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Wealth maximisation and residential energy-efficiency retrofits: Insights from a real options model ☆

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ABSTRACT

The slow adoption of residential energy-efficiency retrofits continues to hamper the energy transition. We study incentives for adoption by proposing a model of optimal investment under uncertainty where the wealth-maximising agent has the option to delay. Stochastic portfolio returns and energy prices are taken into account. An extension of the model where the energy carrier is switched, e.g. from gas to electricity, is also considered. Exercise boundaries for the optimal stopping problem are estimated numerically for recent case studies of German buildings. Investment is generally not optimal at current energy prices and market conditions. Increasing correlation between gas and electricity prices erodes the value of technology switching. Comparative statics reveal that energy-efficiency investments become optimal at relatively lower energy prices as wealth, income, and savings behaviour increase, and portfolio drift and volatility decrease. Consequently, incentive to invest in retrofits is far more heterogeneous along wealth dimensions than standard discounted cash flow analyses suggest. An examination of retrofit subsidies demonstrates how free-riding by wealthier agents occurs when subsidies are not appropriately targeted. We show that the pursuit of economic efficiency in subsidy design might have regressive effects on the wealth distribution.

1. Introduction

1.1. Background

In September 2023, as part of the European Green Deal, the European Union revised and strengthened its “energy efficiency first principle”, requiring that energy efficiency be “considered as the first option in policy, planning and investment decisions” (European Council, 2023). Such official recognition marks a further victory for advocates of energy efficiency, who have 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 policymakers and researchers alike to reconsider the role of energy efficiency in the energy systems of the future. Central to this discussion is household adoption of energy-efficiency technology, which is the focus of this work.

Hausman (1979) is credited as being the first to draw attention to a phenomenon peculiar 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 and Sims, 2016), has become the basis for a hypothesis that has come to be known as the *energy-efficiency gap*, 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 and 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 forty years.

Within this vast literature, a key issue that emerges is the profitability of the energy-efficiency investments themselves (Galvin, 2024). Setting aside non-monetary incentives, for which the evidence is in any case mixed (Aravena et al., 2016; Alberini and Bigano, 2015), if a given energy-efficiency measure is not profitable for a given agent,

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it is rational to avoid adoption. As such, if evidence of widespread non-profitability of energy-efficiency investments could be established, it would be possible to make the case that the energy-efficiency gap is in fact smaller than often claimed. This is the tack taken by many authors, who argue variously that "unobserved or understated costs of adoption, ignored product attributes, heterogeneity in benefits and costs of adoption across potential adopters, use of incorrect discount rates, and uncertainty, irreversibility, and option value" lead to overly optimistic estimates of the benefits of energy-efficiency technology adoption (Gerarden et al., 2017). We situate our contribution within this literature, which seeks to unravel the complex notion of "profitability" in the context of energy-efficiency investments. We will make the case that there is much to gained by switching from profitability analyses to *optimality* analyses of energy-efficiency investments.

1.2. Our contribution

We take the following stylised aspects of energy-efficiency investments as a starting point: (i) they are often large and irreversible, (ii) they involve considerable uncertainty, (iii) the agent often has the option to delay investment, and (iv) the decision to invest is made against the background of a wealth dynamic. Whereas stylised facts (i)–(iii) form the basis for existing real options models of energy-efficiency investments (Tadeu et al., 2016; Kumbaroğlu and Madlener, 2012; Hassett and Metcalf, 1993), point (iv) has received comparatively less attention in the literature. The genesis of the idea might be traced to an article by Thompson (1997), who makes the observation that the consumer investing in energy efficiency is not faced with a traditional investment that produces an uncertain revenue stream, but rather chooses between two uncertain *consumption* streams, to which different discount rates may be applied.[1] And although Thompson teases out some consequences of this line of thinking, he stops short of embedding the agent's energy consumption in a wealth dynamic, and, to the best of our knowledge, only Rockstuhl et al. (2021) have proposed such a model. They demonstrate that an agent who evaluates the energy-efficiency investment within the context of a wealth dynamic invests more in energy efficiency than an agent who does not. Our treatment, which is more formal, goes beyond their contribution by incorporating additional sources of uncertainty, as well as the option to delay investment, which they do not consider.

There are several advantages to our approach. Firstly, if the agent is assumed to be risk-neutral, the investment problem can be posed in such a way that it becomes possible to dispose of the subjective rate of time preference altogether. This concept, a permanent fixture of the energy-efficiency gap debate, has come to serve as a catch-all for time and risk preferences, irrational behaviour, biases, and external barriers, and is fast becoming meaningless as a basis for policy design (Schleich et al., 2016). The analyst must further contend with the large observed variability in discount rates vis-à-vis energy efficiency (Newell and Siikamäki, 2015), as well as the extreme sensitivity of standard discounted-cash-flow methods to the discount rate (Copiello, 2021). Additionally, 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 and de Jager, 2015).

Secondly, a model built around the agent's wealth dynamic allows one to model the movements of energy prices and other income variables in an integrated framework. Whereas it has already been shown that uncertainty in energy prices generates a significant option value of waiting to invest (Tadeu et al., 2016; Kumbaroğlu and Madlener, 2012; Hassett and Metcalf, 1993), investigations into the agent's financial portfolio, which represents an opportunity cost in this context, is largely missing from the literature (Jackson, 2010). Our approach delivers novel insights into the trade-offs between dynamic sources of uncertainty.

Finally, the investment model we propose allows for a more penetrating analysis of agent heterogeneity, a key issue in the energy-efficiency gap debate (Gerarden et al., 2017; Gillingham and Palmer, 2014). In particular, we show how agent wealth and income play a significant role in determining the decision rule for an energy-efficiency investment. This introduces new dimensions for analysing differences in investment incentives among agents, which could have substantial implications for policy development. For instance, we can delineate how agent wealth influences free-riding on subsidies, thereby identifying opportunities to target and improve subsidy programmes.

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

For concreteness and ease of comparison with the literature, we focus our attention on investments that target improvement in the efficiency of energy demand for heating in residential buildings. These installations, often referred to as "retrofits", are a salient and ubiquitous example of the energy-efficiency gap. This is likely due to the fact that the building sector, which is by far the sector with the greatest potential for energy savings according to engineering estimates (Cullen et al., 2011), has shown relatively slow progress in energy-efficiency adoption despite extensive policy interventions (Nejat et al., 2015). Germany, the focus of our case studies, aims to achieve climate neutrality by 2045, and has set the goal of reducing emissions in the building sector to 57 % of 2020 levels by 2030 (Bundesregierung, 2021). Given that the existing building stock is likely to make up around 75 % of the total building stock in 2050 (Esser et al., 2019), this goal necessitates widespread and significant energy-efficiency retrofits of existing dwellings over the coming decades. 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.

