

Making the Implicit Explicit: A Look inside the Implicit Discount Rate

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Abstract

Implicit discount rates (IDRs) are employed in energy models to capture household investment decisions, yet the factors behind the IDR and their respective implications for policy-making usually remain blurred and fractional. The proposed comprehensive framework distinguishes three broad categories of factors underlying the IDR for household adoption of energy-efficient technologies (EETs): preferences (notably over time, risk, loss, debt, and the environment), predictable (ir)rational behavior (bounded rationality, rational inattention, behavioral biases), and external barriers to energy efficiency. Existing empirical findings suggest that the factors underlying the IDRs that differ across household characteristics and technologies should be accounted for in energy models. Furthermore, the framework allows for a fresh look at the interplay of IDRs and policies. We argue that a simple observation of high IDRs (or observing correlations between IDRs and socio-economic characteristics) does not provide guidance for policy-making since the underlying sources cannot be identified. Instead, we propose that some of the factors underlying the IDR - notably external barriers - can be changed (through directed policy interventions) whereas other factors - notably preferences and predictable (ir)rational behavior - are innate and can only be taken into account (through reactive policy interventions).

Keywords: energy efficiency, energy modeling, implicit discount rate, energy policy, behavioral economics;

Highlights

- Implicit discount rates (IDRs) reflect preferences, predictable (ir)rational behaviors and external barriers
- The factors underlying the IDRs can be used to design directed and reactive policies
- IDRs in energy models should vary by household and technology characteristics

1 Introduction

Discount rates play a crucial role in model-based policy evaluations such as energy-efficiency policy assessments. Conceptually, two types of discount rates may be distinguished. First, social discount rates, which essentially compare costs and benefits that accrue at different points in time, typically reflect pure time preferences and decreasing marginal utility of consumption or the government's opportunity costs of capital (e.g. the long term return on government bonds) (e.g. Arrow et al., 1996). Second, so-called subjective discount rates govern decision makers' actual adoption behavior. For parameterization of the subjective discount rates, models typically rely on implicit discount rates (IDRs). An IDR is estimated from observed technology adoption choices and net present value calculations as the discount rate that renders the observed technology choice reasonable (Dubin and McFadden, 1984).¹

Starting with the seminal work by Dubin and McFadden (1984), Hausman (1979), and Train (1985), the empirical literature on household energy technology adoption decisions has found IDRs to typically exceed the opportunity costs of capital. Unlike social discount rates, IDRs also reflect external “barriers to energy efficiency” such as imperfect information, capital constraints or the landlord-tenant (split-incentive) problem. As recognized by Jaffe and Stavins (1994), high IDRs are more of a restatement than the source of the so-called “energy-efficiency paradox”, which postulates that decision makers may fail to invest in energy-efficient technologies (EETs) even though these appear to pay off under prevailing market conditions.² In any event, since IDRs are derived from EET adoption

¹ To illustrate, suppose an energy efficient technology has upfront costs of 120 Euros and annual operating costs of 20 Euros. Yet the consumer decides to purchase an alternative technology with upfront costs of 100 Euros, and annual operating costs of 50 Euros. For simplicity, assume the lifetime of either technology is one year. In this case, the implicit discount rate which explains the adoption of the alternative technology would be $0.5 = (50 - 20) / (120 - 100) - 1$.

² Note that the “energy-efficiency paradox” differs from the “energy efficiency gap” (e.g. Gerarden et al., 2015b). The “energy efficiency paradox” refers to the notion that some energy-efficiency technologies that would be profitable for adopters are nevertheless not adopted. In comparison, the “energy-efficiency gap” means that adoption is lower than socially optimal, e.g. because energy prices do not adequately reflect environmental externalities.

behavior (i.e. IDRs are estimated to be higher when EET adoption is lower), there is a direct link between empirical results obtained about EET adoption and IDR estimates used in models.

Clearly, the two types of discount rates serve very different purposes; yet this distinction is often not made in actual model-based policy assessments. This problem has been recently noted by Hermelink and Jager (2015) and Steinbach et al. (2015), among others, within the discussion of the energy efficiency target in EU's 2030 energy and climate policy framework and the corresponding impact assessment (European Commission, 2014a).³ While there is an extensive body of literature discussing the social discount rate (e.g. Stern, 2006; Nordhaus, 2007), the factors behind the implicit discount rate and their respective implications for policy making usually remain blurred and fractional. In this paper, we aim to contribute to closing this gap. We present a comprehensive framework of the underlying factors of the IDR for household adoption of EET, relying in particular on insights from the behavioral economics literature. More specifically, our framework distinguishes three broad categories of factors underlying the IDR: (i) preferences such as time preferences, risk preferences, reference-dependent preferences and pro-environmental preferences; (ii) predictable (ir)rational behavior, i.e. bounded rationality, rational inattention, and behavioral biases, such as present bias or status quo bias; and (iii) external barriers to energy efficiency such as split incentives, lack of information or lack of capital (e.g. Sorrell et al., 2004).

After describing these underlying factors, we illustrate through selected examples the effects of covariates such as household and technology characteristics on the IDR at the factor level. By combining established concepts from various disciplines, our framework organizes notions around the IDR in a novel way, provides insights into the interplay of IDRs and policy interventions, and offers guidance for improved energy modeling and policy assessment. While all policies aim at lowering the IDR, this framework distinguishes between directed and reactive policies. Directed policies aim at directly lowering

³ Since they are substantially higher than social discount rates, applying IDR rather than social discount rates typically leads to less ambitious energy efficiency targets.

the external barriers (e.g. mandatory building certificates addressing split-incentives). Reactive policies take into account the factors underlying the IDR that cannot be changed such as preferences (e.g. offer loans with fixed interest rates to risk-averse household with a high time discount rate).

The remainder of our paper is organized as follows. Section 2 presents our framework for categorizing the factors underlying the IDR in a comprehensive manner. This section also documents the findings from the literature on the correlation of these factors with selected household and technology characteristics. Based on this framework, Section 3 explores the interplay of policy interventions and the IDR. The concluding Section 4 summarizes the main findings, points to future research, and highlights the contributions of the paper for conceptual underpinning of the IDR, policy making, and modeling household adoption of EETs.

