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Moral Hazard and the Energy Efficiency Gap: Theory and Evidence

Louis-Gaëtan Giraudet,^{*} Sébastien Houde,[†] Joseph Maher[‡]

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Abstract

We investigate how moral hazard problems can cause suboptimal investment in energy efficiency, a phenomenon known as the energy efficiency gap. We focus on contexts where both the quality offered by the energy efficiency provider and the behavior of the energy user are imperfectly observable. We first formalize under-provision of quality and compare two policy solutions: energy-savings insurance and minimum quality standards. Both instruments are second-best, for different reasons. Insurance contracts induce over-use of energy, thereby requiring incomplete coverage in equilibrium. Standards incur enforcement costs. We then provide empirical evidence of moral hazard in home energy retrofits in Florida. We find that for those measures, the quality of which is deemed hard to observe, realized energy savings are subject to day-of-the-week effects. Specifically, energy savings are significantly lower when those measures were installed on a Friday—a day particularly prone to negative shocks on workers’ productivity—than on any other weekday. The Friday effect explains 70% of the discrepancy between predicted and realized energy savings, an increasingly documented manifestation of the energy efficiency gap. We finally specify a model to simulate the Floridian market and find that the deadweight loss from moral hazard is about twice as large as that due to associated carbon-dioxide externalities. Minimum quality standards appear more desirable than energy-savings insurance if externalities remain unpriced.

JEL: D86, Q41

Keywords: Energy efficiency gap, double moral hazard, energy-savings insurance, minimum quality standard, credence good, day-of-the-week effect.

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1. Introduction

Energy efficiency measures are widely advocated as a means of both saving money and cost-effectively reducing externalities associated with energy use. Yet in practice, they are little adopted. This phenomenon is commonly referred to as the energy efficiency gap. One of its manifestations is the increasingly documented discrepancy between realized energy savings and those predicted by engineering models (Metcalf and Hassett 1999; Fowlie, Greenstone, and Wolfram 2015; Zivin and Novan 2016; Maher 2016; Davis, Fuchs, and Gertler 2014; Houde and Aldy 2017). Another long studied manifestation is the abnormally high discount rates (typically 10-30%) implied by energy efficiency sales patterns (Hausman 1979; Train 1985).

A variety of explanations have been investigated to explain the energy efficiency gap (Gillingham, Newell, and Palmer 2009; Allcott and Greenstone 2012). Jaffe and Stavins (1994), who first conceptualized the problem, emphasized the difference between market-failure and non-market-failure explanations of the gap. Market failures such as information asymmetries, positive externalities from innovation or negative externalities associated with energy use may distort incentives for energy efficiency investment. This motivates implementation of corrective policies. Non-market failures such as heterogeneity in consumer preferences or hidden costs (e.g., inconvenience caused by insulation installation) may also prevent widespread adoption of energy efficiency. Yet, unlike market failures, these are normal components of markets. As such, they should be accounted for in economic assessments but do not per se warrant any particular intervention. More recently, the dichotomy has been enriched with the concept of behavioral anomalies to account for apparent under-valuation of energy savings by energy users (Gillingham and Palmer 2014; Allcott, Mullainathan, and Taubinsky 2014).

In this paper, we provide a market-failure explanation for the energy efficiency gap: moral hazard in the provision of quality. We empirically find that the problem can explain a large part of the discrepancy between predicted and realized energy savings. This manifestation of the energy efficiency gap has so far been considered to be due to non-market failures, especially measurement errors or upward biased thermal simulations.¹ Our contribution is

¹Recent explanations of the gap between predicted and realized savings also include: increased intensity of utilization, though with a limited role (Fowlie, Greenstone, and Wolfram 2015); replacement of technologies that were not being used in the first place (Davis, Fuchs, and Gertler 2014); upgrade toward over-sized technologies (Houde and Aldy 2017); overestimation of pre-retrofit energy use in engineering predictions of energy savings (Sunikka-Blank and Galvin 2012; de Wilde 2014).

to show that it can be due to a market failure, namely systematic under-treatment of quality by energy efficiency providers when the informational context gives them the opportunity to do so. We show that the welfare losses due to moral hazard in home energy retrofits, though potentially important, can be partly mitigated by policy interventions such as minimum quality standards and energy-savings insurance.

Our motivation comes from the credence-good nature of energy efficiency, a little-studied aspect of this technology. Just like taxi rides or auto repairs, many energy efficiency measures are subject to verifiability and liability issues which make their performance never completely revealed to the buyer (Sorrell 2004; Dulleck and Kerschbamer 2006). This is especially the case in buildings, where energy use depends on unobservable factors such as weather forecasts, occupants' behaviors and the quality of energy efficiency equipment. These properties are conducive to a set of information asymmetries, of which two have received most attention. One is adverse selection in housing decisions. The intuition is that the energy efficiency of a dwelling is hard to observe and therefore will not be capitalized into sale prices or lease contracts. The intuition is proving correct in rental housing, as rented dwellings are found to be less energy-efficient than owner-occupied ones (Scott 1997; Davis 2012; Gillingham, Harding, and Rapson 2012; Myers 2013; Krishnamurthy and Kriström 2015). The effect is less clear in home sales. More energy-efficient homes, as measured by their energy performance certificate, are found to sell with a premium, but no counterfactual situation without certificates is available for comparison (Brounen and Kok 2011; Murphy 2014; Fuerst, McAllister, Nanda, and Wyatt 2015). Another much-studied information asymmetry associated with energy efficiency is moral hazard in energy demand. It is well established that building occupants use more energy when they face zero marginal cost of usage, for instance because they signed up a utility-included rent contract (Levinson and Niemann 2004; Maruejols and Young 2011; Gillingham, Harding, and Rapson 2012).

The information asymmetry considered here is related but involves different parties. We are interested in under-provision of quality in the installation of energy efficiency measures. We specifically examine home energy retrofits, where a contractor may take advantage of the lack of expertise of the homeowner to perform insulation or duct sealing poorly. This can be interpreted as supply-side moral hazard. As we shall see, full analysis of the problem and solutions thereto requires one to also consider the demand-side moral hazard discussed above.

Our contribution is three-fold. First, we formalize how supply-side moral hazard can cause an energy efficiency gap and examine two little-discussed policy remedies: energy-savings

insurance, a private solution, and minimum quality standards, a public one. The analysis builds on a double-moral-hazard framework borrowed from the literature on warranties (Cooper and Ross 1985). We articulate the mechanism by which asymmetric information induces the contractor to cut quality in equilibrium. This deters adoption of energy efficiency measures. Both policy solutions are found to be second-best: energy-savings insurance reduces marginal energy expenditures, which induces demand-side moral hazard and therefore requires incomplete coverage in equilibrium; minimum quality standards incur enforcement costs.

Second, we provide the first empirical evidence of supply-side moral hazard in home energy retrofits. Using a dataset of 3,000 retrofits sponsored by Gainesville Regional Utilities (GRU) in Florida, we exploit variation in the type of measures (classified as easy or hard to observe) and the day of the week on which they were installed. We find that realized energy savings underperform predicted ones, and in particular that the former can vanish for hard-to-observe measures if those were installed on a Friday. The result is robust to a number of robustness checks, including testing for contractors selecting specific measures on Fridays. It suggests that perhaps due to fatigue, retrofit workers are likely to shirk if the informational context gives them the opportunity to do so. Controlling for the Friday effect, the discrepancy between predicted and realized energy savings shrinks by 70%. Incidentally, the exercise contributes to the empirical literature on day-of-the-week effects on workers' productivity (Campolieti and Hyatt 2006; Bryson and Forth 2007) and more generally to the empirical analysis of moral hazard and credence goods (Abbring, Heckman, Chiappori, and Pinquet 2003; Dulleck, Kerschbamer, and Sutter 2011; Schneider 2012; Balafoutas, Beck, Kerschbamer, and Sutter 2013).

Third, we integrate the theoretical and empirical approaches to assess the welfare consequences of moral hazard in home energy retrofits. The model developed in the theoretical exercise is calibrated to simulate the Floridian market, using data from the GRU program and the U.S. Residential Energy Consumption Survey (RECS). We find that the deadweight loss due to moral hazard could be twice as large as that due to associated carbon-dioxide externalities. This result is robust to a range of specifications and can be approximated by a sufficient statistic that abstracts from consumer preferences. Energy-savings contracts with insurance coverage in the 10-20% range can mitigate losses, while minimum performance standards produce benefits in excess of reasonable enforcement costs. The performance of each instrument is close if carbon-dioxide externalities are absent or fully internalized. If externalities remain unpriced, however, the demand-side moral hazard induced by insurance magnifies losses and standards appear to be a better policy option.

Our analysis is a first step pointing to supply-side moral hazard in home energy retrofits as an important problem, both empirically and economically. Policy instruments already existing in the marketplace could be adjusted to deliver their full potential. Energy performance contracts, which are common in commercial buildings, could be promoted in the residential sector. Certification of professional installers, which is so far mostly voluntary, could evolve toward a mandatory regime. Hybrid instruments combining standards and insurance might also produce substantial benefits.

The outline of the paper is as follows. Section 2 introduces the theoretical model, derives key predictions and examines policy solutions. Section 3 presents the empirical approach and the results. Section 4 provides a numerical welfare assessment. Section 5 concludes.

2. A model of energy efficiency investment with double moral hazard

Our model builds upon the double-moral-hazard model of Cooper and Ross (1985). To fix ideas, we consider the canonical case of home energy retrofits, which involve hidden actions from both the homeowner and the retrofit contractor. Other situations that give rise to one-sided moral hazard, for instance energy efficiency improvements in the commercial and industrial sectors, can be viewed as special cases of this general model.² The exposition here focuses on the key elements and predictions of the model. Formal assumptions, additional propositions, complete proofs and graphical illustrations are provided in an online appendix.

2.1. Setup

Consider a homeowner using energy for air conditioning (or space heating). The energy service s , measured in cooling degree days (alternatively, heating degree days), provides her with increasing comfort $V(s)$, multiplied by a taste parameter $\theta > 0$. For instance, a person living in a hot area would be characterized with a high value of θ (alternatively, a low one).

The homeowner spends $pE^0(s)$ on energy, where $E^0(\cdot)$ is the energy use and p the price of energy. She sets her energy service s_θ^0 so as to maximize the discounted sum of net utility:

$$(1) \quad U^0(\theta, s) \equiv (\theta V(s) - pE^0(s)) \Gamma(r, l),$$

²Moral hazard in the provision of energy efficiency also arises in the car and truck markets. As documented by Reynaert and Sallee (2016), manufacturers may strategically overstate fuel economy values. This gap between stated and realized fuel economy is also an example of supply-side moral hazard.

where Γ is a discount factor function of the discount rate r and the investment horizon l . We assume time invariance of energy price, technology and comfort valuation. The energy service s is therefore constant over time. The discount factor is $\Gamma(r, l) \equiv \sum_{t=1}^l (1+r)^{-t} = (1 - (1+r)^{-l})/r$.

The homeowner can undertake a retrofit investment supplied by a contractor. Each party can take hidden actions that influence ex post energy use, $E(s, q)$. The homeowner's ex post energy service s is unobserved to the contractor. In turn, the quality q with which the contractor completes the retrofit is unobserved to the homeowner, who as a non-expert cannot verify insulation installation or duct sealing, for instance. Energy use, which is reported on the homeowner's utility bill, is common knowledge to both parties, who are also aware that it increases with s and decreases with q . The framework is deterministic and linearity of utility with respect to energy expenditures reflects risk-neutrality.³

Upon investing, the homeowner maximizes utility $U(\theta, s, q)$, net of upfront cost $T > 0$ and includes an idiosyncratic value, δ , capturing for instance aesthetic and acoustic benefits associated with insulation (if positive) or inconvenience incurred for installation (if negative):

$$(2) \quad U(\theta, s, q) \equiv (\theta V(s) - pE(s, q)) \Gamma(r, l) - T + \delta$$

The contractor maximizes profit formed by the revenue from the sale T minus the cost $C(\cdot)$ of providing quality q . We assume zero profit, so that:

$$(3) \quad T = C(q).$$

The assumption is meant to reflect the competitive nature of the industry.⁴ We show in the online appendix that the equilibrium analysis is nevertheless robust to alternative market structures.

We model the energy efficiency contract as a two-stage game in which the homeowner is the principal and the contractor is the agent. In the first stage, the homeowner of type θ invests if her net present value $NPV(\theta)$ is positive, given her energy service s_θ^* and the

³We ignore uncertainties coming from the weather variations determining heating or cooling needs, from measurement errors propagated in the complex engineering models used to predict energy savings, or from the volatility of energy prices. This simplification is equivalent to assuming that the effects of s and q on energy use both satisfy first-order stochastic dominance.

⁴The home energy retrofit industry is highly fragmented. For instance, firms operating in the heating, ventilation and air conditioning (HVAC) industry in California are typically small, offer low wages, face low barriers to entry and an annual turnover as high as 25% (Zabin, Lester, and Halpern-Finnerty 2011).

quality q_θ^* she expects to be offered in equilibrium:

$$(4) \quad NPV(\theta) \equiv U(\theta, s_\theta^*, q_\theta^*) - U_0(\theta, s_\theta^0) \geq 0.$$

In the second stage, both agents determine their optimal action given their belief about the other party's action. We solve the game using backward induction.

2.2. Supply-side moral hazard

We model the social optimum as a cooperative game with perfect information. We show in the online appendix that this game generates strictly increasing reaction functions: a contractor will offer more quality to a homeowner he perceives as demanding more energy service; the homeowner will demand more energy service if she expects to be offered more quality. The intersection of the two reaction functions defines a perfect-information equilibrium that determines the socially optimal level of quality.

