Energy-Efficient Investments in Housing

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Abstract

In recent years, many papers in environmental economics have considered the household's decision to invest in energy-efficient technologies for their home. The vast majority of these studies have concluded that investment levels in these technologies are sub-optimal for a variety of reasons. In this paper, we synthesize the suggested drivers of these investment wedges and propose a dynamic modeling framework of a housing choice and an energy-efficient-investment choice that includes the proposed channels. We discuss the estimation challenges associated with this model and conclude with suggestions for future research.

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1 Introduction

Investments in energy-efficient housing attributes, such as solar panels, heat pumps, and built-in appliances, by households have attracted considerable attention by environmental economists in recent years. These attributes, despite offering both private benefits to households in the form of lower energy expenditures and public benefits in the form of decreased emissions associated with energy production, are usually found to have sub-optimal levels of investment. Under-investment in these housing attributes has been described as the "energy-efficiency gap" and has been explained by myopia, information asymmetries, and a variety of fixed and marginal costs (e.g., Jaffe and Stavins (1994)). Over-investment in these attributes is also possible and could be explained by biased beliefs due to incorrect estimates reported by engineers regarding the efficiency of the attributes (e.g., Fowlie et al. (2015)).

Unlike the revealed-preference literature describing the household's choice of housing amenities like square footage or local air quality, the literature describing investment decisions regarding energy-efficient housing attributes have typically treated the installation choice as a separate financial decision and has modeled the household's consumption decision as being independent of the household's housing decision, even when the housing attribute fully conveys with the house upon resale. In addition, while a growing literature has found that installed energy-efficient housing attributes are not fully capitalized in a house's sale price, these papers typically do not model the magnitude of this financial cost's impact on the household's decision to invest or the household's decision to move in a given period.

We begin by summarizing the key implications from the literature about the many potential drivers of why a household might consume a sub-optimal quantity of energy-efficient housing attributes. We then seek to synthesize these drivers by providing a conceptual framework that jointly models a household's decision of which house to choose and which energy-efficient housing attributes to invest in. Additionally complicating such an exercise is the fact that both decisions are inherently dynamic decision processes. Households face high fixed costs associated with both moving and with upgrading their current residence. The net utility flows are enjoyed over a potentially long time horizon. Important factors such as energy prices are both time-varying and not fully predictable. And, finally, a household may choose to re-optimize in any given future period.

We describe a conceptual framework that specifies households making two decisions in each period. The first decision is whether or not to move; a move allows the household to choose an entirely new vector of housing attributes. The second decision is whether or not to invest in a specific energy-efficient housing attribute at the household's current residence. This allows the household to reoptimize one particular housing attribute while maintaining consumption of other attributes at their existing levels. The model starts with the dynamic location-choice framework described in Bishop and Murphy (2023) and extends it by adding the household's investment decision of energy-efficient housing attributes. Within this framework, we incorporate the literature's explanations of the drivers of investment decisions, including time preferences, risk aversity, and a complex set of costs, including the time and hassle associated with investing, uncertainty (and mis-information) over annual returns on energy-efficient investments, and information asymmetries that lead to less-than-full future market capitalization of energy-efficient investments.

This paper proceeds as follows: Section 2 discusses the existing literature and describes the factors known to drive investments in energy-efficient housing attributes, and Section 3 presents a conceptual framework that includes a secondary investment decision within a model of housing choice. Section 4 describes case study of residential solar systems. Section 5 concludes with a discussion of target areas for future research.

2 Known Factors Driving Investment Decisions

Many studies have examined various factors contributing to sub-optimal investments in energy-efficiency for a wide number of housing attributes. See Gillingham et al. (2009), Allcott and

Greenstone (2012), Gillingham and Palmer (2014), Gerarden et al. (2017), and Gillingham et al. (2018) for comprehensive overviews.

One such factor is imperfect information about the attribute's potential financial returns (e.g., Allcott and Taubinsky (2015)). In a study of households' decision to invest in Energy-Star rated water heaters, Allcott and Sweeney (2017) finds that fifteen percent of the customers who purchased conventional water heaters were unaware of the Energy-Star option altogether. In addition, the provision of information regarding energy efficiency by sales representatives in this context had no impact on the demand for Energy-Star rated water heaters, suggesting that the sales representatives either did not properly convey the information or the consumers did not fully process it. Likewise, Jacobsen (2015) finds no impact of energy prices on the decision to invest in Energy-Star rated appliances.