2 Framework

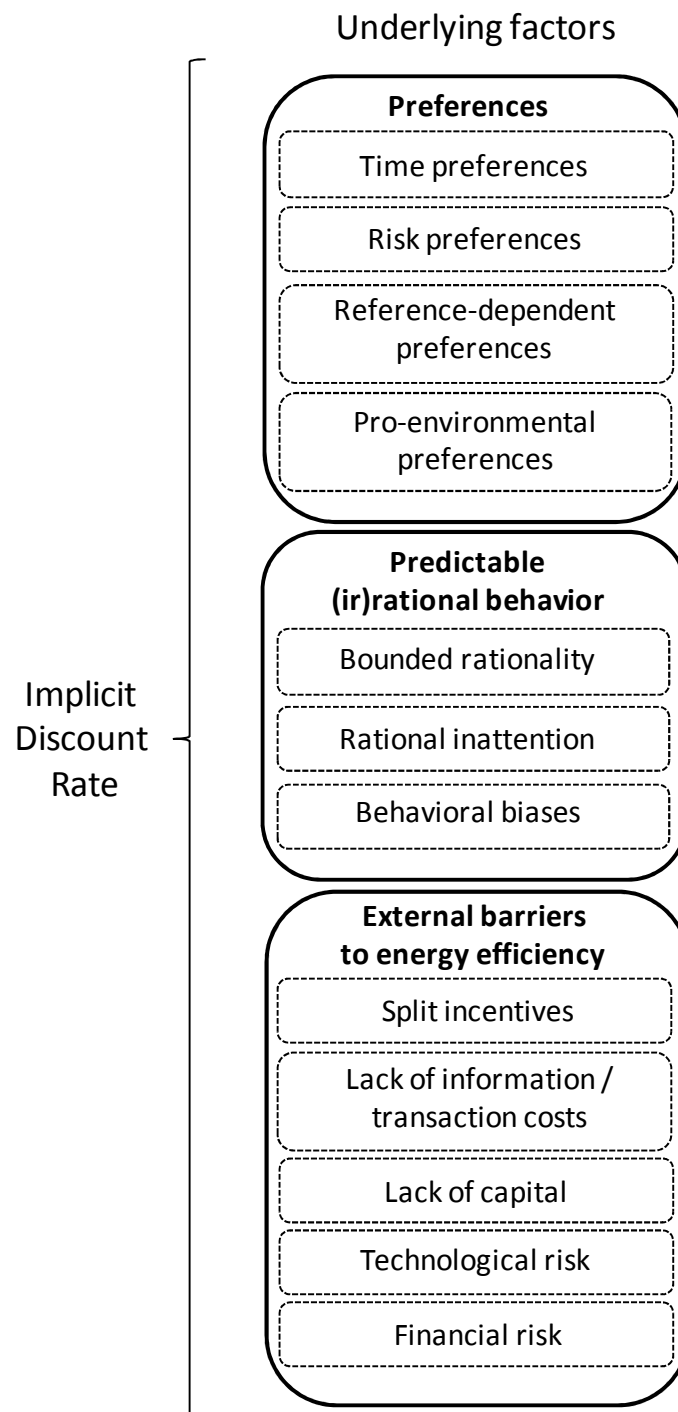
Studies that empirically estimate the IDR for the adoption of EETs, based on observed behavior in private households (e.g. Train, 1985 for an early review), find that the IDRs vary substantially across technologies, but also within similar technology classes. For example, the IDRs for refrigerators range from 34% (Hausman, 1979) to 300% (Meier and Whittier, 1983). Similarly, for an oil-based heating system, IDRs are estimated to be as low as 14% (Corum and O’Neal, 1982) and as high as 127% (Ruderman et al., 1987). Clearly, these figures are higher than the costs of capital, i.e., the rates at which households can borrow money.⁴ The previous empirical literature (e.g. Train, 1985) and modelers (e.g. E3MLab/ICSS PRIMES, 2014) casually note that certain factors, such as barriers to energy efficiency, help explain this difference. The more conceptual literature focuses on factors explaining the “energy efficiency paradox”, thus highlighting external barriers to energy efficiency (e.g. Brown, 2001; Sathaye et al., 2001; Sorrell et al., 2004), emphasizing the distinction between market failures and external barriers (Jaffe and Stavins 1994), or concentrating on behavioral factors (Gillingham et al., 2009; Gillingham and Palmer, 2014). Since the objective of this conceptual literature was not to explain the IDR, it only offered a partial picture, and typically neglected the role of consumer preferences. Consequently, a comprehensive framework of the factors underlying the IDR and their implications for modeling and policy interventions has not yet been presented.

Figure 1 provides a graphical representation of our proposed framework for looking inside the IDR, which includes as overarching factor categories (i) preferences, (ii) predictable (ir)rational behavior, and (iii) external barriers to energy efficiency.⁵ These will be discussed in more detail below.

⁴ More recent studies eliciting IDRs tend to rely on stated (rather than observed) behavior, thus limiting the comparability of findings. Yet those studies also find IDRs to vary substantially and to exceed market interest rates (e.g. Min et al., 2014; Newell and Siikamäki, 2015; Revelt and Train, 1998).

⁵ *Ceteris paribus*, the total size of the IDR depends on the difference in upfront investment costs between the adoption of an EET and an alternative technology, on the difference in operating costs, and on how these are distributed over time. But these differences do not explain the energy efficiency paradox and are neglected in the subsequent discussion.

Figure 1: Factors underlying the implicit discount rate



2.1 Preferences

The first category of factors in our IDR framework reflects individual preferences, which are assumed to govern individual choice between alternatives. In particular, we focus on preferences for time, risk, and the environment, as well as on reference-dependent preferences.

2.1.1 Time preferences

Time preferences reflect how individuals value the future relative to the present. The rate at which individuals discount the future is what economists generally understand as the “discount rate” when modeling investment behavior. In these models, time preferences are typically captured by an exponential discount function, with a single parameter describing the discount rate. Since the adoption of EET usually includes an investment followed by dispersed gains in the future, an individual’s decision to invest in EET should depend on individual time preferences. While the relationship between discount rates and behavior has been explored in the literature for different domains (e.g. Nyhus and Webley, 2006), few studies analyze EET adoption. In particular, Newell and Siikamäki (2015) link individual differences in time preferences to investment in EET and find that more patient households are also more likely to adopt energy-efficient water heaters. However, for a variety of other energy-saving measures, Bradford et al. (2014) and Bruderer Enzler et al. (2014) do not find consistent effects of time discounting.