If actions s and q are not perfectly observable, the parties each maximize their private surplus, given their beliefs about the other party's action. This does not affect the homeowner's first-order conditions and therefore leaves her reaction function unchanged. In contrast, the contractor does not internalize how quality benefits the homeowner. His reaction function is now flat: whatever behavior he expects from the homeowner, he sets quality at the level which minimizes production cost. The intersection of the two reaction functions defines the asymmetric-information equilibrium.

Equilibrium actions under perfect information (*PI*) and asymmetric information (*AI*) can be unambiguously compared:

Proposition 1. *Under asymmetric information, an energy efficiency contract is subject to supply-side moral hazard. The contractor offers less quality to any homeowner of type θ than under perfect information: $q_\theta^{AI} \leq q_\theta^{PI}$. The homeowner responds by using less energy service: $s_\theta^0 < s_\theta^{AI} \leq s_\theta^{PI}$. The two inputs together make investment less profitable: $NPV^{AI}(\theta) \leq NPV^{PI}(\theta)$.*

Comparison is ambiguous when it comes to equilibrium energy use. Undoing moral hazard increases both q and s , which has an opposite effect on $E(\cdot, \cdot)$. In words, the energy savings induced by improved quality are partly offset by an increase in energy service. This phenomenon is known as the rebound effect. At some point, it can backfire, that is, be such that energy use is higher after investment. While conceptually important in the presence

of negative energy-use externalities, as we will see later, backfire rebound effects are empirically limited (Gillingham, Kotchen, Rapson, and Wagner 2013). In most cases, therefore, the energy savings realized under asymmetric information will be lower than those predicted under perfect information (for instance by engineering models).

We now extend the above result to the whole market. Consider a continuum of homeowners of mass 1, all living in a similar dwelling and only differing with respect to their preference for thermal comfort θ . We show in the online appendix that the higher the value of θ , the higher the demand for energy service, hence the higher the quality offered under perfect information. This shifts the homeowner's reaction function upward. In contrast, the quality offered under asymmetric information remains at minimum. As a result, the moral-hazard effect is increasing in θ . We also show that the net present value of investment is increasing in θ . This means that there exists a unique marginal investor of cutoff type θ_0^* such that $NPV(\theta_0^*) = 0$. Combining this with Proposition 1 leads us to the following proposition:

Proposition 2. *Asymmetric information creates an energy efficiency gap at the market level. Both the number of investing consumers and social welfare are lower than under perfect information: $N^{AI} \leq N^{PI}$ and $W^{AI} \leq W^{PI}$,*

where $N^* \equiv 1 - F(\theta_0^*)$ is the equilibrium number of participants, $F(\cdot)$ is the cumulative distribution function of θ , and W^* is aggregate welfare, calculated under zero-profit condition as the sum of utility before investment for non-participants and utility after investment for participants:

$$(5) \quad W^* \equiv \int_0^{\theta_0^*} U^0(\theta, s_\theta^0) dF(\theta) + \int_{\theta_0^*}^{+\infty} U(\theta, s_\theta^*, q_\theta^*) dF(\theta).$$

Anticipation of the quality gap discourages homeowners with low valuations of comfort to invest. As a result, investment is suboptimal on both the intensive and extensive margins. Again, without further specification of the technology $E(\cdot, \cdot)$, we cannot conclude about how aggregate energy use differs in the two equilibria.

2.3. Policy solutions

The textbook remedy to moral hazard is a risk-sharing contract. In the context of home energy retrofits, such a contract can take the form of energy-savings insurance. Alternatively, a regulator may want to address the problem with a verifiable quality standard. A third option, sometimes found in practice, is to combine the two. In this section, we compare the

two solutions in their purest form in order to identify their relative strengths and weaknesses. We find that none can achieve the first-best outcome.

Energy-savings contracts and double moral hazard. Energy-savings contracts or insurance, more commonly referred to as energy performance contracts, have been offered for nearly twenty years in the commercial sector (Mills 2003), less frequently in the residential sector.⁵ Such contracts typically have the contractor pay the homeowner any shortfall in energy savings below a pre-agreed baseline. In our simple framework with no risk-aversion, insurance can be modeled as a contract specifying a share k of energy expenditures borne by the contractor in exchange for an actuarially-fair insurance premium I :

$$(6) \quad I = k pE(s, q)\Gamma(r, l)$$

Such an insurance contract creates an incentive problem which superimposes the one it is meant to address in the first place. The contract can be modeled as a three-stage game, in which the contractor now is the principal and the homeowner is the agent. In the third stage, the parties cooperatively determine optimal insurance coverage k_θ^* ; in the second stage, they privately set their own action, given their belief about insurance coverage k and the other party's action; in the first stage, they decide whether or not to participate.

The insurance induces the contractor to offer some quality, otherwise he would have to make excessive payments to the homeowner. In other words, the risk-sharing contract mitigates supply-side moral hazard. At the limit, it could even eliminate it, as complete coverage ($k = 1$) would induce the contractor to offer socially optimal quality. But at the same time, the contract gives rise to demand-side moral hazard: by lowering the homeowner's marginal value of energy service, it induces her to use more energy. At the limit, complete coverage would drive the homeowner's marginal energy expenditure to zero, thereby inducing her to use energy service up to satiation. Complete coverage is therefore not optimal:

Proposition 3. *Energy-savings contracts create demand-side moral hazard. As a consequence, optimal insurance coverage is incomplete: $0 < k_\theta^* < 1$.*

Note that if the building occupant were not adjusting her energy service (e.g., a tenant subscribing to a utility-included rent contract, or an employee in a commercial building), then the second moral hazard would not occur. The optimal contract would stipulate complete coverage and bring the parties to the social optimum. This may explain why energy

⁵GreenHomes America, Inc., NJ-PA Energy Group, LLC. and EcoWatt Energy, LLC. are the few examples we have found of companies offering energy-savings insurance in the U.S. residential sector.

performance contracts are common in the commercial sector but rarely offered to residential consumers.

Note also that by increasing both q and s , the energy-savings contract generates a rebound effect. Unlike that induced by the simple energy efficiency contract discussed in Section 2.2, this rebound effect can be interpreted as moral hazard. Formally, the rebound effect associated with the energy efficiency contract materializes as the positive slope of the homeowner's reaction function, which is not affected by the informational context. In contrast, the rebound effect associated with the energy-savings contract corresponds to an upward shift of the homeowner's reaction function. This can be interpreted as demand-side moral hazard, just like the downward shift of the contractor's reaction function due to asymmetric information could be interpreted as supply-side moral hazard.

In practice, homeowner types, θ , can be difficult to observe. A uniform contract with undiscriminated coverage is therefore most likely to be offered to all homeowners. Such a contract generates additional deadweight losses, as the coverage might be optimal to one homeowner, but is suboptimal to all others.

Minimum quality standard. A number of voluntary certifications exist in the marketplace, most notably those provided by the Building Performance Institute (BPI) and the Residential Energy Services Network (RESNET) in the United States. These programs typically ensure that professional workers and contracting companies are trained to the best practices and that their performance is regularly verified.

We model such standards as a verifiable minimum quality input \bar{q} , for instance prescribing the grade of materials used and the application taken in installation. The instrument generates two types of inefficiencies. First, compliance needs to be verified, which generates enforcement costs $M(\bar{q})$. These costs do not arise with energy-savings insurance, which rely on a commonly-observed variable, namely, the energy use reported on utility bills. Second, just like a uniform insurance contract, minimum quality standards do not account for consumer heterogeneity.

We show in the online appendix that the value of \bar{q} which minimizes the deadweight loss is such that the marginal disutilities of those homeowners for whom the standard is too tight and the marginal utilities (net of marginal enforcement costs) of those willing to invest beyond the standard are equalized.

To sum up, both insurance and standards can mitigate moral hazard but none can eliminate it. Leaving aside the deadweight loss arising from consumer heterogeneity, which is

equally faced by a uniform insurance contract and a uniform quality standard, the comparison between the two instruments boils down to how the deadweight loss due to demand-side moral hazard induced by insurance compares with enforcement costs incurred with the standard. This is a context-specific question, which we examine numerically in Section 4.

Interaction with energy-use externalities. As we show earlier, undoing moral hazard has an ambiguous effect on energy use due to the rebound effect. To the extent that it backfires while energy-use externalities remain unpriced, implementing policy remedies to moral hazard can have the unintended consequence of exacerbating deadweight losses. In the online appendix, we uncover sufficient conditions for this not to occur. This points to the importance of considering interactions between market failures.

3. Empirical evidence of supply-side moral hazard

We now present three empirical facts that together suggest that energy retrofit contractors engage in moral hazard by poorly installing energy efficiency measures when the quality of their work is hard to verify. We do so using a rich dataset from a utility-sponsored retrofit program ran in Florida.

We first find that realized energy savings after completing an energy retrofit are below predicted engineering savings for several retrofit measures, a puzzle that is increasingly documented (Metcalf and Hassett 1999; Fowle, Greenstone, and Wolfram 2015). The discrepancy is specifically large for measures where the quality of installation is hard to observe *ex post*. For other measures, with easy to observe installation quality, the sign of the gap is ambiguous. We then find that the discrepancy varies as a function of the day of the week on which a measure was installed and that this variation follows a particular pattern—realized savings are lower toward the end of the week, notably on Fridays, but only for measures whose quality is hard to verify *ex post*. Lastly, we find that this Friday effect is not driven by selection. That is, contractors do not choose to install particular measures on a specific day of the week (though they might during the weekend). Crucially, retrofit prices are not lower on Fridays when realized savings fall.

The second and third empirical facts are a novel contribution to the debate about predicted-versus-realized energy savings. Together, they suggest that installation quality is under-supplied on Fridays for measures specifically prone to moral hazard. To explain the Friday

effect, we argue that workers are more likely to experience negative productivity shocks toward the end of the workweek and are thus more likely to shirk on quality if the informational context gives them the opportunity to do so.

3.1. Data

From 2006 to 2012, Gainesville Regional Utilities (GRU) ran rebate programs for home energy retrofits. The programs targeted a variety of measures, including attic insulation, duct sealing, air-conditioners, pool pumps, refrigerators and windows. Eligibility for rebate required that measures be installed by pre-approved contractors. Prior to completion, each project had to undergo an assessment of the potential energy savings associated with the measures, based on ex ante engineering calculations.⁶

We restrict our analysis to homes where only one retrofit measure was undertaken and for which only one technology requiring labor input was installed, which ensures that we focus on households that had only one interaction with the contractors. We further restrict the sample to projects that cost under \$10,000. The reasoning to exclude expensive retrofit projects is that they are likely to take more than one day to complete.⁷ The refrigerator removal program is also excluded from the analysis because there was no installation of a technology required. Under these criteria, our sample contains 2,936 projects for which the following information is available: type of measure completed, predicted engineering energy savings, rebate amount, price paid to the contractor, and, crucially for our empirical exercise, the date on which a measure was installed. Table 1 provides summary statistics. We match the program data with monthly electricity and natural-gas billing data recorded by GRU between 2002 and 2013. This procedure allows us to link the characteristics of a retrofit measure to its impact on energy use.

3.2. Empirical strategy

A first challenge in detecting moral hazard is that quality is not directly observed in our setting. Neither inputs to (e.g., hours worked and skills mobilized by installers, grade of

⁶Engineering estimates of energy savings are measure specific. They take into account home-specific features (building period, etc.) when necessary, namely for all measures except pool pumps. In some cases, they were performed by a third party that came to the house.

⁷The data do not allow us to ascertain that completion of a single measure takes exactly one day, that is, approximately eight hours. We nevertheless think this is a reasonable assumption for the technologies considered.

the products and materials installed) nor outputs of the measures (e.g., number and type of defects) are documented. Our strategy to detect changes in quality then relies on estimating realized energy savings, which is strongly correlated with the quality of installation.

Our empirical strategy consists in uncovering heterogeneity in realized savings along two dimensions. First, we classify the quality of installation as either easy or hard to observe by the homeowners, and distinguish energy savings for these two categories of measures. We consider a measure hard to observe (HTO) if it meets two criteria: (i) the installation is an arduous task that requires significant labor input and (ii) the quality of installation is difficult to verify by a non-expert. Attic insulation and duct sealing, which both require significant installation work and can hardly be verified after completion, belong to this category. Other retrofit measures that mostly consist of replacing equipment, such as air-conditioners, or pool pumps are deemed easy to observe (ETO). Window replacement, which requires significant labor input but leaves few features hidden, could fall in either category. In our preferred specification, we classify this measure as easy to observe. In a robustness check, we exclude it from the ETO category and find little impact. In Table 1, we present how we classify each type of measures considered in our analysis. From the working sample that contains 2,936 projects, 1,025 are HTO measures and 1,911 are ETO measures.

Second, we allow for heterogeneity based on the day of the week that the installation of the retrofit was performed. We hypothesize that workers' productivity is subject to systematic variation over the week which is unaccounted for in the retrofit contract. In particular, we expect workers must deploy more effort to perform a retrofit project of a given quality toward the end of the week, namely on Fridays and during weekends. Therefore, installation quality should tend to be lower at the end of the workweek. This hypothesis is motivated by labor studies showing that productivity tends to be lower on Fridays, especially in the construction sector (e.g., Bryson and Forth, 2007). Workers' fatigue is the reason most frequently invoked. Other explanations that apply in our setting include: staff shortage, e.g., workers calling out "sick" on Friday; quit-time, e.g., workers leaving early to start weekend; backlog, e.g., workers rushing to finish a job to avoid having to revisit a site for a few hours on weekend or the week after.

Our test of existence of moral hazard is that a day-of-the-week effect is more likely to exist for HTO measures because workers can shirk on installation quality if it is hard to observe ex post. HTO measures should then deliver fewer energy savings if they have been completed when workers' productivity is lower, i.e., at the end of the workweek, but ETO measures should not be subject to such a day-of-the-week effect.

