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Optimal Investment in Energy Efficiency as a Problem of Growth-Rate Maximisation: Evidence and Policy Implications

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Abstract

Following recent developments in economic and finance theory, we formulated in a recent article the question of when and how much a consumer might optimally invest in energy efficiency as a problem of wealth-growth-rate maximisation, subject to the diminishing marginal utility of retrofitting. In this contribution, we scale up this framework to unique dataset combining the top three wealth quantiles in Germany and nine generations of single and terraced homes in Germany; this represents around 21% of the total building stock. We calculate the share of dwellings over time whose consumers see incentive to retrofit. We are able to reproduce (i) the dynamic in the uptake of government subsidies, (ii) the tendency of consumers to wait out the lifetime of their current heating system, (iii) the slow diffusion of new heaters, and (iv) the tendency of consumers to shun deep retrofits. We additionally uncover new wealth effects, most notably the tendency of richer consumers whose wealth growth faster to retrofit less, and when they do, to retrofit to shallower depths.

We also compute the effects of the German government's retrofit subsidy schemes, and the proposed carbon tax on heating, employing a counterfactual approach. We discover that wealthier consumers are in general harder to influence via policies. Tracking the effects of policies along several dimensions, among other wealth and policy effects, we show that the tax and subsidy schemes have effects of comparable sizes, but that their effect when combined is greater than the sum of their individual contributions.

All of this has implications for policymakers: the broad conclusion of our work is that household wealth, diminishing marginal utility, and stochasticity in fuel prices can largely explain the diffusion of energy-efficiency measures. Our consequent policy recommendations include a widening of the subsidy base through a reduction or elimination of minimum investment requirements and a redefinition of the relevant thermal standards, increased subsidies for gas "renewable ready" heaters to encourage a step-wise transition towards electricity, and a push for the government itself to become a major player in the renovation market.

Introduction

The energy-efficiency gap is commonly understood as the suggestion that the way individuals make decisions about investing in energy efficiency leads to a slower-than-optimal diffusion of conservation technology. Despite decades of debate in the academic literature (Gerarden, Newell, & Stavins, 2017), there seems to be no concensus on either the existence or size of the gap. In a recent article, we contributed to the theoretical underpinnings of this debate by proposing a decision-making procedure for optimal investment in energy efficiency (Britto, Dehler-Holland, & Fichtner, 2021). We focused on energetic retrofits, and detailed a model which provided a definitive answer to a surprisingly non-trivial question: "When and how much should a risk-neutral consumer invest in energy-efficiency measure for their dwelling?"

Although renovation rates in the EU measured as a share of the total building stock are low (Esser, Dunne, Meeusen, Quaschning, & Wegge, 2019), this fact on its own does not constitute evidence for an energy-efficiency gap: an additional defintion of optimal consumer behaviour is required. In the literature, the dominant approach by far is the discounted-cash-flow analysis. In Britto et al. (2021), we presented an alternative model, based on the novel approach of ergodicity economics, and the fundamental economic and physical reality of diminishing marginal utility in retrofitting. A key difference between these approaches is the following: the discounted-cash-flow method cannot model the consumer's degree of freedom to simply put off an energy-efficiency investment to a later date. It is our contention that being able to quantify this aspect of the decision is crucial to understanding the energy-efficiency gap, which is at heart a *dynamic* process of technological diffusion.

To the best of our knoweldge, our investment model is the first to analytically incorporate the consumer's wealth dynamic and wealth parameters. We showed in the original article that wealthier consumers appear to have smaller incentive than less well-off consumers to invest in energy-efficiency; further theoretical results indicated that wealthier consumers were harder to influence via policies than consumers who were less well-off. In this article, we explore the macro effects of these micro decisions: what overall pattern of retrofit investment emerges from the distribution of wealth, and make-up of the building stock? how do policies such as subsidies and carbon taxes change the retrofit incentive structure between quantiles (i.e. poorer and richer consumers), and within quantiles (i.e. between faster and slower growth-rates for the same level of wealth)?

These questions were considered in a representative-agent model of a sizeable subset of the German building stock: we considered the first nine generations of single and terraced homes in Germany, and the top three wealth quantiles; 21% of the total building stock, altogether told. The effects of varying the growth-rate of wealth were explored through scenarios.

The article proceeds as follows: in order to set the baseline for the discussion, we begin in the next section by presenting some stylised facts of energy-efficiency investment in Germany; in the section following, we present our methodology; this is followed by the results of the simulations, and a final discussion on the implications for policy and topics for further research.

Stylised Facts of Energy-Efficiency Investment in Germany

Given what we have said about energy-efficiency diffusion being a dynamic process, it is important to ask what some indicators of this multi-faceted phenomenon might be. However, due to the severe lack of detailed data on renovations in the EU, we must cull together a narrative from various sources. In the following paragraphs, we detail four important features of energy-efficiency investment in Germany.

SF1. (Stylised Fact 1.) According to the comprehensive study of Esser et al. (2019) on renovation activities in the EU, although deep retrofits are taken up annually in only a tiny share of the building stock (0.2%), the same is not true of below-threshold, light, and medium retrofits (7.1%, 3.9% and 1.1% respectively). This pattern is present across all the member states of the EU; the particular numbers for Germany in the period 2012 – 2016 are a 9.8% annual retrofit rate, with 5.4% of these being investments in below-threshold energy-efficiency measures($<$ 3% final energy savings), 3.5% being in light measures (between 3 and 30% savings) , 0.9% in medium retrofits (between 30 and 60% savings), and only 0.1% in deep retrofits ($>$ 60% savings). This then, is our first stylised fact: consumers invest far more in below-threshold retrofits and light retrofits than they do in medium and deep retrofits; moreover, the overall rate of retrofitting is much higher than the often-cited 1% (Galvin & Sunikka-Blank, 2013). Note that this fact in itself is already motivation for an incorporation of diminishing marginal utility in investment models.