2.1.2 Risk preferences

Risk preferences may affect the adoption of EET, because the decision entails various aspects of uncertainty. Since the profitability of EETs hinges on several uncertain factors, such as future energy prices, technology performance (and reliability), or regulation (e.g. tax rates, CO₂-prices), risk has long been thought to impede EET adoption (Hirst and Brown, 1990; Shama, 1983). Thus, greater risk aversion results in higher IDRs, *ceteris paribus*. Risk preferences have frequently been found to affect the adoption of new technologies in other contexts (e.g. Liu, 2013; Tsur et al., 1990). The scant empirical literature on risk and EET adoption also suggests that more risk-averse households are less likely to adopt energy-efficient ventilation and insulation systems (Farsi, 2010) and light bulbs (Qiu et al., 2014).

Ambiguity

In situations involving risk, a decision maker is able to attach objective probabilities to all possible events. Yet, real life decisions rarely entail objective probabilities, especially when they involve unfamiliar choices. Thus, preferences over *ambiguity* may better reflect individuals' adoption of novel EETs in particular, such as LEDs or modern ventilation systems.⁶ The stronger the preferences to avoid ambiguity are, the higher the IDR. For investment decisions in other domains, including farming (Bougherara et al., 2012), ambiguity preferences have been found to be relevant and to differ from pure risk preferences. However, to the best of our knowledge, ambiguity preferences have not yet been empirically explored for EET adoption.

Prudence

Risk aversion reflects individuals' preferences on variance of outcome; prudence describes the preferences on skewness of outcome and is a key concept when analyzing behavior under risk.⁷ The concept is best explained with an example. Imagine a household has to choose between two retrofit measures, A and B. The total lifetime benefit of these measures depends on initial investment costs and energy cost savings over time; the energy cost savings depend on future fuel costs, which are uncertain. Suppose that Retrofit Measure A has higher initial investment costs than B, but higher energy costs savings over time. A has lifetime benefits of 0€ with a probability of $\frac{1}{4}$ and of 2,000€ with the probability of $\frac{3}{4}$; B has lifetime benefits of 1,000€ with a probability of $\frac{3}{4}$ and of 3,000€ with a probability of $\frac{1}{4}$. These two retrofit measures have the same mean and variance, but B is more skewed to the right, while A is more skewed to the left. Even though A may seem "riskier" (it is said to have more "downside risk"), pure risk aversion cannot explain a preference of B over A. The preference for B is described by prudence, or an aversion to downside risk. Prudence has been shown to explain individuals' decisions in laboratory

⁶ Technically, ambiguity differs from risk by the absence of objective probabilities. It is a more general concept that includes risk as a special case.

⁷ More formally, risk aversion refers to the second derivative of the utility function, while prudence refers to the third derivative of the utility function. Prudence is also a necessary condition for decreasing absolute risk aversion, a commonly accepted assumption in behavioral economics.

experiments quite well (Ebert and Wiesen, 2014) but has not yet been considered in an EET adoption context.

2.1.3 Reference-dependent preferences

Individuals typically do not evaluate benefits associated with outcomes of choice in absolute terms, but relative to reference points. A prime example is *loss aversion*, i.e., the notion that losses relative to a reference point are evaluated more strongly than gains of equal size, i.e. "losses loom larger than gains". Loss aversion was first proposed by Kahneman and Tversky (1979) in the framework of prospect theory. Loss aversion helps resolve the criticism of expected utility put forward by Rabin and Thaler (2001) and Rabin (2000) who show that reasonable degrees of risk aversion for small and moderate investments (stakes) imply unreasonably high degrees of risk aversion for large stakes. Loss aversion is relevant to the adoption of EET if the (additional) costs of investing in EET are evaluated as a loss. In this case, individuals may refrain from engaging in otherwise profitable investment projects because they over-weight the losses associated with them. Thus, loss aversion is likely to increase the IDR, but has not yet been explored empirically in the context of EET adoption. Other forms of reference-dependent preference may also affect decisions to invest in EET. For example, individuals may evaluate their own decisions relative to others, and be more willing to adopt EET if their reference group (e.g. neighbors or colleagues) decides to adopt ("keeping up with the Joneses"). Such social preferences have been shown to cause significant reductions in electricity and natural gas consumption (see for instance Allcott, 2011; Ayres et al., 2012; Nolan et al., 2008; Schultz et al., 2007).

2.1.4 Pro-environmental preferences

Lower energy use typically leads to lower resource use and lower emissions of local and global pollutants, in particular of the greenhouse gas CO₂. Thus, EET adoption may also be driven by pro-environmental preferences (or attitudes). While conventional economic theory predicts that individuals have virtually no incentive to voluntarily contribute to the

provision of public goods like climate protection (e.g. Holländer, 1990), there is substantial evidence that individuals do contribute to environmental protection.⁸ Frey and Stutzer (2008) distinguish four motives to explain this.⁹ First, individuals may exhibit *pro-social preferences* (altruism). Second, individuals may follow *social norms* for pro environmental behavior, thus avoiding social disapproval (Cialdini, 2007; Goldstein et al., 2008). Third, individuals may follow *internalized individual norms*, thus avoiding negative self-evaluations such as feelings of guilt or lower self-respect (Black et al., 1985). Finally, because of intrinsic motivation such as “warm glow” (Andreoni, 1989), individuals may get inherent satisfaction of the activity itself. Both internalized individual norms and intrinsic motivation are derived from individual values. In practical applications it is difficult to disentangle the relevance of the separate motives which tend to vary by context and individual. Most empirical studies exploring the impact of pro-environmental preferences on EET adoption rely on (stated) environmental attitudes. Environmental attitudes have been found to be positively correlated with the adoption of inexpensive measures like light bulbs (Di Maria et al., 2010; Mills and Schleich, 2014), but appear less relevant for predicting more expensive investments like thermal retrofit (e.g. Ramos et al., 2015; Whitmarsh and O’Neill, 2010), thus suggesting a trade-off between financial and environmental concerns. In a similar way, the so-called “low-cost hypothesis” from the social science literature argues that individuals prefer to satisfy their environmental conscience with low-cost measures, which may in actuality have little effect on the environment (Diekmann and Preisendörfer, 1998, 2003; or Whitmarsh 2009).

