced_effect
perception_implementer consult_sat grunn_sum
Note: FREE_bygg_01 FREE_bygg_02 FREE_bygg_03 can not be
regressed with FREE_bygg_cat, as they are a function of each
other. Must impute twice, where use have one or the other. One
imputation for the reporting of proportions, and one for the
regression.

misstable summarize FREE_bygg_01 FREE_bygg_02 FREE_bygg_03
FREE_bygg_cat INT_KR_decile enebolig bo_til_stotte_mediansplit
husdel_sum experienced_effect perception_implementer
consult_sat grunn_sum, generate(miss_, exok)

ologit: FREE_bygg_01 FREE_bygg_02 FREE_bygg_03 INT_KR_decile
consult_sat perception_implementer
logit: FREE_bygg_cat enebolig bo_til_stotte_mediansplit
regress: husdel_sum experienced_effect grunn_sum UrbanRural

1:FREE_bygg_01 FREE_bygg_02 FREE_bygg_03 INT_KR_decile
consult_sat perception_implementer enebolig
bo_til_stotte_mediansplit husdel_sum experienced_effect
grunn_sum UrbanRural
2:INT_KR_decile consult_sat perception_implementer
FREE_bygg_cat enebolig bo_til_stotte_mediansplit husdel_sum
experienced_effect grunn_sum UrbanRural
*/

// -------- Starting the multiple imputation. Different models
exist because in estimating proportions, the imputation model
should catch the variability within questions, making it best
to impute the individual items, and not the resulting index.
This is reversed in the regression, where we are only after a
dictonomus division of the freeriding categoriy, which should
not be "tampered" with before a regression, as MI varibales
should be untouched between imputation and analysis. Commented
out to not run MI every time the do file is run. Run either 1,
2, or 3. Random seed generated from a random number bewteen 1
and 10000 from random.org, resulting in 5119.
/*
```

```
// -- Model 1: Descriptives.
mi set wide
mi register impute FREE_bygg_01 FREE_bygg_02 FREE_bygg_03
INT_KR_decile consult_sat perception_implementer enebolig
bo_til_stotte_mediansplit husdel_sum experienced_effect
grunn_sum UrbanRural v18_001
mi impute chained (reg) FREE_bygg_01 FREE_bygg_02 FREE_bygg_03
perception_implementer (logit) enebolig
bo_til_stotte_mediansplit v18_001 (reg) INT_KR_decile
husdel_sum experienced_effect grunn_sum UrbanRural, add(50)
rseed(5119) force
mi passive: generate FREE_bygg_sum2 = .
mi passive: replace FREE_bygg_sum2 = 1 if (FREE_bygg_01 > 2.5
& FREE_bygg_02 < 2.5 & FREE_bygg_03 < 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
mi passive: replace FREE_bygg_sum2 = 2 if (FREE_bygg_01 < 2.5
& FREE_bygg_02 > 2.5 & FREE_bygg_03 < 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
mi passive: replace FREE_bygg_sum2 = 3 if (FREE_bygg_01 < 2.5
& FREE_bygg_02 < 2.5 & FREE_bygg_03 > 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
mi passive: replace FREE_bygg_sum2 = 4 if (FREE_bygg_01 > 2.5
& FREE_bygg_02 > 2.5 & FREE_bygg_03 < 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
mi passive: replace FREE_bygg_sum2 = 5 if (FREE_bygg_01 > 2.5
& FREE_bygg_02 < 2.5 & FREE_bygg_03 > 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
mi passive: replace FREE_bygg_sum2 = 6 if (FREE_bygg_01 < 2.5
& FREE_bygg_02 > 2.5 & FREE_bygg_03 > 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
mi passive: replace FREE_bygg_sum2 = 7 if (FREE_bygg_01 > 2.5
& FREE_bygg_02 > 2.5 & FREE_bygg_03 > 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
mi passive: replace FREE_bygg_sum2 = 8 if (FREE_bygg_01 < 2.5
& FREE_bygg_02 < 2.5 & FREE_bygg_03 < 2.5) & !
missing(FREE_bygg_01, FREE_bygg_02, FREE_bygg_03)
label values FREE_bygg_sum2 freeriding_bygg
mi estimate, mcerror: proportion FREE_bygg_sum2