SF2. We alluded in the introduction to the dynamic aspect of energy-efficiency diffusion often being lost in the debate around the gap; one source that allows us to definitively highlight this reality is to look at the uptake of government subsidies for retrofits; **Error! Reference source not found.** shows the total subsidies handed out by the government for retrofitting activities via its development bank, the KfW. While it is true that the subsidy program has changed over time, most notably by extending support to individual retrofit measures beginning in 2009, the graphic makes clear that there is a substantial variation in annual retrofit uptake. This dynamic variation is an essential feature of energy-efficiency investment that requires explaining. Indeed, the renovation rates cited in *SF1* were documented by Esser et al. during the period 2012 – 2016, which was a period of heightened activity in the renovation sector as compared to the early 2000's, say. If this meaningful annual variation in these rates is not acknowledged, an incomplete picture of renovation activity results.

SF3. The literature on energy-efficiency investments is full of references to "anyway" investments and costs, i.e. additional costs (such a scaffolding, or repainting) that are not part of the energy-efficiency measures themselves, but which nevertheless play an important part in the consumer's decision to undertake a retrofit (Galvin R. , 2014). A consequence of this is that German homeowners are known to wait out the lifetime of their equipment, and simply add-on an energy-efficiency upgrade when the equipment is due for renovation "anyway"; cf. the age distribution of the heating systems in BDEW (2019). While this is certainly a relatable

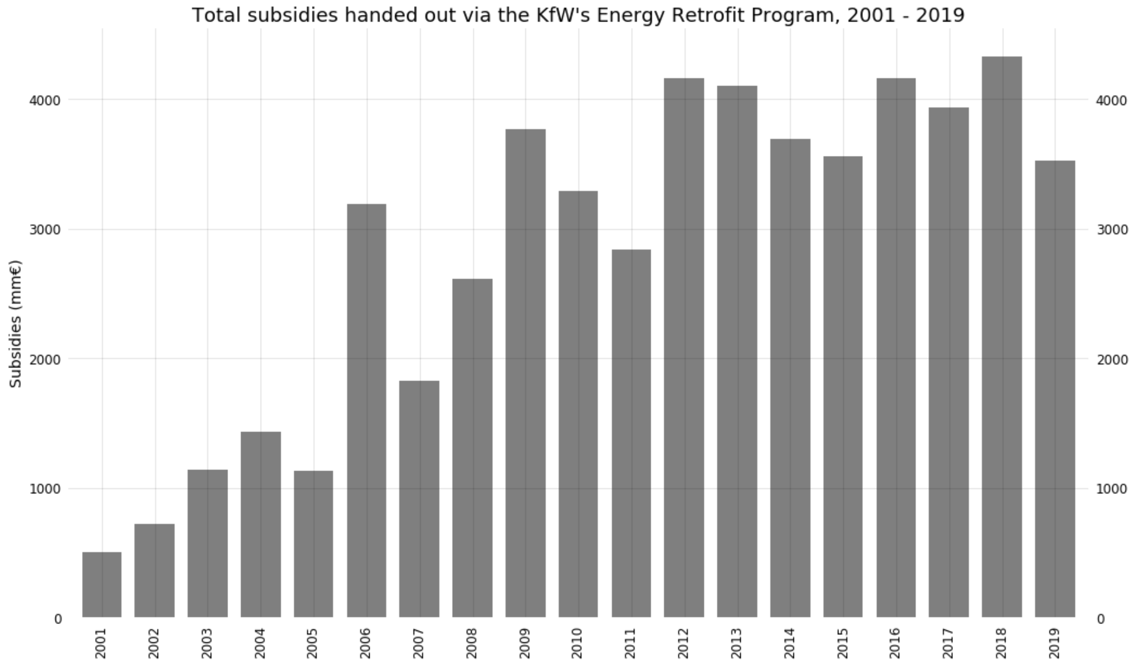

Figure 1. German government spending on retrofit subsidies from 2001 to 2019. Authors' illustration, data from Statista (2020).

investment decision, we wished to know, quite apart from questions of convenience, if this was the economically prudent thing to do.

SF4. Regarding upgrades of the heating systems themselves, the data indicates that not much movement has taken place in terms of switching energy carriers. For instance, analysis by the BDEW (2019) shows (i) that in the 10 years from 2009 to 2019, only around 440k heating systems were upgraded out of a total of almost 19 million (ca. 0.23% p.a.), and (ii) that within this subset of heaters that were renovated, gas was by far the most attractive carrier, with 63% of those consumers who heat with oil, and 20% of those who heat with electricity choosing to move to a gas-fired system. Additionally, despite generous subsidies, 24% of consumers who heat with oil chose to stay with oil. Now it is clear that there is some overlap between point (i) and two of the stylised facts above, namely, that consumers appear to undertake only small retrofits (SF1), and further, that they mostly upgrade when they have to "anyway" (SF3); nevertheless, we wished to understand if there were economic reasons for the extremely low (compared to the retrofit rates listed in *SF1*) turnover rate of heating systems, and for the strong preference for gas as an energy carrier in the event of a upgrade.

Methodology

The investment model

We briefly sketch here the ideas presented in Britto et al. (2021); the interested reader is referred to the original article for the details.

Firstly, we assumed that the consumer carries out retrofits "anyway" in cycles of L years (e.g. 25 years); this can be understood to be the average lifetime of energy-efficiency measures. Secondly, we mathematically formulated the reality of diminishing marginal utility in retrofitting by assuming that the final energy saved $s(\mathrm{kWh/m^2 yr})$ is a function of the investment in energy-efficiency measures $k(€/\mathrm{m}^2)$ of the form

$$s(k) = s_1 k - s_2 k^2 ,$$

where $s_1 > s_2$. This function turns out to have the properties required of diminishing marginal utility (positive first derivative and negative second derivative), so long as k is limited to a maximum possible investment $k_m = s_1/2s_2$, with corresponding maximum possible final energy savings s_m.

