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Wealth, Consumption, and Energy-Efficiency Investments*

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Abstract

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Key words: energy-efficiency gap; energetic building retrofits; wealth dynamics.

JEL classification: D15; D31; D81; H23; O33; Q48; Q49

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1. Introduction

1.1. Background

In December 2019, as part of the Green Deal Package, the EU adopted an "energy efficiency first principle", which "aims to treat energy efficiency as a source of energy in its own right in which the public and the private sector can invest ahead of other more complex or costly energy sources" (European Council, 2018). Such official recognition is surely a victory for the energy-efficiency community, which has for decades been preaching the vast potential of this resource. At the upper limit, for instance, Cullen et al. (2011) calculate that society could get by with 73% less energy supply by applying known engineering best practices to passive systems that transform useful energy to services. Although it is unclear if such drastic reductions in energy demand via energy-efficiency measures are feasible, the accelerating climate crisis has forced consumers, policymakers, and researchers alike to reconsider the role of energy efficiency in the energy systems of the future.[1] In particular, it must be asked: is the current pace of energy-efficiency adoption socially optimal?

Hausman (1979) is credited as being the first to draw economists' attention to a phenomenon particular to energy-efficiency investments: he noted that individuals implicitly seemed to heavily discount future energy savings, thereby passing up investments that were ostensibly net-present-value positive. This phenomenon, which has since been corroborated in several studies (Kim & Sims, 2016), has become the basis for a hypothesis that has come to be known as the *energy-efficiency gap*, or *energy-efficiency paradox*; namely, that "the way individuals make decisions about energy efficiency leads to a slower diffusion of energy-efficient products than would be expected if consumers made all positive net present value investments" (Gillingham & Palmer, 2014). The existence of the gap, its size, and consequent policy recommendations have been the subject of much debate in the economic and energy literature over the past 40 years.

[1] For practitioners, energy-efficiency decisions are central to many energy system models (Patankar et al., 2022; Rogan et al., 2013; Åberg & Henning, 2011). This is particularly true for heat pump uptake in the context of sector coupling (Jokinen et al., 2022; Bernath et al., 2019; Bauermann et al., 2014).

In an influential article, Jaffe and Stavins (1994) put forward a notion of social optimality in the case of energy-efficiency diffusion that has since found widespread acceptance. They noted that along the broad spectrum between the present, baseline energy-efficiency level and the "technologist's economic potential" (Cullen et al.'s hypothetical 73% reduction, say) lie several possible equilibria such as the "narrow social optimum", the "economist's economic potential", and also, the "true social optimum". In their estimation, the true social optimum of energy-efficiency technology penetration is attained by (i) eliminating market failures to adoption whose elimination can pass a benefit/cost test, and (ii) installing any additional efficiency measures justified by environmental externalities. Further, they make a meaningful and important distinction between market barriers and failures. In the former category are those barriers to adoption that do not *per se* merit a policy response, and in the latter are those that do.[2] Seen in this light, quantifying a socially optimal adoption rate boils down to (i) examining the efficiency of the market for energy-efficiency measures and identifying possible market failures, and (ii) determining an appropriate pricing of environmental externalities. Our focus is on the first line of investigation, though we will touch on the second as well.

Returning to the issue of high implicit discount rates, the key question is therefore if these are symptoms of an inefficient market, i.e. of market failures, or if they are only the result of market barriers. For the latter to be true, one would need to explain why the high discount rates are in fact optimal from the point of view of the decision maker. And indeed, the economic literature purports to show exactly this, concluding variously that factors such as hidden costs, consumer heterogeneity, uncertain energy prices, overestimated energy savings, and the rebound effect help account for high implicit discount rates among consumers (Gillingham & Palmer, 2014).

This article is about the relationship between consumer heterogeneity and the energy-efficiency gap; we will however explore this link without resorting to implicit discount rates. There are good reasons to pivot focus away from the implicit discount rate, which has dominated the energy-efficiency literature for decades. Firstly, the concept has come to serve as

[2]Note that even in the case of market barriers, policy intervention may be motivated by other grounds, most prominently environmental externalities.

a catch-all for time and risk preferences, irrational behaviour, biases, and external barriers, and as such provides guidance for policy-making only in so far as these underlying sources are identified and quantified, which is not always possible (Schleich et al., 2016). Further, it is difficult to design policies around implicit discount rates because of the twin problems of (i) the large observed variability in these rates (Newell & Siikamäki, 2015), and (ii) the overwhelming sensitivity of the standard net-present-value method to the discount rate (Copiello, 2021; Copiello et al., 2017). Finally, the concept is often muddled with that of the social discount rate employed by social planners and analysts in model-based policy assessments, resulting in a confounding of prescriptive and descriptive modelling aims (Hermelink & de Jager, 2015).

1.2. Our contribution

Our framework has its roots in an article by Thompson (1997), who was the first to make the observation that the consumer investing in energy efficiency is not in fact faced with a traditional investment that produces an uncertain revenue stream, but rather chooses between two uncertain *cost* streams, to which different discount rates may be applied. And although Thompson teases out some consequences of this line of thinking in his work, he stops short of embedding the agent's consumption in their wealth dynamic, and we are not aware of any other literature that pursues this line of thinking. This is striking given that the natural context to consumer consumption under uncertainty is a wealth dynamic (cf. Miao & Wang, 2007). Additionally, there is ample survey evidence (see Section 1.3 below) that confirms the importance of consumers' wealth in the energy-efficiency decision. Finally, recent investigations (Rockstuhl et al., 2021, 2022) into the differences between the "investment risk" and "energy bill risk" perspectives on energy-efficiency investments have showed that consumers are far more sensitive to energy bill risk, i.e. consumption risk, when considering these investments.

In this article therefore, we present a formulation of the energy-efficiency investment problem as one of a choice between two uncertain cost streams, set against the background of the agent's wealth and wealth dynamic. Our model is based on the framework of Adamou et al. (2021). There, the authors propose a model of temporal discounting built on the single assumption of growth-rate maximisation; they demonstrate that the agent's idiosyncratic discount function can be derived by matching the growth rate of their wealth for two risk-free inter-temporal payments. We show here how their framework can be modified to include consumption under uncertainty and derive a trigger price such that the agent invests the first time their energy carrier hits this trigger from below.

Our proposed investment rule exhibits behaviour commensurate with economic logic and existing results, and the framework within which it is located is the first that is capable of quantifying the effects of the agent's wealth and wealth dynamic on the energy-efficiency investment decision. We show in two case studies that the significant heterogeneities inherent in the distributions of wealth, energy consumption, and other physical parameters of the energy-efficiency investment conspire to produce heavy-tailed investment-trigger distributions with the vast majority of consumers having no incentive to retrofit.

The article is organised as follows. The decision model and investment rule, as well as a demonstration and the first case study, are presented in Section 2. Section 3 re-purposes the decision model to study the market for heat pump investments: we show how the investment rule may be linearised, and explore the design of carbon-tax and retrofit-subsidy policy. We conclude with a discussion and outlook in Section 4.

1.3. The building sector as a prototypical example of the energy-efficiency gap

Although our model is rather general, for concreteness and ease of comparison with the literature, we have chosen to focus on the building sector, which is a salient and ubiquitous example of the energy-efficiency investment problem. In engineering estimates, the building sector is far and away the sector with the greatest potential for energy savings (Cullen et al., 2011). This is just as well, since the building sector accounts for 17.5% of global greenhouse gas emissions, mainly due to energy consumption for heating, and for the generation of electricity for lighting and appliances (Ritchie et al., 2020). For decades now, governments around the world have attempted to mitigate these emissions through energy-efficiency policies, with mixed results (Nejat et al., 2015). Germany, the focus of our case studies, aims to achieve a "virtually climate-neutral building stock by 2050", meaning that primary energy consumption should be reduced by 80% compared to 2008 levels by then (BMWi, 2015). Given that the existing building stock will make up at least 75% of the total building stock in 2050 (Esser et al., 2019), these goal necessitates widespread and significant energetic retrofits of existing dwellings over the coming decades.

The German government's energy efficiency roadmap is predicated upon an annual retrofit rate of 2%, where the average retrofit achieves an efficiency increase of 70% (BMWi, 2015). The gap between these stated policy goals and actual retrofit rates is significant and well-documented. For instance, the comprehensive survey of Esser et al. (2019) uncovered retrofit rates in Germany of only 0.1% for deep retrofits and 0.9% for medium retrofits. They conclude that the building sector would "clearly and significantly fail to deliver on its primary energy reduction targets", should these rates persist.