Related to this, the information being disseminated about the energy efficiency of a housing attribute may be incorrect (e.g., Davis and Metcalf (2016)). This could lead to sub-optimal investment levels and/or discrepancies between households' observed choices and what the econometrician models as optimal. First, engineering estimates about the performance of the energy-efficient investment may be biased. In a paper focusing on a program that improves housing-based energy efficiency for low-income households through retrofits of things like furnaces and insulation, Fowlie et al. (2018) finds that the realized energy savings were only about 30 percent of the projected savings from engineering estimates. Similarly, Allcott and Greenstone (2017) finds that the average realized energy savings were only 58 percent of the predicted savings for similar energy-efficiency retrofits, while Giraudet et al. (2018) find that the realized energy savings were only 60 percent of the predicted saving for attic insulation and 32 percent for duct sealing. This bias in engineering estimates may be driven by the fact that the household uses the energy-efficient attribute differently than does the representative agent of the engineer's model. It may also be due to the fact that the technology is simply not as efficient once installed in the household's home. For example, Giraudet et al. (2018) show that the ex-post gap between predicted savings and realized savings is smaller for investments for which the quality of installation is easier to verify, implying that there in an important quality dimension for installation services.

In addition, there remains considerable uncertainty over many of the variables that drive investment decisions. A number of important demographic characteristics evolve stochastically, like family size or work patterns (e.g., Hotz and Miller (1988)). Housing market descriptives, like mortgage-interest rates and local appreciation rates, also evolve stochastically (e.g., Anenberg and Kung (2017)). Finally, the uncertainty surrounding parameters directly determining the financial flows associated with energy-efficient investments, such as government subsidies for investments and the price of electricity, will play an important role in the household's investment decision (e.g., Anderson et al. (2011), Feger et al. (2022), Kiribrahim-Sarikaya and Qiu (2023), and Davis (2023)). Thus, the household's preferences for risk are likely to impact their decision to invest in energy-efficient housing attributes. In survey-based settings, both Qiu et al. (2014) and Heutel (2019) find inverse relationships between a household's heterogeneous measure of risk and the probability that the household will invest in energy-efficient technologies for their home or in other energy-efficient appliances.

In addition to heterogeneity in risk aversity, household-level heterogeneity will likely be present in most, if not all, drivers of a household's investment decisions (Houde and Myers (2019)). This heterogeneity would enter both measures of benefits and costs. For example, in a study of energy-efficient heat pump installation, Davis (2023) highlights the importance of consumer heterogeneity in the technology's efficacy along dimensions describing the household's local climate. Heat pumps simply work better in certain parts of the country.

Information frictions further complicate the problem as the household will consider how much of the value of its investment will be capitalized into their house's value, if they were to sell the house in the future to a less-than-fully-informed buyer. The literature has found evidence of this concern by forward-looking investing households and evidence of less-than-full capitalization of energy-efficient attributes likely driven by information asymmetries (e.g., Dastrup et al. (2012), Bardhan et al. (2014), Deng and Wu (2014), Kahn and Kok (2014), Walls et al. (2017), Cassidy (2023), and Myers et al. (2022)). It has also found evidence that households treat the decision to invest in housing attributes that convey with the house upon sale differently than they treat housing attributes that do not convey with the house upon sale. Schleich et al. (2020) find that investment rates are depressed by 8 percentage points for appliances that convey with the house compared with appliances that do not convey. Additionally, in a survey of homeowners in California and Arizona, Qiu et al. (2014) find that the probability that the household invests in energy-efficient retrofits and appliances is inversely related to the probability that the household plans on moving in the next five years, again highlighting the joint decision processes of location choice and installation of energy-efficient housing attributes. The discounted expected value of financial returns is not the only factor that drives households' decisions to invest in energy-efficient housing attributes.[1] Another important factor is the multitude of non-monetary, heterogeneous benefits and costs that are associated with investment. The household may receive positive utility flows from the investment. For example, the household may enjoy being green, particularly if the consumption of the attribute is conspicuous (e.g., Sexton and Sexton (2014)). Or, the household may enjoy increased comfort in the form of indoor temperatures, commonly referred to as the "rebound effect" of the household's substitution toward consumption of energy when the price of energy usage is reduced through energy-efficient housing attributes (e.g., Gillingham et al. (2016), Qiu et al. (2019), Liang et al. (2018), and Deng and Newton (2017)). In addition, there are likely large non-monetary costs associated with investments such as administrative costs, time costs, and tolerating renovations in the houshold's home that would be highly heterogeneous. Fowlie et al. (2015) describe how these large non-monetary costs negatively impact the take-up rates

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[1] In our model, presented in Section 3, we assume that households live in owner-occupied houses and, therefore, reap any financial returns. However, in rented houses, there is an additional channel of split-incentive problems between landlords and tenants. See Davis (2012), Gillingham et al. (2012), Myers (2020), and Cellini (2021).

for energy-efficient weatherization investments.