We estimate realized energy savings using a difference-in-differences estimator where the estimate can vary with respect to the two categories of measures and the day of installation. The estimation strategy follows the quasi-experimental approach of Fowlie, Greenstone, and Wolfram (2015), Zivin and Novan (2016), and Maher (2016), only extended with interactions with day-of-the-week dummies, denoted DW , and dummies that identify HTO and ETO measures. We consider the following regression model:

$$(7) \quad \log(kWh_{it}) = \eta HTO_{it} + \phi ETO_{it} + \eta_d \cdot DW_{id} \cdot HTO_{it} + \phi_d \cdot DW_{id} \cdot ETO_{it} \\ + \lambda_{im} + \nu_t + \epsilon_{it},$$

where the dependent variable is the logarithm of the total monthly energy use (electricity plus natural gas) of a particular household. The rationale to combine the two energy sources is to account for possible substitution effects where the reduction in usage from one energy source induces an increase in usage from the other. For this reason, we consider the regression with total energy use the most conservative. As a robustness check, we also run the same regression with only electricity or natural gas as the dependent variable. The dummy HTO_{it} turns from zero to one the month t household i invests in a HTO retrofit measure. The dummy ETO_{it} is defined similarly for investments in ETO measures. The terms λ_{im} and ν_t denote household-calendar-month fixed effects and month-of-sample fixed effects, respectively, and implement the difference-in-differences estimator to estimate energy savings. Finally, DW_{id} is a dummy that identifies a specific day of the week, denoted with subscript d , and estimates heterogeneity in average realized energy savings with respect to the day of installation. Each dummy takes a value of one if household i got the measure installed on day d and zero otherwise. The coefficient η_d estimates the specific effect of installation day d on realized energy savings for HTO measures; we expect it to be positive if moral hazard exists. The coefficient η estimates the savings for HTO measures installed on one of the remaining days of the week. For instance, “Friday effects” are estimated by having a dummy, $DW_{iFriday}$, that turns on if the measure was completed on a Friday. In this specification, the coefficient η then estimates the savings for a retrofit installed on any day between Monday and Thursday. The coefficients ϕ and ϕ_{Friday} estimate the same effects for ETO measures.

Our formal hypothesis test to detect the existence of moral hazard is the null hypothesis: $H_0 : \eta_d = \phi_d$. The rejection of this null hypothesis combined with $\eta_d > 0$ implies that HTO measures save less energy on day d of the week.

3.3. Identification

The difference-in-differences estimator is implemented by two sets of fixed effects. The dummies λ_{im} capture all household-specific characteristics that influence energy use. Note that we allow for variation by calendar month m , which captures any seasonal pattern in household-specific energy usage. Exploiting several years of monthly consumption allows us to identify the coefficients λ_{im} . The month-of-sample fixed effects, ν_t , control for weather and any other contemporaneous shocks that may affect monthly consumption. Our large sample of retrofits allows us to identify the coefficients ν_t . We thus effectively assume that conditional on λ_{im} and ν_t , households were subject to similar trends in energy usage prior to the retrofit measure. By the end of our time horizon, all households are treated.

The validity of the test for moral hazard relies on the assumption that contractors do not select the day of the week on which they installed a particular measure. Such selection can be directly tested by comparing projects along key dimensions using observable attributes of the retrofit contracts. Table 2 compares the average retrofit prices, average predicted energy savings, average rebate amounts, and number of retrofit performed across day (or period) of completion. For all four variables, we observe no statistically significant difference during the days of the workweek. Importantly for our identification, Friday jobs are of the same size as other jobs, as measured by both their price and predicted energy savings; any difference in realized energy savings is therefore due to other factors. In contrast, weekend projects, which happen to be very few, do exhibit some differences. This suggests that selection might be at play during the weekend, which leads us to treat weekends separately in the estimation with a dummy for measures installed on weekends. The selection problem on weekends could come from the way contractors either favor certain projects or decide to work during the weekend.

3.4. Results

The second and third columns of Table 1 replicate the findings of Maher (2016). Most retrofit measures subsidized by GRU exhibit a discrepancy between predicted and realized savings. For the two main retrofit measures classified as hard-to-observe—attic insulation and duct repair—realized savings are 60% and 32% of predicted savings, respectively.⁸ For ETO measures, the discrepancy varies widely in magnitude but also in sign. For three out of six of them, realized savings are in fact well above predicted ones.

⁸The estimate of the realized savings for duct repair is not statistically different from zero, while predicted saving are 107.5 kWh/month.

We present the regression results that account for heterogeneity with respect to the day-of-the-week and observability of the measure (Equation 7) in Table 3. Each column corresponds to a specification that identifies a specific day-of-the-week effect on energy savings. The interaction terms are the additional savings for the day identified. For instance, for the model that estimates the Friday effect (fifth column), the coefficient represents the additional savings relative to the average savings for Monday to Thursday. A positive estimate suggests that realized savings on Fridays are lower than for other days of installation. The last row of Table 3 reports the p -value (F test) of the two-tailed hypothesis test: $H_0 : \eta_d = \phi_d$.

For HTO measures, we find a positive Friday effect that is statistically different from the Friday effect for the ETO measures (p -value = 0.0547). However, we do not find any such effect for other days of the workweek. All models include an interaction for weekend effect, which is always positive but not statistically significant. The end-of-the-week effect is still present if we group Friday and weekend estimates together (sixth column, p -value = 0.0234). The magnitude of the estimates, obtained by adding the coefficients for the dummies HTO and $HTO \cdot DW_{Friday}$ imply that the realized energy savings for HTO measures completed at the end of the week are close to zero and not statistically significant. For other days of the workweek, the savings are of the expected sign, economically large and statistically significant.

The magnitude of the Friday effect for HTO measures is economically large and explains a large fraction of the discrepancy between realized and predicted savings. Table 5 displays estimates of the realized savings with and without controls for the Friday effect, and compares them to the predicted savings. After controlling for the Friday effect for HTO retrofit measures, the discrepancy between predicted and realized energy savings shrinks by as much as 70%.

The above results are robust to numerous robustness checks presented in the online appendix. We show that our designation of HTO and ETO categories has little impact on the results. For instance, if we exclude from the analysis the measures that are the most ambiguous—low-interest loans, low-income weatherization grants, and home performance projects—it has little impact on the estimates (Table A2). Removing windows replacement from the ETO category does not qualitatively change the results either. Table A3 also presents an extensive set of robustness checks for different ways of classifying measures and shows that the estimated Friday effect for HTO and ETO measures is very stable across designations, and suggests that duct sealing is an important driver of the effect for HTO measures.

Performing the estimation in level instead of logarithm still produces a positive Friday effect for HTO measures. The coefficient is, however, marginally statistically significant.⁹

If we run regressions using only electricity or natural gas as the dependent variable, we find that the Friday effect is driven predominantly by electricity consumption. Table 4 presents the results where the log of monthly electricity use is the dependent variable and a similar table is presented in the online appendix for natural gas. Given that the sample focuses on energy efficiency retrofits in Florida, this result is not surprising. The two important technologies that we classified as prone to moral hazard, i.e., attic insulation and duct repair, should have most of their effect on energy use during the hot summer days of Florida, i.e., on air conditioning usage and thus electricity.

Altogether, the results give support to our hypothesis that under-treatment occurs on Fridays for measures where quality is hard to verify. Though essentially a positive test of existence of moral hazard, our analysis additionally indicates that the problem is important, perhaps enough to undo a large fraction of energy savings.

4. Numerical welfare analysis

We now integrate the theoretical and empirical approaches to assess the welfare consequences of moral hazard in home energy retrofits. Building on the theory developed in Section 2, we specify a model simulating the interactions between retrofits, air conditioning and electricity usage in Florida. We calibrate the model using data from the GRU program and the U.S. Residential Energy Consumption Survey (RECS).

We reach three main findings. First, the deadweight loss due to moral hazard is substantial, typically twice as large as that due to associated carbon-dioxide externalities, a finding robust to model specifications. Second, welfare effects can be accurately approximated by a sufficient statistic that abstracts from consumer behavior. Third, minimum quality standards tend to be more effective in addressing moral hazard than energy-savings insurance, especially when externalities remain unpriced.

4.1. Model specifications

We consider a market involving a homogeneous, competitive industry of home retrofits and a population of home owner-occupiers with heterogeneous preferences for energy services.

⁹The p -value for the two-tailed test $H_0: \eta_d = \phi_d$ on Friday is p -value = 0.135.

Consistent with the empirical analysis, technology is a combination of insulation and duct sealing, and we examine its impact on electricity use for air conditioning. We impose minimal structure on the functional forms so as to satisfy the basic convexity assumptions introduced in Section 2. We calibrate the model using empirical moments obtained from the GRU and RECS data.

Demand side. We consider a population of heterogenous homeowners using electricity for air conditioning. Homeowners demand an energy service, denoted s , measured in cooling degree days (CDDs with base temperature of 65F). The utility derived from using s is:

$$U(\theta, s, q) \equiv (\theta V(s) - pE(s, q)) \Gamma(r, l) - T + \delta,$$

where the comfort and usage functions are respectively specified as follows:

$$(8) \quad V(s) \equiv V_{max} \left(1 - e^{-\alpha(s-s_{min})}\right),$$

$$(9) \quad E^0(s) \equiv \beta(s - s_{min})^\gamma,$$

with $s_{min} \leq s \leq s_{max}$, $\alpha > 0$, $\beta > 0$ and $\gamma > 1$. We assume that parameter θ , which represents preferences for thermal comfort, follows a log-normal distribution.

As detailed in the online appendix, we use a RECS sample of 503 Floridian households to set the values of p , s_{min} , s_{max} , V_{max} , α , β , γ and δ , and the distribution of θ . Parameter values are presented in Table 6.

Supply side. We consider a homogeneous competitive industry providing duct sealing and insulation installation. Contractors deliver with some dimensionless quality q , ranging from 0% to 100%, which affects the homeowner's electricity use as follows:

$$(10) \quad E(s, q) \equiv \left(1 - G_{min} - (G_{max} - G_{min}) \left(1 - e^{-aq}\right)\right) E^0(s).$$

with $a > 0$. Parameters G_{min} and G_{max} capture the minimum and maximum energy savings that a retrofit can technically generate. They are set to 1% and 30%, respectively.

Contractors have a quadratic cost function to provide quality q

$$(11) \quad C(q) \equiv b + \frac{c}{2}q^2,$$

with $b > 0$ and $c > 0$.

As detailed in the online appendix, parameters a , b and c are calibrated to match empirical moments obtained from the GRU program.

Market environment. Based on the RECS data, the electricity price p is set to \$0.1254/kWh. It is held constant in current value over the time horizon l , set to 35 years, the conventional lifetime of insulation measures. The discount rate r is set to 7%, the value recommended by the U.S. Office of Management and Budget (OMB 2009) to assess private investment.

We consider that electricity use generates carbon-dioxide externalities contributing to global warming. Externalities are valued at \$31/tCO₂ (Nordhaus 2017), which, given an emission rate of 550 gCO₂/kWh for power generation in Florida (EPA 2015), translates into a social cost $p_{CO_2} = \$0.0169/\text{kWh}$. We assume that this cost increases at the discount rate, hence is constant in present value.

Under these assumptions, saving 1 kWh of electricity monthly has a private value of \$1.62 and a social value of \$0.59 in lifetime discounted terms.

4.2. Quantification of the energy efficiency gap

Reference case. We consider various market environments—perfect and asymmetric information, with and without a Pigouvian price on carbon-dioxide externalities. For each environment, we compute the equilibrium actions for all market participants. We then aggregate participants and map the resulting market equilibria in the framework proposed by Jaffe, Newell and Stavins (2004),¹⁰ so as to visualize the trade-offs between economic efficiency (measured as present discounted welfare) and energy efficiency (Figure 3). Detailed numerical results are presented in Table 7.

Undoing moral hazard—which is calculated by comparing perfect- and asymmetric-information equilibria—produces present-value benefits of about \$600 per retrofit.¹¹ If, in addition, carbon-dioxide externalities were internalized through a \$0.0169/kWh price, welfare improvement would be about \$300 larger. In the context studied here, moral hazard is therefore about twice as large a market failure as carbon-dioxide externalities. This ratio is partly determined by the 2.7 ratio (i.e., 1.62/0.59) between the marginal private and social values of energy savings that characterizes our market environment.

¹⁰This is the ultimate version of a diagram which first appeared in Jaffe and Stavins (1994).

¹¹Moral hazard can also be restated as an implied discount rate of 15%. This value is computed by solving and averaging the θ -specific discount rates that match the quality offered under perfect information with the 7%-discounted net present value enjoyed by the homeowner under asymmetric information. It is consistent with the estimates reported in the empirical literature on energy efficiency investments (Hausman 1979; Train 1985).

Sensitivity analysis. We vary the key parameters of the model according to assumptions outlined in Table 8. Each scenario is meant to mimic different barriers to energy efficiency, which, according to the taxonomy referred to in the introduction, are categorized either as market failures, non-market failures or behavioral anomalies. Figure 2 displays the resulting deadweight losses and their elasticities with respect to each parameter (in absolute value).

In all but two scenarios, moral hazard still generates more deadweight loss than externalities, in proportions ranging from 1.3 to 2.3. The reverse however occurs when discounting is sharp and the time horizon is short. Both scenarios imply shortsightedness, which necessarily lowers the deadweight loss associated with moral hazard, which is decreasing in present value, relative to that of externalities, which is constant in present value.

Elasticity values point to electricity price and the time horizon as the most sensitive determinants of the deadweight loss. This illustrates the extent of interactions between moral hazard and other market failures, namely distortions in energy markets and other information asymmetries in housing markets. Technology cost and efficiency are the next important determinants. This underlines the importance of reducing measurement errors in engineering tests to perform accurate welfare analysis of energy efficiency programs. The discount rate also exerts some influence on the deadweight loss. In contrast, other demand-side parameters such as homeowners' comfort valuation and heterogeneity have negligible influence.