// -- Model2: Regression.
//Reverse FREE_bygg_cat for easier comparison to original
study, where freerider is 0.
replace FREE_bygg_cat = 1 - FREE_bygg_cat
mi set wide
mi register impute INT_KR_decile consult_sat
perception_implementer FREE_bygg_cat enebolig
bo_til_stotte_mediansplit husdel_sum experienced_effect
grunn_sum UrbanRural v18_001
mi impute chained (reg) INT_KR_decile perception_implementer
husdel_sum experienced_effect grunn_sum (logit) FREE_bygg_cat
```

```
enebolig bo_til_stotte_mediansplit UrbanRural v18_001, add(50)
rseed(5119) force augment
mi impute regress consult_sat INT_KR_decile
perception_implementer i.enebolig UrbanRural, replace force
// Reduced estimation because very low n on freeriders. Two
indipendent variables according to litterature.
mi estimate, or: logistic FREE_bygg_cat perception_implementer
v18_001
mi estimate, mcerror: logistic FREE_bygg_cat
perception_implementer v18_001

// -- Model 3: Decile distribution of income
mi set wide
mi register impute FREE_bygg_01 FREE_bygg_02 FREE_bygg_03
INT_KR contact_sum consult_sat perception_implementer enebolig
bo_til_stotte_mediansplit husdel_sum experienced_effect
grunn_sum UrbanRural
mi impute chained (reg) FREE_bygg_01 FREE_bygg_02 FREE_bygg_03
contact_sum perception_implementer (logit) enebolig
bo_til_stotte_mediansplit (reg) INT_KR husdel_sum
experienced_effect grunn_sum UrbanRural, add(50) rseed(5119)
force
mi passive: generate INT_KR_kpi = INT_KR * 0.9783
mi passive: generate INT_KR_decile_imputed = .
mi passive: replace INT_KR_decile_imputed = 10  if INT_KR_kpi
< 1000000000000000000
mi passive: replace INT_KR_decile_imputed = 9 if INT_KR_kpi <
1526000
mi passive: replace INT_KR_decile_imputed = 8 if INT_KR_kpi <
1194000
mi passive: replace INT_KR_decile_imputed = 7 if INT_KR_kpi <
986000
mi passive: replace INT_KR_decile_imputed = 6 if INT_KR_kpi <
813000
mi passive: replace INT_KR_decile_imputed = 5 if INT_KR_kpi <
666000
mi passive: replace INT_KR_decile_imputed = 4 if INT_KR_kpi <
551000
mi passive: replace INT_KR_decile_imputed = 3 if INT_KR_kpi <
452000
mi passive: replace INT_KR_decile_imputed = 2 if INT_KR_kpi <
351000
mi passive: replace INT_KR_decile_imputed = 1 if INT_KR_kpi <
256000
mi estimate: proportion INT_KR_decile_imputed if STØ_02 == 1
mi estimate: mean INT_KR_decile_imputed if STØ_02 == 1
```

2.2. Retrival of income data

```
version 16
clear
// Insert local file path
use "[Please insert the path correct datafile here]"

recode persincome houseinc (98 = .)
recode perswinc EIER Age_house ISO_walls ISO_roof HSTYPE (9999
= .) (9996 = .)
recode posloan (. = .a) if EIER == 3 //Respondentes not
presented with option to answer posloan if stated they rent in
survey design. This was possibly a poor choice in survey
design. We have three options (1) drop all renters from
analysis. (2) Impute values on all renters. (3) Not impute and
stay away from varables they are excluded from. Imputing
renters with non-renters data not a good solution. Staying
away from posloan could be even worse, at it seems important.
Functionally 1 and 3 is very similar. For now we pick option
1.
drop if EIER == 3

// Adjusting income, loan and loaning capabilities between feb
2014 to mar 2019, according to norwegian consumer price index
(https://www.ssb.no/priser-og-
prisindekser/statistikker/kpi/maaned/2014-09-10)
// We adjust the income before imputations, as variables such
as ownership status, work and location should be unchanged and
have the same effect on income in 2014 and 2019.
replace income = income*1.37 if DATASET == 1
replace loan = loan*1.37 if DATASET == 1
replace posloan = posloan*1.37 if DATASET == 1
replace persincome = persincome*1.37 if DATASET == 1


gen incomesqrt = sqrt(income)
label variable incomesqrt "Household income, squareroot"

recode loan (0 = .)
gen loansqrt = sqrt(loan)
label variable loansqrt "Household total residental loan,
squareroot"

gen valhssqrt = sqrt(valhs)

gen posloansqrt = sqrt(posloan)
label variable posloansqrt "Household realisticly largest
capital+loan spent on renovation, squareroot"

gen sizelog = log(SIZE)
```

```
rename EER_plan_do eer_do
rename EER_plan_plan eer_plan
rename ENE4_done_code_sum eer_done