In order to introduce a stochastic element into the analysis, we assumed that the price of the energy carrier p_t follows a geometric Brownian motion with trend μ and variance σ:

$$\mathrm{d}p_t/p_t = \mu\,\mathrm{d}t + \sigma\,\mathrm{d}z_t ,$$

where z_t is a standard Wiener process (cf. Hassett & Metcalf, 1992). The *time-average* growth of this Brownian motion turns out to not be the simple trend μ, but rather $\mu - \sigma^2/2 =: \nu$; according to ergodicity economics, it is this trend that is relevant for the consumer's decision. More generally, the decision axiom of ergodicity economics can be stated as follows: *the consumer acts so as to maximise the time-average growth rate of their* *wealth under the specified wealth dynamic*. As such, the axiom requires the specification of a wealth dynamic, which is the final element of our framework.

A wealth dynamic is simply a model of how wealth grows. The two fundamental examples are the additive dynamic, where the consumer earns a fixed income, and the multiplicative dynamic, where wealth grows at some fixed rate. Given a wealth dynamic, one is able to identify a canonical growth rate of wealth and corresponding utility function; these would be income and a linear utility function in the additive case, and force of interest and a logarithmic utility function in the multiplicative. This is perhaps easier to see in equations; in the case of the multiplicative dynamic, where wealth grows exponentially at rate δ, the dynamic is given by

$$w(t+\Delta t) = w(t)\exp[\delta \Delta t]\,.$$

The aforementioned growth rate and logarithmic utility function can then be directly read off the following equation, which is a simple rearrangement of the preceding one:

$$\delta = \frac{1}{\Delta t}\log\frac{w(t+\Delta t)}{w(t)}\,.$$

Given these ideas, the connection to our topic of interest, investments in energy-efficiency is the following: the consumer invests in energy efficiency because energy costs are a “drag” on the growth rate of wealth. Mathematically, the growth rate function g can be written as a function of retrofit investment k and time of investment t as follows:

$$g(k,t) = \frac{1}{L+t}\log\Bigg[\exp[\delta(L+t)] - \frac{a}{w_0}\Bigg(\underbrace{p_0\frac{u}{\eta}\frac{e^{\delta L}\left(e^{\delta t}-e^{\nu t}\right)}{\delta-\nu}}_{\substack{\text{net discounted pre-retrofit}\\ \text{energy expenses}}} + \underbrace{(k+h)e^{\delta L}}_{\text{investment}} + \underbrace{q_0\frac{u-s\left(ke^{\delta L}\right)}{\zeta}\frac{e^{\alpha t}\left(e^{\delta L}-e^{\nu L}\right)}{\delta-\alpha}}_{\substack{\text{net discounted post-retrofit}\\ \text{energy expenses}}}\Bigg)\Bigg].$$

Despite its unwieldy appearance, the function has very simple structure: from the usual growth rate δ, we simply subtract the annualised net discounted total energy expenses, plus the retrofit investment itself. From left to right, the new notation we have introduced is the heated floor-area a (m^2), the consumer’s starting wealth w_0(€), the starting fuel price p_0(€/kWh), the final-energy need u ($\mathrm{kWh/m^2yr}$), the efficiency of the current heater η, the normalised cost of the new heater h(€/m^2), the price of the new energy carrier q_0(€/kWh) with corresponding effective trend α, and finally, the efficiency of the new heater ζ. By maximising this growth-rate function, the consumer locates an optimal $(k^\star, t^\star) \in [0, k_m] \times [0, L]$; this is the direct answer to the question of “how much and when” she optimally invests in energy efficiency. Notice, crucially, that this solution will depend on the consumer’s wealth parameters w_0 and δ.

This investment model allows the consumer to compare between possible future energy carriers by simply rank-ordering the maximised growth rates for the different possible options of the set $\{h, \zeta, q_0, \alpha\}$, and selecting the option that leads to the highest growth-rate of wealth (each possibility of heater-upgrade comes with its own cost h and corresponding efficiency ζ, and price parameters q_0 and α).

Developing the diffusion model

The model described in the previous section was scaled up to the building stock as follows. Firstly, with the help of a free-to-use renovation calculator, the diminishing marginal utility function parameters s_1 and s_2 were determined for generations two through nine (construction years 1860 – 2001) of representative single-family and terraced homes in the TABULA database (Loga, Stein, & Diefenbach, 2016).[1] The calculator generated possible constellations of renovation measures for each representative dwelling; these were then fit to a function of the form $s(k)$ in order to determine the constants s_1 and s_2. In fact, since s_1 has units $(\mathrm{kWh/m^2yr})$ /€, i.e. the number of units of final energy saved per euro invested, it is of some interest to know that the mean value over the 27 types of dwellings we considered was 0.51, with a standard deviation of 0.23. Unsurprisingly, the German building stock exhibits significant heterogeneity in this regard.

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[1] The renovation calculator was developed by Bosch Thermotechnik and Fraunhofer IBP, and is available at <https://application.effizienzhaus-online.de/sanierungsrechner/> (last accessed 18.03.21).