By way of further motivating and contextualising our contribution, we briefly review some relevant literature which lends support to the thesis that wealth and uncertainty play prominent roles in household retrofit investments. The survey of 6600 homeowners by Schleich et al. (2021) shows that higher-income households with relatively better access to capital are far more likely to invest in energy efficiency. Achtnicht and Madlener (2014) find 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. Alberini et al. (2013), in a survey of 473 Swiss homeowners, also find evidence that the greater the uncertainty in prices, the less likely the agent was to choose a hypothetical energy-efficiency renovation. These findings are echoed by Novikova et al. (2011), who in a survey of 2000 German homeowners, find 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. Similar, a survey by Stieß et al. (2010) of over 500 German homeowners on barriers to retrofitting finds that 45 % of respondents were unsure if the retrofit investment would pay back, and 44 % admitted a lack of financial means. Since heat-pump adoption is also explored in this article, we mention here the literature review and survey by Peñaloza et al. (2022) which finds that for German homeowners, the only significant barrier to investment in heat pumps is the large investment. Michelsen and Madlener (2012) find that potential adopters pay careful attention to costs, and also

[1] For recent empirical support of this observation, see the survey by Rockstuhl et al. (2022).

that an increasing income is associated with a higher probability of heat-pump adoption.

The remainder of the article is organised as follows. After introducing the investment model in Section 2.1, we examine a case study in Section 2.2, carry out a comparative statics analysis in Section 2.3, an exploration of agent heterogeneity along the wealth dimension in Section 2.4, and an analysis of retrofit subsidies in Section 2.5. Section 3 is a brief presentation of an extension of the investment model to the case where the energy carrier is switched, e.g. from gas to electricity. We conclude with a discussion and outlook in Section 4.

2. An investment model for residential energy-efficiency retrofits

2.1. The investment model

Let $0 < T < \infty$ be some fixed finite time horizon, e.g. the remaining lifetime of the present heating system, such that a retrofit is mandatory at time T. Then let $t = 0, 1, \ldots, N$ denote time steps with equal spacing $\Delta T := T/N$ in the interval $[0, T]$. To examine the interplay between financial wealth and energy price, we employ the following model of income in the sequel,

$$\Delta W_t = (1-x)(\mu_s W_t + J - C P_t)\Delta T + \sigma_s W_t \Delta B_t^{(s)}, \tag{1}$$

where the following notation and assumptions have been introduced: (i) W_t is the agent's financial wealth at time t, (ii) $\mu_s > 0$, $\sigma_s > 0$, and $\Delta B_t^{(s)} \sim \mathrm{Norm}(0, \sqrt{\Delta T})$ are the drift, volatility and random innovations respectively of the agent's portfolio, (iii) $J > 0$ is the flow of labour income, (iv) $0 < x < 1$ is the fixed share of disposable income spent on non heating-energy goods at each time step, (v) $C > 0$ is heating-energy consumption, and (vi) $P_t > 0$ is the price of the heating-energy carrier, which is assumed to follow a geometric random walk,

$$\Delta P_t = \mu_p P_t \Delta T + \sigma_p P_t \Delta B_t^{(p)}, \tag{2}$$

where $\mu_p > 0$ is the drift, $\sigma_p > 0$ the volatility, and $\Delta B_t^{(p)} \sim \mathrm{Norm}(0, \sqrt{\Delta T})$ the random innovations as above. For simplicity, we assume that $B_t^{(s)}$ and $B_t^{(p)}$ are uncorrelated. For brevity, "heating-energy consumption" is shortened to "energy consumption" in the following.

At each $0 \le \tau < N$, the agent has the option to invest some fixed amount K in a retrofit of their dwelling resulting in energy consumption being reduced to some new level $\widetilde{C} < C$. Thus, for a given τ, wealth evolves to the horizon as follows:

$$\Delta W_t = (1-x)(\mu_s W_t + J - C P_t)\Delta T + \sigma_s W_t \Delta B_t^{(s)}, \qquad t = 0, 1, \ldots, \tau - 1, \tag{3}$$

$$W_\tau := W_\tau - K, \qquad (\text{investment at } t = \tau), \tag{4}$$

$$\Delta W_t = (1-x)(\mu_s W_t + J - \widetilde{C} P_t)\Delta T + \sigma_s W_t \Delta B_t^{(s)}, \qquad t = \tau, \tau+1, \ldots, N-1. \tag{5}$$

The agent is required to invest at the horizon, which is denoted by $\tau = N$.

Let $w, p > 0$ be specified initial conditions for the wealth and energy price diffusions, and let $\{W_t^{w,p;\tau} \mid 0 \le t \le N\}$ denote a solution to the system of equations (3)–(5) for a given $0 \le \tau \le N$. The agent wishes to select an investment time which maximises expected wealth at the horizon T, yielding the value function

$$F_0(w, p) := \max_{0 \le \tau \le N} \mathbb{E}\left[W_N^{w,p;\tau}\right] . \tag{6}$$

This is a finite-horizon optimal stopping problem (Peskir and Shiryaev, 2006). It can be solved by a backwards iteration of the Bellman equation:

$$F_t(w, p) = w - K, \qquad t = N, \tag{7}$$

$$F_t(w, p) = \max\left\{ \mathbb{E}\big[\widetilde{W}_{N-t}^{w,p}\big],\ \mathbb{E}\big[F_{t+1}(W_1^{w,p}, P_1^p)\big] \right\}, \qquad t = N-1, N-2, \ldots, 0, \tag{8}$$

where $\widetilde{W}_t^{w,p}$ denotes a solution to

$$\Delta \widetilde{W}_t = (1-x)(\mu_s \widetilde{W}_t + J - \widetilde{C} P_t)\Delta T + \sigma_s \widetilde{W}_t \Delta B_t^{(s)}, \tag{9}$$

$$\widetilde{W}_0 = w - K, \tag{10}$$

i.e. wealth evolution after investment, and $W_1^{w,p}$ (resp. P_1^p) denotes the solution at $t = 1$ of (3) (resp. (2)) with initial conditions $W_0 = w$ and $P_0 = p$. Hence, the first term in the max operator in (8) is the expected value of terminal wealth conditional on immediate investment, and the second the expected value of continuation. For a given t and a wealth-price pair (W_t, P_t), the agent invests only if the option value of waiting, defined as

$$\Omega_t(W_t, P_t) := F_t(W_t, P_t) - \mathbb{E}\big[\widetilde{W}_{N-t}^{w,p}\big] \tag{11}$$

is identically zero; else, waiting is optimal.