Our framework presupposes that the wealth of the agent and energy-price uncertainty play central roles in the retrofit decisions. The rich literature on this sector affords us the opportunity to bolster this conjecture with panel evidence. For instance, a survey by Stieß et al. (2010) of over 500 German homeowners on barriers to retrofitting found that 45% of respondents were unsure if the retrofit investment would pay back, and 44% admitted a lack of financial means. These findings are echoed by Novikova et al. (2011), who in a survey of 2000 German homeowners, found that the most common reason for homeowners reducing or dropping retrofit measures that they had initially intended to install was the expense; uncertainty about the investment paying back was the second-most common reason. Similarly, Achtnicht and Madlener (2014) found that 59% of the 400 German homeowners they surveyed lacked the financial resources to undertake a retrofit, and for 51%, uncertainty surrounding the economic viability of the retrofit was a barrier to investment. Lastly, Alberini et al. (2013), in a survey of 473 Swiss homeowners, also found evidence that the greater the uncertainty in prices, the less likely the agent was to choose a hypothetical energy-efficiency renovation.

Since the surveys above did not consider wealth directly, bur rather financial means and credit, it is important to clarify the connection between the two. Wealth and access to credit typically go hand-in-hand, and the building retrofit sector is no exception. In evaluating an energy-efficiency subsidy program on Rhode Island, Van Clock and Henschel (2017) found that lower-income households often applied for loans and didn't receive them; additionally, wealthier households were more likely to complete an energetic retrofit without using loans. On the other hand, Allcott et al. (2015) find unambiguous evidence that retrofit subsidies are regressive, since they preferentially accrue to wealthier consumers. Such findings indicate the importance of the agent's wealth in the retrofit decision and policy design.

Our case study in Section 3.3 is concerned with the uptake of heat pumps, a pillar of the Germany's plan to decarbonise the residential heating sector (BMWi, 2015). The adoption of this technology has been slow, with the heating market in fact pivoting strongly towards gas in previous years (BDEW, 2019), though recent volatility in the gas market has contributed to surging heat pump sales (Naylor, 2022). We highlight here a few relevant studies. Firstly, exploratory modelling by Merkel et al. (2017) agrees with the German government's targets for heat-pump uptake. A recent report by Breisig et al. (2020) summarises the opportunities and risks for Germany's heating industry with a special emphasis on heat pumps: the authors conclude that existing buildings must install at least 210 000 heat pumps annually to meet 2050 climate goals, and recommend carbon prices of between 150 and 200 €/tCO2 in the short term to make heat pumps competitive with fossil fuel alternatives.

As regards consumer preferences, the literature review and survey by Peñaloza et al. (2022) find that for German homeowners, the only significant barrier to investment in heat pumps is the large investment. Similarly, Michelsen and Madlener (2012) find that in contrast to heat pump adoption for new homes, homeowner preferences matter less for existing homes; instead, homeowners pay careful attention to costs (monthly income was a statistically significant predictor) and the specific attributes of the technology. The authors urge policy-makers to tailor subsidies to the dwelling characteristics (cf. Section 3.3).

2. A Decision Model for Energy-Efficiency Investments

2.1. Setup

The cornerstone of the decision model is the agent's wealth and wealth dynamic, specified in the form of a differential equation with initial conditions. For instance, at the two extremes, the agent's wealth might be purely additive,

$$\mathrm{d}W_t = J\,\mathrm{d}t\,, \tag{1}$$

where J is income, or purely multiplicative

$$\mathrm{d}W_t = \rho W_t\,\mathrm{d}t\,, \tag{2}$$

where ρ is the agent's expected return on wealth; this is typically larger than the risk-free rate (Bach et al., 2020). Whatever the agent's wealth and wealth dynamic, these are specified at the outset, but are not to be viewed as an arbitrary degree of freedom: they are to be taken as given, being imposed upon the agent by their personal circumstances (cf. Adamou et al., 2021). As such, this initial specification constitutes the idiosyncratic context within which the retrofit decision is made.

Energy costs are included in the wealth dynamic as a consumption term. For instance, for the multiplicative dynamic in Equation 2 we would write

$$\mathrm{d}W_t = (\rho W_t - CP_t)\,\mathrm{d}t\,, \tag{3}$$

where C is the energetic need, which we assume is constant, and P_t the price of the relevant energy carrier. For concreteness, we focus on consumption due to heating in the following. Further, as the multiplicative wealth dynamic is intuitive, relevant as a first-order approximation to a large class of wealth dynamics, and exhibits non-linear effects that highlight the importance of a decision rule based on wealth, we restrict ourselves to considering the same in the remainder of this article (see Section 4).

For the wealth dynamic in Equation 3, the consumption term is the sole source of uncertainty in the agent's decision to retrofit their dwelling, which may be described as follows: the agent has the choice to invest some amount K to upgrade the thermal condition of their dwelling by investing in better insulation or a more efficient heater say, resulting in energy consumption being reduced by a factor $\phi = \phi(K) < 1$ to the level ϕC. If we make the simplifying assumption that the agent's present equipment is infinitely-lived, a translational time symmetry emerges: at each moment in time, the agent has the choice to either invest immediately or wait until the next time step, at which point they will be confronted again with the same choice. Our goal is to derive a trigger price $P^\star$ such that the agent invests the first time P_t crosses this threshold from below.

2.2. *Defining the price trigger*

This setup may be a modelled as a finite-horizon decision problem: faced with an uncertain future, the agent maximises their utility over a horizon H commensurate to the decision at hand. In order to proceed therefore, some choice for the utility function must be made; naturally, the argument below is agnostic to the particular functional form chosen. For our multiplicative wealth dynamic, we opt for a logarithmic-type utility function, in line with the reasoning of Peters and Gell-Mann (2016).[3] To wit, we define the agent's utility as the growth rate of their wealth over the decision horizon:

$$U := \frac{1}{H} \log \frac{W^H}{W^0} \,, \tag{4}$$

where W^0 is the wealth at the moment of decision, and W^H is the wealth at the horizon. Utility so defined will be a random variable, since W_t is a stochastic process with evolution defined by Equation 3.

We denote by U^0 and U^1 the utilities of investing immediately and waiting a year respectively. Note that the horizons of the two cases differ by a year: if N is the lifetime of the thermal measure that the agent is contemplating investing in, we have $H^0 = N$, and $H^1 = N + 1$. Finally, both U^0 and U^1 are functions of wealth and energy price at the moment of decision; this follows from its dependence on the specified wealth dynamic and initial conditions, the latter being used to model the moment of decision. We demonstrate this in the following.

[3]Peters and Gell-Mann argue that given a wealth dynamic, the *growth rate of wealth* is a natural choice for utility function. In particular, if wealth grows multiplicatively, the logarithmic-type utility function is the canonical choice for evaluating gambles under uncertainty because it is ergodic, meaning that its expectation value agrees with its time-average. For more details see Peters and Gell-Mann (2016) and Peters (2019).

Let us assume discrete time with $\Delta t = 1\,\text{yr}$. Distinguishing now between W_0 and P_0, the initial conditions for the wealth dynamic differential equation, and W^0 and P^0, variables that we are free to vary, representing respectively the wealth of the agent and the price of the energy-carrier at the moment of decision, if investment is immediate, wealth evolves according to

$$\begin{aligned} W_0 &= W^0 - K\ , \\ P_0 &= P^0\ , \\ \Delta W_t &= \rho W_{t-1} - \phi C P_{t-1}\ , \qquad 1 \leq t \leq H^0\ ; \end{aligned} \tag{5}$$

whereas if the agent waits a year, wealth evolves according to the piecewise differential equation

$$\begin{aligned} W_0 &= W^0\ , \\ P_0 &= P^0\ , \\ \Delta W_t &= \rho W_{t-1} - C P_{t-1} - K\ , \qquad t = 1\ , \\ \Delta W_t &= \rho W_{t-1} - \phi C P_{t-1}\ , \qquad 2 \leq t \leq H^1\ . \end{aligned} \tag{6}$$

We will thereby have wealth at the horizon, and consequently the expected utilities $\mathbb{E}[U^0]$, $\mathbb{E}[U^1]$ be functions of P^0 and W^0.

The canonical approach in such a situation, i.e. one with two relevant state variables, is to define a composite variable such as P^0/W^0, and locate a corresponding investment trigger in terms of the same (cf. Hassett & Metcalf, 1992). However, in order to streamline our argument and keep the focus of the presentation on the energy-carrier price, we make the following simplifying assumption. If P_t changes much faster than W_t, and also $CP_t, K \ll W_t$, we can, for the purposes of locating the investment trigger, hold the agent's wealth constant and study P^0 alone. The case study in the following section makes clear that this assumption holds for many cases of interest.