Finally, as the investment decision is an inherently dynamic one, the household will discount future streams of net benefits with a heterogeneous discount factor representing their preferences over time (e.g., Busse et al. (2013), Newell and Siikamäki (2015), Bradford et al. (2017), Schleich et al. (2019)). Hausman (1979) and Leard et al. (2019) find evidence of considerable heterogeneity in discount rates across households, in addition to evidence of high discount rates, on average, speaking to a present bias. Hausman (1979) estimates an average discount rate of twenty percent in an analysis of air conditioners. De Groote and Verboven (2019) finds an average discount rate of 15 percent in an analysis of residential solar systems. In separate analyses of vehicle choice, Allcott and Wozny (2014), Leard et al. (2023), and Grigolon et al. (2018) also find that, on average, households employ discount rates above the average cost of borrowed funds.[2] Likewise, the cost of borrowed funds for energy-efficient investments is likely heterogeneous and based on factors such as the household's credit history, location, and nature of the investment.

3 A Model of Energy-Efficient Investments

In this section, we outline a dual-choice, dynamic model of hedonic demand that incorporates the key channels of energy-efficient housing investments identified by the literature: time preferences, risk aversity, and a complex set of costs, including the time and hassle associated with investing in a house, uncertainty over annual returns on energy-efficient investments, and information asymmetries that lead to less-than-full future market capitalization of energy-efficient investments.

This model specifies home-owning households as making a sequence of decisions that maximize the expected discounted stream of per-period flow utilities. The model is closely

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[2] Sallee et al. (2016) and Busse et al. (2013) find that households, on average, have discount rates roughly equal to the interest rate.

related to the model of Bishop and Murphy (2023) and extends it by additionally including the household's decision of energy-efficient investments to their house in each period, along with the decisions of whether to move and how much neighborhood and housing attributes to consume. The purpose of outlining the model is to describe key features of the household decision-making process. We defer any discussion of estimation, so do not distinguish here whether attributes are observable to the econometrician, and revisit estimation of dynamic models in Section 3.6.

3.1 Housing Attributes

We begin by specifying two groups of potentially time-varying attributes that are associated with a household's residence. The first group, which we denote x_1, is the class of house and neighborhood attributes for which consumption levels cannot be endogenously changed without moving; if the household wishes to consume a different quantity of one of these attributes in the current period, the household must change residence, incurring a large heterogeneous adjustment cost associated with moving, and choose a new house with their desired bundle of attribute levels. We assume that all neighborhood attributes (such as air quality, school quality, and crime exposure) are included in x_1.[3]

The second group, which we denote x_2, is the class of housing attributes for which consumption levels can be changed in the current period without moving; if the household wishes to consume more of one of these attributes, they simply incur a heterogeneous adjustment cost associated with the new investment in the attribute. New investments in energy-efficient housing attributes described in the preceding section (e.g., weatherization, conveying appliances, residential solar systems, and heat pumps) are all included in x_2.[4] This segmentation of the vector of housing attributes is an important addition to the model of Bishop and Murphy

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[3] Many housing attributes, such as square footage, could appear in both x_1 and x_2. Square footage at the time of purchase would, by definition, be included in x_1, while additions to square footage during the household's tenure in the house would be included in x_2.

[4] Energy-efficient housing attributes at the time of purchase would be included in x_1.

(2023), as it will allow us to model the decision of the household to invest in a housing attribute without changing residence. While our proposed framework is suitable to consider any housing-related investments by the household, like increases to square footage with an addition to the current residence, we focus our language henceforth on energy-efficient investment decisions.

Finally, we note that many housing attributes could be included in both x_1 and x_2. For example, installed energy-efficient technologies at time of purchase would be, by definition, included in x_1, while any energy-efficient investments since that time would be included in x_2.