Due to the absence of analytical solutions, we solve the system (7)–(8), and consequently (11), numerically, employing the Least Squares Monte Carlo (LSMC) algorithm of Longstaff and Schwartz (2001) to estimate the conditional expectations. In doing so, we obtain a set of exercise boundaries $\{\pi_t(W_t) \mid 0 \le t < N\}$ which define lines in the $W_t - P_t$ plane, indicating for which wealth-price tuples (W_t, P_t) the option value is positive ("continue") versus zero ("invest") at each time step t. As such, the set of exercise boundaries characterises the solution to the agent's decision problem.

Table 2.1
Constants for the case study in Section 2.2. Sources are found in the main text.

Parameter	Description	Value
T	Decision horizon	20 yr
μ_s	Portfolio drift	4.1 % yr^{-1}
σ_s	Portfolio volatility	2.4 % yr^{-1}
J	Labour income	41 k€ yr^{-1}
x	Non-energy consumption (as share of income)	80 %
C	Energy consumption (gas)	30,000 kW h yr^{-1}
K	Retrofit cost	120 k€
$\widetilde{C}$	Post-retrofit energy consumption (gas)	6000 kW h yr^{-1}
μ_p	Gas price drift	2.9 % yr^{-1}
σ_p	Gas price volatility	3.7 % yr^{-1}

2.2. Case study

To illustrate the above ideas, we consider in this section an agent with wealth and dwelling parameters as listed in Table 2.1, using a time resolution of $\Delta T = 1$ yr. The drift and volatility parameters of the portfolio are taken from Radke and Rupprecht (2019).[2] Income J is taken to be the mean for a German homeowner without a mortgage, and the share of non-energy consumption x is estimated from the savings rate of the corresponding income quantile (Bundesbank, 2023; Brenke and Pfannkuche, 2018). Energy consumption C as well as the retrofit cost K and post-retrofit energy consumption $\widetilde{C}$ are taken from a case study in Galvin (2024), where a dwelling representative of German single-family homes built during the period 1969–1978 is retrofitted to a relatively high energy-efficiency standard.[3] The energy price parameters μ_p and σ_p are estimated from the German consumer price index for gas during the period 1991–2023 (Destatis, 2023).[4]

As a warm-up exercise, and to demonstrate some of the features of the investment model, we define $\overline{w} := 140$ k€, being the mean financial wealth of a German homeowner (Bundesbank, 2023), and solve the decision problem (6) at $w = \overline{w}$ and $p = 10$ cent/kWh. Ten thousand scenarios for the development of the gas price were used for the calculation of the stopping times; exemplary scenarios are indicated in Fig. 2.1. Wealth development under optimal investment conditional on these energy-price scenarios as well as scenarios for the portfolio return

[2] Radke and Rupprecht (2019) report average real returns of 2.05 % for German households, to which an inflation assumption of 2 % was added.

[3] The dwelling and energy-efficiency standard are labelled "EFH78" and "EH-70" respectively in the original publication.

[4] Only returns within 3 standard deviations of the mean were used for this estimation.

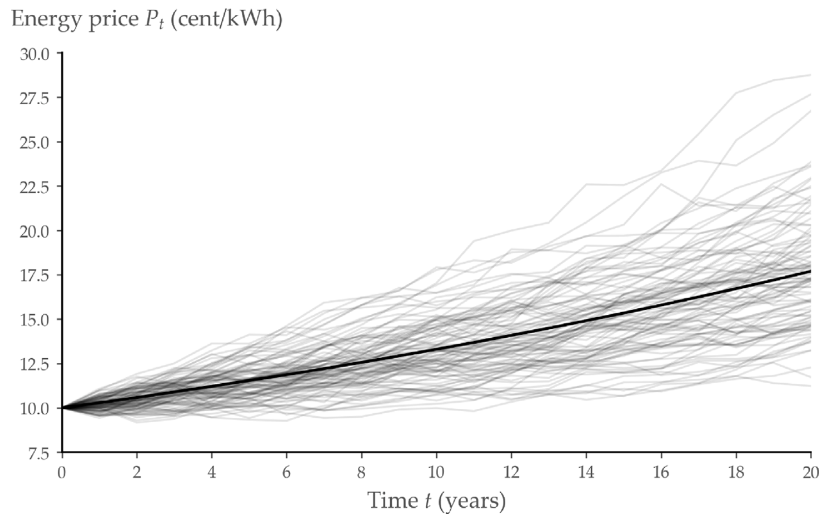

Fig. 2.1. Exemplary scenarios for the development of the gas price. One hundred exemplary scenarios (thin grey lines), as well as the average over all ten thousand scenarios (thick black line) are shown.

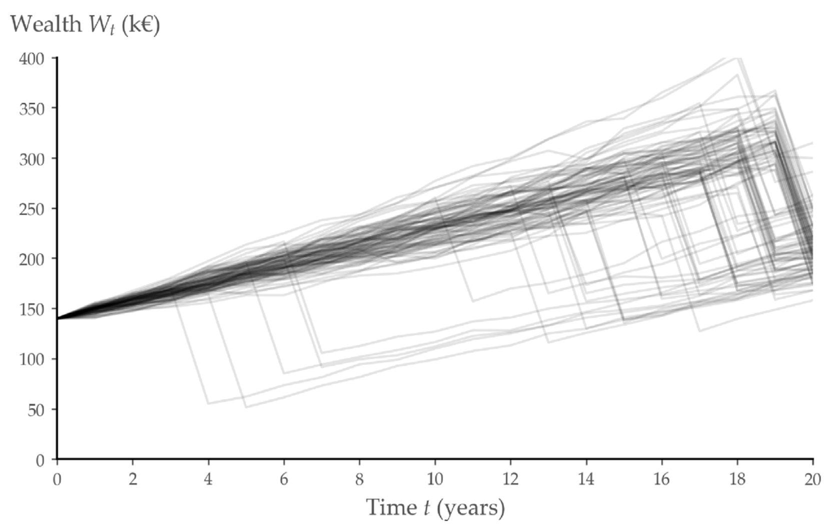

Fig. 2.2. Exemplary optimal stopping conditional on the gas price scenarios from Fig. 2.1 as well as scenarios for the portfolio return. A downward jump in wealth indicates investment in that scenario.

(not shown) is indicated in Fig. 2.2.[5] The stopping times associated to optimal investment in each scenario are best summarised in a frequency plot, as in Fig. 2.3; for comparison, we have also indicated estimated stopping times for initial conditions $p = 1$ cent/kWh and 30 cent/kWh. The agent invests at the horizon in most scenarios for $p = 1$ cent/kWh, invests earlier than this generally for $p = 10$ cent/kWh, and invests immediately in every scenario for $p = 30$ cent/kWh. Evidently, higher initial gas prices lead to scenarios where it is optimal for the agent to invest earlier, which accords with intuition. The dispersion in the frequency plots also makes clear that the option to delay investment can in fact prove extremely valuable.