No matter the choice of wealth dynamic and utility function, higher energy prices equal greater consumption, and should therefore encourage immediate investment, ceteris paribus. Hence, we expect that as we increase P^0 from smaller to larger values, the quantity

$$\gamma(P^0) := \mathbb{E}[U^0|P^0] - \mathbb{E}[U^1|P^0] \tag{7}$$

TABLE 1. *Parameters used in the demonstration.*

Description	Variable	Value	Unit
Starting wealth[1]	W^0	198k	€
Expected returns[1]	ρ	3.92	% p.a.
Energy carrier	–	Gas	–
Energy consumption[2]	C	16 600	kWh/yr
Cost of thermal measure[3]	K	15k	€
Reduction factor[3]	$\phi(K)$	0.8	–
Lifetime	N	20	yr

[1] Median homeowner wealth and associated growth rate; see Appendix A.
[2] Median energy consumption for heating; see Table 3 and Figure 10.
[3] Typical values for wall or roof insulation, or new windows (Kloth, 2022b).

transitions from negative to positive values, indicating increasing utility by early investment as opposed to waiting. This leads to a natural definition of the trigger price as the smallest energy-carrier price for which the expected utility of investing immediately equals the expected utility of waiting a year:

$$P^\star := \min\{P^0 \in (0, \infty) \mid \gamma(P^0) = 0\} . \tag{8}$$

We present in the following section a demonstration of our methodology. In section 3, as part of our policy case study, we show further how the trigger price may be approximated by a linear function, whereby the effects of wealth, consumption etc. on the trigger can be easily quantified and compared.

2.3. *A demonstration*

For this demonstration, we consider an agent with wealth and dwelling characteristics as in Table 1. The starting wealth and energy consumption are median values for Germany, and the agent has the option to invest € 15k to reduce their energy consumption by 20%: these numbers are typical for several measures including wall or roof insulation, or new windows (Kloth, 2022b).

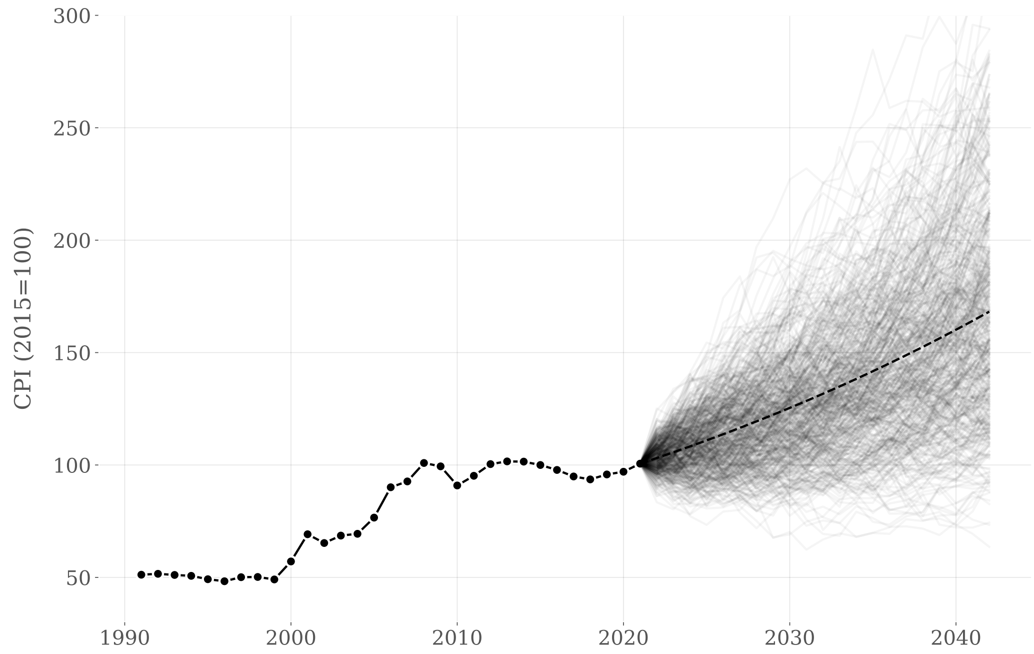

FIGURE 1. *Historical development of the consumer price index for heating gas (heavy dot-dashed line), together with generated scenarios (thin grey lines) and mean forecast (thin dashed black line) for its development over twenty-one years from 2021.*

For the development of energy-carrier price, we fit an ARMA(0,0) model to the historical returns on the consumer price index for heating gas (Statistisches Bundesamt, 2021).[4] The model produces a mean forecast and scenarios as in Figure 1. This suffices to generate scenarios for the development of wealth for the two possibilities "invest" or "wait" using Equations 5 and 6; the only parameter we have to fix is the energy-carrier price at the moment of decision P^0. For instance, setting P^0 equal to the 2021 national average gas price of 7.14 cent/kWh and simulating 10,000 price paths for wealth development results in Figure 2. The utilities (growth rates) in the two cases are consequently computed via Equation 4; their histograms are shown in Figure 3 together with their expected values. One sees clearly that the expected value of U^1 (wait) is larger than than of U^0 (invest); their difference is the quantity γ (Equation 7).

[4]The fitted parameters (standard errors in parentheses) are $\mu = 0.0248$ (0.017) and $\sigma^2 = 0.043$ (0.001). The model was chosen for its simplicity and ease of comparison with the literature. More sophisticated models, e.g. including jumps and volatility processes (cf. Shafiee & Topal, 2010) might be fitted instead and deployed identically in our framework.