3.2 Endowed Housing Attributes and Costs of Adjustment

We specify a dynamic framework with periods denoted $t \in \{1, \ldots, T\}$. Households, denoted $i \in \{1, \ldots, N\}$, have heterogeneous preferences over the vector describing contemporaneous housing-related attributes, $x_{i,t} = [x'_{1,i,t}\ \ x'_{2,i,t}]'$.[5] Household i begins each period t in a house that provides an endowment vector of attributes. This vector of attributes is determined by the household's current residence and is denoted $x^e_{i,t} = [x^{e\prime}_{1,i,t}\ \ x^{e\prime}_{2,i,t}]'$. The household chooses how much of each attribute in the vector $x_{i,t}$ to consume. If the household chooses to consume a vector of attributes that is different than $x^e_{i,t}$, it must pay a non-zero adjustment cost to re-optimize. When this adjustment cost is sufficiently high (relative to any potential gains from re-optimizing), the household will forego re-optimizing and consume the endowed quantity of attributes. In this case, the household's realized adjustment cost will be zero.

If a household chooses to re-optimize its consumption of x_2, i.e., change its consumption of an energy-efficient housing attribute through a new installation, the household must pay a non-zero, heterogeneous adjustment cost, AC_2. As we will assume that the financial cost of this investment is financed (discussed in the following subsection), AC_2 captures all of the non-pecuniary costs associated with the adjustment. Examples include the time costs, hassles

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[5] One make treat the choice of housing attributes as continuous following Rosen (1974) or discrete following McFadden (1973). The same conclusions may be derived is either case.

and disruptions, and other psychological costs of investing in one's current place of residence, as described in Fowlie, Greenstone, and Wolfram (2015).

If a household chooses to re-optimize its consumption of x_1, it must move to a new house and incur a more substantial heterogeneous adjustment cost, AC_1.[6] This adjustment cost captures both the one-time psychological cost of moving to a new house and the one-time financial cost of moving to a new house. The fixed financial costs associated with moving include both the realtor fees (6% of the value of the current residence), the financial cost of moving one's belongings, and, importantly, any remaining gap between the household's balance on prior financed investments in x_2 and the new buyer's willingness to pay for such attributes, directly addressing the investment wedge described by the literature that is created by this gap. In the model, we specify the adjustment costs as functions, $AC(x_{i,t}, s_{i,t}) = AC_1(x_{1,i,t}, s_{i,t}) + AC_2(x_{2,i,t}, s_{i,t})$. These adjustment costs are specified to be function of the household's choice of attributes in period t and the vector of state variables in period t, $s_{i,t}$, that is comprised of all variables that affect the household's decisions at time t. We describe $s_{i,t}$ in more detail in the following section.

3.3 The State Vector and Transition Probabilities

The state vector, $s_{i,t}$, is comprised of all variables that would affect the household's choice of $x_{i,t}$ in period t, including many of which that vary through time. This includes, but is not limited to, the household's endowment attributes ($x^e_{i,t}$), demographic characteristics (e.g., income, education, and age and number of children), market characteristics (e.g., interest rates and energy prices), and characteristics describing the energy-efficient technologies (e.g., engineering estimates of the technology's lifespan). The state vector also includes the household's information set at time t.

When making a decision at time t, the household observes the current state $s_{i,t}$ and has

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[6] We note that the household would, of course, be able to re-optimize their level of energy-efficient technologies by moving, and these technologies would be included in x_1 for a new residence.

expectations over the future state $s_{i,t+1}$. The household's beliefs about the transition probability of the state from $s_{i,t}$ to $s_{i,t+1}$ is assumed to be Markovian and is given by $q(s_{i,t+1}|s_{i,t}, x_{i,t})$.[7] This transition is dictated by a variety of factors. First, it is endogenously determined by the household's period t decisions; the household's choice of housing attributes in period t will stochastically influence its endowment attributes in period $t+1$. Second, it is also determined by factors beyond the household's control. For example, the household takes the variation in energy prices as given.

The household will integrate out over their beliefs governing the distribution of future states of the world, dictated by $q(s_{i,t+1}|s_{i,t}, x_{i,t})$. Thus, in the model, this function will capture the uncertainty that the household faces. It will also capture the impact of forces such as incorrect engineering estimates about energy-efficient investments or gaps in information sets.