2.1.5 Summary on the role of preferences

To summarize, impatience, risk aversion, ambiguity, loss aversion, and prudence all increase the IDR, while pro-environmental preferences lower the IDR. If pro-environmental preferences are sufficiently strong, they may even render the IDR negative.

⁸ Adoption of EET constitutes an impure public good, reflecting properties of a private good (providing energy services) and a public good (e.g. lowering greenhouse gas emissions).

⁹ See Wilson and Dowlatabadi (2007) for an overview of different social science concepts including conventional and behavioral economics, psychology and sociology.

Of course, preferences are more comprehensive and may also include other factors than those considered. For example, *debt aversion* is expected to be a particularly relevant concept in the context of EET adoption. Debt aversion refers to the idea that people may intrinsically dislike being in debt, and thus forgo otherwise profitable investment projects, if they need to be financed with credit. Debt aversion has recently been found to affect individuals' decisions to pursue a higher education degree (Eckel et al., 2007; Field, 2009) and life-cycle consumption and saving decisions (Fenig et al., 2013; Meissner, 2016). Since the financing of capital-intensive investments in EET (such as thermal insulation or a new heating system) may require households to rely on credit, debt aversion may inhibit the adoption of EET (even in the absence of credit market failures). Thus, debt aversion would lead to a higher IDR, but has not been explored in the context of EET adoption.

In any case, conventional economics assumes that individuals make rational choices based on their preferences. This assumption will be challenged by the factors underlying the IDR considered next.

2.2 Predictable (ir)rational behavior

The second category of factors in our IDR framework comprises of bounded rationality, rational inattention and behavioral biases, and may lead to systematic deviations from rationality when making investment decisions, and thus impact observed implicit discount rates.

2.2.1 Bounded rationality

Because of cognitive limits, individuals are constrained in their ability to compute, process, and evaluate information. Bounded rationality is the notion that individuals behave optimally *given* these constraints. Thus, bounded rationality may lead to sub-optimal technology choices even if individuals have all of the available information (Simon, 1959; Stern, 1986). Instead of processing this information thoroughly, individuals rely on rules of thumb (heuristics) that facilitate decision making. For example, households may just

consider the purchasing price rather than total lifetime costs when choosing a new appliance. While in principle, bounded rationality may increase or decrease the IDR, the empirical literature suggests that bounded rationality mostly impedes the adoption of EETs, i.e. increases the IDR (Gerarden et al., 2015a; Gillingham and Palmer, 2014).

2.2.2 Rational inattention

Closely related to the concept of bounded rationality is rational inattention. For example, consider the decision to buy a light bulb for a room that is rarely used. Calculating the costs and benefits for this simple decision is extremely cumbersome, involving estimating the remaining lifetime of the old light bulb, usage, the development of electricity prices, etc. Due to the relatively low cost of a light bulb, it might not be worthwhile to actually conduct such a cost benefit analysis (because of the opportunity costs of time and effort). As a consequence, individuals may rationally decide to only update their information irregularly (Allcott, 2013; Reis, 2006). Sallee (2014) argues that inattention to energy efficiency may indeed be rational in the market for home appliances and automobiles. Depending on which information is not paid attention to, rational inattention may affect IDRs positively or negatively; extant research suggest however that it generally leads to larger IDRs. Overall, rational inattention may be hard to distinguish from bounded rationality but we keep them separate because they have different policy implications.

2.2.3 Behavioral biases

Based on concepts from psychology and behavioral economics, a (non-exhaustive) set of anomalies of individual behavior can be identified, which an emerging literature has started to analyze in the energy efficiency domain (e.g. Allcott and Mullainathan, 2010; Allcott, 2011).¹⁰ Generally, any behavioral anomaly can be due to non-standard preferences or due to behavioral biases. In the following, we classify a behavioral anomaly as a bias (as opposed to preference), if choice is affected unconsciously by it, if individuals

¹⁰ See also Ramos et al. (2015) for a collection of behavioral biases.

who are conscious of a bias would want to change their behavior, or if welfare can be improved by accounting for and reacting to a particular bias.¹¹

Status quo bias

Status quo bias refers to the empirical observation that individuals tend to stick with the status quo even if changing behavior would be preferable. Most prominently, individuals adhere to (externally set) defaults. As evidenced by Madrian and Shea (2001) participation in retirement plans increases dramatically if the default is set to participation. Likewise, Abadie and Gay (2006) find that organ donorship is higher in countries where donating is the default compared to countries where donating is not the default. Thus, the status quo bias tends to increase the IDR. The few applications in the context of energy efficiency include Brown et al. (2013), who find that setting defaults for thermostats (slightly) lowers the average temperature in an OECD office building.

Present bias

A vast body of literature in experimental psychology and experimental economics, including Laibson (1997), Loewenstein and Prelec (1992), and Thaler (1991), has documented that individuals tend to systematically overvalue the present compared to the future by an amount that cannot consistently be explained with exponential discounting (typically assumed in classical economic theory). This present bias is typically modeled with a (quasi) hyperbolic, rather than an exponential discounting function (Ainslie, 1974; Laibson, 1997). As an illustrative example of present bias, consider the choice between €100 today and €150 a year from today. Many people will prefer the €100 today, but when facing the choice between €100 in four years and €150 in five years, almost everyone will prefer €150 in five years. In effect, present-biased individuals behave time-inconsistently. For example, they plan to quit smoking, or to start a diet, but continuously

¹¹ If a certain behavioral "anomaly" is due to preferences, then trying to counteract this anomaly will generally not be welfare improving. For example, if a debt-averse person is forced to take on a loan to invest in EET, this person's welfare will not be higher compared to the situation without intervention.

defer acting upon, even when recognizing that this would be beneficial. Clearly, a present bias would lead to a higher IDR. Only few studies have explored the effects of present bias in the context of EET. For automobile purchases, Allcott and Wozny (2014) find evidence for a small present bias, while Busse et al. (2013) conclude that there is no present bias. The results of Cohen et al. (2015) suggest that present bias moderately impedes the adoption of energy-efficient refrigerators.