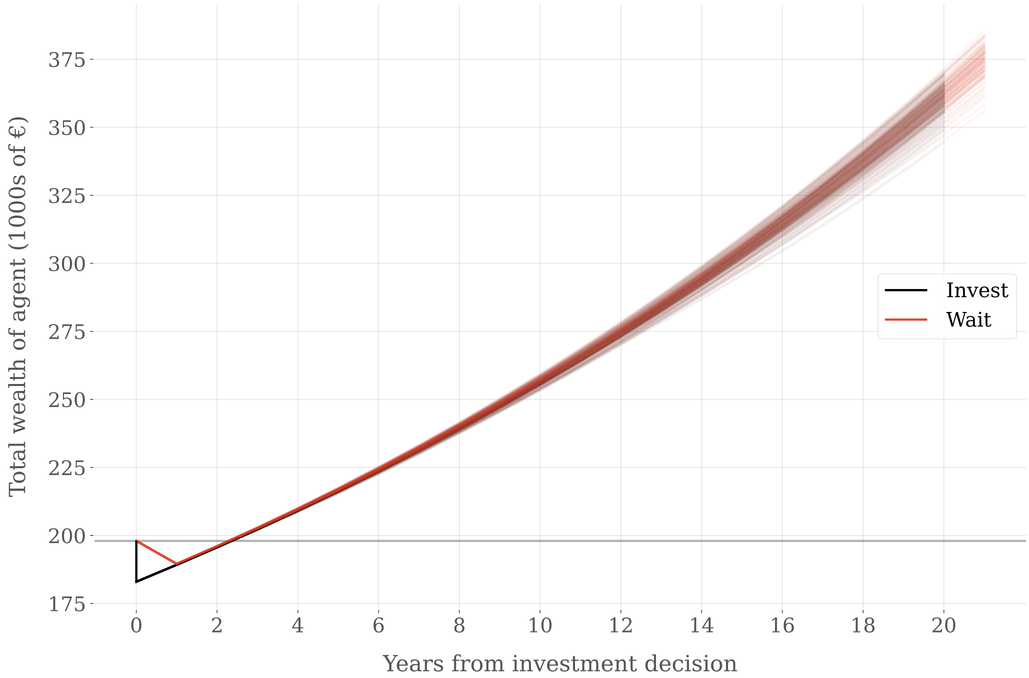

FIGURE 2. *Wealth development according to Equations 5 and 6.*

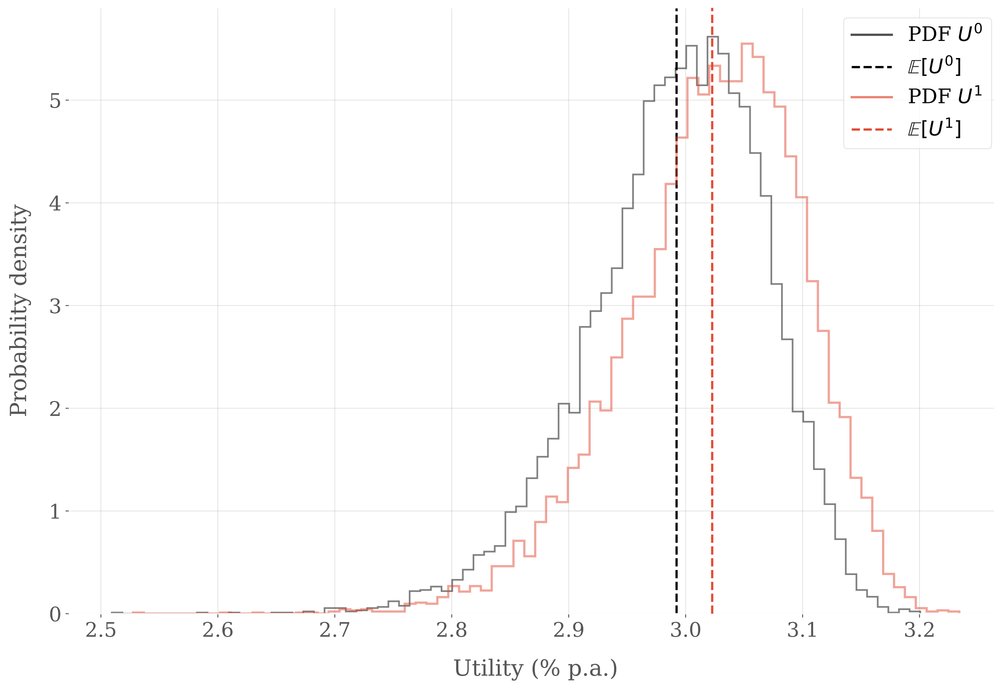

FIGURE 3. *The simulated probability density functions for U^0 and U^1 (Equation 4) together with expected values.*

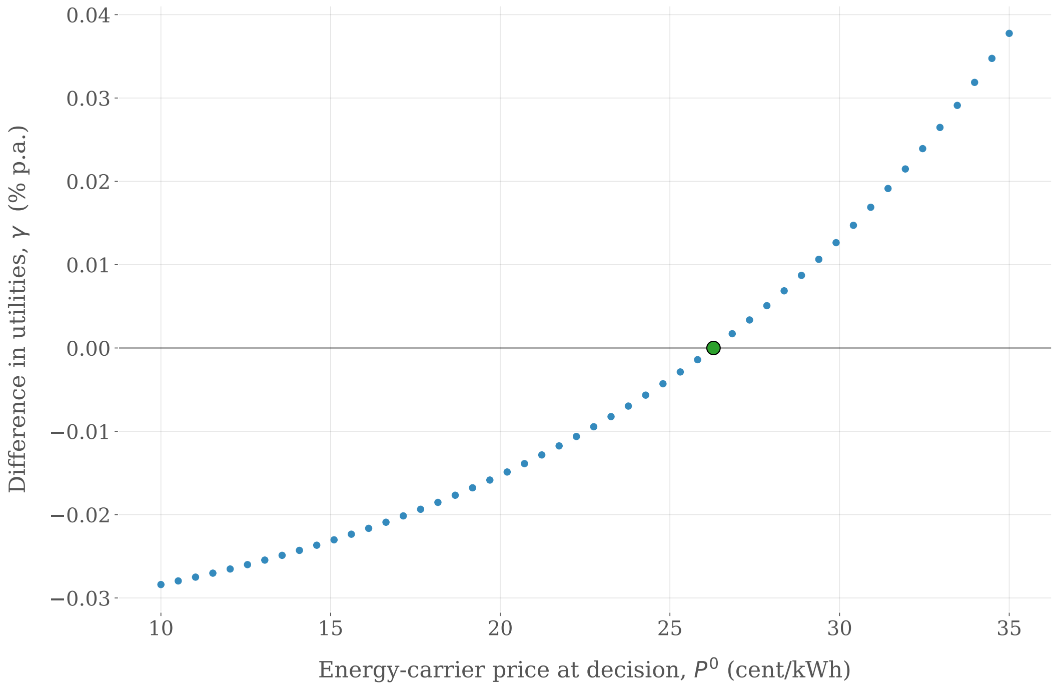

FIGURE 4. *The utility difference γ (Equation 7) as a function of gas price at the moment of decision P^0. The trigger price $P^\star$ is indicated in green.*

Locating the trigger price for investment is as straightforward as repeating the above process for different values of P^0 and recording γ each time; the result of this process is depicted in Figure 4. Using linear interpolation, the trigger price $P^\star$ is then readily computed as 26.28 cent/kWh. The agent invests in the thermal measure the first time the gas price hits this level from below.

2.4. *Wealth heterogeneity and the trigger price*

We now examine in more detail the consequences of introducing wealth into the energy-efficiency decision. In order to do so, we fix the physical parameters of the dwelling C, K ϕ and N as in Table 1 for the remainder of this section.

Firstly, we demonstrate in Figure 5 that the agent's growth rate and wealth at the time of the decision exerts a sizeable influence on the trigger price. The figure was generated by fixing ρ at the indicated values and varying W^0 between €200k and €1000k. The price trigger increases approximately linearly with the logarithm of wealth, with the consequence that

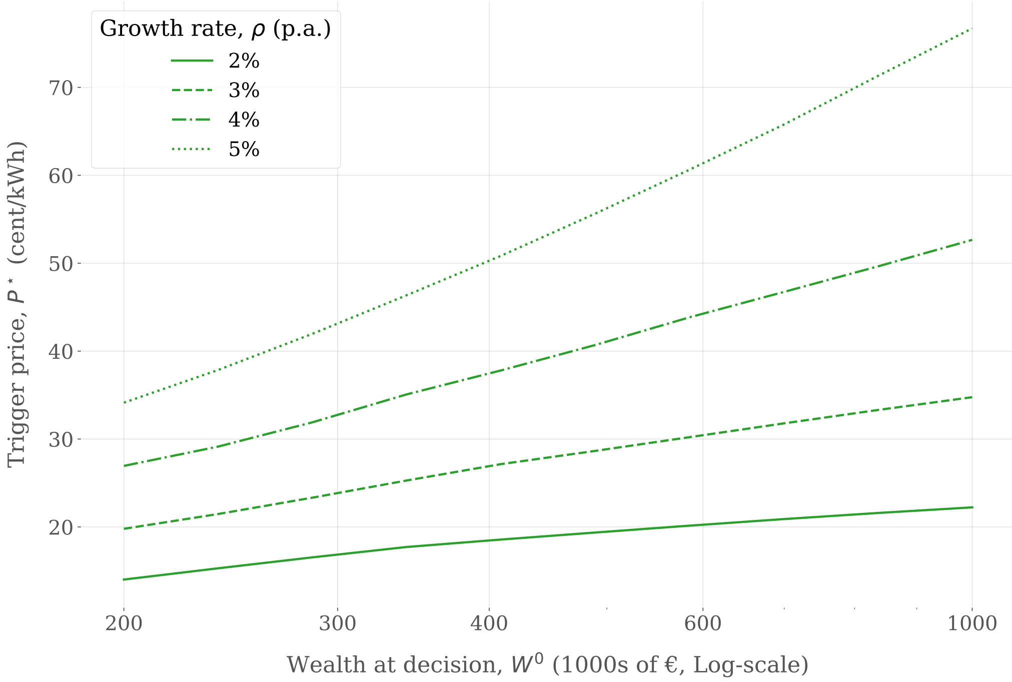

FIGURE 5. *The trigger price $P^\star$ as a function of ρ and W^0.*

wealthier agents, and those whose wealth grows faster,[5] wait for higher prices before investing in energy-efficiency measures. This wealth dependence of the investment trigger is a novel result, the consequences of which are explored more fully in following sections.

Further insight into the effects of wealth heterogeneity can be gained by extending the above calculation to the entire wealth distribution of homeowners to produce a corresponding distribution of trigger prices for this particular set of physical parameters. In order that this estimation be realistic, we culled together from several sources a distribution of wealth of German homeowners as described in Appendix A. Additionally, the growth rate ρ, being correlated with wealth (Bach et al., 2020), was assigned via an algorithm described again in Appendix A. Given these assumptions, we sampled 10,000 times from the homeowner wealth distribution and calculated the trigger price for each sample: the resulting histogram was then fit by a transformed normal distribution (Johnson, 1949). This is depicted in Figure 6 (in green).

The mean trigger price is 39.7 cent/kWh, the median 33.2 cent/kWh, and the standard deviation 25.2 cent/kWh. The distribution exhibits a heavy tail due to the heavy tail of the

[5]The two typically go hand-in-hand; see Appendix A.