// --- IMPUTATION
// Setting local directory as it is faster, and faster is
needed for imputations.
cd "C:\stata local"
save income_decile_imputation1, replace
use income_decile_imputation1
mi set wide
mi register impute posloansqrt incomesqrt loansqrt
mi register regular perswinc persincome age edu EIER sizelog
dinFylke sex work boligstatus REH_done_tot_score eer_done
eer_do eer_plan
mi impute chained (regress) posloansqrt incomesqrt loansqrt =
perswinc persincome age i.edu i.EIER sizelog i.dinFylke i.sex
i.work i.boligstatus REH_done_tot_score eer_done eer_do
eer_plan [pweight = Vekt], force add(50) rseed(1775)
save income_decile_imputation2, replace
use income_decile_imputation2, clear

//--- CREATING DECILES
mi passive: generate INT_KR_kpi = incomesqrt*incomesqrt *
0.9783
mi passive: generate INT_KR_decile_imputed = .
mi passive: replace INT_KR_decile_imputed = 10  if INT_KR_kpi
< 1000000000000000000
mi passive: replace INT_KR_decile_imputed = 9 if INT_KR_kpi <
1526000
mi passive: replace INT_KR_decile_imputed = 8 if INT_KR_kpi <
1194000
mi passive: replace INT_KR_decile_imputed = 7 if INT_KR_kpi <
986000
mi passive: replace INT_KR_decile_imputed = 6 if INT_KR_kpi <
813000
mi passive: replace INT_KR_decile_imputed = 5 if INT_KR_kpi <
666000
mi passive: replace INT_KR_decile_imputed = 4 if INT_KR_kpi <
551000
mi passive: replace INT_KR_decile_imputed = 3 if INT_KR_kpi <
452000
mi passive: replace INT_KR_decile_imputed = 2 if INT_KR_kpi <
351000
mi passive: replace INT_KR_decile_imputed = 1 if INT_KR_kpi <
256000
mi estimate: proportion INT_KR_decile_imputed if eer_done > 0
& eer_done < 99 & TILG_2 != 1
```

2.3. Anonymization of county-data

```
// This file minimizes and scrambles the location data of the large data file.
// Although the survey company thinks this is not needed, I disagree. This syntax is not to be shared and if you somehow see this without "REDACTED" below, please contact the main author Lars Even Egner.

version 16
clear
use "[Please insert the path correct datafile here]"

keep DATASET persincome houseinc perswinc EIER Age_house ISO_walls ISO_roof HSTYPE posloan EIER income loan posloan persincome valhs posloan SIZE EER_plan_do EER_plan_plan ENE4_done_code_sum age edu age dinFylke sex work boligstatus REH_done_tot_score Vekt TILG_2

label define dinFylke [redacted], replace

save "[Please insert the path correct datafile here]", replace
```

3. Paper 3

Please note: At the time of writing 15.12.2021, the paper is under review, and this syntax can be subject to change.

3.1. Baseline data generation

```
// This syntax transforms the experiment 1 data to a stata
".dta" file, so that it can be used as a baseline for the
other policies.

version 16
clear

//Set det working directory. This script assumes all relevant
datafiles are located in this folder.
cd "[Please insert the path to the folder of the HERB output
data here]"

//---- Data treatment
// Import from the table data
import delimited "herb_v1 experiment1_no_subsidies-table.csv",
delimiter(comma) varnames(7) stripquote(yes)

keep runnumber step countturtles
subsidy_relative_threshold_adjus meanenergy_useofturtles
sumsubsidies_distributed  meantechnical_kwhm2aofturtles
drop if step == 0  // As the adjust step is after the tick,
kwh/m2a is collected before the adjustment. Therefore we drop
the first step.