We now consider the exercise boundaries. Fig. 2.4 plots the estimated option value $\widehat{\Omega}_0(w, p)$ from the LSMC algorithm for a random sample of tuples in the $w - p$ plane, as well as the estimated exercise boundary $\widehat{\pi}_0(w)$. The latter divides the $w - p$ plane into "wait" and "invest" regions, so that for each initial wealth condition w, the agent invests if $p > \widehat{\pi}_0(w)$ and waits otherwise. Hence, $\widehat{\pi}_0(w)$ might be referred to as the ***investment trigger*** at time $t = 0$ for a given wealth level w. For $\overline{w}$, the investment trigger is approximately 24 cent/kWh, which explains why in Fig. 2.3 the agent invests in every scenario for $p = 30$ cent/kWh. For reference, the average gas price for households in Germany in 2023 was 14.8 cent/kWh (Bundesnetzagentur, 2023). A feature of the exercise boundary worth noting is the wealth dependence: *ceteris paribus*, a higher level of initial wealth is associated with a smaller investment trigger. It is possible to obtain some intuition about this fact by keeping in mind that it must result from the interaction between w and p, as well as the relative size of the investment K. All else being equal, a higher w is associated with a higher expected terminal wealth, but also with higher volatility due to the multiplicative effect of the portfolio. A similar multiplicative effect in the dynamic of the energy prices means that a higher p is associated with higher and more volatile expected energy costs at the horizon. Since investment is mandatory at the

[5] It is interesting to note that wealth does not appear to grow at a greater rate after the retrofit investment, indicating that the investment does not necessarily leave the agent better off in the long run. Ultimately, this has to do with two core assumptions of the model: (i) the finite time horizon, and (ii) forced investment at the horizon. Within this setup, investment generally appears to be detrimental to the agent, who might have been better off investing much later than the horizon that we consider or perhaps not at all. Investigating these alternatives requires dropping assumptions (i) and (ii); we make some suggestions in this direction in Section 4.

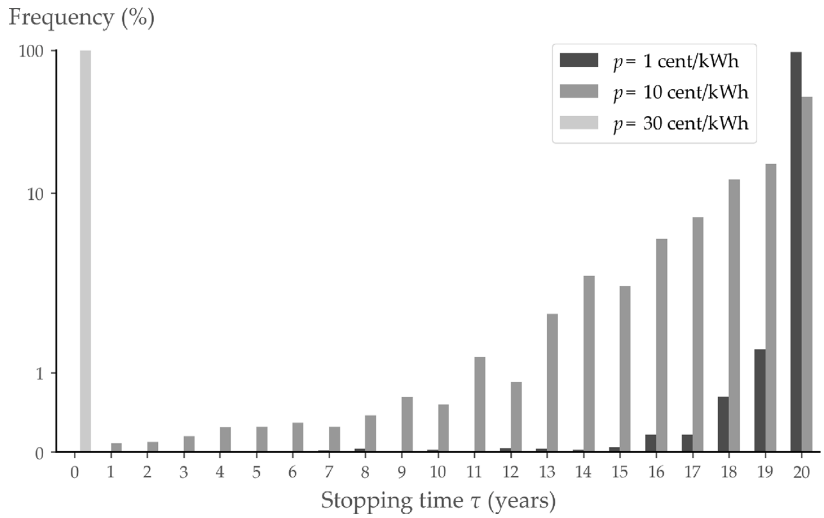

Fig. 2.3. Frequency plots of estimated stopping times for three initial energy prices p over ten thousand scenarios each. The frequency-axis is linearly scaled between 0 and 1, and log scaled between 1 and 100.

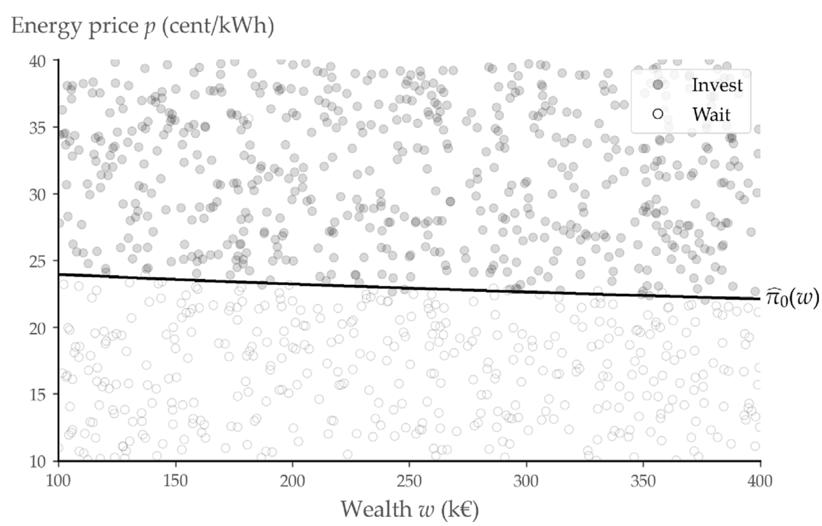

Fig. 2.4. Estimated option value $\widehat{\Omega}_0(w,p)$ and exercise boundary $\widehat{\pi}_0(w)$ for a sample of points in the $w-p$ plane. For a given (w,p), the agent invests if $p > \widehat{\pi}_0(w)$ and waits otherwise.

horizon, the upshot is that wealthier agents, for whom the investment represents a relatively smaller expense, find it optimal to invest at comparatively lower energy prices. This allows them to avoid exposure to larger energy-price spreads and to mitigate the risk of being forced into investments later, when it may be too late to recover from poor portfolio performance and/or high energy prices.

Similar exercise boundaries $\widehat{\pi}_t(w)$ can be estimated for each of the time time steps $0 \leq t < N$, as indicated in Fig. 2.5. Their graphs have a natural ordering, $(W_t, \widehat{\pi}_t(W_t)) < (W_{t+1}, \widehat{\pi}_{t+1}(W_{t+1}))$ for each t, so that as time t approaches the decision horizon T, increasing levels of wealth and energy price are required to trigger an investment. The set of estimated boundaries $\{\widehat{\pi}_t(W_t) \mid 0 \leq t < N\}$ constitutes the numerical solution to the investment problem (6).