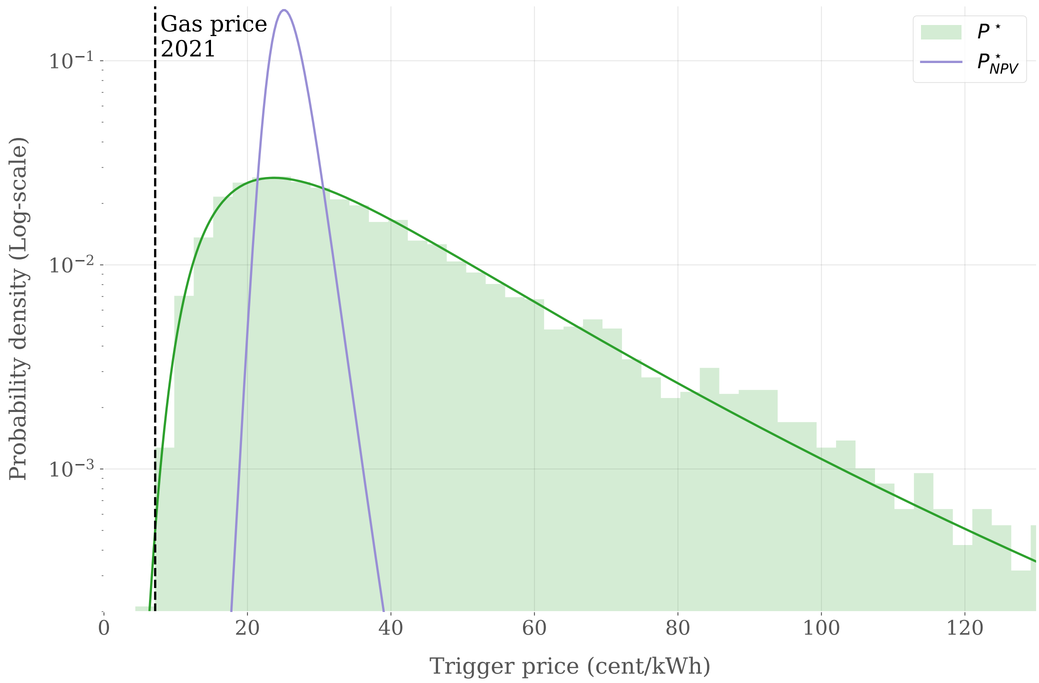

FIGURE 6. *The histogram and fitted probability distribution of the trigger prices $P^\star$, along with the fitted probability distribution for $P^\star_{NPV}$.*

wealth distribution. Moreover, given any gas price (e.g. 7.14 cent/kWh, the price in 2021) the cumulative distribution function gives immediately the percentage of homeowners with incentive to retrofit at this price (resp. 0.04%). All of this is extremely helpful for the social planner, who at a single glance obtains a picture of the trigger prices that homeowners in possession of a dwelling with these physical characteristics are "waiting for", as it were. Naturally, the most complete picture of homeowner incentive is obtained by jointly considering distributions of wealth and dwelling parameters; see Section 3.2 and the following for a demonstration.

Finally, by way of comparison, we consider the standard net present value model, which allows for agent heterogeneity solely through the discount rate. Concretely, the net present value of an energy-efficiency investment is

$$(1-\phi)CP^0 \sum_{i=1}^{N} \left(\frac{1+\mu}{1+r}\right)^i - K\,, \tag{9}$$

where r is the discount rate. If we set $r = \rho$, the discount rate is the cost of capital, and the two valuation methods can be directly compared. To wit, a trigger price for investment $P^{\star}_{NPV}$ can be obtained by setting Equation 9 equal to zero and solving for P^0. If we compute these trigger prices for the 10,000 ρ's from above, we obtain a second distribution, depicted also in Figure 6 (in purple). The net-present-value distribution displays far less heterogeneity than our model's: 11.8% of agents have triggers smaller than the smallest net-present-value trigger, and 39.9% of agents have triggers larger than the largest net-present-value trigger. In other words, we are able to produce significant heterogeneity in energy-efficiency investment decisions by introducing the agent's wealth dynamic into the picture, without having to resort to implicit discount rates. The consequences of this heterogeneity for the energy-efficiency gap are discussed in Section 4.

3. A Model for Technology Switching: Examining the Market for Heat Pump Upgrades

In the previous section, we defined an investment rule to answer the question, "at what energy-carrier price should an agent with a given wealth dynamic invest in an energy-efficiency measure with given characteristics?" We show in this section how one might extend this reasoning to the case where the agent is contemplating a different heating technology altogether.

3.1. Defining the investment problem

We adapt the decision framework presented in Section 2 as follows. For concreteness, we assume that the agent is in possession of an infinitely-lived gas heater and intends to upgrade to a heat pump with lifetime N at cost K. In the case where the agent invests immediately, wealth evolves according to

$$
\begin{aligned}
W_0 &= W^0 - K \,, \\
Q_0 &= Q^0 \,, \qquad\qquad (10) \\
\Delta W_t &= \rho W_{t-1} - \eta^{-1} C Q_{t-1} \,, \qquad 1 \le t \le N \,;
\end{aligned}
$$

where η is the seasonal performance factor of the heat pump, and Q_t the price of electricity. If the agent waits to invest, wealth evolution is described by

$$\begin{aligned}
W_0 &= W^0 \, , \\
P_0 &= P^0 \, , \\
Q_0 &= Q^0 \, , \\
\Delta W_t &= \rho W_{t-1} - CP_{t-1} - K \, , \qquad t = 1 \, , \\
\Delta W_t &= \rho W_{t-1} - \eta^{-1} C Q_{t-1} \, , \qquad 2 \leq t \leq N+1 \, .
\end{aligned} \tag{11}$$

Given these two equations, it is possible to repeat the steps as described in Section 2.2 to compute a conditional trigger electricity price $Q^\star(P^0)$. Note that in contrast to the previous case, the trigger $Q^\star$ will be one that must be crossed from *above*, i.e. the price of electricity must be cheap enough to justify the switch. We again model the returns on the consumer price index of electricity by an ARMA(0,0) model.[6]

3.2. Linearising the trigger price function $Q^\star$

Consider now the social planner who seeks to understand the market for heat pump upgrades. He would be aided substantially in this regard by (i) a function mapping wealth and physical parameters to trigger prices, which would tell him which agents had incentive to invest at current market conditions, and (ii) a distribution of a trigger prices, which would paint a picture of total demand for heat pumps. A linearisation of the trigger price function $Q^\star(P^0)$ helps address both points, and clarifies the issues at stake due to its simple form. Computing such an approximation is the goal of this section.

Note first that according to our framing of the problem in the previous section, $Q^\star$ will be a function of the following eight variables: the agent's wealth parameters W^0 and ρ, energy consumption C, the heater parameters M, N, K and η, and the price of gas at the moment of decision P^0. By drawing randomly from suitably-scaled uniform distributions for each of these parameters and computing the resulting $Q^\star$ for each draw, it is possible to generate a

[6]The fitted parameters (standard errors in parentheses) are $\mu = 0.0292$ (0.006) and $\sigma^2 = 0.0011$ (0.000).

Table 2. *Regression results for Equation 12.*

Variable, V_i	Coefficient, β_i	t-statistic
P^0	0.697***	34.427
C	0.668***	31.558
ρ	-0.616***	-29.322
K	-0.331***	-16.732
η	0.318***	16.207
W^0	-0.140***	-7.015
N	0.112***	5.671
Observations		500
R^2 (uncentered)		0.818

*, **, *** indicate significance at the 90%, 95%, and 99% level, respectively.

cross-sectional dataset of trigger prices and variables. Then via ordinary least squares, a linear approximation to the function $Q^\star$ may be computed.

We generated such a sample of 500 data points and fit the equation

$$\overline{Q^\star} = \sum_{i=1}^{8} \beta_i \overline{V_i} \,, \tag{12}$$

where all variables are standardised for ease of comparison; the results are presented in Table 2. All estimates are highly significant, and the effect of each variable is in the expected direction. Three variables are seen to exert a sizeable influence on the price trigger, with the price of gas having the largest effect. The wealth parameters of the agent ρ and W^0 have negative effects on the trigger price, as in the previous section. That is, the wealthier the agent, and the larger their expected return on wealth, the less incentive they have to invest in a heat pump.