3.4 Rental-Equivalent Costs of Housing Attributes

Investing in energy-efficient attributes for the current residence, x_2, entails a variety of costs, as detailed by the literature. Some one-time, fixed costs are non-pecuniary and are captured in AC_2, as previously discussed. Some ongoing, annual costs may also be non-pecuniary, e.g., the installation of a residential solar system may negatively impact the household's scenic view. These costs will be captured in the utility function shown in Section 3.5. Many costs, however, will be financial. One such financial cost, of the household not receiving the full market value of the investment upon a possible future sale of the property, is captured in AC_1 at the future time of sale, as previously discussed. All other financial costs will be captured by an annual rental-equivalent cost function. This function effectively smooths all housing-related costs into a per-period measure. Specifically, in each period, the household must pay for its consumption of housing attributes, both x_1 and x_2, at rental-equivalent prices. We specify the vector of these costs as a function, $r(x_{i,t}, s_{i,t}) = r_1(x_{1,i,t}, s_{i,t}) + r_2(x_{2,i,t}, s_{i,t})$. We partition this rental-

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[7] In this theoretical model, we do not impose any structure on these beliefs, such as rational expectations.

equivalent function into the costs driven by x_1 and those driven by x_2 for discussion purposes regarding investment decisions.

The implicit rental-equivalent cost of consuming x_1, $r_1(x_{1,i,t}, s_{i,t})$, is often referred to as the user-cost of housing.[8] This user-cost captures the true, economic cost of owning a house in each period. It is a function of the attributes of the house at time t, excluding any investments that the household has undertaken, and a function of the state vector at time t. While market factors, such as appreciation, would offset costs within $r_1(x_{1,i,t}, s_{i,t})$ in a given period, we assume that $r_1(x_{1,i,t}, s_{i,t})$ is positive (i.e., we assume that the household foregoes numeraire consumption in order to pay for housing).

The rental-equivalent cost of consuming x_2, $r_2(x_{2,i,t}, s_{i,t})$, includes all relevant costs associated with the investment of energy-efficient attributes. Like the purchase of x_1 with a mortgage, we assume that all investments in x_2 are fully financed at the time of installation. Thus, x_2, $r_2(x_{2,i,t}, s_{i,t})$ may be interpreted as the net return on investment in period t and is sensitive to the upfront cost of the attribute (net of subsidies/rebates) and to the depreciation of the energy-efficient attribute, energy prices, and the financing rate. These are all contained in $s_{i,t}$.

In the case of a purely financial investment, a natural comparison would be to compare $r_2(x_{2,i,t}, s_{i,t})$ against zero, i.e., the net returns on the investment would be negative in that period if $r_2(x_{2,i,t}, s_{i,t})$ were negative. In the case of energy-efficient housing attributes, there may be per-period utility gains associated with investment, and these positive gains may vary across attributes, e.g., according to the saliency of the attributes.

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[8] Typically, the user cost is calculated as a simple percentage of the value of a house, such as 7.5%. See Bieri et al. (2022) and Bishop et al. (2022) for examples where user costs vary over time and space.

3.5 The Household's Decision Problem

In each period, the household receives flow utility,

$$u^f(x_{i,t}, s_{i,t}) = u(x_{i,t}, s_{i,t}) - r(x_{i,t}, s_{i,t}) - AC(x_{i,t}, s_{i,t}). \tag{1}$$

The first component of this flow utility, $u(x_{i,t}, s_{i,t})$, is concave in $x_{i,t}$ and captures the direct effect of the housing attributes on utility. It is a function of the household's consumed attributes in period t, $x_{i,t}$ in addition to the state vector. The concavity of this function allows for risk aversion with respect to the household's choice of $x_{i,t}$.

The second component is the annual rental-equivalence cost of housing-attribute consumption. This component enters with a negative sign, illustrating that a higher consumption of $x_{i,t}$ reduces the household's consumption of numeraire goods and services.[9] The third component is the adjustment cost. This term takes a value of zero if the household consumes its endowment level of housing attributes. It, too, enters with a negative sign, illustrating that the choice to re-optimize in period t reduces the household's utility.

We write the household's problem as choosing x in each period to maximize the expected discounted sum of per-period flow utilities, which is given by:[10]

$$u^f(x_{i,t}, s_{i,t}) + E\Big[\sum_{\tau=t+1}^{\infty} \beta_i^{\tau-t}\big(u^f(x_{i,\tau}, s_{i,\tau})\big)\Big] \tag{2}$$

where β_i is the household-specific subjective discount factor and captures the household's time preference.