//Recodes the subsidy rule so that 1 unit is on or off, and
names it accordingly
recode subsidy_relative_threshold_adjus (1.7 = 1)
rename subsidy_relative_threshold_adjus subsidies
label define subsidies 1 "No subsidies" 0 "Subsidies"
label values subsidies subsidies

// Recalculates to weekly energy use, then creates a
cumulative measurement.
gen weekly_energy_use = (meanenergy_useofturtles / 52)
sort runnumber step
by runnumber: gen cum_kWh_use_100_years =
sum(weekly_energy_use)
bysort step subsidies: egen supermean_energy_use =
mean(meanenergy_useofturtles)
bysort step subsidies: egen supermean_cum_kWh_use_100_years =
mean(cum_kWh_use_100_years)

save baseline_data.dta, replace
```

3.2. Small world parameterization

```
// This script find the ideal "distance odds" and number of
friends to reach certain clustering coefficients and average
path lengths.

version 16
clear

//Set det working directory. This script assumes all relevant
datafiles are located in this folder.
cd "[Please insert the path to the folder of the HERB output
data here]"

//---- Data treatment
// Import from the table data
import delimited "herb_v1 small_worlds_parameterization-
table.csv", delimiter(comma) varnames(7) stripquote(yes)

keep runnumber number_of_aimed_for_friends averagepathlength
clusteringcoefficient distant_odds

// Drop case if path length is more than 100. This means the
network was not interconnected, the average path length and
the clustering coefficient calculations does not work, and the
case is not viable for data analysis.
drop if averagepathlength > 100

// After some exploratory analysis, the two best regressions
seems to be:
reg averagepathlength
c.number_of_aimed_for_friends##c.number_of_aimed_for_friends
c.distant_odds##c.distant_odds
// At R2 = .80

reg clusteringcoefficient number_of_aimed_for_friends
distant_odds
// At R2 = .98
// The above confirms that the two measures are indeed
strongly dependent on the input.

reg averagepathlength
c.number_of_aimed_for_friends##c.number_of_aimed_for_friends
c.distant_odds##c.distant_odds
margins, at (number_of_aimed_for_friends=(0(1)15)
distant_odds=(0(0.1)1))
marginsplot

reg clusteringcoefficient number_of_aimed_for_friends
distant_odds
```

```
margins, at (number_of_aimed_for_friends=(0(1)15)
distant_odds=(0(0.1)1))
marginsplot

// Starting the dropping procedyre.
drop if clusteringcoefficient < 0.147 | clusteringcoefficient
> 0.167
drop if averagepathlength < 3.35 | averagepathlength > 3.75

hist number_of_aimed_for_friends
hist distant_odds
scatter number_of_aimed_for_friends distant_odds, jitter (20)
msize(vsmall)

sum number_of_aimed_for_friends distant_odds
```

3.3. Validation data

```
version 16
clear

//Set det working directory. This script assumes all relevant
datafiles are located in this folder.
cd "c:\Users\larseegn\OneDrive - NTNU\Thesis\Revision\Herb_v1
output"


//---- Data treatment
// Import from the table data
import delimited "herb_v1 validation-table.csv",
delimiter(comma) varnames(7) stripquote(yes)

keep runnumber step countturtleswithtime_since_retro
lengthtotal_freeridestrackstotal
lengthfilterii3total_freeridestr
countturtleswithretrofit_stage4a
drop if step == 0  // Data is collected before the adjustment.
Therefore we drop the first step.
replace countturtleswithretrofit_stage4a = "." if
countturtleswithretrofit_stage4a ==
"<RuntimePrimitiveException>"
destring countturtleswithretrofit_stage4a, replace

rename countturtleswithtime_since_retro retrofit_rate
rename countturtleswithretrofit_stage4a consecutive_rate

gen freerider_ratio = (lengthfilterii3total_freeridestr /
lengthtotal_freeridestrackstotal) // Some missing are
generated because dividing by 0. Probably best to keep it at
missing. They have no impact on the analysis, as no data is
missing in the last year.