3.3. *The distribution of trigger prices; implications for policy design*

As in Section 2.4, the logical next step for the social planner is to generate distributions of trigger prices. These are computed easily and quickly with the linearisation above. We consider in this section all single-family and terraced homes which heat with gas, constituting around 40% of the German residential building stock (Metzger et al., 2019). Table 3 lists assumed and inferred distributions for four of the five physical parameters C, K, η and N for these

TABLE 3. *Assumed distributions for the variables in the heat pump upgrade problem. See Appendix B for visualisations.*

Variable	Assumed distribution[1, 2]	Remarks
C	Log-norm $(126.24, 0.44) \times$ Log-norm$(131.72, 0.33)$	The distribution of annual energy consumption for heating is modelled as the product of distributions of per-squared-meter annual energy consumption and total heated area, calibrated to data from Metzger et al. (2019) and Sagner (2021) respectively. When sampling, only values below 50 000 kWh/yr are retained.
K	$0.65 \times \big($Unif$(8750, 18\,750)+$ Unif$(2500, 22\,500)\big)$	The two uniform distributions model typical equipment and installation costs respectively of the various types of heat pumps on the German market Kloth (2022a). The pre-factor is due to the subsidy of 35% on heat pump upgrades in 2021 (BAFA, 2022).
η	Unif$(2.1, 4.3)$	Corresponds to observed values in a long-term German heat-pump monitoring project (Miara et al., 2017).
N	Unif$(15, 25)$	From Kloth (2022a).

[1] Log-norm (μ, σ) is the distribution of the random variable $X = e^{\mu+\sigma Z}$, where Z is a standard normal variable.
[2] Unif(a, b) denotes the continuous uniform distribution with bounds a and b.

dwellings. Corresponding visualisations can be found in Appendix B. As mentioned above, the distribution of wealth of German homeowners is described in Appendix A.

With these assumptions in hand, we fix the gas price P^0 at the 2021 national average,[7] sample 10,000 times from the assumed distributions for the independent variables, and generate a histogram and fitted probability distribution of trigger electricity prices via the linearisation of $Q^\star$. The result is shown in Figure 7.

The distribution of trigger prices $Q^\star$ is well-approximated by Johnson's S_U distribution (Johnson, 1949). It is heavy tailed, with an excess kurtosis of 1.175. A significant share of agents, 33.4%, had negative trigger prices, meaning that at 2021 market conditions, their wealth would never grow fast enough for these homeowners to recover their heat pump investment over N years. More interestingly, we see that only a small share of agents, 3.12% to be precise, had trigger prices greater than the price of electricity in 2021, which is close to the observed share of heat pump upgrades of approximately 1.24%.[8] As such, we find no evidence of a pervasive

[7]We assume a normal distribution with standard deviation 1 cent/kWh to account for regional differences, differences in energy contracts etc.

[8]According to BWP (2021), approximately 100k heat pumps were sold in the renovation sector in 2021. If all

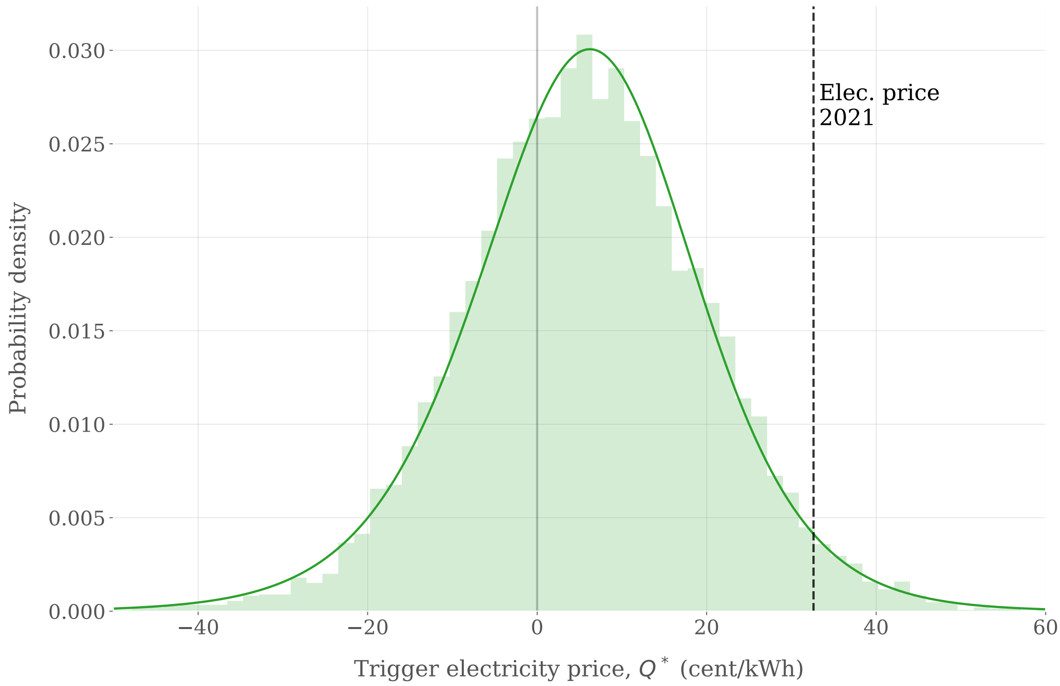

FIGURE 7. *The simulated histogram and fitted Johnson S_U distribution of trigger electricity prices $Q^\star(P^0)$.*

energy-efficiency gap in the market for upgrades from gas heaters to heat pumps.

Consider now the social planner who wishes to encourage investment in heat pumps. Concretely, suppose that she had had a target of 100k heat pump upgrades in 2021 in the subset of the building sector that we have been considering. Assume further that the prices of electricity and gas, the two relevant energy carriers were fixed by markets. The two tools most readily available to the planner to influence consumer incentives are carbon taxes and subsidies on the heat pump investment. To mimic the effect of taxes and subsidies, we repeated the calculations in the previous section for shifted distributions for P^0 and K, and generated estimates for heat pump sales in 2021 as a function of these parameters, all other things being equal. This is summarised in Figure 8. The intersection of the plane z = 100k with the surface depicted in the figure defines a line delineating the options available to the social planner to

of these were sold to homes that heat with gas, given a total of 5.64 million gas heaters for single and two-family dwellings (BS-ZIV, 2020), this would translate to a rate of 1.77%. On the other hand, since the share of dwellings that we consider is 40% of the total building stock, if we assume that only 40k homes switched from gas heaters to heat pumps, this would be a rate of 0.71%. The average of these rates is 1.24%.

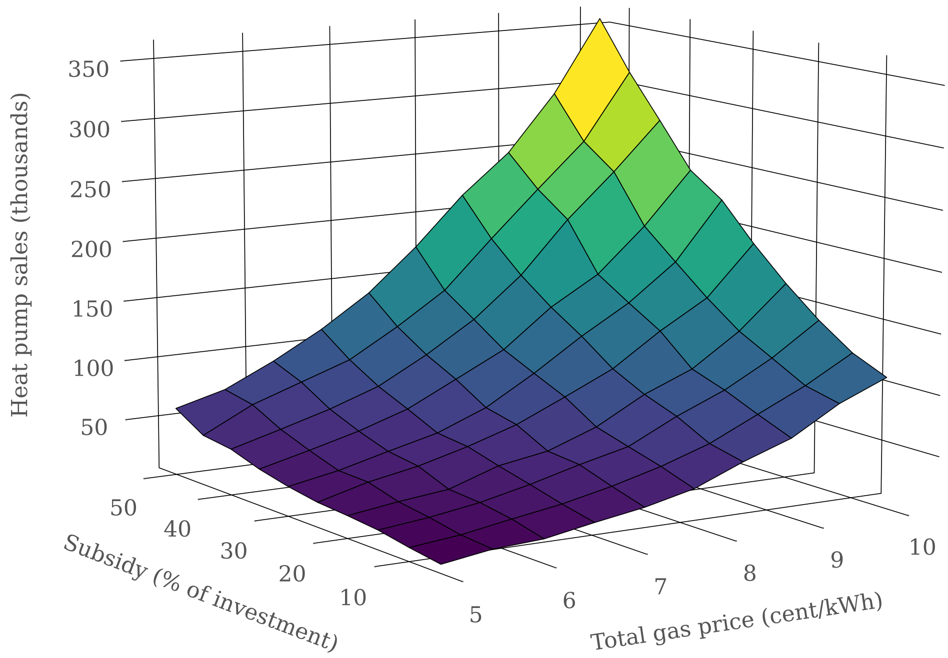

FIGURE 8. *Projected heat pump sales as a function of total gas price (i.e. base price plus carbon surcharge) and subsidy level in for single-family and terraced homes that heat with gas.*

meet her target.

For instance, in 2021, Germany introduced a carbon tax of 25 €/tCO_2 on heating and transportation, which translated to a surcharge of approximately 0.5 cent/kWh on the gas price seen by households (Wettengel, 2021). At this carbon price, ceteris paribus, we estimate that increasing the subsidy level from 35% to 40% of the total investment would have sufficed to attain the 100k target. On the other hand, were the social planner, due to budget constraints for example, only have been able to commit to a subsidy level of 15%, a carbon tax of roughly 90 €/tCO_2 (surcharge 1.8 cent/kWh) would have been necessary to meet the same goal. And so on.