Probability distortion

Individuals have been found to distort objective probabilities in their subjective probability assessment (Kahneman and Tversky 1979). More specifically, they tend to over-weight small probabilities and to under-weight high probabilities of events. While probability distortion may explain real life decisions like buying lottery tickets, its relevance has not been explored in the context of EET adoption. For example, the IDR would be higher if individuals over-weighted the probability of technology failure for EET or under-weighted the probability of energy cost savings. Probability distortion which has been found to impede the adoption of new technologies in other domains (e.g. Liu, 2013) has not yet been explored in the context of EET adoption.

2.3 External barriers to energy efficiency

While preferences and predictable (ir)rational behaviors may be classified as internal barriers to energy efficiency, the third category of factors underlying the IDR in our framework captures barriers which are external to the decision maker and depend on institutional settings. According to Sorrell et al. (2004), barriers to energy efficiency may be defined as mechanisms inhibiting the adoption of profitable EET (Sorrell et al., 2004). Over the last two decades, an extensive literature has explored barriers to energy efficiency and produced different taxonomies, typically developed from various (partially overlapping) disciplinary concepts (Gerarden et al., 2015b; Gillingham and Palmer, 2014; Jaffe and Stavins, 1994; Sorrell et al., 2004, Brown, 2001; or Sathaye et al., 2001). Evidently, barriers to energy efficiency increase the IDR. We only briefly document the main

barrier types and related empirical findings, since these are rather well-known to the literature, and are organized in similar taxonomies (e.g. Brown, 2001; Sathaye et al., 2001; Sorrell et al., 2004).

Split incentives

Because of split incentives, investments in profitable EETs are likely to be foregone if actors cannot appropriate the benefits of the investment, as in the landlord-tenant problem. Since the landlord pays for insulation, but the tenant benefits from a smaller energy bill, the landlord has no financial incentive to invest in insulation, unless the landlord can pass on the extra costs through the rent. Empirical findings confirm that owner-occupied homes are more likely to adopt insulation measures (e.g. Ameli and Brandt, 2015; Gillingham et al., 2012; Krishnamurthy and Kriström, 2015; Scott, 1997) and energy-efficient appliances (Ameli and Brandt, 2015; Davis, 2011; Krishnamurthy and Kriström, 2015; Mills and Schleich, 2010a), but not energy-efficient light bulbs (Mills and Schleich, 2014, 2010b).

Lack of information and transaction costs

Lack of information about EET and cost-savings potential has also been found to inhibit adoption (Palmer et al., 2012). Similarly, transaction costs for gathering and analyzing information about EET, energy consumption, or profitability may be a barrier. For thermal insulation measures, these may include costs for installing sub-metering devices.

Technological and financial risks

If households cannot get access to credit or can only borrow money at high costs (e.g., because they cannot provide collateral, or because of credit market failures), *lack of capital* may become a barrier to the adoption of EET with high upfront costs. In section 2.1.2, we already highlighted the implications of technological and financial risks for the IDR. Barriers may also interact with factors from other categories: the financial risk barrier will be more relevant for decision makers with higher risk aversion than for decision makers

with lower risk aversion. In addition, individual factors underlying the IDR may be correlated. For example, more risk-averse individuals have been found to have less patience (e.g. Anderhub et al., 2001).

Errors in the measurement of costs and benefits

Our discussion so far assumes that – as is typically implied in engineering-economic models – EET and non-EET are perfect substitutes, providing identical services to the adopter (e.g. identical quality, comfort, etc.). Some barrier taxonomies also include “*hidden costs*” as a barrier (e.g. Sorrell et al., 2004), arguing that these additional costs of EET adoption are hidden to the observer, but not to the decision maker. Thus, hidden costs (or benefits) may not be adequately quantified in engineering-economic investment appraisals. In essence, hidden costs reflect errors in the measurement of costs and benefits. Examples include perceived inferior lighting quality of compact fluorescent light bulbs compared to incandescent bulbs, or cavity wall insulation causing damp. By the same token, adopting EET may generate hidden benefits, such as with LED light fixtures, which can more effectively improve air sealing for recessed lighting due to their proper-sealing feature. Likewise, double or triple glazed windows not only reduce heating needs in the winter and cooling needs in the summer, but may also lower noise transmission. Thus, unless properly accounted for, these hidden costs (or benefits) may bias the IDR upward or downward.¹²

2.4 Covariates of underlying factors of the IDR

The IDRs implemented in energy models to govern household investment decisions are based on the scant empirical literature, which estimates IDRs based on observed technology choices (e.g. Hausman, 1979). In particular, the IDRs implemented typically do

¹² Accounting for “hidden costs” and heterogeneity across users (see Section 2.4) may explain a substantial part of the “energy efficiency paradox” (e.g. Sorrell et al. 2004, Gillingham et al. 2009).

not vary by household type or technology. For example, PRIMES, the leading model employed by the European Commission for EU energy policy assessment, uses a fixed subjective discount rate of 17.5% for all technology choices made by a representative household (European Commission, 2014a).

It is intuitively clear that IDRs should be adjusted to account for household or technology differences. However, such adjustments are not straightforward, because household or technology characteristics may affect different underlying factors of the IDR differently. Analyzing how the underlying factors of the IDR (rather than the aggregate IDR) vary with household or technology characteristics allows for a better understanding of the observed variations in the IDR, and is expected to offer additional insights for modeling investment behavior in energy models. To illustrate this point, we summarize the literature on some of the most commonly used household and technology characteristics.