We denote the value function associated with the maximization of Equation (2) as $V(s_{i,t})$,

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[9] If the household gets utility from the presence of an energy-efficient investment in their home (either positive or negative), the net benefit in each period (ignoring adjustment costs) would come from a comparison of $u(x_{i,t}, s_{i,t})$ and $r_2(x_{i,t}, s_{i,t})$ versus the financial calculation of whether $r_2(x_{i,t}, s_{i,t})$ is negative.

[10] For ease of exposition, we specify this problem as an infinite-horizon problem. To write this problem with a finite horizon, one would need to account for the non-stationarity of the problem by making the function $V(s_{i,t})$ itself period-t specific.

and write the Bellman equation as,

$$V(s_{i,t}) = max_{x_{i,t}}\{u^f(x_{i,t}, s_{i,t}) + \beta_i \int V(s_{i,t+1})q(ds_{i,t+1}|s_{i,t}, x_{i,t})\}, \tag{3}$$

integrating out over the transition probabilities of the state variables.

It is convenient to additionally define choice-specific value functions associated with any given value of $x_{i,t}$,

$$v(x_{i,t}, s_{i,t}) = u^f(x_{i,t}, s_{i,t}) + \beta_i \int V(s_{i,t+1})q(ds_{i,t+1}|s_{i,t}, x_{i,t}). \tag{4}$$

This function specifies the household's expected lifetime utility associated with a given choice of $x_{i,t}$. Households choose $x_{i,t}$ to maximize $v(x_{i,t}, s_{i,t})$, i.e.,

$$x^*_{i,t}(s_{i,t}) = argmax_{x_{i,t}}\ v(x_{i,t}, s_{i,t}).$$

We can describe the choice separately by type of housing attribute. The household will choose to invest in an energy-efficient attribute while remaining in the same house (i.e., to adjust $x_{2,i,t}$) if there exists an $x_{2,i,t}$ such that,

$$v(x^e_{1,i,t}, x_{2,i,t}, s_{i,t}) > v(x^e_{1,i,t}, x^e_{2,i,t}, s_{i,t}).$$

Similarly, the household will choose to change their residence (i.e., to adjust $x_{1,i,t}$) if there exists an $x_{1,i,t}$ such that,

$$v(x_{1,i,t}, 0, s_{i,t}) > v(x^e_{1,i,t}, x^e_{2,i,t}, s_{i,t}).$$

This describes the case where the household would choose to move and update their consumption of x_1. In this case, any energy-efficient technologies would be included in x_1 and the move would reset the household's new investments term, x_2 to zero.

3.6 Summary and Discussion of Estimation

In this section, we have presented a comprehensive conceptual framework that unifies the joint decision processes of where (and when) to move and whether (and when) to invest in housing-related energy-efficient technologies. In modeling these choices, we specify a flexible dynamic framework with household-specific heterogeneity in preferences, discount rates, monetary and non-monetary costs, and information sets.

We define a heterogeneous utility function where households receive flow utility (positive or negative) from the presence of the energy-efficient housing attribute. This would capture preferences for being "green" and non-monetary costs of living with an undesirable technology in the home. The degree of concavity of the heterogeneous function allows for the household's risk aversion. Likewise, we define a heterogeneous rental-equivalent function where households amortize the costs of housing attributes (at a household-specific cost of borrowed funds) and reap the financial benefits of energy savings (at a household-specific rate of efficiency). The heterogeneity in this function allows for many of the channels the literature has focused on in describing the efficiency gap – financing rates and the realized efficiency of the technology. We define heterogeneous adjustment costs associated with re-optimizing that include all fixed costs, both monetary and non-monetary. This terms captures the costs in time and hassle associated with installing energy-efficient technologies in the home, as well as any under-capitalization losses upon sale of the house. Importantly, the household's information set and expectations over the transition of the state drives much of the household's decision-making process.

The estimation of the full model as presented here would present a number of challenges. First, the data requirements would be large, as the researcher would need to have access to panel data accurately describing the household's choice set of housing attributes in each period, the household's choice in each period including any investment decisions, and the household's demographic characteristics. In addition, the researcher would need to collect information about the heterogeneous cost of borrowed funds separately for mortgages and investment decisions, information about the transitions of the state variables, as well as information about the household's beliefs.