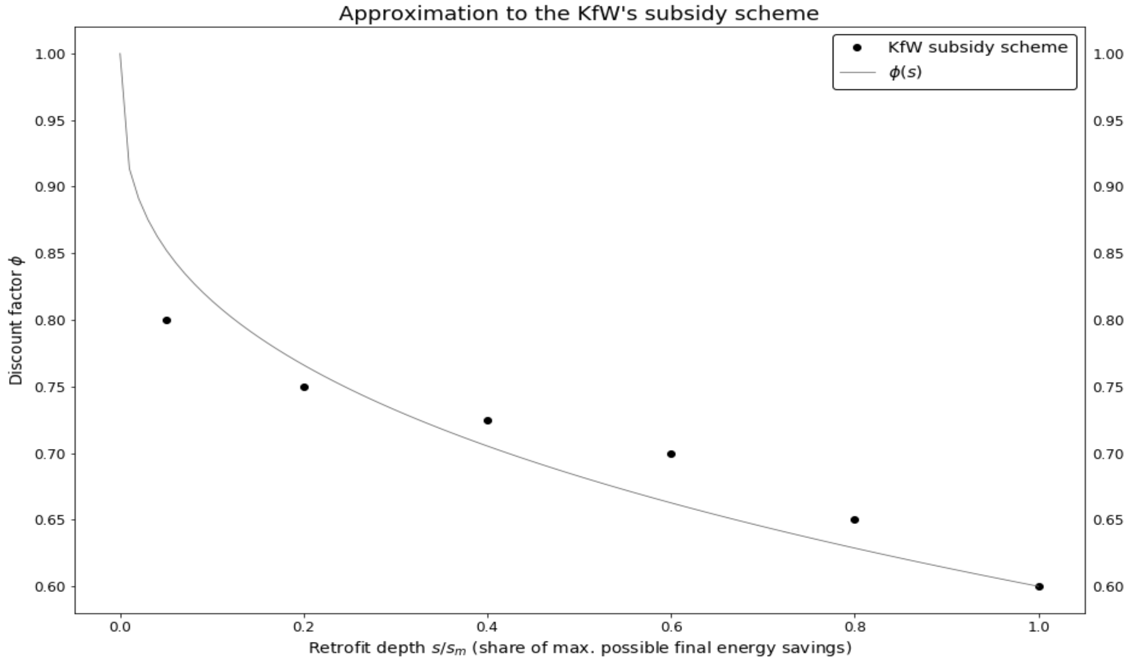

Figure 2. Depicted here is the approximation to the KfW's subsidy scheme (KfW, 2020) that we employed in our simulations.

Data on the efficiency of the heater systems η and ζ and the corresponding cost of heater upgrade h was similarly obtained through TABULA and the renovation calculator.

The wealth parameter w_0 was taken from Bundesbank data (Deutsche Bundesbank, 2019). In this article, we restrict ourselves to multiplicative wealth, since it is a prototypical example of our framework, and readily comparable to other results in the literature due to the shared form of the exponential discounting function. Multiplicative growth is clearly an approximation to the type of wealth experienced by richer consumers; as such, we restricted ourselves to the top three wealth quantiles in Germany, covering 40% of the population. Median wealth in these quantiles is €215,400, €428,400 and €861,600 respectively. We were unable to locate data on the growth-rate of wealth in these scenarios, and hence considered scenarios of 2.5, 3, and 5% for the growth parameter δ. Finally, as there was also no data available concerning which wealth quantile owned which type of dwelling, we simply assumed that these were distributed among the dwellings according to the size of the respective quantile.

The fuel price parameters were readily calculated from data from the Federal Ministry of Economics and Technology (BMWi, 2019). Time series of annual prices for the various energy carriers for the years 1991 – 2019 were available; this therefore became the timeframe of our diffusion model. We restricted ourselves to the energy carriers oil and gas, which together account for 70% of Germany's heating market—gas' share is 45%, and oil's 25% (BDEW, 2019). We assumed that this distribution of energy carriers was valid for our representative buildings as well.[2] As for the energy carrier post-retrofit, we allowed homes which heat with oil to either stay with oil or switch to either gas or electricity, whereas homes which heat with gas were allowed to choose between gas and electricity.

These assumptions taken together sufficed to generate a picture of total retrofit potential, i.e. an estimate of the share of the total building stock for which an energy retrofit made economic sense, in each of the three δ-scenarios. This is however only the first object of interest: the results of the simulation also contained information on differences between and within wealth quantiles, incentive to undertake retrofits of varying depths, the economic viability of heater upgrades, and the choice of energy carriers. In addition to being a baseline for the energy-efficiency gap, these metrics served as a baseline with respect to which the effectiveness of policy instruments could be measured.

Modelling subsidy and carbon tax schemes

The main policy levers at the social planner's disposal for generating incentive to invest in energy efficiency are subsidies for energetic retrofitting, and a tax on carbon generated due to heating. We found it instructive to employ a counterfactual approach in order to study the effects of these policies, i.e. we applied them *ex post* to the time frame 1991 – 2019. This allowed us to avoid having to multiply the number of assumptions in our

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[2] This in fact means that the database we considered corresponds to $0.7 \times 0.75 \times 0.4 = 21\%$ of the German building stock.

model, thereby enabling us to simply extract the main features of the effects of these policy instruments. While the aggregate quantity of interest here is no doubt the excess retrofit potential generated due to these policies, their effects could be additionally tracked along several other dimensions, as we shall see in the next section.

As of 2021, there is a carbon tax on heating and transportation in Germany, which has been implemented as follows: the starting fixed price of $25\ €/\mathrm{tCO2}$ for 2021 will be increased by $10\ €/\mathrm{tCO2}$ each year until 2026, after which it will likely be traded in a price corridor of $55 - 65\ €/\mathrm{tCO2}$ (Wettengel, 2020). For the counterfactual narrative therefore, we simply added this proposed carbon tax to the prices of oil and gas from 1991 – 2019, with emission factors taken from (Koffi, et al., 2017). For the price-corridor phase of the carbon tax, we assumed that the upward trend in the price of carbon was equal to the mean of the trends of oil and gas prices; since both of these increase quite slowly, the price of carbon ends up at around $70\ €/\mathrm{tCO2}$ in 2019. This corresponds to a surcharge of $2.1\ €\mathrm{cents/kWh}$, or a 35% increase over base price for oil, and $1.7\ €\mathrm{cents/kWh}$, or a 26% increase over the base price for gas in that year.