// Simple analysis. Retrofit rate is "surveyed" every tick,
but freerider measures the total. Therefore we take into
account all steps in retrofit rate, but only the last one in
freeriding.
sum retrofit_rate
sum freerider_ratio if step == 5200
sum consecutive_rate



//---- Sample size estimation
// To estimate the sample size, we use Lee et. al (2015) post-
hoc tests. Instead of running standalone simulations, we just
use the data from the first and second experiment, as they
```

```
have 1000 and 4000 runs. If the CV difference, aka. "E" is
less than 0.01, we accept 1000 runs as sufficient.
clear
import delimited "herb_v1 experiment2_ambition_pushing-table",
delimiter(comma) varnames(7) stripquote(yes)

// Drop variables not in use, create the outcome variable.
keep if step == 5200
keep meanenergy_useofturtles
gen weekly_energy_use = (meanenergy_useofturtles / 52)
gen cum_kWh_use_100_years = sum(weekly_energy_use)

// Retrieve the CV and store in local memory.
sum cum_kWh_use_100_years
local CV_4000 = (r(sd) / r(mean))

//Repeat for other dataset.
clear
import delimited "herb_v1 experiment1_no_subsidies-table",
delimiter(comma) varnames(7) stripquote(yes)
gen weekly_energy_use = (meanenergy_useofturtles / 52)
gen cum_kWh_use_100_years = sum(weekly_energy_use)
sum cum_kWh_use_100_years
local CV_1000 = (r(sd) / r(mean))

// Calculate the difference and display it.
local CV_diff = (`CV_1000' - `CV_4000')
display `CV_1000'
display `CV_4000'
display `CV_diff'
// The CV difference is 0.00036, which is less than 0.01, and
we thus consider 1000 runs sufficient. As 1000 runs is the
smallest number of runs among the experiments, we consider all
of them to have a sufficient  number of runs.
```

3.4. Policy experiment 1

```
/*
LEGEND.
Mean = average of households in that runnumber
Supermean = average of all households in all runs in that
setting (eg. subsidy setting)
*/

version 16
clear

//Set det working directory. This script assumes all relevant
datafiles are located in this folder.
cd "[Please insert the path to the folder of the HERB output
data here]"

//---- Data treatment
// Import from the table data
import delimited "herb_v1 experiment1_no_subsidies-table.csv",
delimiter(comma) varnames(7) stripquote(yes)

keep runnumber step countturtles
subsidy_relative_threshold_adjus meanenergy_useofturtles
sumsubsidies_distributed meantechnical_kwhm2aofturtles
drop if step == 0  // As the adjust step is after the tick,
kwh/m2a is collected before the adjustment. Therefore we drop
the first step.

//Recodes the subsidy rule so that 1 unit is on or off, and
names it accordingly
recode subsidy_relative_threshold_adjus (1.7 = 1)
rename subsidy_relative_threshold_adjus subsidies
label define subsidies 1 "No subsidies" 0 "Subsidies"
label values subsidies subsidies

// Recalculates to weekly energy use, then creates a
cumulative measurement.
gen weekly_energy_use = (meanenergy_useofturtles / 52)
sort runnumber step
by runnumber: gen cum_kWh_use_100_years =
sum(weekly_energy_use)
bysort step subsidies: egen supermean_energy_use =
mean(meanenergy_useofturtles)
bysort step subsidies: egen supermean_cum_kWh_use_100_years =
mean(cum_kWh_use_100_years)

//---- Figures
// Mean energy use over time
sort runnumber step
```

```
twoway (line meanenergy_useofturtles step, lwidth(vvthin)
by(subsidies) connect(ascending))

// Supermean energy use over time
sort runnumber step
twoway ///
(line supermean_energy_use step if subsidies == 0,
lwidth(vthin) connect(ascending)) ///
(line supermean_energy_use step if subsidies == 1,
lwidth(vthin) connect(ascending))

// Supermean cumulative energy use over time
sort step
twoway ///
(line supermean_cum_kWh_use_100_years step if subsidies == 0,
connect(ascending)) ///
(line supermean_cum_kWh_use_100_years step if subsidies == 1,
connect(ascending))

// ---- Analysis
//The average difference in kWh consumed for a household over
100 years when subsidies are in place or not.
reg cum_kWh_use_100_years ib(1).subsidies if step == 5200

// The average differnce in kWh/m2a in the end.
reg meantechnical_kwhm2aofturtles ib(1).subsidies if step ==
5200