2.3. Comparative statics

If one fixes the time resolution ΔT at the outset, the investment model requires ten exogenous parameters to be fully specified. If a parameter is changed, the solution to the decision problem (6) in terms of the set of exercise boundaries also changes. This is in fact already clear in Fig. 2.5, since the estimated exercise boundaries at $t = 0, 5$, and 10 yr correspond exactly to $\widehat{\pi}_0(w)$ were the decision horizon of the problem to be changed to $T = 20, 15$, and 10 yr respectively, keeping all other parameters in Table 2.1 fixed. Hence, a shorter time horizon T requires a relatively higher energy price and wealth level to trigger an investment. Similar results hold for the exercise boundaries $\pi_1, \pi_2, \ldots, \pi_{N-1}$; together, these insights constitute the desired comparative statics analysis for the parameter T.

Nevertheless, since the model does contain ten parameters, rather than qualitatively examining changes in the set of exercise boundaries as each parameter is independently varied, we employ a regression analysis to directly quantify the elasticity of the estimated investment trigger with respect to each parameter. We focus on the investment trigger at $t = 0$, and include wealth w as a predictor in the model. A total of 500 draws were simulated from uniform distributions extending from 80 % to 120 % of the wealth level $\overline{w}$, as well as the parameter values in Table 2.1, and a log–log regression model was fitted with $\widehat{\pi}_0(w)$ as the dependent variable.[6] The results are found in Table 2.2.

[6] The sample size follows from a power analysis where the number of predictors equals 11, the correlation coefficient ρ^2 is set to 0.05, the α error probability is set to 0.05, and the power $1-\beta$ is set to 0.95 (Faul et al., 2009).

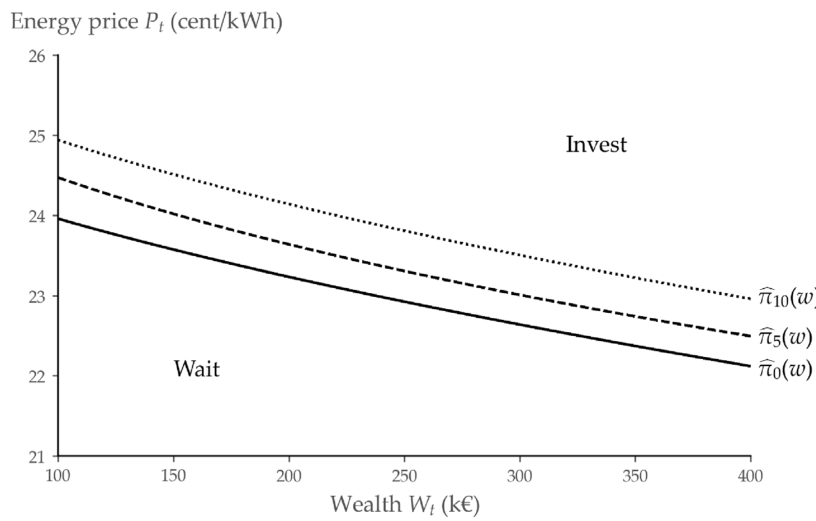

Fig. 2.5. Estimated exercise boundaries for $t = 0, 5$, and 10 yr. For each t and a given W_t, the agent invests if $P_t > \hat{\pi}_t(W_t)$ and waits otherwise.

Table 2.2
Regression results for the comparative statics, with dependent variable $\hat{\pi}_0(w)$. The parameters are sorted in order of descending absolute elasticity.

Parameter	Description	Elasticity	t-statistic
x	Non-energy consumption	1.2713***	13.897
K	Retrofit cost	1.0972***	13.691
C	Energy consumption	−0.9061***	−10.606
μ_s	Portfolio drift	0.7704***	12.933
$\widetilde{C}$	Post-retrofit energy consumption	0.2627***	4.612
J	Labour income	−0.2002**	−2.174
σ_s	Portfolio volatility	0.1467**	2.417
w	Wealth	−0.1453**	−2.129
μ_p	Gas price drift	−0.0658	−1.052
σ_p	Gas price volatility	0.0466	0.522
T	Decision horizon	−0.0027	−0.040
R^2		0.650	

** $p < 0.05$
*** $p < 0.01$

A few remarks are in order. (i) The largest effect on the trigger comes from the wealth parameter x; since $1 - x$ is the saving behaviour of the agent, the conclusion is that the greater the propensity to save, which may be interpreted as increased risk-aversion in this model, the lower the investment trigger. (ii) Retrofit cost K and energy consumption C also have large effects in the expected directions; however, the effect of post-retrofit consumption $\widetilde{C}$ is considerably smaller than that of C. This is due to the fact that the effect of $\widetilde{C}$ is largely dictated by the length of the decision horizon T. (iii) The effect of the agent's portfolio drift μ_s is also large and significant, indicating the importance of the opportunity cost of the retrofit investment. Further, as portfolio volatility σ_s increases, so does the investment trigger; this is due to the increased uncertainty of the retrofit investment being recovered, which occurs not only through reduced expenditure on energy, but also portfolio returns. (iv) Wealth w and labour income J have relatively smaller yet statistically significant effects on the investment trigger: larger levels of wealth and income cause investment in energy-efficiency to be optimal at relatively lower prices, as discussed in Section 2.2. (v) The effects of the energy price parameters μ_p and σ_p, as well as the horizon T, are each in the expected direction but not statistically significant; this is likely because the parameters were only varied within ±20 % of their Table 2.1 values. An interesting implication of this finding is that the investment trigger is robust to minor misspecifications in these parameters, which can be difficult to determine precisely. (vi) For ease of interpretation, we have omitted interaction terms from the analysis; however, given the difference of R^2 from 1, these are likely to have some explanatory power.

2.4. Agent heterogeneity along the dimension of wealth

We now turn to agent heterogeneity, an important theme in the energy-efficiency gap debate. Stated simply, the central idea is that estimates of the energy-efficiency gap often do not sufficiently account for agent heterogeneity, in the sense that an energy-efficiency investment which is profitable for the average agent may not be attractive for all agents (Gillingham and Palmer, 2014). By introducing wealth into the investment decision, our framework opens up new possibilities for modelling agent heterogeneity. To illustrate this, we fix the "physical" parameters of the retrofit, T, C, K, $\widetilde{C}$, μ_p, and σ_p at their Table 2.1 values, generate 500 agents by sampling the parameters w, x, J, μ_s, and σ_s from independent uniform distributions with bounds ±20 % of their Table 2.1 values, and estimate the investment trigger $\hat{\pi}_0(w)$. The resulting kernel density estimate of the distribution of investment triggers is depicted in Fig. 2.6. For comparison to models typically found in the literature, we also depict the distribution of trigger prices obtained by setting the net present value (NPV) of the retrofit investment,

$$\mathrm{NPV}(p) = p(C - \widetilde{C}) \sum_{i=0}^{T} \left(\frac{1 + \mu_p}{1 + \mu_s} \right)^i - K, \tag{12}$$

equal to 0 and solving for p using the same set of parameters.[7] The NPV model distribution displays significantly less heterogeneity than the distribution of the wealth-maximisation model, providing further evidence of the importance of wealth parameters in determining incentive to invest in a retrofit.