A sufficient statistic of the deadweight loss. We now propose a sufficient statistic that helps rationalize the sensitivity analysis discussed above. The deadweight loss from suboptimal quality can be approximated by the following formula (see online appendix for a complete derivation):

$$(12) \quad \overline{\Delta_q W} = -p\Gamma(r, l)\Delta_q E - \Delta_q C.$$

Recall from Equation 5 that welfare is defined as the sum of utilities derived by homeowners from comfort, net of electricity expenditures, and contractors' profits. The formula above expresses its variations simply as a net present value balancing the cost of quality against its effect on energy expenditures. Crucially, it does not require knowledge of homeowners' characteristics, namely her comfort valuation $V(\cdot)$ or electricity usage $E^0(\cdot)$. The rebound effect can therefore be ignored when assessing the deadweight loss from moral hazard.

The results of sensitivity analysis are fully consistent with the sufficient statistic. All parameters which we found have non-negligible elasticities (above 0.4) enter its expression.

Reciprocally, the formula does not include those parameters that have negligible elasticities, namely the homeowner's characteristics V_{max} and σ (0.07 and 0.05, respectively).

Lastly, as we show in the online appendix, the sufficient statistic provides a lower bound of the size of the deadweight loss. Our simulations confirm this and the accuracy of the formula, which is found to never underestimate the exact deadweight loss by more than 9% across scenarios.

4.3. Insurance versus standard

Figure 3 displays the welfare effects of energy-savings insurance and minimum quality standards in the reference scenario, with and without carbon-dioxide externalities. Optimal insurance contracts, which are homeowner-specific, have a coverage of 16% and involve a present-discounted cost of \$1,862 for insurance premia, on average. Since homeowner types may not be perfectly observable, it is also worth considering uniform insurance contracts. As depicted in the figure, incremental coverage initially improves both energy efficiency and welfare, up to a point where higher efficiency becomes so expensive that it starts deterring participation, hence a backward bend in both efficiency and welfare trajectories. The best such contract is located farthest to the right of the horizontal axis. The associated coverage is 19% without externalities and only 1% otherwise. The welfare gains with the best uniform insurance are only slightly below those produced by optimal homeowner-specific contracts. This means that in the context considered here, ignoring consumer heterogeneity in policy design has little implication. The point also applies to minimum quality standards. Just like uniform insurance, standards draw an ellipse driven by increasing stringency. The best standard mandates a quality of 37% absent externalities and 42% otherwise. In all cases, it brings the market very close to the social optimum.

Overall, the insurance mitigates about a third of the deadweight loss due to moral hazard if externalities are absent or perfectly internalized. Otherwise, it is counter-productive. The best standard appears substantially more efficient, regardless of the environment. Yet unlike insurance, standards require verification, monitoring and enforcement. As reported by Palmer, Walls, Gordon, and Gerarden (2013), the cost of an audit for retrofits is on average \$347 in the United States. Accounting for this as enforcement cost substantially reduces the benefits from standards, thus making policy comparison ambiguous.

An important takeaway is that unlike insurance, standards are relatively unaffected by carbon-dioxide externalities. This is due to the nature of the rebound effect induced by each instrument. Both policies induce a direct rebound effect, as they increase energy efficiency

and thus lower the marginal cost of energy services. In addition, insurance coverage further reduces marginal energy expenditures. This causes demand-side moral hazard—over-use of energy which exacerbates externalities. Minimum quality standards should therefore be preferred to energy-savings insurance if externalities remain unpriced.

5. Conclusion

Many energy efficiency measures can be thought of as credence goods, the performance of which is never fully revealed to the buyer. This characteristic creates a variety of information asymmetries, some of which can generate a discrepancy between predicted and realized energy savings. Ultimately, investment in energy efficiency is under-provided, a phenomenon known as the energy efficiency gap. In this paper, we investigate the existence of and solutions to one such information asymmetry, namely moral hazard in the quality of installation.

We provide empirical evidence of the problem in home energy retrofits. Using data from a utility-sponsored retrofit program implemented in Florida, we find that for measures such as attic insulation and duct sealing, the quality of which is hard to observe *ex post*, energy savings are significantly lower when the retrofit was completed on a Friday—a day particularly prone to negative shocks on workers’ productivity—than on any other weekday. We interpret this outcome as evidence of supply-side moral hazard and show that it can explain a large fraction of the discrepancy between predicted and realized energy savings. In theory, the problem can be addressed by private interventions, such as energy-savings insurance, or public interventions, such as minimum quality standards. We show that neither intervention can eliminate the welfare loss: insurance contracts induce demand-side moral hazard, as lower marginal expenditures encourage over-use of energy; standards incur enforcement costs. The comparison between the two is therefore context-specific. Our numerical model suggests that while energy-savings contracts with small insurance coverage (typically 10-20%) can significantly mitigate the moral hazard, they also amplify carbon-dioxide externalities. Minimum quality standards therefore seem more desirable if externalities are left unpriced.

We see several interesting extensions to our analysis. On the theoretical front, attention should be focused on reputation strategies. The finding that energy efficiency providers do offer some quality during most of the workweek suggests that reputational concerns might be important. On the empirical front, new experiments allowing for direct observation of quality should be designed in order to directly investigate the link between installation defects and

realized energy savings. On the policy front, efforts should be devoted to ex post evaluation of energy performance contracts, quality certifications and other remedies to moral hazard.

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TABLE 1. Summary statistics by energy efficiency measure

	Predicted energy savings (MWh/year) mean (SD)	Predicted energy savings (kWh/month) mean (SD)	Maher (2016)'s DiD energy savings (kWh/month) coefficient (SE)	Project price mean (SD)	Rebate amount mean (SD)	Day of installation median	Observability	# Obs.
Attic Insulation	1.55 (0.04)	129.17 (3.33)	78.65*** (26.91)	\$761 (\$501)	\$199 (\$77)	Wednesday	Hard	575
Duct Repair	1.29 (0.04)	107.46 (3.31)	38.36 (33.57)	\$861 (\$911)	\$359 (\$98)	Wednesday	Hard	366
Low-Interest Loan	- -	- -	73.04 (79.79)	- -	\$1,089 (\$505)	Wednesday	Hard	84
Super-SEER Central AC	1.93 (0.53)	160.83 (44.17)	208.9*** (27.11)	\$7,291 (\$1,467)	\$555 (\$62)	Wednesday	Easy	623
SEER-15 Central AC	0.55 (0.12)	45.83 (10.00)	161.3*** (37.60)	\$5,672 (\$1,412)	\$295 (\$44)	Wednesday	Easy	297
Pool Pump	1.76 (0.16)	146.67 (13.33)	101.6** (47.05)	\$1,452 (\$505)	\$284 (\$97)	Wednesday	Easy	394
Low-Income Grant	1.12 (0.82)	93.33 (68.33)	52.87 (38.52)	\$301 (\$339)	\$2,170 (\$1,528)	Wednesday	Easy	227
Whole Home Performance	2.49 (1.00)	207.50 (83.33)	131.1*** (43.88)	\$654 (\$239)	\$967 (\$289)	Wednesday	Easy	342
Low-E Window	0.66 (0.36)	55.00 (30.00)	155.2** (72.66)	\$3,511 (\$2,205)	\$159 (\$81)	Wednesday	Easy	28
Total								2,936

Notes: The estimates in the column labelled “Maher (2016)’s DiD” are technology-specific estimates of energy savings taken directly from Maher (2016). They are computed using a difference-in-differences estimator similar to that used to estimate the savings with day-of-the-week effects. The regression model does not consider heterogeneity with respect to the day of installation and estimates average savings for each measure. Standard errors are clustered at the household level (* $p < .10$ ** $p < .05$ *** $p < .01$). The column “Observability” classifies the quality of a measure as “Easy” or “Hard” to observe ex post.

TABLE 2. Summary statistics by day of the week

Retrofit Observability	Day of the Week Installed						Mean	Diff Mean	# Obs (M-F)	# Obs (All)
	M	T	W	Th	F	WE	M-Th (SD)	(M-Th vs. F) (SE)/[<i>p</i> -val]		
A. Ex-ante energy savings prediction (MWh per year)										
HTO	1.44 (.14)	1.45 (.14)	1.44 (.14)	1.44 (.13)	1.44 (.14)	1.52 (.11)	1.44 (.14)	-0.000849 (.01) [.94]	830	941
ETO	1.6 (.71)	1.56 (.73)	1.57 (.77)	1.43 (.78)	1.59 (.78)	1.47 (.87)	1.54 (.75)	0.0582 (.05) [.22]	1,550	1,641
B. Project price (dollars)										
HTO	806 (648)	868 (770)	891 (1,029)	754 (503)	813 (662)	672 (617)	831 (768)	-18.22 (70.4) [.8]	653	732
ETO	4,348 (3,108)	3,935 (3,042)	4,389 (3,099)	4,452 (3,038)	4,332 (3,014)	3,063 (2,595)	4,277 (3,072)	55.11 (239.1) [.82]	993	1,048
C. Rebate amount (dollars)										
HTO	286 (181)	335 (250)	373 (369)	412 (375)	295 (243)	254 (236)	351 (308)	-12.52 (9.62) [.19]	905	1,025
ETO	767 (871)	689 (746)	690 (716)	774 (887)	666 (718)	752 (921)	729 (808)	-75.48 (51.01) [.14]	1,805	1,911
Observations	504	534	556	547	569	226	2,141		2,710	2,936

Notes: Mean and standard deviation (in parentheses) for the three main variables, presented separately in panels A, B, and C. Differences in the number of observations across variables are due to missing information. The number of observations for a given day include all contracts with information for at least one variable. The label HTO refers to hard-to-observe measures and ETO refers to easy-to-observe measures. The last column reports the difference in means between Friday and the rest of the workweek (Mon-Thu), the standard error for this difference (SE), and the p-value [*p*-val] for a two-tailed t-test where the null hypothesis is that the difference between a Friday mean and Mon-Thu mean is equal to zero. We find no difference in means that is statistically significant at the 10% level.

TABLE 3. Day-of-the-week effects: all energy sources

Dep. Variable: Log(kWh+Nat. Gas/month)	Monday Effect	Tuesday Effect	Wednesday Effect	Thursday Effect	Friday Effect	Friday+WE Effect
HTO=1	-0.0371** (0.0156)	-0.0416** (0.0167)	-0.0410** (0.0169)	-0.0520*** (0.0166)	-0.0625*** (0.0171)	-0.0625*** (0.0171)
ETO=1	-0.0592*** (0.0112)	-0.0642*** (0.0113)	-0.0593*** (0.0114)	-0.0693*** (0.0114)	-0.0618*** (0.0112)	-0.0618*** (0.0112)
HTO=1 X Monday	-0.0511 (0.0470)					
ETO=1 X Monday	-0.0191 (0.0209)					
HTO=1 X Tuesday		-0.0268 (0.0336)				
ETO=1 X Tuesday		0.00724 (0.0215)				
HTO=1 X Wednesday			-0.0276 (0.0308)			
ETO=1 X Wednesday			-0.0163 (0.0192)			
HTO=1 X Thursday				0.0272 (0.0335)		
ETO=1 X Thursday				0.0314 (0.0204)		
HTO=1 X Friday					0.0718** (0.0318)	
ETO=1 X Friday					-0.00463 (0.0239)	
HTO=1 X Friday + WE						0.0581** (0.0274)
ETO=1 X Friday + WE						-0.0750** (0.0346)
HTO=1 X WE	0.00939 (0.0391)	0.0139 (0.0399)	0.0133 (0.0401)	0.0243 (0.0399)	0.0347 (0.0401)	
ETO=1 X WE	-0.0625* (0.0377)	-0.0575 (0.0377)	-0.0623* (0.0378)	-0.0525 (0.0378)	-0.0599 (0.0376)	
Constant	7.204*** (0.00647)	7.204*** (0.00647)	7.204*** (0.00647)	7.204*** (0.00647)	7.204*** (0.00646)	7.204*** (0.00647)
R-squared	0.652	0.652	0.652	0.652	0.652	0.652
F- $H_0 : \eta_d = \phi_d$	0.388	0.725	0.0970	0.0116	3.695	5.146
Prob > F- H_0	0.534	0.394	0.755	0.914	0.0547	0.0234

Notes: Standard errors are clustered at the household level (* $p < .10$ ** $p < .05$ *** $p < .01$). The number of observations is 490,954. The first two rows of estimates correspond to the energy savings for the days of the week not captured by the interaction effect in the lower rows. The last column groups Fridays and weekends together. All regressions include fixed effects for house-by-month and month-of-sample.