// ---- Plot
gen cum_GWh_use_100_years = cum_kWh_use_100_years / 1000000 //
Generate GWh because 1.9 GWh is simpler to read than 1900000
kWh on an Y-axis.
reg cum_GWh_use_100_years ib(1).subsidies if step == 5200
margins, at (subsidies=(0 1))
marginsplot
```

3.5. Policy experiment 2

```
/*
LEGEND.
Mean = average of households in that runnumber
Supermean = average of all households in all runs in that
setting (eg. subsidy setting)
*/

version 16
clear

//Set det working directory. This script assumes all relevant
datafiles are located in this folder.
cd "[Please insert the path to the folder of the HERB output
data here]"


//---- Data treatment
// Import from the table data
import delimited "herb_v1 experiment2_ambition_pushing-
table.csv", delimiter(comma) varnames(7) stripquote(yes)

keep runnumber step countturtles ambition_pushed
subsidy_relative_threshold_adjus meanenergy_useofturtles
sumsubsidies_distributed  meantechnical_kwhm2aofturtles
drop if step == 0  // As the adjust step is after the tick,
kwh/m2a is collected before the adjustment. Therefore we drop
the first step.

//Recodes the subsidy rule so that 1 unit is on or off, and
names it accordingly
recode subsidy_relative_threshold_adjus (1.7 = 1)
rename subsidy_relative_threshold_adjus subsidies
label define subsidies 1 "No subsidies" 0 "Subsidies"
label values subsidies subsidies

// Recalculates to weekly energy use, then creates a
cumulative measurement.
gen weekly_energy_use = (meanenergy_useofturtles / 52)
sort runnumber step
by runnumber: gen cum_kWh_use_100_years =
sum(weekly_energy_use)
bysort step subsidies: egen supermean_energy_use =
mean(meanenergy_useofturtles)
bysort step subsidies: egen supermean_cum_kWh_use_100_years =
mean(cum_kWh_use_100_years)

// Import baseline data. Note that data treatment has been
completed in the baseline syntax.
append using "Baseline_data", generate(baseline)
```

```
recode ambition_pushed (.=0) // This sets 0 in the ambition
pushed to baseline, as in "no ambishion pushed".

reg cum_kWh_use_100_years i.ambition_pushed i.subsidies if
step == 5200
reg meantechnical_kwhm2aofturtles i.ambition_pushed
i.subsidies if step == 5200

// Marginsplot
// NOTE: This takes about 10 minutes to perform on laptop-
level hardware (year 2021).
gen cum_GWh_use_100_years = cum_kWh_use_100_years / 1000000 //
Generate GWh because 1.9 GWh is simpler to read than 1900000
kWh on an Y-axis.
reg cum_GWh_use_100_years i.ambition_pushed i.subsidies if
step == 5200
margins, at (ambition_pushed=(0(10)200))
marginsplot
```

3.6. Policy experiment 3

```
version 16
clear

//Set det working directory. This script assumes all relevant
datafiles are located in this folder.
cd "[Please insert the path to the folder of the HERB output
data here]"


//---- Data treatment
// Import from the table data
import delimited "herb_v1 experiment3_final_push-table.csv",
delimiter(comma) varnames(7) stripquote(yes)

keep runnumber percentage_affected sd_moved
subsidy_relative_threshold_adjus step meanenergy_useofturtles
sumsubsidies_distributed countturtles
meantechnical_kwhm2aofturtles
drop if step == 0  // As the adjust step is after the tick,
kwh/m2a is collected before the adjustment. Therefore we drop
the first step.

//Recodes the subsidy rule so that 1 unit is on or off, and
names it accordingly
recode subsidy_relative_threshold_adjus (1.7 = 1)
rename subsidy_relative_threshold_adjus subsidies
label define subsidies 1 "No subsidies" 0 "Subsidies"
label values subsidies subsidies

// Recalculates to weekly energy use, then creates a
cumulative measurement.
gen weekly_energy_use = (meanenergy_useofturtles / 52)
sort runnumber step
by runnumber: gen cum_kWh_use_100_years =
sum(weekly_energy_use)
bysort step subsidies: egen supermean_energy_use =
mean(meanenergy_useofturtles)
bysort step subsidies: egen supermean_cum_kWh_use_100_years =
mean(cum_kWh_use_100_years)
gen cum_GWh_use_100_years = cum_kWh_use_100_years / 1000000