More generally, the analysis buttresses the argument for moving beyond the concept of mere "profitability", and towards a notion of "optimality", in the energy-efficiency gap debate. For the sake of comparison, consider that Galvin (2024), using a discounted cash flow analysis, concludes that the case study of Table 2.1 is extremely unprofitable since it does not pay back even over a 75 yr period at current market conditions. While we largely agree with this assessment, the distribution in Fig. 2.6 suggests that at the 2023 gas price of

[7] For ease of comparison with our model, we assume here that the required return is given by the portfolio drift μ_s, and that the NPV is calculated over the decision horizon T. Other choices for these parameters are certainly possible, such as using a subjective discount rate in place of μ_s or considering the technical lifetime of the retrofit instead of T.

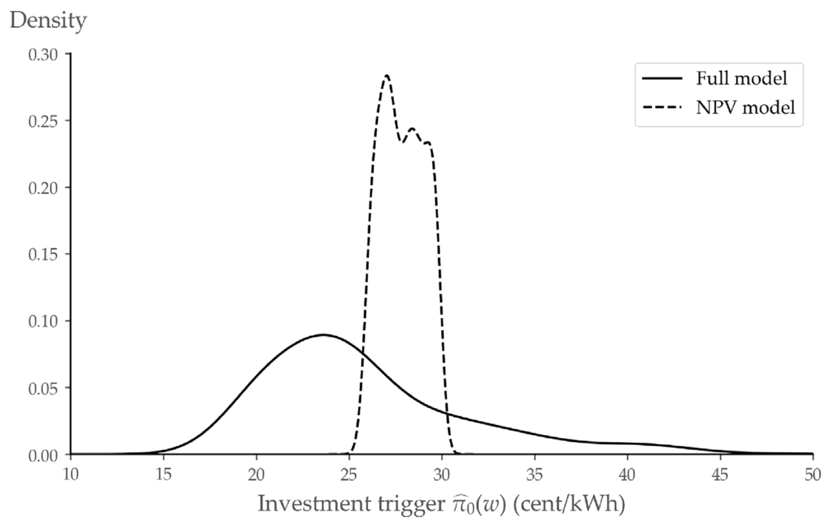

Fig. 2.6. Exemplary distribution of investment triggers across agents with different wealth parameters. For comparison, a distribution of investment triggers from an NPV model is also shown.

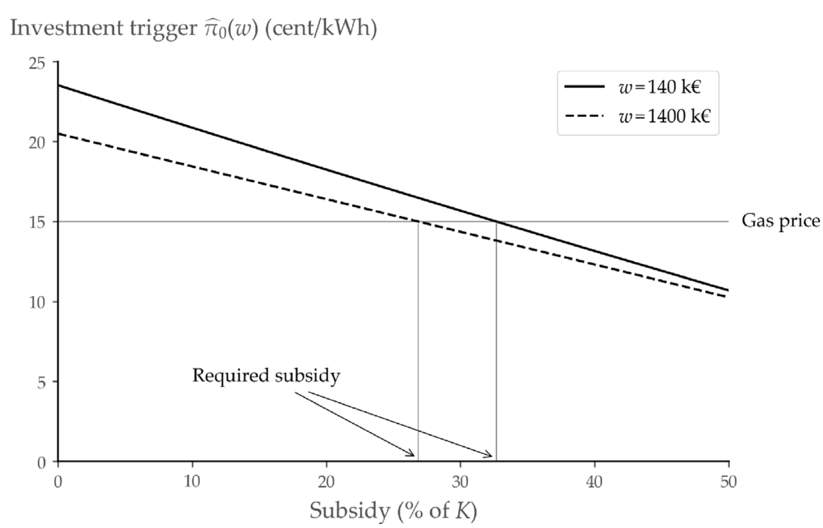

Fig. 2.7. The effect of subsidies on the investment trigger at $t = 0$ for two wealth levels. The potential for free-riding loss is the difference between the two required subsidy levels.

14.8 cent/kWh, there would have been some agents for whom immediate investment would in fact have been optimal. From Table 2.2 we surmise that these are wealthy, high-income, risk-averse agents with low-risk portfolios.

2.5. Retrofit subsidies

We now investigate in more detail retrofit subsidies, modelled here as a lump-sum cash transfer from the social planner to the agent. Fig. 2.7 depicts how the investment trigger of an agent with wealth level $\overline{w}$ and parameters as in Table 2.1 changes depending on the subsidy offered; for the purposes of comparison, an analogous computation was made for an agent with ten times the wealth level $\overline{w}$. And although the subsidy has the intended effect of incentivising both agents to invest at comparatively lower energy prices, the potential for free-riding is quite clear. In particular, at the indicated gas price of 15 cent/kWh, a subsidy of 33 % is appropriate for the wealth level $\overline{w}$, but incurs a free-riding loss in the case of the wealth level $10\,\overline{w}$ of approximately 6 % of K, or 7.2 k€.

A second lesson concerns the importance of economic efficiency in subsidy design. For instance, the social planner's "return" on the 33 % subsidy for the wealth level $\overline{w}$ can be expressed in terms of annual energy savings as 0.61 kWh/€. Keeping all other parameters fixed, if the level of energy consumption is increased to $C = 36{,}000\,\mathrm{kW\,h\,yr^{-1}}$, the subsidy level required to trigger investment decreases to 21 %, and is almost twice as efficient, achieving a return of 1.15 kWh/€. Extrapolating from this example, it is clear that intelligent subsidy design, e.g. targeting agents with relatively large consumption, and/or relatively low marginal costs of retrofitting, can greatly increase the economic efficiency of public spending on retrofit subsidies. Nevertheless, even in this stylised setting, the difficulty of optimising for economic efficiency along multiple dimensions while seeking to avoid free-riding loss is evident; specifically, conflicts between the multiple goals of subsidy design are inevitable. For instance, in Fig. 2.7, the 27 % subsidy to the wealthier agent would be more efficient in terms of energy savings than the 33 % subsidy to the less-wealthy agent, but would have a regressive effect on the wealth distribution.

Table 3.1
Additional constants for the case study in Section 3.2. Sources are found in the main text.