Finally, in order to further sharpen policy, and thereby better optimise social welfare by penalising free-riding (Egner et al., 2021; Allcott et al., 2015), the social planner might wish to specifically target homeowners in the tail of the trigger price distribution who *almost* have incentive to invest.[9] In our framework, the planner she could proceed as follows. In the trigger price distribution, households immediately to the left of the present electricity price should be prime targets for the social planner. In order to identify these households, we utilise the linearisation from the previous section; if we use the mean values for the assumed distributions for W^0, K, η and N, along with the 2021 price of gas, we obtain the following approximation[10]

$$C^{\star}(Q^0) = \frac{1}{8.68 \times 10^{-6}} \left(Q^0 + 10.22 \times 10^{-2} \right) \, . \tag{13}$$

This means that at the 2021 electricity price of 32.61 cent/kWh, assuming average levels for all other variables, households with a heating demand of 49 350 ± 4796 kWh or greater had incentive to invest in a heat pump anyway.[11] Since we are interested in household just below this threshold, we might insert 90% of the 2021 electricity price into the above equation to obtain $C^{\star}$ = 45 593 ± 4758 kWh. Therefore, in light of the lower bounds on these estimates, the social planner would do well to offer, say, the extra 5% subsidy computed above specifically to households with consumption between 40 000 kWh and 45 000 kWh.

4. Discussion and Outlook

In this article, we derived an investment rule for an agent who has the option to invest in an energy-efficiency measure. Apart from the physical parameters of the problem, the rule relies on (i) a specification of the agent's wealth, wealth dynamic and utility function, and (ii) models for the stochastic variables in the problem. In particular, the decision framework has

[9]With regards to energy consumption for instance, a policy based on this idea has been recently implemented in Germany whereby the "worst-performing" buildings, i.e. buildings whose energetic components are among the 25% worst performing in Germany, receive additional retrofit subsidies (KfW, 2022). This is a laudable attempt at subsidy targeting.

[10]For this calculation, regression coefficients from the unstandardised equivalent of Equation 12 were used. We omit writing the confidence intervals around the constants in the equation.

[11]For reference, according to our assumption in Table 3, mean annual energy consumption for heating in Germany is 19 207 kWh.

no free parameters.[12] We employed the decision model to demonstrate that in the building sector, heterogeneity in agent wealth and retrofit parameters come together to produce skewed, heavy-tailed distributions, with only homeowners in the tails of these distributions typically having incentive to invest in energy-efficiency.

We draw the following broad conclusions from the case studies in this article.

- In Germany, for single-family and terraced homes that heat with gas, the energy-efficiency gap for typical insulation measures and heat-pump upgrades is small to non-existent. We speculate that this holds true for the retrofit market in general.
- In the short term, encouraging annual retrofit rates of e.g. 2% of the building stock is possible with realistic levels of subsidies and taxes. This is due to the fact that the agents with the most incentive to invest need only a slight nudge to trigger an investment.
- The flip side of the coin is that subsidies must be targeted wherever possible, e.g. at consumers with the largest consumptions, in order to maximise their marginal effects. Recent analysis indicates that although energy subsidy volume in Germany has been sharply increasing in recent years, their positive impacts are unfortunately not keeping pace (Amelang, 2021); it would appear that the time is ripe for a renewed focus on marginal benefits. Indeed, the logical conclusion of the policy experiments in the previous section is the formulation of something like the following optimisation problem (cf. Allcott et al., 2015; Allcott & Greenstone, 2012). For a fixed price of carbon (corresponding to the German context), the planner's aim should be to design a subsidy policy to meet a specified retrofit target subject to (i) minimising the total amount spent on subsidies, and (ii) maximising the total marginal utility (including social utility) produced by the subsidies. This is a goal of future work.
- Energy prices are often volatile, sometimes highly so, meaning that the social planner should attempt to anticipate and correspondingly adjust market interventions at times of increased market volatility, when "renovation shocks" are most likely to occur. At the time of writing, due to historic levels of energy market volatility, unprecedented demand

[12] Unless of course a utility function with free parameters is chosen by the modeller. Peters (2019) argues that this is in general not necessary, since wealth dynamics map naturally onto utility functions.

for energy-efficiency subsidies forced the German government to pull the emergency break on the energy-efficiency building and retrofitting programs due to a lack of funds (Meza & Wettengel, 2022). Total social utility might have been better served in this case by a rolling back of these programs as energy prices started to rise, and kept on rising.

- Wealth matters: all other things being equal, wealthier agents, and those whose wealth grows faster, have fewer incentives to invest in energy efficiency. As such, the marginal utility of subsidies and taxes is smallest for these agents: the social planner would do well to offer wealthier agents smaller discounts or higher credit rates.

Finally, in addition to the social-utility optimisation problem above, we identify the following limitations in our model, and corresponding avenues for future work.

- We limited ourselves in this article to a noiseless multiplicative wealth dynamic, which is relevant for a large swath of homeowners. Future work might focus on introducing noise around the expected return on wealth, as well as investigating the energy-efficiency investment problem in the context of other wealth dynamics and corresponding utility functions.
- A simplification in our approach was the assumption of an infinitely-lived present heating system. This restriction can be lifted and the corresponding retrofit decision investigated in a real-options model. This is the subject of active research.
- Additionally, our model might be extended and adapted to incorporate relevant incentives and barriers uncovered in the energy-efficiency-gap literature into the agent's utility function. Consider for instance the landlord/tenant dilemma: in the event that an agent owns and rents out a dwelling, it may be that the tenant's energy consumption does not in fact directly slow down the agent's growth rate, in which case they have less incentive to retrofit than if they lived in the dwelling themselves; Kumbaroğlu and Madlener (2012) demonstrate how the net-present value calculation might be modified in this case; the agent's utility function in our framework may be similarly adapted.
- We assumed for in our simulations that all of the relevant distributions were independent. But this is only an approximation, since, for instance, older buildings have a larger energy need, cost more to retrofit, etc. Such information could be included for a more realistic

modelling of the building stock and retrofit possibilities. Additionally, some work exists on the relationship between wealth and energy consumption (Bao & Li, 2020; Galvin, 2019); it would be worthwhile including these links in simulations as well, wherever possible. On the other hand, we see the potential for much more work to be done to gather data on the interaction between the wealth distribution and the building stock.

- Extending our work to investigate policy design in the medium- to long-term would be a particularly interesting exercise, not least because these horizons are of the same length at the retrofit decision, and in the best-case scenario, all the low-hanging fruit would have been picked. Such investigations should be possible with the help of a dynamic building-stock model, and present an exciting avenue for future work. Nevertheless, this is only attainable to the extent that data exists: mapping the ever-changing building stock is a large, complex, and sustained undertaking, but it is essential to good policy design (Loga et al., 2016).
- Finally, the uptake of energy-efficiency and technology switching has complex interactions with the entire entire energy system, including energy prices; we therefore look forward to explorations of the effects of our framework, particularly wealth heterogeneity, in energy system models (Bernath et al., 2019; Rogan et al., 2013; Åberg & Henning, 2011).

Declaration of Interests

The authors declare no competing interests.

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Appendix A The Wealth and Expected Returns of German Homeowners

We describe here our approach to determining the distribution of wealth W^0 and expected returns ρ for the subset of the building stock considered in this article.

First W^0. We began with a Log-normal distribution for wealth, which has been shown to be a good approximation for the distribution of wealth below the 97th percentile (Clementi & Gallegati, 2005). In the case of Germany, given a mean net personal wealth level W_M = € 232,800 and a Gini coefficient $g = 0.75$, (Bundesbank, 2019), a Log-normal with parameters $\sigma = 2\,\mathrm{erf}^{-1}(g) = 1.63$ and $\mu = \log(W_M/1000) - \sigma^2/2 = 61.98$ is the appropriate approximation to the German wealth distribution (with wealth rescaled to 1000s of Euros). In order to infer from this the wealth distribution of homeowners, we relied on more data from the Bundesbank, namely the share of households with ownership of main residence for different wealth percentiles (see Table 4). We then sampled accordingly from the wealth distribution of the total population to approximate the distribution of homeowner wealth. The resulting histogram was then fit with the flexible Johnson's S_U distribution. Both distributions are visualised in Figure 9.

For ρ we applied the following procedure. Given a random sample w^0 (e.g. 200) from the homeowner-wealth distribution, its percentile was identified via the cumulative distribution function (resp. 0.82), and the appropriate growth rate of net wealth from the data in Table 4 assigned (resp. 4.12%).[13] Note that due to the lack of reliable data and relevance to the case study, samples below the 20% percentile of wealth were discarded.