TABLE 4. Day-of-the-week effects: electricity only

Dep. Variable: Log(kWh/month)	Monday Effect	Tuesday Effect	Wednesday Effect	Thursday Effect	Friday Effect	Friday+WE Effect
HTO=1	-0.00181 (0.0157)	-0.0115 (0.0168)	-0.0132 (0.0166)	-0.0188 (0.0168)	-0.0313* (0.0168)	-0.0313* (0.0168)
ETO=1	-0.0512*** (0.0113)	-0.0529*** (0.0114)	-0.0485*** (0.0113)	-0.0606*** (0.0115)	-0.0534*** (0.0114)	-0.0534*** (0.0114)
HTO=1 X Monday	-0.0711 (0.0450)					
ETO=1 X Monday	-0.0116 (0.0200)					
HTO=1 X Tuesday		-0.0193 (0.0319)				
ETO=1 X Tuesday		-0.00213 (0.0210)				
HTO=1 X Wednesday			-0.00926 (0.0323)			
ETO=1 X Wednesday			-0.0228 (0.0194)			
HTO=1 X Thursday				0.0183 (0.0309)		
ETO=1 X Thursday				0.0351* (0.0204)		
HTO=1 X Friday					0.0735** (0.0321)	
ETO=1 X Friday					0.000544 (0.0234)	
HTO=1 X Friday + WE						0.0537** (0.0271)
ETO=1 X Friday + WE						-0.0669** (0.0340)
HTO=1 X WE	-0.00986 (0.0377)	-0.000155 (0.0385)	0.00165 (0.0385)	0.00711 (0.0385)	0.0196 (0.0385)	
ETO=1 X WE	-0.0642* (0.0373)	-0.0625* (0.0372)	-0.0668* (0.0373)	-0.0548 (0.0373)	-0.0620* (0.0371)	
Constant	6.909*** (0.00676)	6.909*** (0.00676)	6.909*** (0.00676)	6.909*** (0.00676)	6.909*** (0.00676)	6.909*** (0.00676)
R-squared	0.680	0.680	0.680	0.680	0.680	0.680
F- $H_0 : \eta_d = \phi_d$	1.461	0.203	0.128	0.204	3.390	4.338
Prob > F- H_0	0.227	0.652	0.720	0.652	0.0657	0.0374

Notes: Standard errors are clustered at the household level (* $p < .10$ ** $p < .05$ *** $p < .01$). The number of observations is 489,217. All regressions include fixed effects for house-by-month and month-of-sample.

TABLE 5. Gap realized-predicted savings without friday-effect

	Realized Savings MWh/year	Predicted Savings MWh/year	Gap Predicted-Realized Savings
HTO Mon-Th	1.17 (0.33)	1.44 (0.14)	0.27
HTO Mon-Fri	0.98 (0.28)	1.44 (0.14)	0.47
Difference (%)	-16.49	-0.02	70.4

Notes: The realized savings in the first row of the first column are computed after controlling for the Friday effect using a regression similar to column 6 in Table 3, but where the dependent variable is in level. The monthly estimates are scaled by twelve to obtain an annual estimate. The realized savings in the second row of the first column is for a similar regression that does not control for the Friday effect. Regressions estimates are reported for HTO measures only. The estimates in the first and second rows of the second column are sample means for all HTO measures installed on Monday through Thursday or Monday through Friday, respectively. Controlling for the Friday effect reduces the discrepancy between realized and predicted savings (third column) by 70.4%.

TABLE 6. Model parameters

Parameter	Symbol	Value	Unit	Source
<i>Demand side</i>				
Minimum cooling service	s_{min}	2,139	CDD	Minimum of the RECS sample
Maximum cooling service	s_{max}	5,246	CDD	Maximum of the RECS sample
Maximum valuation of comfort	V_{max}	2,816	\$	95th percentile of the income share dedicated to air conditioning (3.9%) applied to the median income (\$55,000) of the RECS sample
Comfort sensitivity	α	0.0011		Calibrated with the RECS data (see online appendix)
Scale of energy use	β	2.0749		Calibrated with the RECS data (see online appendix)
Sensitivity of energy use	γ	1.0643		Calibrated with the RECS data (see online appendix)
Non-energy attributes	δ	260	\$	Calibrated with the RECS data so that the median homeowner is the marginal investor under asymmetric information (see online appendix)
First parameter of the log-normal distribution of θ	μ	0		Ensures that $\theta = 1$ is the median type
Second parameter of the log-normal distribution of θ	σ	0.5		Best fit of the distribution of CDDs found in the RECS data (see online appendix)
<i>Supply side</i>				
Minimum energy efficiency	G_{min}	1%		Conventional value
Maximum energy efficiency	G_{max}	30%		Conventional value
Efficiency sensitivity	a	1.0694		Calibrated with the GRU data (see online appendix)
Fixed cost of retrofit	b	373	\$	Calibrated with the GRU data (see online appendix)
Slope of marginal retrofit cost	c	5,090		Calibrated with the GRU data (see online appendix)
<i>Market environment</i>				
Price of electricity	p	0.1254	\$/kWh	Median price paid for electricity for air conditioning in the RECS sample
Social cost of CO ₂	p_{CO_2}	0.0169	\$/kWh	Social cost of \$31/tCO ₂ (Nordhaus 2017) applied to an emission factor of 550gCO ₂ /kWh for power generation in Florida (EPA 2015)
Discount rate	r	7%		Value recommended to assess private investment (OMB 2009)
Physical lifetime of retrofits	l	35	years	Conventional value

TABLE 7. Welfare analysis of the reference case

Model output	Unit	Without Pigouvian price				With Pigouvian price			
		Before investment	Asymmetric information	Perfect information	Optimal insurance	Before investment	Asymmetric information	Perfect information	
Welfare improvement, without externalities	\$	0	10	488	150	-267	-256	243	
Welfare improvement, with externalities	\$	0	20	634	-133	299	317	909	
Homeowners' equilibrium energy service	CDD	3,667	3,676	3,762	3,867	3,395	3,404	3,495	
Annual electricity use for air conditioning	kWh	5,110	5,094	4,864	5,553	4,156	4,144	3,987	
Annual electricity expenditure	\$	641	639	610	696	521	520	500	
Annual CO ₂ emissions	tCO ₂	2.8	2.8	2.7	3.0	2.3	2.3	2.2	
Annual external cost of CO ₂ emissions	\$	87	86	82	94	70	70	68	
Contractor's equilibrium quality			0%	36%	10%		0%	39%	
Energy efficiency of retrofit			0.5%	10.1%	3.5%		0.6%	10.7%	
Rebound effect			38%	53%	345%		51%	62%	
Cutoff type of the marginal participant			1.00	0.30	0.56		0.88	0.35	
Participation rate			50%	99%	88%		60%	98%	
Zero-profit retrofit price	\$		343	690	375		343	761	
Homeowner's net present value	\$		20	493	171		31	622	
Insurance premium	\$				1,862				
Insurance optimal coverage					16%				

Notes: "Energy efficiency" is averaged over the whole population of mass 1. The average over participants is obtained by dividing "Energy Efficiency" by "Participation rate". Welfare improvements are measured against present discounted welfare before investment, without a Pigouvian price (\$18,068 without externalities, \$15,036 with externalities).

TABLE 8. Sensitivity analysis

Parameter varied	Symbol	Reference value	Scenario value	Scenario interpretation and nature of the economic problem addressed	Size of moral hazard	Size of externalities	Elasticity	Precision of sufficient statistic
Electricity price	p	\$0.1254/kWh	\$0.1054/kWh	Lower price reflecting marginal cost pricing (market failure*)	\$482	\$321	1.57	-8.6%
Time horizon	l	35 years	10 years	Low capitalization of energy efficiency due to information asymmetries in housing markets (market failure)	\$253	\$479	0.93	-6.4%
Technology efficiency	G_{max}	30%	35%	Better technology (non-market failure)	\$563	\$277	-0.56	-8.0%
Discount rate	r	7%	20%	Under-valuation of energy savings by homeowners (behavioral anomaly)	\$158	\$638	-0.44	-5.4%
Technology cost	c	5,090	10,000	Costlier technology (non-market failure)	\$370	\$284	-0.42	-6.2%
Comfort valuation	V_{max}	\$2,165	\$2,500	Higher valuation of comfort (non-market failure)	\$621	\$274	0.07	-8.7%
Preference heterogeneity	σ	0.5	0.2	Narrower distribution of homeowners' valuations (non-market failure)	\$589	\$275	0.05	-4.8%

Notes: The size of moral hazard is the difference in welfare (with externalities) between perfect- and asymmetric-information equilibria, both without a Pigouvian price. The size of externalities is the difference in welfare (with externalities) between perfect-information equilibria with and without a Pigouvian price. Elasticities are calculated as the percentage change in the size of moral hazard compared to the reference scenario, divided by the percentage change in the parameter value. The precision of the sufficient statistic is calculated by comparing formula 12 to the exact deadweight loss, calculated without externalities. The precision in the reference scenario, not reported in this table, is -7.7%. *In this scenario variant, a market failure is actually *removed*, namely the average cost pricing that prevails in the reference scenario.

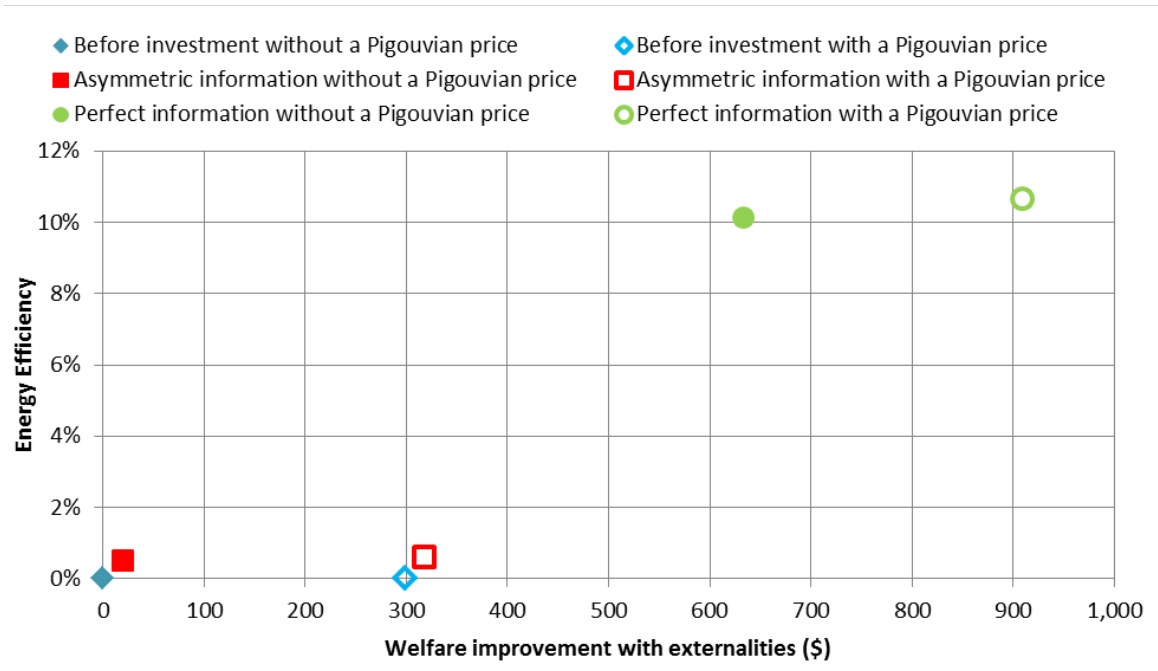


FIGURE 1. Energy-efficiency gap in the reference scenario.