Due to its divers programs and energy standards, the KfW's subsidy scheme (KfW, 2020) is quite complex, and modelling its intricacies is beyond the scope of this article. Noting that the program subsidises individual energy-efficiency measures for up to 20% of their total costs, with coverage extending to a maximum of 40% for deep-retrofit measures, we approximated the subsidy scheme by a discount factor of the form

$$\phi(s) = 1 - \frac{4}{10}\left(\frac{s}{s_m}\right)^{1/3};$$

we remind the reader that s is the final-energy savings resulting from the investment k, with s_m is the maximum savings possible; the discount factor ϕ with range $[1, 0.4]$ then multiplies the investment k to yield the subsidised investment; see Figure 2. While this model captures the main effects of the KfW scheme, it is more generous in at least two respects: firstly, it applies discounts even for small, "below threshold" retrofits, which the KfW currently does not subsidise, and second, it does not take into account the stringent *Energieeffizienzhaus* thermal standard employed by the KfW, being based instead on each dwelling's maximum possible energy savings according to the TABULA data and the renovation calculator. The German Federal Office of Economics and Export Control additionally offers steep discounts ($20 - 45\%$ depending on the situation) on heating system upgrades, which we directly implemented in the model (BAFA, 2021). Both the retrofit and heating-system subsidy schemes were applied throughout the 1991 – 2019 timeframe in the scenario where we considered this policy.

With these assumptions in hand, we quantified the effects of the subsidy and the carbon tax, separately and in tandem, by comparing the resulting retrofit potentials to the baseline scenario, where these policies were not implemented.

Results

Baselining the energy-efficiency gap

In **Error! Reference source not found.**, we depict the premier aggregate quantity of interest: the share of the total building stock with economic incentive to retrofit in each of the three wealth growth-rate scenarios. There are several aspects to unpack here, the most important of which is undoubtedly the following: the faster the consumer's wealth grows, the less incentive there is to retrofit. Indeed, the differences between the δ-scenarios are quite drastic, and it is clear that retrofit incentive vanishes completely if wealth grows fast enough. Even in the $\delta = 2.5\%$ scenario, the largest annual retrofit potential—attained in the year 2012 when the prices of oil and gas peaked simultaneously—is only about half of the maximum-attainable potential for the buildings in our dataset. At the very least, this suggests that we must be cautious in speaking of a large energy-efficiency gap for this dataset; the calculation indicates that investments in energy-efficiency are generally not helpful in increasing the growth-rate of wealth.

The next quantity of interest is the distribution of renovation activity between the wealth quantiles. Although the ratio of retrofit activity as a share of total activity is relatively equally distributed between the quantiles in the $\delta = 2.5\%$ scenario—$37{:}\,32{:}\,31$ for oil and $39{:}\,31{:}\,30$ for gas—the gap between wealth quantiles widens the faster wealth grows: the above ratios change to $48{:}\,32{:}\,30$ and $52{:}\,26{:}\,23$ in the $\delta = 5\%$ scenario.

We restrict ourselves now to the $\delta = 2.5\%$ scenario for the purposes of discussing other results. A comparison of Figure 1 with Figure 3 reveals that we are able to broadly reproduce the dynamic of retrofit interest as measured by subsidy uptake: lower interest in the early 2000's, with a dramatic increase starting 2006 which persists through 2016. In other words, the model is capable of providing an explanation for *SF2*, with the main driver being the relative prices of the various energy carriers. It bears underlining here that our model shows that

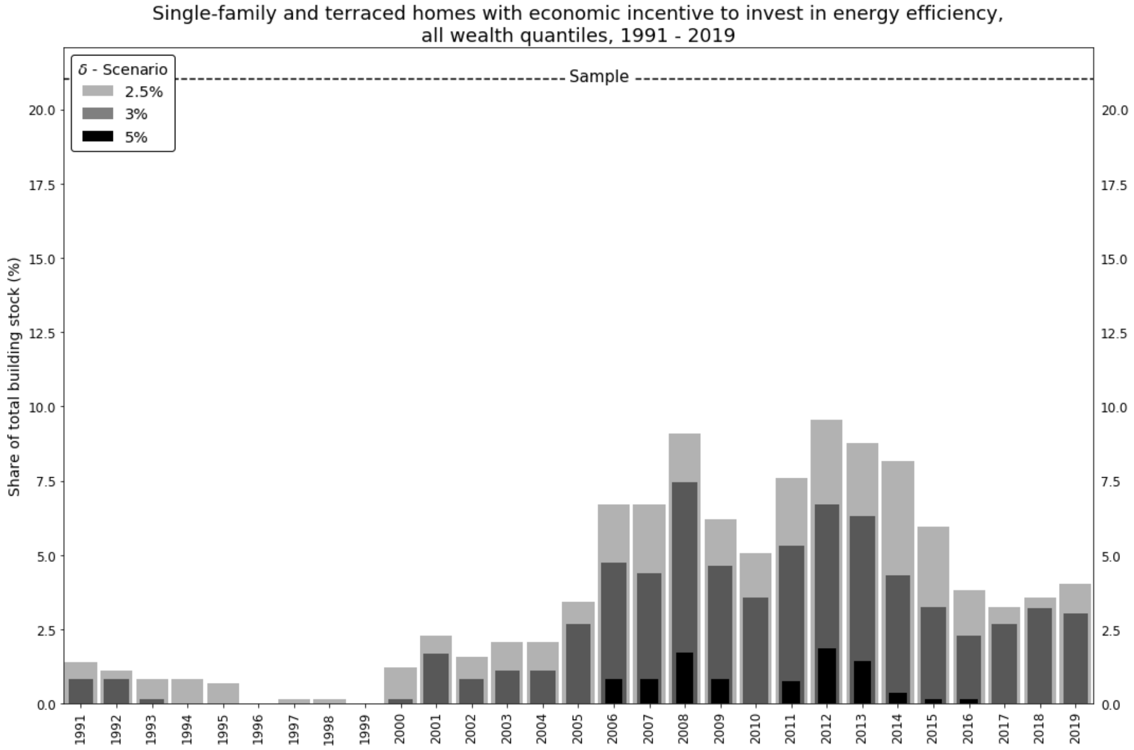

Figure 3. Economic incentive to retrofit for single-family and terraced homes which heat with oil and gas for the top three wealth quantiles in Germany. The plot has many features in common with Figure 1.