Parameter	Description	Value
C	Energy consumption (gas)	$8900\,\mathrm{kW\,h\,yr^{-1}}$
K	Retrofit cost	30 k€
$\widetilde{C}$	Post-retrofit energy consumption (electricity)	$2700\,\mathrm{kW\,h\,yr^{-1}}$
μ_q	Electricity price drift	$1.8\,\%\,\mathrm{yr}^{-1}$
σ_q	Electricity price volatility	$1.9\,\%\,\mathrm{yr}^{-1}$
ϱ	Correlation gas-electricity returns	0.17

3. An investment model for residential energy-efficiency retrofits including an energy-carrier switch

3.1. The investment model

The model presented in the previous section can be straightforwardly extended to the case where the retrofit option includes an energy carrier switch, e.g. from gas to electricity. Denote the price of the post-retrofit energy carrier by Q_t, and assume that it too follows a geometric random walk

$$\Delta Q_t = \mu_q Q_t \Delta T + \sigma_q Q_t \Delta B_t^{(q)}, \tag{13}$$

where $\mu_q, \sigma_q > 0$ and correlation between P_t and Q_t is allowed so that $\mathbb{E}[\Delta B_t^{(p)} \Delta B_t^{(q)}] = \varrho \Delta T$ for $\varrho \in [-1, 1]$. Then with the agent's wealth dynamic and the rest of the setup as in Section 2.1, given an investment time $0 \le \tau \le T$, wealth evolves to T as follows:

$$\Delta W_t = (1-x)(\mu_s W_t + J - C P_t)\Delta T + \sigma_s W_t \Delta B_t^{(s)}, \qquad t = 0, 1, \dots, \tau - 1, \tag{14}$$

$$W_\tau := W_\tau - K, \qquad \text{(investment at } t = \tau), \tag{15}$$

$$\Delta W_t = (1-x)(\mu_s W_t + J - \widetilde{C} Q_t)\Delta T + \sigma_s W_t \Delta B_t^{(s)}, \qquad t = \tau, \tau+1, \dots, N-1\,. \tag{16}$$

Once again, the agent is required to invest at the horizon T. Consequently, the value function is given by

$$G_0(w, p, q) := \max_{0 \le \tau \le N} \mathbb{E}\left[W_N^{w,p,q;\,\tau}\right] \tag{17}$$

where $\left\{W_t^{w,p,q;\,\tau}, 0 \le t \le N\right\}$ denotes a solution to (14)–(16) for given initial conditions $w, p, q > 0$ and a given investment time τ. The definition of the option value of waiting and the method of solution are analogous to those in the previous model.

3.2. Case study

We consider in this section an agent with dwelling parameters as in Table 3.1. The retrofit parameters are taken from a case study in Galvin (2024), where a dwelling representative of German multi-apartment buildings built during the period 1969–1978 is retrofitted to accommodate a heat pump.[8] The energy price parameters μ_q, σ_p, and ϱ are estimated from the German consumer price index for electricity and gas during the period 1991–2023 (Destatis, 2023).[9] The remaining parameters are taken from Table 2.1.

Since the decision problem (17) contains three state variables, p, q, and w, we simplify the presentation and decision criterion for the agent by solving for the option value and exercise boundary in terms of the ratio of energy prices, p/q. Fig. 3.1 plots data points from the LSMC estimation of the option value $\widehat{\Omega}_0(w, p/q)$, as well as the estimated exercise boundary $\widehat{\pi}_0(w)$. As in the previous case, the boundary divides the $w - (p/q)$ plane into "wait" and "invest" regions, and is decreasing in wealth. For $\overline{w}$, the investment trigger is approximately $p/q = 0.98$, significantly higher than the average ratio of 0.33 seen by German households in 2023 (Bundesnetzagentur, 2023). Similarly to the previous case, exercise boundaries $\widehat{\pi}_t$ can be estimated for each of the time steps $0 \le t < N$, and here too the ordering $(W_t, \widehat{\pi}_t(W_t)) \le (W_{t+1}, \widehat{\pi}_{t+1}(W_{t+1}))$ is observed.

With regards to the comparative statics of the model, the analogue of Table 2.2 is omitted since the results and conclusions are similar to the previous case. However, a parameter of particular interest in the case of a switch from gas to electric heating is the correlation coefficient ϱ. Indeed, as electricity markets undergo a transition from conventional to renewable generation, the role of natural gas in setting electricity prices continues to increase, meaning that ϱ is likely to increase as well (Zakeri et al., 2023). Fig. 3.2 provides evidence that a larger ϱ causes the investment-trigger ratio to move upwards, meaning that for a fixed gas price p, a relatively cheaper electricity price q is required to trigger investment. The driving mechanism is likely to be the loss of the opportunity for diversification due to the increased correlation between the energy prices. Nevertheless, it must be noted that the effect is small in absolute size.

4. Conclusions

In this article, we have studied incentive to adopt residential retrofits by proposing a model of optimal investment under uncertainty. The model is built around the agent's wealth dynamic and includes stochastic portfolio returns and energy prices, as well as the option to delay investment. With the help of case studies and comparative statics, we demonstrated the economic reasonableness of the resulting decision criteria, and quantified the effects of wealth and other model parameters on the decision to retrofit.

The case studies, which are representative of large cohorts of German residential buildings, indicate that retrofit investments are largely unattractive at present: for retrofits of gas-heated dwellings where the energy carrier is not switched, current gas prices lie well below levels required to trigger investment; similarly, for retrofits where the energy carrier is switched from gas to electricity, the present ratio of gas to electricity prices is significantly lower than required investment thresholds. Future research might focus on extending this work to other energy carriers, wealth quantiles, and cohorts of typical buildings in order to widen investigations into the claim that agents are "leaving money on the table" by not investing in energy efficiency measures. We do not believe this to be the case, but more work, especially in data-gathering through high-quality retrofit case studies, is required to substantiate this hypothesis.

The savings behaviour and portfolio parameters of the household were seen to have large effects on the investment trigger, with increasing savings, decreasing opportunity costs, and decreasing portfolio volatility each leading to retrofits being optimal at relatively lower energy prices. The latter finding in particular contrasts strongly with the idea that retrofits represent an alternative investment to the agent's portfolio; in fact, the analysis demonstrates that the context of the agent's wealth dynamic is of signal importance, since the retrofit investment is recovered through the interaction of the reduced energy consumption and the agent's portfolio returns. An implication of this finding is that interest in retrofits is likely to wane during periods of low returns and/or high volatility.