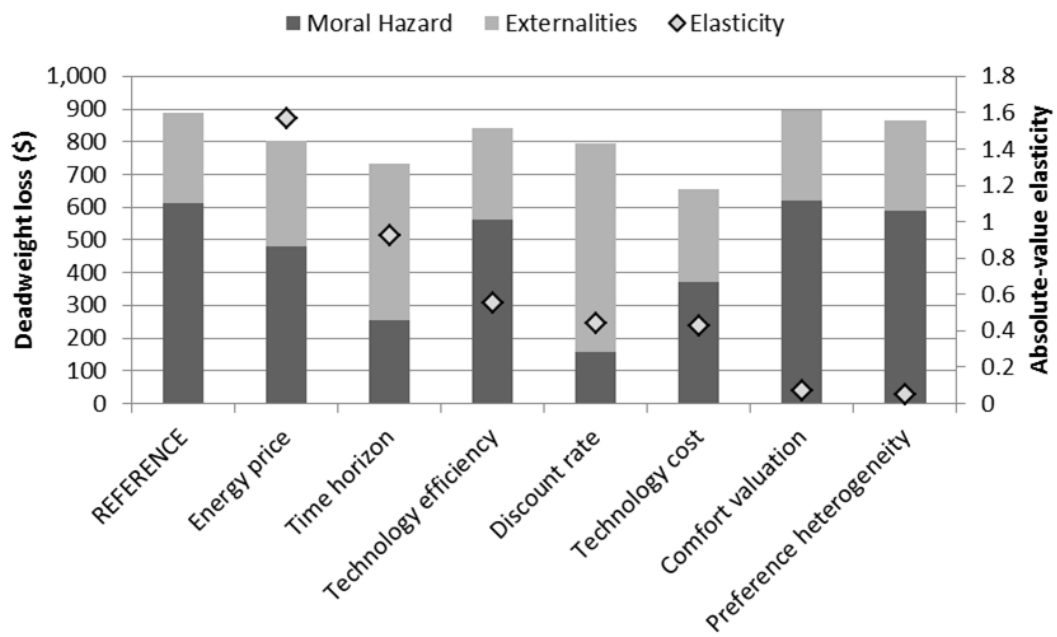


FIGURE 2. Sensitivity analysis

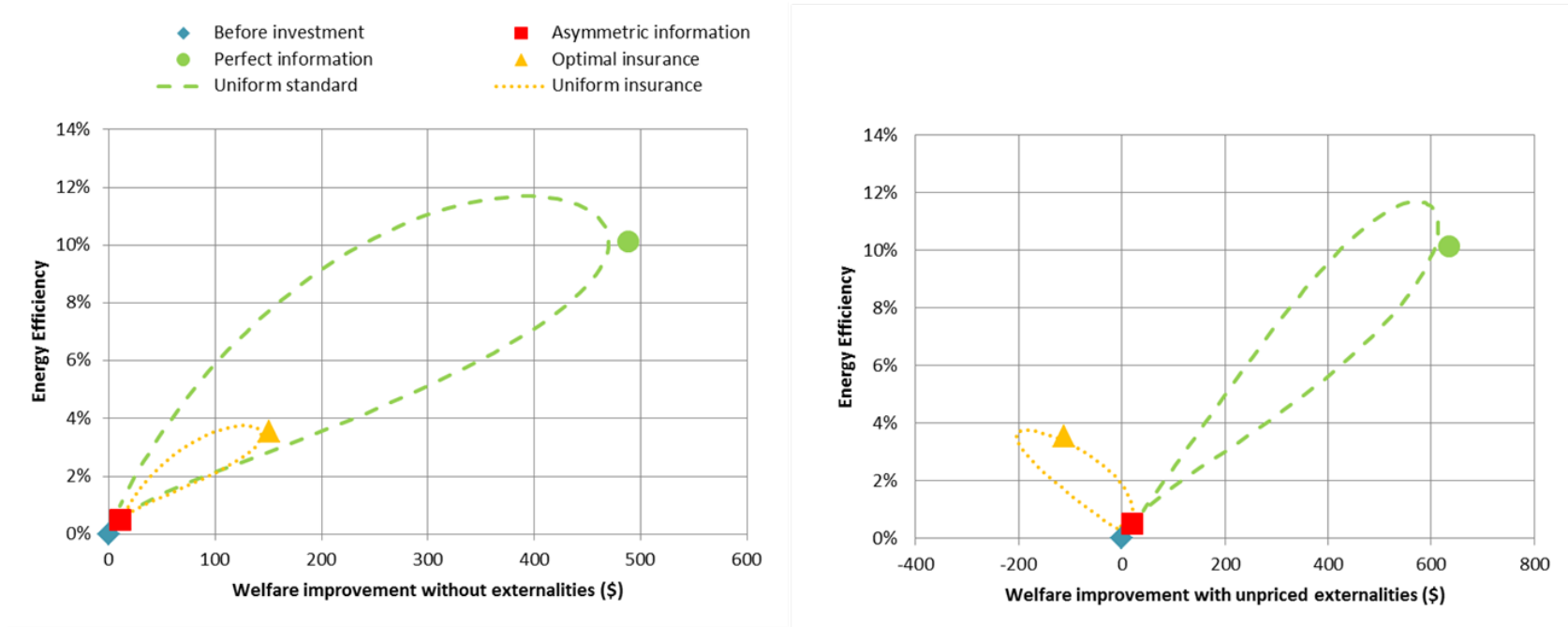


FIGURE 3. Policy comparison in the reference scenario

Notes: Uniform insurance draw a parametric curve with coverage increasing counter-clockwise by 1%, from 0% to 100%. Similarly, uniform standards draw a parametric curve with mandated quality increasing counter-clockwise by 1%, from 0% to 100%.

Online Appendix

Moral Hazard and the Energy Efficiency Gap: Theory and Evidence

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CONTENTS

A1. Supply-side moral hazard	2
A1.1. Setup	2
A1.2. Energy efficiency contract	3
A1.3. Energy efficiency gap at the market level	6
A1.4. Comparative statics	8
A2. Policy solutions	9
A2.1. Energy-savings contracts and demand-side moral hazard	9
A2.2. Minimum quality standard	11
A2.3. Interaction between moral hazard and energy-use externalities	12
A3. Sufficient statistics	13
A3.1. Deadweight loss from supply-side moral hazard	13
A3.2. Policy efficiency	14
A4. Specification of the numerical model	15
A4.1. Demand side	15
A4.2. Supply side	16
A5. Additional Regression Results	23

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A1. Supply-side moral hazard

This online appendix provides formal assumptions, additional propositions and complete proofs to the theoretical part developed in Section 2 of the main text. It also provides background for parameterization of the numerical model and the sufficient statistic discussed in Section 4. Lastly, it provides additional regression results.

A1.1. Setup

The homeowner maximizes lifetime-discounted utility $U^0(\cdot, \cdot)$ with respect to an intertemporal energy service vector \mathbf{s} :

$$(1) \quad U^0(\theta, \mathbf{s}) \equiv \sum_{t=1}^l [\theta V_t(s_t) - p_t E_t^0(s_t)] (1+r)^{-t}$$

where $V(\cdot)$ is the value derived from energy service (e.g., thermal comfort), $\theta > 0$ is a taste parameter, $E^0(\cdot)$ is energy use, p is the price of energy, l is investment lifetime and r is the discount rate.

The homeowner's lifetime-discounted net utility after retrofit $U(\theta, \mathbf{s}, q)$ reads

$$(2) \quad U(\theta, \mathbf{s}, q) \equiv \sum_{t=1}^l [\theta V_t(s_t) - p_t E_t(s_t, q)] (1+r)^{-t} - T + \delta$$

where q is the quality of installation offered by the contractor, $T > 0$ is the price of the retrofit and δ is the value derived from non-energy attributes (e.g., acoustic or aesthetic benefits if positive, inconvenience due to job completion if negative).

In what follows, we assume time invariance of energy price, technology and the homeowner's valuation of comfort. We remove t subscripts and consider vector \mathbf{s} as a scalar s constant over time. We further simplify notation with a discount factor Γ such that:

$$(3) \quad \Gamma \equiv \Gamma(r, l) \equiv \sum_{t=1}^l (1+r)^{-t} = \frac{1 - (1+r)^{-l}}{r}$$

Firms are homogenous in the industry. The profit of a representative contractor is the revenue from the sale minus the cost of the quality provided:

$$(4) \quad \Pi(q) \equiv T - C(q)$$

The following assumptions hold (subscripts denote partial derivatives):

Assumption 1. Technology

(i) At constant homeowner behavior s , investment reduces energy use: $E(s, q) < E^0(s) \forall q \geq q_{min}$, where q_{min} is the minimum input.

(ii) Contracting parties' actions have opposite effects: $E_s^0 > 0$, $E_s > 0$ and $E_q < 0$

(iii) Energy savings exhibit decreasing returns: $-E_{ss}^0 \leq 0$, $-E_{ss} \leq 0$ and $-E_{qq} \leq 0$

(iv) Contracting parties' actions are substitutes: $E_{qs} < 0$ and $E_s < E_s^0$

(v) Non-energy benefits are not sufficient to motivate investment: $\delta \leq C(q_{min})$

Assumption 2. Preferences

Contracting parties are (i) value-maximizers, (ii) risk-neutral and (iii) have twice differentiable, concave value functions: $V'(\cdot) > 0$, $V''(\cdot) \leq 0$ and $-C'(\cdot) < 0$, $-C''(\cdot) \leq 0$

Assumption 3. Market structure

The industry is competitive with free entry: $\Pi(q) = 0$.

Corollary. $T = C(q)$

Remarks. Assumptions 1(i)-(v) are mild: The energy service has a convex effect on energy use, and quality has diminishing returns on energy savings. Moreover, both factors impede each other: The marginal increase in energy savings due to increased quality is larger when the underlying energy service is high (e.g., air conditioning in a hot area) rather than low (e.g., air conditioning in a cold area). Reciprocally, the marginal increase in energy use due to increased energy service is lower when the quality installed is high rather than low.

Assumptions 2(i)-(iii) are meant to be as standard as possible, in order to isolate the moral-hazard problem from possibly interacting market failures and behavioral anomalies.

Assumption 3 is not essential. Whatever the structure of the market, home energy retrofits are very specific to a bundle of home and homeowner characteristics, and hence do not lend themselves to arbitrage. A monopolist could thus perfectly price discriminate. This would not change equilibrium quantities in the model, but only the surplus repartition.

The energy efficiency contract can be modeled as a two-stage game, of which the homeowner is the principal and the contractor is the agent. In the first stage of the game, a homeowner of type θ invests if the j -equilibrium net present value of investment $NPV^j(\theta)$ is positive, given her beliefs about her future optimal energy service s_θ^j and the optimal quality q_θ^j she will be offered by the contractor:

$$(5) \quad NPV^j(\theta) \equiv U(\theta, s_\theta^j, q_\theta^j) - U_0(\theta, s_\theta^0) \geq 0$$

In the second stage, both agents determine their own action given their belief about the other party's action.

A1.2. Energy efficiency contract

We compare the equilibrium of the game under two information structures, namely perfect and asymmetric information. The resulting equilibria can be seen as the social and private optimum, respectively.

Perfect information (PI). The contract between the contractor and a homeowner of type θ is set cooperatively so as to maximize joint surplus, subject to boundary conditions $s \geq s_{min}$ and $q \geq q_{min}$. The optimal actions s_θ^{PI} and q_θ^{PI} that solve the first-order conditions for maximization¹ below will be such that their marginal benefit (in terms of value to the homeowner and cost savings to the firm) equates their marginal effect on homeowner's energy bill:

$$(6) \quad \forall t \quad \theta V' \begin{cases} = pE_s & \text{if } s_\theta^{PI} > s_{min} \\ < pE_s & \text{otherwise} \end{cases}$$

$$(7) \quad C' \begin{cases} = -pE_q \Gamma & \text{if } q_\theta^{PI} > q_{min} \\ < -pE_q \Gamma & \text{otherwise} \end{cases}$$

The perfect-information equilibrium $(s_\theta^{PI}, q_\theta^{PI})$ can be characterized as a reaction function equilibrium. Assuming interior solutions and applying the Implicit Function Theorem to the first-order conditions, we find that the reaction functions $s_\theta^*(q)$ and $q^*(s)$ are strictly increasing:

$$(8) \quad \forall t \quad \frac{ds_\theta^*}{dq} = \frac{pE_{qs}}{\theta V'' - pE_{ss}} > 0$$

$$(9) \quad \frac{dq^*}{ds} = \frac{-pE_{sq}}{C''/\Gamma + pE_{qq}} > 0$$

Asymmetric information (AI). The agreement is no longer cooperative. Both parties maximize their private value, given their beliefs about the other party's action and subject to boundary conditions $s \geq s_{min}$ and $q \geq q_{min}$. While this yields the same reaction function as in the cooperative agreement $s_\theta^*(q)$ for the homeowner, this does not hold for the contractor. He fails to internalize the benefits his action delivers to the homeowner and simply chooses the level of quality q^{AI} that minimizes his cost:

$$(10) \quad \forall s \quad q^{AI}(s) = \arg \min_{q \geq q_{min}} C(q) = q_{min}$$

Lemma 1. *For a participating homeowner of given type θ :*

- (i) *the asymmetric-information equilibrium $(s_\theta^{AI}, q_\theta^{AI})$ exists and is unique*
- (ii) *the perfect-information equilibrium $(s_\theta^{PI}, q_\theta^{PI})$ exists and is unique if and only if:*

¹Throughout, the objective functions are well-behaved and the first-order conditions discussed are necessary and sufficient for maximization.

$$(11) \quad \frac{dq}{ds^*} > \frac{dq^*}{ds}$$

Proof. (i) The asymmetric-information equilibrium is uniquely defined as $(s_\theta^*(q_{min}), q_{min})$. (ii) Likewise, if for at least one agent his or her optimal cooperative action is a corner solution, then the perfect-information equilibrium is uniquely defined. If optimal actions are interior for both agents, condition (11) implies that the composite function $s_\theta^*(q^*(s))$ defined for all $s \geq s_{min}$ is a contraction mapping. Hence, by the Banach fixed-point theorem, it admits a unique fixed point. \square

Figure A1 illustrates the reaction function equilibria. The following proposition implies that the perfect- and asymmetric-information equilibria can be unambiguously compared:

Proposition 1. *Assuming condition (11) holds, a participating homeowner of given type θ :*

- (i) *is offered less quality under asymmetric information: $q_\theta^{AI} \leq q_\theta^{PI}$*
- (ii) *uses less energy service under asymmetric information: $s_\theta^0 < s_\theta^{AI} \leq s_\theta^{PI}$*
- (iii) *faces a lower net present value under asymmetric information: $NPV^{AI}(\theta) \leq NPV^{PI}(\theta)$*

Proof. (i) For a given θ , $q_\theta^{PI} \geq q_{min} = q_\theta^{AI}$. (ii) Since $s_\theta^*(\cdot)$ is increasing, $s_\theta^{PI} = s_\theta^*(q_\theta^{PI}) \geq s_\theta^*(q_\theta^{AI}) = s_\theta^{AI}$. For all s , $E_s^0 > E_s$ implies $U_s > U_s^0$. Therefore, assuming interior solutions: $U_s^0|_{s_\theta^0} = 0 = U_s|_{s_\theta^{AI}} > U_s^0|_{s_\theta^{AI}}$. Since U^0 is concave in s , U_s^0 is decreasing in s and $s_\theta^{AI} > s_\theta^0$. (iii) Comparing net present values $NPV^{PI}(\cdot)$ and $NPV^{AI}(\cdot)$ is equivalent to comparing the utility functions after investment $U(\theta, s_\theta^{PI}, q_\theta^{PI})$ and $U(\theta, s_\theta^{AI}, q_\theta^{AI})$. Under the assumption of perfect competition, the utility after investment is equivalent to the joint surplus. Therefore, the net present value of investment is maximized under perfect information: $NPV^{PI}(\theta) \geq NPV^{AI}(\theta)$. \square

Note that the resulting quality gap would occur even if the homeowner's behavior did not respond to energy expenditures.² In contrast, energy uses $E(s_\theta^{PI}, q_\theta^{PI})$, $E(s_\theta^{AI}, q_\theta^{AI})$ and $E(s_\theta^0)$ cannot be unambiguously compared. We shall now make a distinction between two types of backfire rebound effect, which will prove useful later in the analysis.

Definition 1. Investment-induced backfire

An investment-induced backfire rebound effect occurs if energy use after investment is larger than before investment: $s > s^0$ and $E(s, q) > E^0(s^0)$.

Definition 2. Policy-induced backfire

A policy-induced backfire rebound effect occurs between two policy options H and L if energy use after investment is larger in the more energy-efficient option H : $q^H > q^L$, $s^H > s^L$ and $E(s^H, q^H) > E(s^L, q^L)$.