the dynamics of retrofitting are more complicated than "higher fuel prices = more retrofits". In point of fact, statistical analysis of KfW subsidy spending and fuel price data show that subsidy uptake is only mildly positively correlated to the lagged prices of oil ($r = 0.3$) and gas ($r = 0.4$)—this is not enough to inform policy-making. An investment model such as ours, capable of providing causal explanations for the connection between changing fuel prices and retrofit uptake, is required.

Related to the above is the substantial annual variation in retrofit potential mentioned in *SF2* above. Figure 3 confirms that such averages, while important, tell only part of the story: the dynamic variation in retrofit potential is a real and essential component of the diffusion process.

One of the main purposes in developing our framework was to model the consumer's freedom in being able to put off an investment to a later date. It is therefore somewhat surprising that every single investment, in all of the scenarios, is of the "now or never" variety; i.e. the consumers in this database have no reason to delay the investment to a later date. But this means that the logarithmic utility function, coupled with diminishing marginal utility and the energy-carrier price parameters, have conspired (at least over the last three decades) to justify the large swathes of consumers who simply choose to wait out the lifetime of their equipment (*SF3*). This observation in particular persists even when subsidies and taxes are in the mix.

A related aspect of the simulation was the presence of "retrofit windows" for a particular dwelling. For instance, consumers who own single-family homes built in the early 80s would have profited from retrofitting in any of the years 1991 – 1995, and 2000 – 2019. Determining at what point in time during these retrofit windows the decision to retrofit is taken (or not taken) is the object of future research. One thing is for certain: the longer these windows stay open, the higher the chance that the homeowner might eventually decide to retrofit. On the other hand, some of the newer, more efficient dwellings never show up on the list of homes that are profitable to retrofit at all.

Regarding retrofit depth, the ratio of medium retrofits to deep retrofits to retrofits that include heater upgrades is $65{:}\,29{:}\,6$ for dwellings that heat with oil, and $57{:}\,32{:}\,11$ for those that heat with gas over the three decades and wealth quantiles. This fact partially accounts for *SF1*, but there are important differences which we will return to at a later point. Bear in mind also that these numbers are for the $\delta = 2.5\%$ scenario; in the $\delta = 5\%$ scenario, the ratios are $80{:}\,0{:}\,20$ and $100{:}\,0{:}\,0$ respectively. That is, consumers whose wealth grows faster shun deep retrofits completely; in fact the trend of retrofit depth between scenarios makes clear that consumers whose wealth grows faster not only have less incentive to retrofit when measured as a share of the total building stock, but also when measured with respect to retrofit depth.

With respect to the choice of energy carrier post-retrofit, similar calculations to the one outlined in the previous paragraph show that of the consumers who heat with oil who would benefit from a heater upgrade, about 74% switch to gas with the remaining 26% staying with oil; there are no movers to electricity. For consumers who

Figure 4. We depict here the excess retrofit potential due to the carbon tax scheme. On the y-axis, each unit corresponds to an extra, relative to the baseline in Figure 2, percentage point of the building stock with economic incentive to retrofit.

heat with gas, since we disallowed a move back to oil, all consumers stay with their carrier, so none move to electricity. In the $\delta = 5\%$ scenario, all consumers who heat with oil move to gas, and no consumer who heats with gas has an incentive to upgrade their heating system.

The effects of carbon taxes on retrofit activity

Figure 4 shows the main quantity of interest in the case when the carbon tax is implemented, namely, the number of excess consumers with respect to the baseline who end up with incentive to retrofit due to the tax. We see that this number depends very strongly on the growth-rate scenario: whereas for $\delta = 2.5\%$, the mean excess retrofit potential over the time period is 16% of the total building stock, this quantity drops to 13% and 4% for $\delta = 3\%$ and 5% respectively. In other words, the carbon tax is less effective on consumers whose wealth grows faster. This mirrors the discussion in the previous section, where we saw that retrofit incentive drops to zero if wealth grows fast enough; we see here that the effect of a carbon tax also drops to zero for δ large.

A direct corollary of the above is that the tax broadens the base of the type of dwellings which can be retrofit economically. For instance, for homes that heat with oil in the $\delta = 2.5\%$ baseline scenario, the first seven generations of single-family homes, and the first five of terraced homes, have economic incentive to retrofit; with the tax in place, this expands to the first eight generations for both single-family and terraced homes. A similar broadening of the economic appeal of retrofits occurs for gas, and in the other δ scenarios as well.

An important feature in the graphic is the substantial variation in the year-to-year effect of the tax, both within and between the growth-rate scenarios. Although this is certainly related to the prices of the energy carriers in these years, we emphasise again that observing such an effect requires a non-trivial investment model.

Other effects of the tax can be seen in Table 1 and Table 2, where we list key performance indicators for the $\delta = 2.5$ and 5% scenarios and the different policy instruments (the analogous table for $\delta = 3\%$ was omitted for brevity). We see that as a result of the tax, consumers have extra incentive to upgrade their heating system, and they retrofit deeper than they would have without the tax; however, this is again dependent on the growth-rate of wealth. In the $\delta = 2.5\%$ scenario, the ratio of instances of medium retrofits to deep retrofits to heater upgrades changes from $65: 29: 6$ to $27: 47: 26$ for oil, and from $57: 32: 11$ to $32: 55: 13$ for gas; thus, for this growth-rate segment, the carbon tax works as expected. But in the $\delta = 5\%$ scenario, these same ratios change from $80: 0: 20$ to $88: 0: 12$ for oil, and from $100: 0: 0$ to $96: 0: 4$ for gas; hence, even with the carbon tax in place, wealthier consumers have no economic incentive to pursue deep retrofits.