Household characteristics

The impact of income on IDR is often discussed. Hausman (1979) and Train (1985) argue that IDRs vary inversely with income, thus suggesting heterogeneity across households by income. The empirical literature typically finds that richer households have more patience (e.g. Newell and Siikamäki, 2015; Tanaka et al., 2010) and are unlikely to be highly risk-averse (Binswanger 1980, 1981; Tanaka et al., 2010; Wik et al., 2004). Richer households also tend to be associated with stronger pro-environmental preferences (e.g. Franzen, 2003; Torgler and García-Valiñas, 2007) and adoption of EETs (e.g. Michelsen and Madlener, 2012; Mills and Schleich, 2010a, 2014; Ramos et al., 2015). Thus, observing an inverse relationship between the IDR may not be meaningful since it may stem from richer households being more patient, less risk-averse or exhibiting stronger pro-environmental preferences, for example. A qualitatively similar argument can be made for other household covariates like education, age, or gender.

Technology characteristics

In addition to household characteristics, IDRs are also likely to vary by technology characteristics. Poortinga et al. (2003) stress that individual preferences generally differ by technology type. Weber et al. (2002) suggest that individual risk attitudes vary by context. To illustrate, we consider two aspects of technology: novelty and stakes.

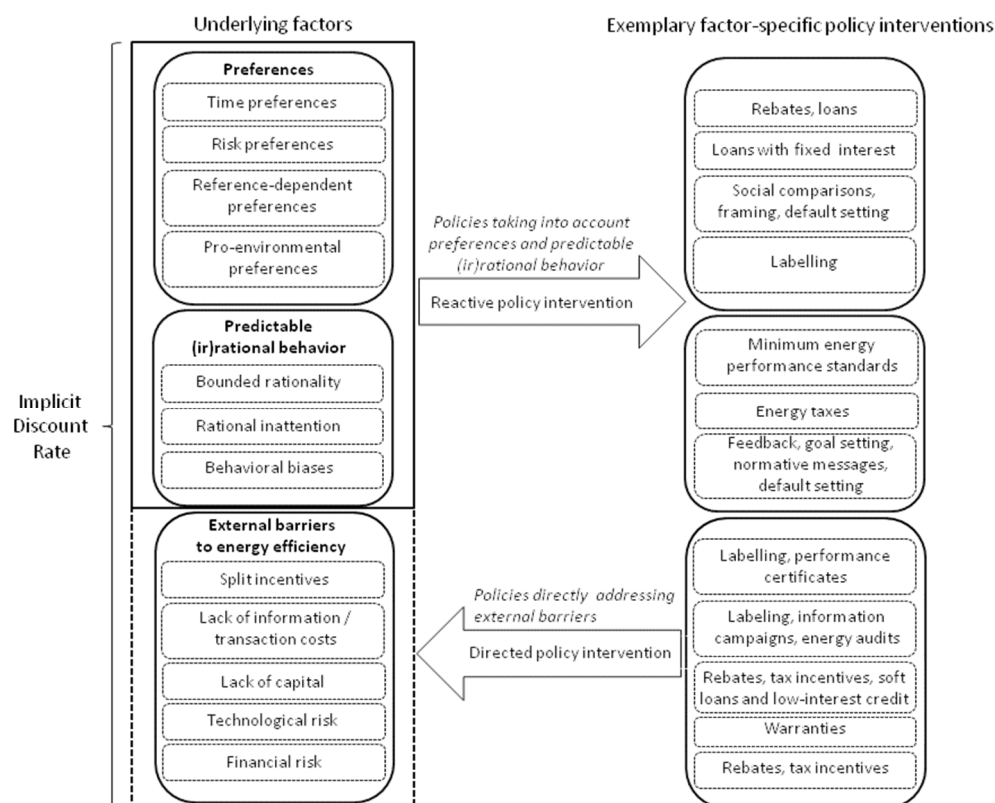
As discussed in Section 2.3, uncertainty about the costs and benefits of EETs may be an external barrier to energy efficiency for novel technologies (see also Hassett and Metcalf, 1993; Van Soest and Bulte, 2001). In addition, for irreversible investments like insulation measures, there is an option value associated with postponing adoption (Dixit and Pindyck, 1994; McDonald and Siegel, 1986). Thus, risk-aversion should be negatively correlated with the adoption of novel and irreversible EETs, in particular (e.g. Farsi, 2010). In addition, the behavioral economics literature suggests that risk and time preferences differ by stakes: risk aversion tends to increase when stakes are higher (Binswanger, 1981; Holt and Laury, 2002), as does patience (Frederick et al., 2002). This literature therefore suggests that the degree of novelty and the financial stakes of the technology will affect different underlying factors of the IDR differently; understanding these effects will allow for better model adoption in energy models.

Aside from household and technology characteristics, the IDR is also related to policies. The relationship between policy interventions and the IDR will be explored in depth in the subsequent section.

3 Interplay of Implicit Discount Rate and Policy Interventions

Since energy models are typically employed in energy policy assessment, adequately capturing and interpreting the effects of policies on the IDR is crucial. Effective energy efficiency policies can be designed which lower the IDR. We distinguish between two types of interventions. First, directed policy interventions address the factors of the IDR that can be changed, that is, the external barriers to energy efficiency. Second, reactive policy interventions take into account the factors of the IDR that either cannot be changed or are difficult to change, that is preferences, bounded rationality, rational inattention and behavioral biases. This presumption follows from economics, which supposes that preferences are innate and cannot be affected by policy interventions. In contrast, psychology and consumer behavior theory treat preferences as malleable. Figure 2 illustrates the interplay of policies and the IDR providing illustrative, yet typical policies addressing each underlying factor.

Figure 2: Interplay of policy interventions and the implicit discount rate



3.1 Directed policy interventions

Our subsequent discussion focuses on exemplary directed policy interventions which are typically in place in the EU and other industrialized countries (e.g. ODYSSEE-MURE, 2015).

In this section, we first discuss two examples of policies directed towards specific underlying factors of the IDR, before discussing more generally the implications of directed policy interventions for energy models and policy evaluation.

Financial support.

In particular, rebates, tax incentives, soft loans and low-interest credit may help overcome capital market constraints. Rebates have been particularly effective for household appliances (e.g. Datta and Filippini, 2016; Datta and Gulati, 2014; Davis et al., 2014; Galarraga et al., 2016, 2013; Houde and Aldy, 2014; Revelt and Train, 1998). Soft loans and low-interest credit are expected to foster investments in energy-efficient heating systems or thermal insulation (e.g. Bullier and Milin, 2013; Guertler et al., 2013).