²This is for instance the case with a tenant subscribing to a utility-included rent contract, or an employee in a commercial building. Then, the occupant's reaction function would be flat. The contractor's reaction function under perfect information would also be flat but set at the maximum quality level, which internalizes the effect of quality on energy expenditures.

A1.3. Energy efficiency gap at the market level

We now turn to a continuum of homeowners of mass 1. Applying the Implicit Function Theorem to Equation 6:

$$(12) \quad \forall t \quad \frac{ds_{\theta}^*}{d\theta} = \frac{-V'}{\theta V'' - pE_{ss}} > 0$$

Therefore, for any given quality q offered by the contractor, a higher valuation of energy service shifts the homeowner's reaction function upward:

$$(13) \quad \forall q, \forall \theta_h > \theta_l \quad s_{\theta_h}^*(q) > s_{\theta_l}^*(q)$$

This effect is illustrated in Figure A2.

As long as condition (11) is satisfied, new equilibria are determined with the properties below:

Lemma 2. *If condition (11) is satisfied for two participating homeowners of types θ_h and θ_l , with $\theta_h > \theta_l$, then the higher θ implies higher actions by either contracting party, in either equilibrium:*

- (i) $q_{\theta_h}^{AI} = q_{\theta_l}^{AI} = q_{min}$
- (ii) $s_{\theta_h}^{AI} \geq s_{\theta_l}^{AI}$
- (iii) $s_{\theta_h}^{PI} \geq s_{\theta_l}^{PI}$
- (iv) $q_{\theta_h}^{PI} \geq q_{\theta_l}^{PI}$.

Proof. (i) is straightforward. (ii) Combined with (13), it implies: $s_{\theta_h}^{AI} = s_{\theta_h}^*(q_{\theta_h}^{AI}) \geq s_{\theta_l}^*(q_{\theta_l}^{AI}) = s_{\theta_l}^{AI}$. (iii) Likewise, (13) implies, for all s , $s_{\theta_h}^*(q^*(s)) \geq s_{\theta_l}^*(q^*(s))$. In particular, $s_{\theta_h}^{PI} = s_{\theta_h}^*(q^*(s_{\theta_h}^{PI})) \geq s_{\theta_l}^*(q^*(s_{\theta_h}^{PI}))$. From (11), $s_{\theta_l}^*(q^*(\cdot))$ is increasing with slope lower than 1. Any point that is greater than its image by $s_{\theta_l}^*(q^*(\cdot))$ is thus greater than the fixed point of $s_{\theta_l}^*(q^*(\cdot))$: $\forall a > s_{\theta_l}^{PI}$, $s_{\theta_l}^*(q^*(a)) - s_{\theta_l}^*(q^*(s_{\theta_l}^{PI})) < a - s_{\theta_l}^{PI} \Leftrightarrow s_{\theta_l}^*(q^*(a)) < a$. Therefore, $s_{\theta_h}^{PI} \geq s_{\theta_l}^{PI}$. (iv) Lastly, since $g^*(\cdot)$ is increasing, $q_{\theta_h}^{PI} = g^*(s_{\theta_h}^{PI}) \geq g^*(s_{\theta_l}^{PI}) = q_{\theta_l}^{PI}$. \square

For any equilibrium situation $j \in \{PI, AI\}$, we have, by the Envelope Theorem:

$$(14) \quad \frac{dNPV^j}{d\theta} = [V(s_{\theta}^j) - V(s_{\theta}^0)] \Gamma$$

As $V(\cdot)$ is increasing and $\forall \theta \quad s_{\theta}^j > s_{\theta}^0$, the net present value of investment strictly increases with θ . This is illustrated in Figure A3 with the numerical model. For any equilibrium situation j , participation will depend on the limits of the net present value function, the sign of which is indeterminate:

$$(15) \quad NPV^j(\theta) \equiv \underbrace{\left[\theta \left(V(s_\theta^j) - V(s_\theta^0) \right) - p \left(E(s_\theta^j, q_\theta^j) - E^0(s_\theta^0) \right) \right]}_{\geq 0} \underbrace{\Gamma}_{\leq 0} \underbrace{-T + \delta}_{\leq 0}$$

The right inequality is given by Assumption 1(v). The left inequality comes from the following inequalities: $\theta V(s_\theta^0) - pE^0(s_\theta^0) \leq \theta V(s_\theta^0) - pE(s_\theta^0, q_\theta^j) \leq \theta V(s_\theta^j) - pE(s_\theta^j, q_\theta^j)$. The former is due to technological assumptions about E and E^0 and the latter is due to s_θ^j maximizing U .

According to Lemma 2, equilibrium actions s_θ^j and q_θ^j decrease with θ . As they are bounded below by s_{min} and q_{min} , the limit of $NPV(\theta)$ when θ tends toward zero is finite. Three cases arise:

- If $\lim_{\theta \rightarrow 0} NPV(\theta) \geq 0$ then all homeowners participate. Participation is given by $N^j \equiv \int_0^{+\infty} dF(\theta) = 1$.
- If $\lim_{\theta \rightarrow 0} NPV(\theta) < 0$ and $\lim_{\theta \rightarrow +\infty} NPV(\theta) > 0$ then by Equation 14, there exists a unique cutoff type θ_0 such that $NPV^j(\theta_0) = 0$.
- If $\lim_{\theta \rightarrow 0} NPV(\theta) < 0$ and $\lim_{\theta \rightarrow +\infty} NPV(\theta) \leq 0$ then participation is nil. In this case, the gross utility gains accruing to the homeowner never offset the increase in the payment to the contractor.

In what follows, we are interested in the most relevant case where the cutoff type is uniquely defined. Assuming that $F(\cdot)$ is the cumulative distribution function of θ , participation to investment N^j is given by:

$$(16) \quad N^j \equiv 1 - F(\theta_0^j)$$

Finally, under zero-profit condition, aggregate welfare is the sum of utility before investment for non-participating homeowners ($0 \leq \theta < \theta_0$), plus the utility after investment for participants ($\theta \geq \theta_0$):

$$(17) \quad W^j \equiv \int_0^{\theta_0^j} U^0(\theta, s_\theta^0) dF(\theta) + \int_{\theta_0^j}^{+\infty} U(\theta, s_\theta^j, q_\theta^j) dF(\theta)$$

We can now provide a definition of the energy efficiency gap:

Proposition 2. *Assuming that condition (11) is satisfied for all homeowners with $\theta > 0$:*

- (i) *the market is thinner under asymmetric information: $N^{AI} \leq N^{PI}$*
- (ii) *aggregate welfare is lower under asymmetric information: $W^{AI} \leq W^{PI}$*

Proof. (i) Assume θ_0^{PI} (respectively θ_0^{AI}) is the cutoff value of θ in the social (respectively private) optimum. Proposition (2iii) imposes the following inequality: $NPV^{PI}(\theta_0^{PI}) = 0 =$

$NPV^{AI}(\theta_0^{AI}) \leq NPV^{PI}(\theta_0^{AI})$. Since $NPV^j(\cdot)$ is increasing, $\theta_0^{PI} \leq \theta_0^{AI}$. Hence, $N^{PI} - N^{AI} = \int_{\theta_0^{PI}}^{\theta_0^{AI}} dF(\theta) \geq 0$. (ii) $W^{PI} - W^{AI} = \int_{\theta_0^{PI}}^{\theta_0^{AI}} NPV^{PI}(\theta) dF(\theta) + \int_{\theta_0^{AI}}^{+\infty} [U(\theta, s_\theta^{PI}, q_\theta^{PI}) - U(\theta, s_\theta^{AI}, q_\theta^{AI})] dF(\theta) \geq 0$. \square

A1.4. Comparative statics

We discuss below further comparative statics with respect to a composite indicator of all market and behavioral parameters: $\zeta \equiv p\Gamma(r, l)$. Any value of p , r or l that does not reflect perfect competition, perfect rationality or perfect information translates into a biased ζ . Specifically, a higher ζ is equivalent to a higher energy price p or a higher Γ , that is, a lower discount rate r or a longer lifetime l . Comparative statics of ζ thus provides insight into the interaction between moral hazard and other market failures or behavioral anomalies.

Applying the Implicit Function Theorem to Equations 6 and 7, we see that an increase in ζ shifts reaction functions $s_\theta^*(\cdot)$ downward and $q^*(\cdot)$ upward:

$$(18) \quad \forall t \quad \frac{ds_\theta^*}{d\zeta} = \frac{E_s}{\theta V''/\zeta - E_{ss}} < 0$$

$$(19) \quad \frac{dq^*}{d\zeta} = \frac{-E_q}{C''/\zeta + E_{qq}} > 0$$

This is illustrated in Figure A1 with energy-use externalities.

By the same reasoning as in Lemma 2, a higher ζ entails a higher energy service under asymmetric information. But optimal actions cannot be compared unambiguously under perfect and asymmetric information.

The influence of ζ on NPV^* , established by the Envelope Theorem, depends on the homeowner's reaction to higher energy efficiency:

$$(20) \quad \frac{dNPV^*}{d\zeta} = - [E(s_\theta^*, q_\theta^*) - E^0(s_\theta^0)]$$

As long as energy efficiency investments decrease energy use for all homeowners, the net present value is increasing in ζ . By the same type of reasoning as in Lemma 2, this leads to a higher participation and a higher average welfare. This conclusion is reversed if all homeowners are subject to an investment-induced backfire rebound effect, i.e., $\forall \theta E(s_\theta^*, q_\theta^*) > E^0(s_\theta^0)$. In this case, a higher ζ decreases participation and average welfare.

A2. Policy solutions

A2.1. Energy-savings contracts and demand-side moral hazard

In our simple framework with no risk-aversion, insurance can be modeled as a contract in which the contractor bears a share k of energy expenditures:

$$(21) \quad U(\theta, s, q) \equiv [\theta V(s) - (1 - k)pE(s, q)]\Gamma - T - I + \delta$$

$$(22) \quad \Pi(q) \equiv I + T - C(q) - kpE(s, q)\Gamma$$

According to Assumption 3, the payment to the contractor is $T + I$, where $I = k pE(s, q)\Gamma$ is the actuarially-fair insurance premium.

A new, opposite principal-agent relationship superimposes to the previous one: Since the contractor now provides insurance, he is a principal and the homeowner is an agent. The implementation of this contract can be solved backward as a three-stage game played by the parties. In the third stage, each party determines non-cooperatively his or her own effort, given insurance coverage k and his or her belief about the other party's action. First-order conditions for maximization are:

$$(23) \quad \forall t \quad \theta V' \begin{cases} = (1 - k)pE_s & \text{if } s_\theta^i(k) > s_{min} \\ < (1 - k)pE_s & \text{otherwise} \end{cases}$$

$$(24) \quad C' \begin{cases} = -kpE_q\Gamma & \text{if } q_\theta^i(k) > q_{min} \\ > -kpE_q\Gamma & \text{otherwise} \end{cases}$$

The optimal homeowner's response is bounded above by a satiation value s_{max} .³ By the Implicit Function Theorem, the insurance reaction functions $s_\theta^{**}(q, k)$ and $q^{**}(s, k)$ are both increasing in k :

$$(25) \quad \forall t \quad \frac{ds_\theta^{**}}{dk} = \frac{-pE_s}{\theta V'' - (1 - k)pE_{ss}} > 0$$

³Without satiation, full insurance ($k = 1$) would bring the marginal value of energy service in Equation 23 to zero, hence inducing infinite energy service. Satiation could be introduced as the argument of the maximum of a parabolic utility function. Alternatively, in our numerical model, it is introduced as an upper bound on the value of s . This specification allows for more flexibility in the numerical section, without loss of generality.

$$(26) \quad \frac{dq^{**}}{dk} = \frac{-pE_q}{C''/\Gamma + kpE_{qq}} > 0$$

The implementation of such a contract partly solves the moral hazard, as it induces the contractor to offer some quality (Equation 24). At the same time, however, it gives rise to a second moral hazard: By lowering the homeowner's marginal value of energy service, it induces her to use more energy. The energy service in Equation 23 is used to the socially optimal level defined by Equation 6 when the homeowner is not insured ($k = 0$), whereas the quality in Equation 10 is offered to the socially optimal level defined by Equation 7 when the firm offers full insurance ($k = 1$). Since k cannot be simultaneously equal to 0 and 1, insurance cannot achieve the social optimum. At best, both parties will agree on an incomplete insurance contract $k \in (0, 1)$. For any insurance k , the agreement $(s_\theta^i(k), q_\theta^i(k))$ will be a Nash equilibrium determined by the intersection of each party's reaction function $s_\theta^{**}(q, k)$ and $q^{**}(s, k)$. These inputs will be higher than in the private optimum; however, their location relative to the perfect-information equilibrium is ambiguous.

Proposition 3. *Optimal energy-savings insurance stipulates incomplete coverage: $0 < \hat{k}_\theta < 1$.*

Proof. See text above. □

Various insurance contracts are illustrated in Figure A4.

Note that if homeowner's types are imperfectly observable to the contractor, a screening issue arises. Homeowners with the highest use of energy service may self-select into the insurance contract that offers the highest energy savings coverage. Assuming this away, the optimal value \hat{k}_θ that sustains the Nash equilibrium to each type is determined cooperatively in the second stage of the game, so as to maximize joint surplus:

$$(27) \quad \forall \theta \quad \hat{k}_\theta = \arg \max_{k \in [0,1]} [U(\theta, s_\theta^i(k), q_\theta^i(k)) + \Pi(q_\theta^i(k))]$$

In the second stage, the first-order condition for finding the optimal insurance contract from Equation 27 is:

$$(28) \quad p\Gamma \left(\frac{ds_\theta^{**}}{dk} [\theta V' - pE_s] - \frac{dq^{**}}{dk} \left[\frac{C'}{\Gamma} + pE_q \right] \right) = 0$$

Plugging in Equations 23 and 24 and further rearranging gives the equation that solves the optimal coverage \hat{k} :

$$(29) \quad \forall t \quad p\Gamma \left(kE_s \frac{ds_\theta^{**}}{dk} + (1-k)E_q \frac{dq^{**}}{dk} \right) = 0$$

Lastly, in the first stage, the homeowner chooses whether or not to invest, depending on her net present value for the investment and given her beliefs about the contractor's action and the optimal insurance coverage.