Table 1. Key performance indicators for the policy instruments; δ=2.5% growth-rate scenario.

Scenario: $\delta = 2.5\%$	*Mean retrofit potential, 1991-2019, all quantiles (share of building stock)*	*Difference to baseline (share of building stock)*	*Share of the wealth quantiles in retrofit activity, 1991-2019 (share of total)*		*Type of retrofit activity, 1991-2019, all quantiles (medium : deep : heater, share of total)*		*Choice of energy carrier, 1991-2019, all quantiles (oil : gas : elec. , share of total)*	
			Oil	*Gas*	*Oil*	*Gas*	*Oil*	*Gas*
Baseline	3.9	-	37:32 :31	39:31:30	65:29:6	57:32:11	29:71:0	0:12:0
Subsidy	7.6	3.7	35:32:32	35:33:32	51:46:3	46:54:0	0:100:0	-
Tax	9.2	5.3	40:31:29	38:31:31	27:47:26	55:32:13	14:86:0	0:100:0
Subsidy + tax	13.0	9.1	37:32:31	36:32:32	21:62:17	23:69:8	6:88:6	0:100:0

The effects of a KfW-style subsidy

The analogue of Figure 4 for the case of the subsidy scheme is quite similar in appearance so we omit it; just as in that case, the annual variation in retrofits is a key feature of the effects of the policy. Table 1 and Table 2**Error! Reference source not found.** contain most of the information we need: for instance, if we compare the mean retrofit potential generated by the subsidies, it performs slightly worse than the taxes in the first two growth-rate scenarios, but this is reversed for $\delta = 5\%$ scenario. More research is required to determine if the effect of the tax weakens the faster wealth grows.

Implicit in the above is the fact that the tax does a better job at broadening the appeal of retrofits to dwelling types not already implicated in the baseline scenario. On the other hand, both taxes and subsidies have an “equalising” effect, reducing the gap between wealth quantiles—this is particularly clear in the $\delta = 5\%$ scenario.

Interestingly, the extremely steep discounts on heating-system upgrades appear to be less effective than the subsidies offered on other retrofit measures: the ratio of medium retrofits to deep retrofits to heater upgrades in fact changes from $65{:}\,29{:}\,6$ to $51{:}\,46{:}\,3$ for oil, and from $57{:}\,32{:}\,11$ to $46{:}\,54{:}\,0$ for gas in the $\delta = 2.5\%$ scenario. In the 5% scenario, this ratio is $100{:}\,0{:}\,0$ for both oil and gas: no deep retrofits, no heater upgrades. The reason for this dominance of insulation appears to be the following: in our framework, consumers could reduce their heating expenses by either retrofitting, upgrading their heating system, or a combination of both. Both retrofits and heater upgrades were heavily subsidised, but the retrofits ended up the more profitable investment in terms of final energy saved than the much more significant investment in a new heater—once again, diminishing marginal utility is at work. Notably, this is the reverse of what happens with the carbon tax, at least for the $\delta = 2.5\%$ scenario.

On the plus side, due to steep discounts on heaters that are not oil-fired, for the few cases where heater upgrades were undertaken, oil is completely phased out as a viable energy carrier: all consumers switch to gas.

Table 2. Key performance indicators for the policy instruments; δ=5% growth-rate scenario.

Scenario: $\delta = 5\%$	*Mean retrofit potential, 1991-2019, all quantiles (share of building stock)*	*Difference to baseline (share of building stock)*	*Share of the wealth quantiles in retrofit activity, 1991-2019 (share of total)*		*Type of retrofit activity, 1991-2019, all quantiles (medium : deep : heater, share of total)*		*Choice of energy carrier, 1991-2019, all quantiles (oil : gas : elec. , share of total)*	
			Oil	*Gas*	*Oil*	*Gas*	*Oil*	*Gas*
Baseline	0.3	-	48:32:20	52:26:23	80:0:20	100:0:0	0:100:0	0:100:0
Subsidy	2.3	2.0	36:32:32	36:32:32	100:0:0	100:0:0	-	-
Tax	1.9	1.6	40:31:29	38:31:31	88:0:12	96:0:4	0:100:0	0:100:0
Subsidy + tax	6.3	6.0	37:32:31	36:32:32	99:0:1	100:0:0	0:100:0	-

The effects of combining the carbon tax with a subsidy scheme

We refer again to the numbers in Table 1 and Table 2 to quantify the effects of combining taxes and subsidies**Error! Reference source not found.**. Firstly, retrofitting has a maximally broad appeal here: every single dwelling type sees incentive to retrofit at some point of time in the $\delta = 2.5\%$ scenario. The excess retrofit potential generated by the policies is a healthy 9.1% of the building stock for the 2.5% scenario, and 8.8% and 6% for the 3% and 5% scenarios respectively. Notice that these policies working in tandem accomplish more than the sum of them working individually.

As regards the type of retrofit, the ratio of medium to deep to heater retrofits is now $21: 62: 17$ for oil and $23: 69: 8$ in the $\delta = 2.5\%$ scenario, but again only $99: 0: 1$ and $100: 0: 0$ in the $\delta = 5\%$ case. In other words, even though the 2.5% scenario indicates deep retrofits finally becoming viable in the majority of cases due to the combined pressure of taxes and subsidies, the 5% scenario refuses to budge in this regard.

Finally, heat pumps show up for the first time as an economically viable option for a small share of consumers who heat with oil: 6% and 9% of heater upgrades in the 2.5% and 3% growth-rate scenarios respectively would go for this option. In both cases this occurs in the period 2006 – 2008, in the three generations of single-family homes built in the period 1969 – 1994 (i.e. single-family homes of the sixth, seventh, and eighth generations in the TABULA notation).