Provision of information

Energy labeling systems, such as the US Energy Star or the EU labeling scheme, are typically designed to make consumers aware of the relative energy-efficiency of appliances and associated potential cost savings through the provision of observable, uniform, and credible standards (e.g. Truffer et al., 2001). In this sense, energy labeling schemes are often considered to be a cost-effective measure to overcome external barriers related to lack of information and other transaction costs (Howarth et al., 2000; Sutherland, 1991). Evaluation studies typically find that the existing energy labeling programs for household appliances are effective in terms of energy and carbon reductions (e.g. Banerjee and Solomon, 2003; Bertoldi, 1999; Houde and Aldy, 2014; Sanchez et al., 2008). Similarly, building performance certificates have been shown to effectively reduce the lack of information and split-incentive barriers, with energy-labeled dwellings achieving higher rents or higher sale prices (Brounen et al., 2013; Fuerst et al., 2013). Finally,

(subsidized) energy audits are also expected to help overcome information-related barriers to energy efficiency. Most empirical findings confirm that such audits are effective (Hirst et al., 1981; Frondel et al., 2013; Alberini and Towe, 2016).

Implications for energy models and policy evaluation

When assessing the impacts of directed policy interventions, modelers need to know the effect of a particular policy on the magnitude of the IDR, thereby taking into account that the external barriers and hence policy effectiveness may vary with individual characteristics. For example, capital market imperfections are less prone to affect investment decisions of high-income compared to low-income households. Thus, high income-households are less likely to respond to policy interventions addressing lack of capital. Similarly, highly educated households are less prone to lack of information, since higher education is expected to reduce the costs of information acquisition and improve information processing (Schultz et al., 1975). From this perspective, highly educated households would be less likely to change EET adoption behavior in response to information campaigns, for example. Finally, the financial risks of an EET investment may be higher for older people. The risk of not living long enough to recuperate the high upfront costs associated with lower energy costs in the long run increases with age. In addition, policy effectiveness differs across individuals because individuals differ in terms of preferences and predictable (ir)rational behavior. This point will be elaborated on in the subsequent subsection.

Clearly, a particular policy intervention may be employed to address various external barriers and other underlying factors of the IDR. In addition, since a single policy intervention may typically not be effective in addressing multiple barriers, multiple policy interventions will be required (e.g. Jochem and Gruber, 1990). There may also be interaction effects between policy interventions, i.e. policies may weaken or strengthen the effectiveness of other policies. For example, Newell et al. (1999) found that energy taxes will be more effective when applied together with other policies such as performance standards or labelling.

3.2 Reactive policy interventions

Akin to the discussion of directed policy interventions, space constraints limit our discussion to exemplary reactive policy interventions. Similarly, we first present here two examples of reactive policies that take into account specific underlying factors of the IDR, before discussing more generally the implications of reactive policy interventions for energy models and policy evaluation.

Minimum energy performance standards

Minimum energy performance standards (MEPS) are command-and-control type policies that remove the worst performing appliances from the markets. Thus, by limiting technology availability, MEPS address, in particular, bounded rationality and rational inattention. Most prominently, in the EU and other countries, MEPS have resulted in a gradual phase-out of non-directional incandescent light (IL) bulbs. Mills and Schleich (2014) find that the EU ban on ILs was effective in accelerating the transitions from ILs to more energy efficient CFL and LED bulbs.

Nudging

So called nudging policies have lately become fashionable in various policy domains, including energy efficiency policy. Nudging policies are non-coercive, paternalistic interventions, which attempt to change behavior (here: increase the adoption of EET) by manipulating the framing of a decision problem. Thus, nudging policies take into account behavioral biases and preferences, yet they do not attempt to change them. Nudging policies generally include feedback, goal setting, normative messages or default setting (e.g. Croson and Treich, 2014; Abrahamese et al., 2005, 2009; McCalley and Midden, 2002; Schultz et al., 2007). Feedback on electricity use is typically transmitted via monthly or yearly energy bills or via modern information and communication technologies in combination with smart metering. Providing households with information on their electricity consumption has generally been found to be effective (e.g. Wilhite and Ling, 1995; Ehrhardt-Martinez 2010; Glerup et al., 2010; Gans et al., 2012; Schleich et al., 2013). Abrahamse et al. (2005) conclude that in general, feedback is particularly effective when

it is combined with information on energy-efficient measures. In her review of field studies, Fischer (2008) concludes that the effectiveness of feedback on household electricity consumption depends on frequency (ideally real-time energy use), the level of disaggregation (ideally appliance-specific breakdown), duration (the longer the better), and the presentation of the information (understandable, appealing design). But the effects of feedback may be transitory only (Allcott, 2011), and may backfire for households with below-average usage (Allcott, 2011), in particular, if households are politically conservative (Costa and Kahn, 2013; Gromet et al., 2013). Default setting “exploits” reference dependency of preferences and has been shown to work well in other areas (outside of EET adoption), including online purchases or activations, with a pre-checked option that requires a consumer to actively uncheck the option (e.g. Carroll et al., 2009; Madrian and Shea, 2001). However, there are only few known applications of default settings to energy efficiency. Notably, a field experiment by Brown et al. (2013) implies that office workers respond to defaults settings for thermostats. Finally, providing information via labeling tackles bounded rationality and rational inattention on the part of technology purchasers, and may also be classified as a nudging strategy (e.g. Newell and Siikamäki, 2013).

Implications for energy models and policy making

As was the case for directed policy interventions, modelers also need to know the change in the IDR in response to the reactive policy interventions. By definition, evaluations of reactive policy interventions must take into account differences in preferences or predictable (ir)rational behavior across individuals. For example, tax incentive programs that anticipate tax reductions in the distant future (e.g. over several years) are more appealing to patient investors (with a lower time discount rate). A similar argument holds for investment subsidies, which are often spread out over several years. In comparison, less patient and more risk-averse investors are expected to favor contracting schemes since these schemes do not require initial outlays and allow for rather stable payments over time. Similarly, risk-averse investors are expected to be more likely to participate in soft loan programs involving fixed rather than variable interest rates, or respond to warranty schemes. However, if individuals exhibit an intrinsic aversion towards debt, soft loans

might prove ineffective. Providing information on environmental performance will render EETs more attractive for individuals with particularly strong pro-environmental preferences. Likewise, the effectiveness of command-and-control type regulation may vary with the strength of individuals' pro-environmental preferences. Following Frey and Stutzer (2008), this type of policy intervention may lower the self-determination of individuals with strong pro-environmental preferences, thus lowering the adoption of EETs. On the other hand, command-and-control regulations signal social norms and may accelerate a broader uptake of EET.