//Regressions
reg cum_kWh_use_100_years c.percentage_affected##c.sd_moved
i.subsidies if step == 5200
reg meantechnical_kwhm2aofturtles
c.percentage_affected##c.sd_moved i.subsidies if step == 5200

// Figure.
```

```
reg cum_GWh_use_100_years c.percentage_affected##c.sd_moved
i.subsidies if step == 5200
margins, at(percentage_affected=(5(5)25) sd_moved=(0.25 0.75
1.5 2)) // Please note that this takes 5-10 minutes on
standard issue industrialised country university laptop
hardware (year 2021)
marginsplot

// Non-linearity test
// We draw the same figure with nominal regression values and
see if the results are linear or not.
generate sd_moved_upscaled = sd_moved * 100 // First we need
to make all values in the variable integrer, because Stata
needs this to handle them as nominal data for some reason.
reg cum_kWh_use_100_years
i.percentage_affected##i.sd_moved_upscaled i.subsidies if step
== 5200
margins, at(percentage_affected=(5(5)25) sd_moved_upscaled=(25
75 150 200)) // Please note that this takes 5-10 minutes on
standard issue industrialised country university laptop
hardware (year 2021)
marginsplot, noci // As the CI's naturally becomes huge when
we assume all the points have nothing to do with each other,
we remove them.
```

3.7. Policy experiment 4

```
/*
LEGEND.
Mean = average of households in that runnumber
Supermean = average of all households in all runs in that
setting (eg. subsidy setting)
*/

//Set det working directory. This script assumes all relevant
datafiles are located in this folder.
cd "[Please insert the path to the folder of the HERB output
data here]"

version 16
clear
//---- Data treatment
// Import from the table data
import delimited "herb_v1
experiment4_absoute_threshold_adjusting-table.csv",
delimiter(comma) varnames(7) stripquote(yes)

keep runnumber step countturtles meanenergy_useofturtles
sumsubsidies_distributed meantechnical_kwhm2aofturtles
absolute_threshold_adjusting
drop if step == 0  // As the adjust step is after the tick,
kwh/m2a is collected before the adjustment. Therefore we drop
the first step.

// Recalculates to weekly energy use, then creates a
cumulative measurement.
gen weekly_energy_use = (meanenergy_useofturtles / 52)
sort runnumber step
by runnumber: gen cum_kWh_use_100_years =
sum(weekly_energy_use)

// Generaltes a scale representing the actual worst kWh/m2a
requirement amongst the subsidies.
generate kwhm2a_required = (absolute_threshold_adjusting +
120)

// ---- Analysis
//The average difference in kWh consumed for a household over
100 years when subsidies are in place or not.
reg cum_kWh_use_100_years ib(120).kwhm2a_required if step ==
5200
reg meantechnical_kwhm2aofturtles ib(120).kwhm2a_required if
step == 5200

// Marginsplot
```

```
// NOTE: This takes about 10 minutes to perform on laptop-
level hardware (year 2021).
gen cum_GWh_use_100_years = cum_kWh_use_100_years / 1000000 //
Generate GWh because 1.9 GWh is simpler to read than 1900000
kWh on an Y-axis.
reg cum_GWh_use_100_years ib(120).kwhm2a_required if step ==
5200
margins, at (kwhm2a_required=(70(5)220))
marginsplot
// As this realtionship is pretty curvilinear, we treat it as
that and test for a interaction effect.
reg cum_kWh_use_100_years c.kwhm2a_required##c.kwhm2a_required
if step == 5200
reg meantechnical_kwhm2aofturtle
c.kwhm2a_required##c.kwhm2a_required if step == 5200
// And we draw the same table again
reg cum_GWh_use_100_years c.kwhm2a_required##c.kwhm2a_required
if step == 5200
margins, at (kwhm2a_required=(70(10)220))
marginsplot

// Marginsplot for the final energy standard. This table is
not included in the paper as none of the varibles are
significant.
reg meantechnical_kwhm2aofturtles
c.kwhm2a_required##c.kwhm2a_required if step == 5200
margins, at (kwhm2a_required=(70(10)220))
marginsplot
```

ISBN 978-82-326-5835-0 (printed ver.)
ISBN 978-82-326-5183-2 (electronic ver.)
ISSN 1503-8181 (printed ver.)
ISSN 2703-8084 (online ver.)

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Science and Technology