Policy Implications and Outlook

Before we offer the conclusions of this study, it is important to critically review our methodology. We situate our work in the tradition of representative-agent modelling: the goal of such models is primarily to discover the macroeconomic patterns that emerge from simple microeconomic decision models. While these patterns are sometimes expected, they can often be hard to forsee: examples of the latter from the previous section include the substantial annual variation in retrofit potential of the building stock, the fact that all retrofit instances in all scenarios are of the "now or never" variety, or the fact that competition between subsidy schemes exists. Nevertheless, such conclusions are only as good as the assumptions that go into the model. As such, a shortcoming of our approach is the assumption of pure multiplicative wealth: future research will focus on the extension of this model to other wealth quantiles via more realistic models of household wealth, including a mixture of fixed income and savings (Britto et al., 2021). In a similar vein, our data on the costs of retrofitting the share of building stock we considered was generated by a free-to-use renovation calculator: better quality data from real use-cases, along with more up-to-date information on the actual present status of dwellings would greatly improve the model's predictive power. Finally, our calculation of the consumer's total expenses on heating could be further refined by incorporating more sophisticated models from building physics.

In essence, we have shown in this article how framing the problem of optimal investment in energy efficiency as one of growth-rate maximisation allows one to reproduce and model, with a high degree of differentiation, the dynamics of retrofit uptake, and the effects of policy. If we were to sum up our findings in a sentence for the social planner, it would be this: *wealth matters, the diminishing marginal utility of retrofitting matters, and the stochasticity of fuel prices matters.*

We begin with wealth: the above calculations indicated that wealth, in particular the growth-rate of wealth, is by far the most decisive factor in how consumers choose to retrofit, and how they are affected by policies. In general, the richer the consumer is, and the faster wealth grows, the less incentive consumers have to retrofit: wealthier consumers retrofit less, and if they retrofit, they invest in shallower retrofits. Our first policy suggestion, which is rather general, is for a greater recognition of the role of the dynamics of household wealth in retrofit decision-making: policymakers and academics of both disciplines urgently need to collaborate.

With regards to the depth of retrofitting, our analysis points tentatively an energy efficiency gap: consumers are opting for "below threshold" and "light" retrofits when their growth-rate can be optimised with medium and deep retrofits. It is our contention that the policymaker's best bet to combat this is to embrace the diminishing marginal utility of retrofitting, and pick the low-hanging fruit. Subsidies for cheap and effective measures, such as roof insulation, boiler adjustment, and hydraulic equalisation, can be expanded. The current 20% subsidy offered by the BAFA for single energy-efficiency measures only covers investments of 2000 € or more (BAFA, 2021); this minimum investment is unnecessary.[3] A similar point can be made about the decoupling of the retrofit subsidies offered by the KfW from their extremely stringent *Effizienzhaus* standard; far better, in our opinion, to base these subsidies on the relative improvement in a dwelling's energy performance, so that these discounts can be made available as widely as possible.

Another point that we encountered in our calculation was that some of these subsidy schemes are at cross-purposes; in particular, separate subsidy schemes for retrofit measures and heater upgrades leads to a reduction in the effectiveness of the heater scheme. Similar complications should be examined and weeded out.

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[3] For instance, Galvin & Sunikka-Blank (2013) estimate that cheap and effective roof insulation can be installed for as little as 600 €.

Broadly speaking, heater upgrades were unattractive investments, even in the low growth-rate scenarios. The German government and its advisors seems to have acknowledged this fact, and after years of subsidising and cajoling, recently banned the installation of new oil heaters starting 2026 in buildings where more climate-friendly alternatives are available (Eriksen, 2020).[4] A cost-benefit analysis of this particular policy is beyond the scope of this paper: what we can say is that if the long-term goal is the electrification of the heating sector, since a similar ban on gas-fired heating is unthinkable in the near future, the price of electricity in Germany must come down. In the meantime, in the spirit of diminishing marginal utility, the government can accelerate a country-wide transition to "renewable ready" gas heating systems by increasing the subsidy from the current 20% to the $40-45\%$ level provided for other heating systems.

Regarding carbon taxes, the above analysis indicates that this relatively blunt policy instrument will indeed generate some economic incentive to retrofit, but it will do so at the risk of widening the gap between rich and poor consumers. Additionally, the calculations suggest that the efficacy of these taxes drops quickly, the faster wealth grows. In sum then, we stand with the economic orthodoxy in affirming that the task of the policymaker here is to simply guide the price discovery of carbon so that the harmful externality is sufficiently internalised, and not necessarily to use the tax to achieve any particular energy-efficiency goal.

The final aspect of energy-efficiency investment that we must acknowledge is the prominent role played the stochasticity of fuel prices; it was second only to the wealth parameters in the effect that it had on energy-efficiency investments. Nevertheless, apart from the case of electricity, which we have discussed already, the German government can hardly be expected to exert control over internationally-traded, highly-volatile commodities. As such, the signalling effect of the carbon tax is probably the government's best tool in this regard.

A final recommendation here to ensure steady progress in the realm of energy efficiency is for the central and state governments itself to invest in energy efficiency as widely as they can in all buildings that they own, including the over 1.1 million social-housing dwellings (Statista, 2021). Since it is perhaps the only market actor who can commit to an annual renovation rate regardless of random shocks in fuel prices, this will stimulate the market for retrofits, and perhaps encourage private consumers, in particular large players such as the *Immobiliengesellschaften* (real estate companies) to follow their example.

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[4] We would not be surprised if this led to an increase in the installation of oil heaters over the next few years, similar to the understandable reaction of consumers each time new building standards are announced. In Figure 1, consumers rushing to get in renovations before the EnEV regulations entered into force in 2007 likely contributed to the spike in subsidy spending in 2006.

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