Reactive policy interventions may also be combined to amplify effectiveness. In particular, providing information on energy use together with goal setting, or normative messages about a households' electricity use compared to that of its neighbors, has been shown to be particularly effective (Allcott, 2011; Ayres et al., 2012; Schultz et al., 2007).

4 Conclusion and Policy Implications

Implicit discount rates are key parameters in model-based policy evaluations, since they are employed to govern decision makers' energy-efficiency technology choices in models. Empirically derived implicit discount rates vary substantially and typically exceed the opportunity costs of capital. By looking at the factors underlying the implicit discount rate for household adoption of EETs in a comprehensive way, we also derive insights for policy making and modeling.

More specifically, by combining established concepts from various disciplines our framework distinguishes three broad categories of factors underlying the IDR: (i) preferences such as time preferences, risk preferences, reference-dependent preferences, and pro-environmental preferences; (ii) predictable (ir)rational behavior such as bounded rationality, rational inattention, and behavioral biases such as present bias, status quo bias or probability distortion; and (iii) external barriers to energy efficiency such as the landlord-tenant problem, lack of information or limited access to capital. While the extant literature has extensively explored external barriers to energy efficiency, the focus on behavioral factors and preferences offers promising insights for EET adoption, which will merit further empirical research. In particular, we argue that loss aversion may factor into households' adoption of EET to the extent that the (additional) costs of investing in EET are evaluated as a loss. In this case, loss-averse individuals may over-weight the associated losses and prefer not to adopt otherwise profitable EETs. Likewise, in addition to risk preferences, preferences over ambiguity may affect individuals' adoption of novel EETs, since objective probabilities of costs and benefits of these technologies are typically not available. Moreover, households may be prudent, when deciding on adopting an EET. To avoid downside risk, prudent households may shy away from adopting EET. Finally, debt-averse households may refrain from investing in capital-intensive insulation measures, for example, because they are reluctant to take out an economically advantageous loan to finance the investment. We argue that loss aversion, ambiguity preferences, prudence and debt-aversion likely result in higher IDRs. Future work could extend

the analysis of these factors from laboratory experiments (typically with university students) to representative, country-specified samples, and thus provide more realistic and robust findings for policy making. For example, debt-averse households would likely not respond to soft loans, which are a frequently used policy to accelerate the adoption of retrofit measures in many countries.

Our framework more generally allows for a fresh look at the interplay of IDRs and policies, thereby distinguishing between directed and reactive policy interventions. Directed policies aim to lower the IDR by adequately targeting the external barriers to energy efficiency, i.e. the factors that are external to the decision maker. In comparison, the design of reactive policies takes into account preferences and predictable (ir)rational behaviors. A key challenge for interpretation of the IDR and for policy design is to identify separately the individual factors underlying the IDR, e.g. isolate the contribution of time preferences from risk preferences (and their possible interaction), or rational inattention from bounded rationality. For example, raising energy taxes is expected to address rational inattention because higher taxes increase the costs of inattention (e.g. Alcott and Wozny, 2014). However, raising energy taxes is unlikely to address bounded rationality. Thus, if the objective of an energy tax increase was to spur adoption of EETs, but the factor impeding adoption was bounded rationality rather than rational inattention, raising energy taxes would be ineffective. By the same token, observing high IDRs does not provide guidance for policy making, since the underlying source cannot be identified (Jaffe and Stavins, 1994). Representing decision-makers' actual choices in a given context, IDRs exhibit a high external validity. The internal validity of IDRs, however, is low, since the elicitation method does not allow to adequately measuring decision makers' preferences with control over other factors. Thus, the IDRs are rather poor starting points for policy interventions. Our review of the empirical literature reports how the individual factors underlying the IDR correlate with household and technology characteristics, and thus contribute to a better understanding of the IDRs used in energy models. For example, observed correlations of the IDR with socio-economic characteristics such as income, provide only limited insights since the nature of the correlation cannot be identified. In this case, a negative

correlation between income and the magnitude of the IDR may be observed because richer households are less likely to face credit constraints, or are less risk-averse, or are more patient, or exhibit stronger pro-environmental preferences. Put differently, observing that low income households are associated with a high IDR provides little information on the type of policy intervention that may be called for.

In terms of modeling household adoption behavior via IDRs, our findings also imply that IDRs should vary based on household characteristics and technologies. For instance, new technologies or technologies with high investment costs should be associated with a higher IDR, *ceteris paribus*. This contrasts sharply with conventional model specifications, which do not differentiate IDRs by household types or technology. Failure to account for heterogeneity in the IDR and also for household responses to policy interventions likely biases model-based evaluations of policy effectiveness. Gerarden et al. 2015b argue that this shortcoming leads to overestimating the magnitude of the energy efficiency paradox. In the same way, it helps explain why energy-engineering analyses tend to overstate the profitable energy efficiency potential compared to ex-post estimates (Davis et al., 2014). Thus, additional representative empirical analyses based on households' observed or stated adoption behavior may supply modelers with more realistic IDRs. Similarly, field experiments or representative stated choice experiments may provide insights into household-specific responses to policy interventions. In particular, one of the objectives of empirical studies could be to prioritize the factors to determine which may have the greatest effect on the IDR and should therefore explicitly be included in the models.

Role of funding source

Part of this work was funded by the European Union's Horizon 2020 Framework Programme under the project BRISKEE - Behavioral Response to Investment Risks in Energy Efficiency (project number 649875) (briskee.eu) .

Acknowledgements

We are grateful for the insightful comments provided by two anonymous reviewers. The paper also benefitted from early discussions and feedback by Sibylle Braungardt, Wolfgang Eichhammer, Barbara Schlomann and Lorraine Whitmarsh.

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