As regards agent heterogeneity, the introduction of wealth parameters into the discussion opens up new directions for mapping retrofit incentive and evaluating policy. Our analysis, though stylised, demonstrates that incentive to retrofit is extremely heterogeneous along dimensions of wealth such as income, and expected portfolio return. Future work could focus on modelling more explicitly the dependence

[8] The dwelling, labelled "GMFH78" in the original publication, consists of 42 apartments. We consider a single owner-occupied apartment, assuming that the reported costs are shared equally between the units. The difference in costs to the case study in Section 2.2 is striking evidence of economies of scale in retrofitting.

[9] Again, only returns within 3 standard deviations of the mean were used for the estimation. Spearman's ρ was used as a measure of correlation between the gas and electricity price returns.

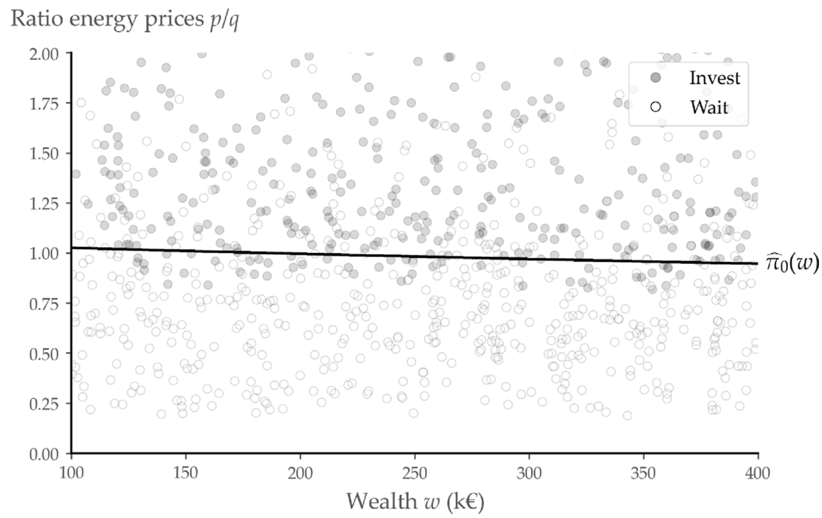

Fig. 3.1. Estimated exercise boundary at $t = 0$. For a given (w, p, q), the agent invests if $p/q > \widehat{\pi}_0(w)$, and waits otherwise.

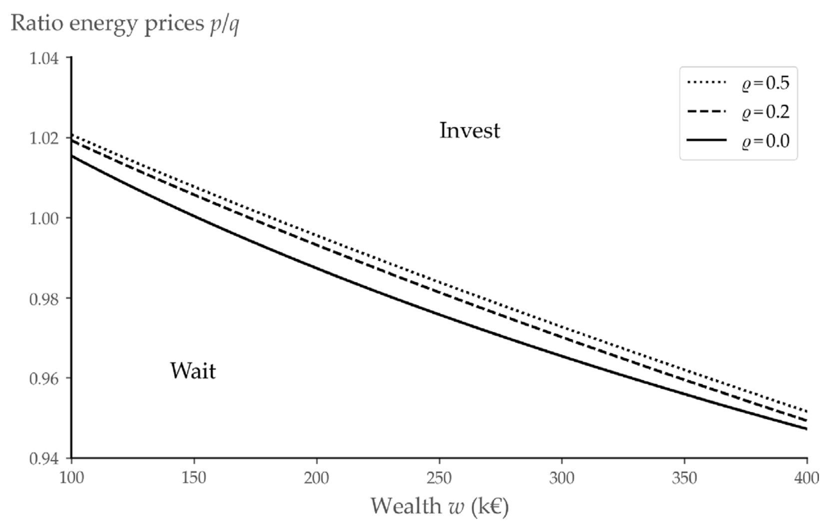

Fig. 3.2. Estimated exercise boundaries at $t = 0$ for three levels of gas-electricity price correlation ϱ.

of the investment trigger on the agent's wealth quantile, which correlates strongly with savings behaviour, income, portfolio returns, and energy consumption (Bundesbank, 2023; Bach et al., 2020; Karatasou and Santamouris, 2019; Brenke and Pfannkuche, 2018). We mention in this context the need for additional empirical work on the interaction between wealth parameters and the building stock. Such research is also likely to lead to fruitful connections to the literature on energy poverty and sufficiency.

Our analysis of energy subsidy programs highlighted the mechanisms that lead to free-riding, the importance of economic efficiency in subsidy-program design, and the subsequent difficulty of appropriately tailoring such subsidies. Taken together, these points underscore the known general principle that subsidies are a second-best corrective for externalities arising from energy consumption (Allcott and Greenstone, 2012). That said, we offer the concrete policy suggestion that subsidy programs be routinely adjusted to take into account changing energy prices and market conditions. For instance, the recent surge in energy prices triggered by the war in Ukraine caused a run on German government subsidies for energy-efficiency, and the earmarked funds were exhausted in a single day (Meza and Wettengel, 2022); it would have been appropriate in this case to roll back subsidies in response to the shocks in energy prices. A second policy proposal concerns a renewed commitment to economic-efficiency in subsidy programs, e.g. by focusing on agents with relatively lower marginal costs of retrofitting, cf. Galvin (2023).[10] More generally, future investigations into optimal subsidy design as a welfare-maximisation problem based on a framework similar to ours could prove highly fruitful in uncovering ways to make subsidy programs more progressive.

Broadly speaking, we attempted to make the case that when it comes to analysing decision making in the realm of energy-efficiency investments, much can be learned by moving from "profitability" thinking to "optimality" thinking. This approach may be extended in several directions. Firstly, we considered a risk-neutral wealth-maximising agent in order to situate this work within the literature on energy-efficiency investment profitability. However, a more classical economic treatment would consider a utility-maximising agent instead, with risk-aversion being introduced via the utility function. Further, instead of fixing the agent's non-energy and energy consumption, it would be appropriate to model these as controls, thus setting up the problem as one of optimal consumption and investment under uncertainty. In this context, dropping the finite investment horizon imposed in this

[10] Some steps in this direction have been taken in Germany by recent subsidy policy aimed at the "worst-performing" buildings (KfW, 2022).

work would yield new insights into optimal behaviour vis-à-vis long-run utility maximisation. Additional uncertainty, e.g. in labour income, in retrofit cost etc. might also be considered. However the analyst, who must in any case strike a balance between complexity and interpretability, will quickly be confronted with the "curse of dimensionality", should too many sources of uncertainty be introduced. This was one reason for excluding a carbon tax from consideration in this article, the other being that an analysis of the welfare effects of a carbon tax requires a setup with demand controls and multiple agents. We leave this to future work.

CRediT authorship contribution statement

Anthony Britto: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Joris Dehler-Holland:** Writing – review & editing, Validation, Supervision. **Wolf Fichtner:** Writing – review & editing, Supervision.

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.

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