Second, computational difficulties arise due to the fact that $v(x_{i,t}, s_{i,t})$ is defined recursively. As the state space in this application would be very large, the full model would be computationally costly to solve and estimate using a full-solution, nested fixed-point solution method as in Rust (1987). Modern developments in the dynamic literature, such as Hotz and Miller (1993), Bajari et al. (2007), and Arcidiacono and Miller (2011) facilitate estimation by using choice probabilities estimated directly from the data to circumvent the need to iteratively solve the model. There has been a recent literature in the urban and environmental economics that incorporates these tools. See, for example, Bishop and Murphy (2011), Ryan (2012), Bishop (2013), Bayer et al. (2016), Caetano (2019), Diamond et al. (2019), De Groote and Verboven (2019), Davis et al. (2021), Almagro and Domínguez-Iino (2022), and Bishop and Murphy (2023).

Finally, even with access to rich panel data, there would most likely exist a vast set of descriptives that would remain unobserved to the econometrician. This could present identification challenges, as these unobservables could bias estimates. For example, certain housing attributes may be unobservable leading to omitted variable bias in the estimation of the price function, $r(x_{i,t}, s_{i,t})$ or individual-specific determinants of utility may be unobserved leading to bias in the estimation of $u^f(x_{i,t}, s_{i,t})$.[11]

4 Case Study: Solar Panels in Arizona

An energy-efficient housing attribute that has received considerable attention in the literature is the residential solar system (e.g., Hughes and Podolefsky (2015), Burr (2016), Gillingham

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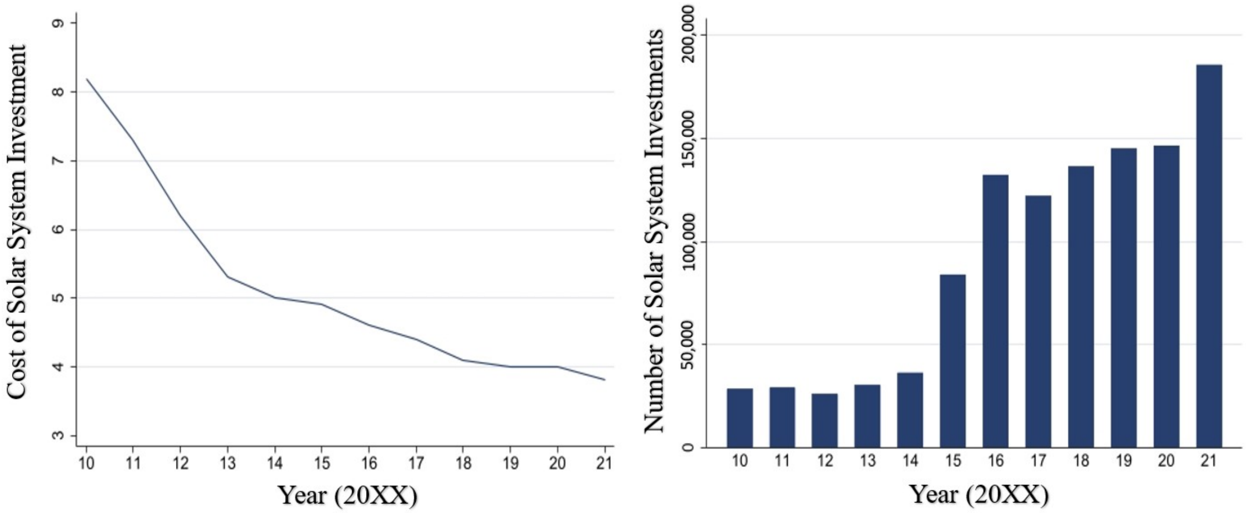
[11] For discussions of identification of utility parameters in the hedonic model, see Brown and Rosen (1982), Mendelsohn (1985), Bartik (1987), Epple (1987), Ekeland et al. (2004), Heckman et al. (2010), and Bishop and Timmins (2019). For discussions of identification of discount parameters in dynamic models, see Rust (1994) and Magnac and Thesmar (2002).

and Tsvetanov (2019), De Groote and Verboven (2019), Snashall-Woodhams (2019), Feger et al. (2022), Langer and Lemoine (2022), and Kiribrahim-Sarikaya and Qiu (2023)). This is a costly investment that is inextricably tied to the household's residence, as it conveys upon sale of the house. Nonetheless, the residential solar market has grown rapidly due to falling prices and government-incentive programs like the Federal Residential Renewable Energy Tax Credit over the past decade, as shown in Figure 1.