[13] The growth rates are taken from column 4 of Table 2 in Bach et al. (2020). We assume here that the data for Swedish households in (Bach et al., 2020) is a reasonable approximation to the German data, for which we were unable to locate a similar source. In order to increase the heterogeneity of the sampling, we further introduce a fudge factor of 1% p.a. around the expected return. For instance, for the example above, the expected return is drawn from a Log-normal distribution with mean 0.0412 and standard deviation 0.01.

Table 4. *Home ownership and expected returns on net wealth of households for different brackets of the net wealth distribution. Data from Bundesbank (2019) and Bach et al. (2020).*

Wealth group	Share of households with ownership of main residence (%)	Expected excess log returns on net wealth (% p.a.)
P0 - P10	7	–
P10 - P20	2	-2.00
P20 - P30	5	1.09
P30 - P40	7	2.62
P40 - P50	25	3.14
P50 - P60	52	3.52
P60 - P70	75	3.76
P70 - P80	87	3.92
P80 - P90	89	4.12
P90 - P95	92	4.35
P95 - P97.5	92	4.53
Top 2.5 percent	92	4.74

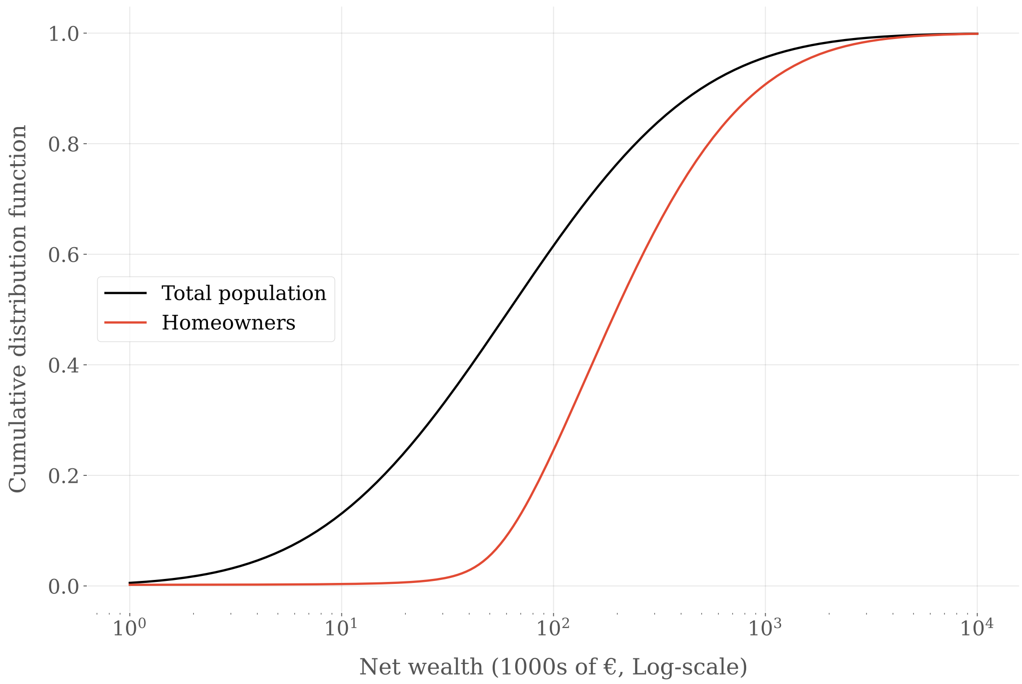

Figure 9. *Inferred cumulative distribution functions for the net wealth of the total population and of German homeowners.*

Appendix B Visualisations of Select Assumed Distributions for the Heat-Pump Case Study

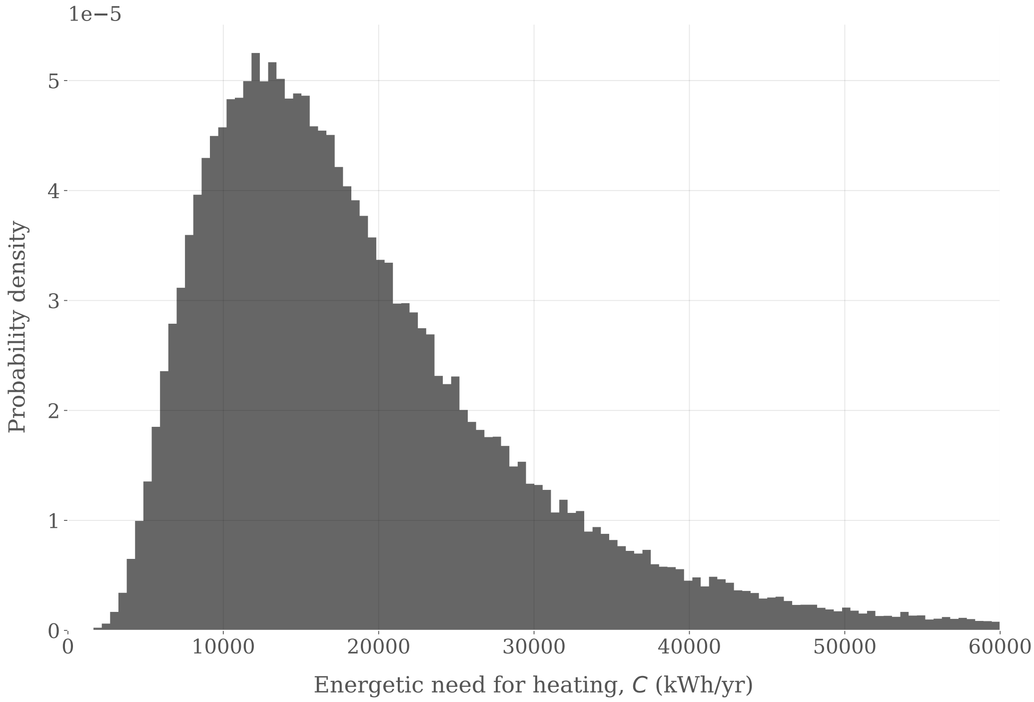

FIGURE 10. *Histogram of 100k samples from the assumed distribution for consumption C as in Table 3.*

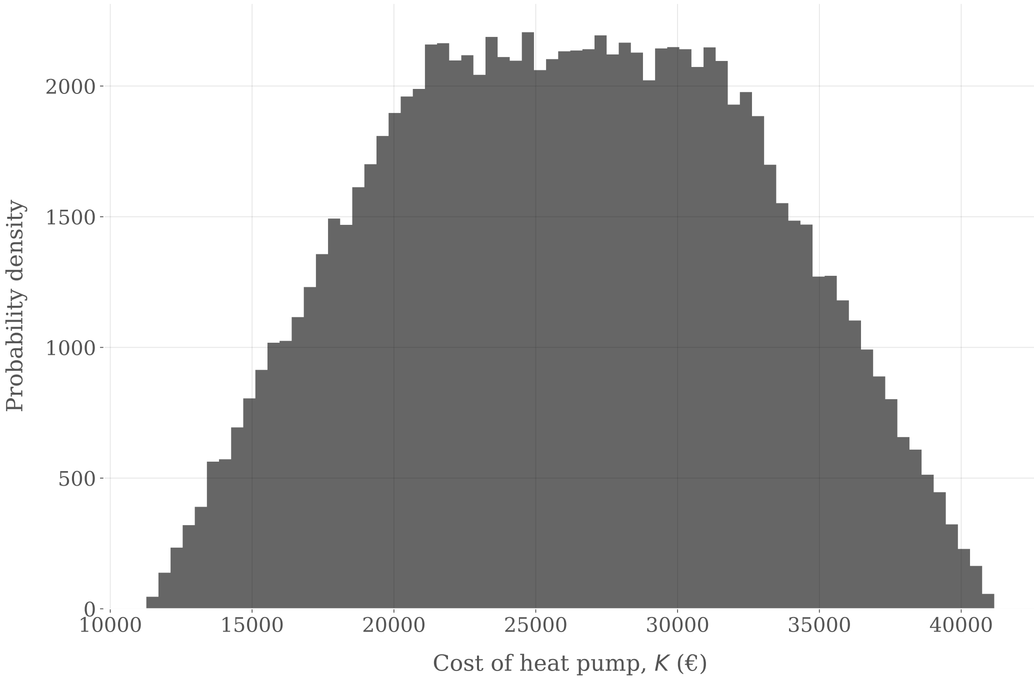

FIGURE 11. *Histogram of 100k samples from the assumed distribution for the total cost of the heat pump K as in Table 3.*

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