Figure 1: Cost and Investment Trends of Residential Solar Systems Between 2010-2021



Note: Data come from the Lawrence Berkeley National Laboratory's Tracking the Sun Database. Cost is measured as the median price per unit of capacity (watt-per-hour) of the system in dollars.

The majority of studies that investigate households' demand for residential solar systems model the decision process as a dynamic problem (e.g., De Groote and Verboven (2019)). These studies assume that households are forward-looking and have rational expectations over future financial returns. The dynamic feature of the decision process comes from high upfront investment costs combined with the time variation in investment costs, government-incentive policies, and energy prices.

Kiribrahim-Sarikaya and Qiu (2023) develops a dynamic discrete-choice model of households' investment decisions and a key contribution of that paper is that it allows for household-level heterogeneity along the observable characteristic of household income. That model includes upfront financial costs and expected future electricity savings. An important distinction from the model laid out in Section 3, is that the investment decision is treated as independent of the location/housing decision. That model does, however, include many of the channels previously discussed.

Using novel household-level data from the Phoenix Metropolitan Area, Kiribrahim-Sarikaya and Qiu (2023) finds that households are responsive to the upfront investment cost, and the effect is highly heterogeneous along the dimension of income. In that paper, the realized value of government incentives is allowed to vary with household income. This allows the authors to match the empirical evidence that low-income households are less likely to receive the full benefits of the incentive. This is because the non-refundable tax credits depend on the household's total tax liability, which is decided by income level.

Kiribrahim-Sarikaya and Qiu (2023) also finds substantial heterogeneity in discount rates along the dimension of household income. For example, high-income households value a \$1 increase in future energy savings more than they value a \$1 decrease in the upfront cost of investment, implying a negative discount rate among this income group. In a more comprehensive framework, these results could also speak to heterogeneous utility flows from the presence of a residential solar system along observable dimensions, in line with the results in Dastrup et al. (2012) that show the home-price premium for a residential solar system is higher in locations with more registered hybrid vehicles, more registered members of the Green Party, and more contributors to environmental organizations. Likewise, Kiribrahim-Sarikaya and Qiu (2023) finds that households get negative utility from the installation of a residential solar system, all else equal. This again suggests non-monetary utility costs, such as the time and hassle costs described in Fowlie et al. (2015).

5 Conclusion

Research in environmental economics has consistently revealed households' sub-optimal levels of investment in energy-efficient housing attributes. And, unlike many housing attributes that only offer benefits privately to the household, these energy-efficient technologies potentially offer environmental benefits publicly by reducing emissions through decreased energy consumption. The presence of this externality channel makes understanding the household's attribute-choice decisions essential for devising appropriate policy measures.

The existing body of literature has provided empirical support for various factors that drive sub-optimal investment in energy-efficient housing attributes, including information gaps, time preferences, and a variety of fixed and marginal costs. In this paper, we aim to consolidate and integrate the literature's findings and present a comprehensive conceptual framework that could be estimated and used to analyze counterfactual policy environments. Our model jointly specifies the related choices of (1) when and where to move and (2) if and when to invest in energy-efficient housing attributes, and could be applied to a number of housing investment decisions.

This theoretical model would, however, present a number of challenges for the econometrician. First, there are few available household-level panel datasets that are sufficiently rich to describe the choice problems. Accessing data describing energy-investment investment decisions and linking it to housing-transaction data is an important next step for the literature. Second, future research is tasked with learning much more about households' information sets regarding energy-efficient housing attributes and households' beliefs about future states of the world, including what drives beliefs about the transitions of the state variables. These are complicated tasks that require either a policy-induced change in information sets or survey methods to elicit beliefs.

We present a case study of the investment in a residential solar system. This application has been modeled by the literature as a dynamic decision process. We focus on Kiribrahim-

Sarikaya and Qiu (2023) that includes household-level heterogeneity with respect to income. The investment decision for a residential solar system, however, has yet not been jointly modeled with the household's housing decision. And, given the large upfront costs of both investment and moving, and the less-than-full housing-market capitalization of the investment (Dastrup et al. (2012), Hoen et al. (2017)), this presents an important challenge for the empirical literature to tackle.

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