A2.2. Minimum quality standard

The optimal minimum standard will be set at a value \bar{q} that maximizes collective surplus, net of monitoring cost $M(\bar{q})$, subject to the participation constraint:

$$(30) \quad \begin{aligned} & \text{Maximize}_{\bar{q}} \quad \left[\int_0^{\theta_0} U^0(\theta, s_\theta^0) dF(\theta) + \int_{\theta_0}^{+\infty} [U(\theta, s_\theta^*(\bar{q}), \bar{q}) - M(\bar{q})] dF(\theta) \right] \\ & \text{subject to} \quad NPV(\theta_0, s_{\theta_0}^*(\bar{q}), \bar{q}) - M(\bar{q}) \geq 0 \end{aligned}$$

Assuming that the cutoff type exists and is unique, the constraint in Equation 30 is binding. The optimization program can be solved by simply maximizing the objective function and assuming that θ_0 is an implicit function $\theta_0(\bar{q})$ defined by the constraint. Applying the Leibniz integral rule and the Envelope Theorem leads to the following first-order condition for maximization:

$$(31) \quad \frac{d\theta_0}{d\bar{q}} \left(U^0(\theta_0(\bar{q}), s_{\theta_0}^0) - U(\theta_0(\bar{q}), s_{\theta_0}^*(\bar{q}), \bar{q}) + M(\bar{q}) \right) + \int_{\theta_0(\bar{q})}^{+\infty} \left[\frac{\partial U(\theta, s_\theta^*(\bar{q}), \bar{q})}{\partial \bar{q}} - M' \right] dF(\theta) = 0$$

Recognizing that $U^0(\theta_0(\bar{q}), s_{\theta_0}^0) - U(\theta_0(\bar{q}), s_{\theta_0}^*(\bar{q}), \bar{q}) = -NPV(\theta_0(\bar{q}), s_{\theta_0}^*(\bar{q}), \bar{q})$ and using the binding constraint leads to:

$$(32) \quad \int_{\theta_0}^{+\infty} \left[\frac{\partial U(\theta, s_\theta^*(\bar{q}), \bar{q})}{\partial \bar{q}} - M' \right] dF(\theta) = 0$$

In fact, since marginal participants are indifferent between investing and not investing, marginal changes in participation can be ignored.

In words, the optimal standard will equalize the sum of marginal disutilities (net of marginal monitoring costs) of participants for whom the standard is too tight with the sum of marginal utilities (net of marginal monitoring costs) of participants who would have been willing to invest beyond the standard.

Note that if participation to investment is nil without the standard, no standard will be welfare-improving. In contrast, if participation is complete without the standard, the constraint will not be binding and the optimal standard will be defined by the following first-order condition: $\int_0^{+\infty} [\partial U(\theta, s_\theta^*(\bar{q}), \bar{q}) / \partial \bar{q} - M'] dF(\theta) = 0$.

A2.3. Interaction between moral hazard and energy-use externalities

Public intervention to address moral hazard problems may not be systematically justified if they interact with energy market failures. Assume that every unit of energy used generates a linear external cost p_x valued with a specific discount factor Γ_x . For instance, p_x is positive for pollution or energy-security externalities, and negative for average-cost energy pricing. Homeowners' utilities before and after investment is now:

$$(33) \quad \begin{cases} U_x^0(\theta, s) \equiv U^0(\theta, s) - p_x E^0(s) \Gamma_x \\ U_x(\theta, s, q) \equiv U(\theta, s, q) - p_x E(s, q) \Gamma_x \end{cases}$$

These new utility functions allow one to define new net present value NPV_x and aggregate welfare W_x functions as in Equations 5 and 17, respectively. Equilibria are denoted with superscript PE if externalities are internalized through a Pigouvian price p_x and UE if they remain unpriced.

Proposition 4. *In an economy subject to both energy market failures and energy efficiency moral hazard:*

(i) *When energy market failures are corrected, it is desirable to also undo moral hazard:*

$$W_x^{PI+PE} \geq W_x^{AI+PE}$$

(ii) *If no homeowner is prone to an investment-induced backfire rebound effect, then it is desirable to correct energy market failures. This holds whether or not moral hazard is addressed: $\forall \theta E(s_\theta^{PI}, q_\theta^{PI}) \leq E^0(s_\theta^0) \Rightarrow W_x^{PI+PE} \geq W_x^{PI+UE}$ and $E(s_\theta^{AI}, q_\theta^{AI}) \leq E^0(s_\theta^0) \Rightarrow$*

$$W_x^{AI+PE} \geq W_x^{AI+UE}$$

(iii) *If homeowners are prone to neither an investment nor a policy-induced backfire rebound effect, then it is desirable to undo moral hazard. This holds even if energy market failures are not corrected: $\forall \theta E(s_\theta^{PI}, q_\theta^{PI}) \leq E(s_\theta^{AI}, q_\theta^{AI}) \leq E^0(s_\theta^0) \Rightarrow W_x^{PI+UE} \geq W_x^{AI+UE}$*

Proof. We illustrate with pollution externalities ($p_x > 0$).

(i) For all θ , since $(s_\theta^{PI+PE}, q_\theta^{PI+PE})$ maximizes U_x in the social setting, $U_x(\theta, s_\theta^{PI+PE}, q_\theta^{PI+PE}) \geq U_x(\theta, s, q)$ for all (s, q) , and for $(s_\theta^{AI+PE}, q_\theta^{AI+PE})$ in particular. Likewise, we have $U_x^0(\theta, s_\theta^{0,PE}) \geq U_x^0(\theta, s_\theta^0)$. By Proposition 3, it follows that $W_x^{PI+PE} \geq W_x^{AI+PE}$.

(ii) Again, for all θ , since $(s_\theta^{PI+PE}, q_\theta^{PI+PE})$ maximizes U_x in the social setting, $U_x(\theta, s_\theta^{PI+PE}, q_\theta^{PI+PE}) \geq U_x(\theta, s_\theta^{PI+UE}, q_\theta^{PI+UE})$. In addition, we have $NPV_x(\theta) = NPV(\theta) - p_x \Gamma_x [E(s, q) - E^0(s)]$. Assume θ_0^{PE} is the cutoff type in an equilibrium where both energy-use externalities and moral hazard are addressed, while θ_0^{UE} is the cutoff type in an equilibrium where only moral hazard problems are addressed. We have $NPV_x(\theta_0^{PE}) = 0 = NPV(\theta_0^{UE})$. In the absence of an investment-induced backfire rebound effect, we thus have $NPV_x(\theta_0^{PE}) = 0 \leq NPV_x(\theta_0^{UE})$. Since NPV is increasing in θ , $\theta_0^{PE} \leq \theta_0^{UE}$, that is, participation is higher if externalities are internalized. The difference in aggregate welfare between the two equilibria is $\Delta W = \int_0^{\theta_0^{PE}} \Delta U_x^0 dF(\theta) + \int_{\theta_0^{PE}}^{\theta_0^{UE}} [U_x(\theta, s_\theta^{PE}, q_\theta^{PE}) - U_x^0(\theta, s_\theta^0)] dF(\theta) + \int_{\theta_0^{UE}}^{+\infty} \Delta U_x dF(\theta)$. The first and third integrands of the right-hand side are positive (see proof (i) just above). The second integrand

is also positive, since $\forall \theta \geq \theta_0^{PE} U_x(\theta, s_\theta^{PE}, q_\theta^{PE}) \geq U_x^0(\theta, s^{0,PE}) \geq U_x^0(\theta, s^0)$. Therefore, aggregate welfare is larger when externalities are internalized: $W_x^{PI+PE} \geq W_x^{PI+UE}$. The exact same reasoning leads to $W_x^{AI+PE} \geq W_x^{AI+UE}$. This is because since $(s_\theta^{AI+PE}, q_\theta^{AI+PE})$ maximizes U_x under asymmetric information, $U_x(\theta, s_\theta^{AI+PE}, q_\theta^{AI+PE})$ is greater than $U_x(\theta, s, q)$ for any other actions s and q determined under asymmetric information, e.g., $(s_\theta^{AI+UE}, q_\theta^{AI+UE})$.

(iii) Externalities are unpriced here but superscript UE is dropped for the sake of parsimony. Assume θ_0^{PI} (resp. θ_c^{AI}) is the cutoff type in the social (resp. private) optimum. From proposition (4i), we have $\theta_0^{PI} \leq \theta_0^{AI}$. Therefore, the aggregate welfare difference between the two situations is $\Delta W_x = \int_{\theta_0^{PI}}^{\theta_0^{AI}} NPV_x(\theta, s_\theta^{PI}, q_\theta^{PI}) dF(\theta) + \int_{\theta_0^{AI}}^{+\infty} [U_x(\theta, s_\theta^{PI}, q_\theta^{PI}) - U_x(\theta, s_\theta^{AI}, q_\theta^{AI})] dF(\theta)$. In the absence of an investment-induced backfire rebound effect, the first term of the right-hand side is positive (see proof (ii) just above). In the absence of a policy-induced backfire rebound effect, the second term of the right-hand side is also positive. To see this, note that $\forall \theta E(s_\theta^{PI}, q_\theta^{PI}) \leq E(s_\theta^{AI}, q_\theta^{AI}) \Rightarrow -p_x \Gamma_x E(s_\theta^{PI}, q_\theta^{PI}) \geq -p_x \Gamma_x E(s_\theta^{AI}, q_\theta^{AI})$. This, added to $U(\theta, s_\theta^{PI}, q_\theta^{PI}) \geq U(\theta, s_\theta^{AI}, q_\theta^{AI})$ (which is given by definition of the maximum) leads to $U_x(\theta, s_\theta^{PI}, q_\theta^{PI}) \geq U_x(\theta, s_\theta^{AI}, q_\theta^{AI})$. To conclude, the aggregate welfare difference is positive: $W_x^{PI} \geq W_x^{AI}$. □

As long as energy efficiency does not backfire, correcting energy market failures is desirable, regardless of whether or not the contracting parties overcome moral hazard. Indeed, social welfare cannot be maximized if the parties do not account for the broader distortions associated with their actions. However, the reciprocal needs not be true: If energy market failures are not (or cannot be) corrected, then it might be desirable to maintain, rather than undo, the moral hazard. This can actually occur if energy efficiency backfires. As a result, energy market failures would be larger.

A3. Sufficient statistics

A3.1. Deadweight loss from supply-side moral hazard

We seek to approximate the deadweight loss associated with the quality shortfall caused by the moral hazard: $\Delta_q W \equiv W^{PI} - W^{AI}$. A first step is to examine the marginal welfare change induced by a marginal change in quality. Since marginal participants are indifferent between investing and not investing, we can ignore changes in participation (see optimal standard). Similar envelope conditions allow us to also neglect the benefits from increased heating comfort. Rewriting Equation 32 with $M(\bar{q}) = 0$, the marginal benefits from a higher quality to participating homeowner are thus:

$$(34) \quad \frac{dW}{d\bar{q}} = -pE_q \Gamma - C'$$

Integrating between q^{AI} and q^{PI} (with $q^{AI} \leq q^{PI}$ according to Proposition 2i) at s^{AI} gives the following approximation for $\Delta_q W$:

$$(35) \quad \overline{\Delta_q W} = -p\Delta_q E(s^{AI}, q)\Gamma - \Delta_q C(q)$$

The error associated with integrating infinitesimal changes is positive and equal to the private benefits from increased heating comfort and the social benefits from increased participation. Indeed, for a participating homeowner, the exact deadweight loss $\Delta_q W$ is:

$$(36) \quad W^{PI} - W^{AI} = \sum_{t=1}^l \left[V(s^{PI}) - V(s^{AI}) - p \left(E(s^{PI}, q^{PI}) - E(s^{AI}, q^{AI}) \right) \right] \Gamma - \left[C(q^{PI}) - C(q^{AI}) \right]$$

We recognize that:

$$(37) \quad \Delta_q W = \overline{\Delta_q W} + \underbrace{\left[V(s^{PI}) - V(s^{AI}) - p \left(E(s^{PI}, q^{PI}) - E(s^{AI}, q^{PI}) \right) \right]}_{\geq 0} \Gamma$$

The term in brackets is positive because s^{PI} maximizes the function $V(\cdot) - E(\cdot, q^{PI})$. Therefore, $\Delta_q W \geq \overline{\Delta_q W}$. In words, $\overline{\Delta_q W}$ provides a lower bound of the exact average deadweight loss.

The formula is quite intuitive. It weighs the cost of quality against its benefits in terms of gross energy savings. This corresponds to a net present value calculation that only takes into account technological information. It does not require knowledge of the utility function for energy service $V(\cdot)$ nor its specific effect on energy use E_s . Therefore, the direct rebound effect can be ignored. Still, the formula contains the key parameters of the market and behavioral environment p , l and r .

A3.2. Policy efficiency

Minimum quality standard. The marginal welfare effect of a quality standard is simply given by Equation 35, enhanced with $-M'$ on the right-hand side. Computation of this formula requires knowing the technology E_q , the production cost $C(\cdot)$, and the cost of random post-implementation audits $M(\cdot)$.

Minimum quality standard. The marginal effect of incremental insurance coverage k to the parties willing to engage in the contract is given by Equation 29 (see optimal standard). It can be rewritten as follows:

$$(38) \quad \frac{dW}{dk} = p\Gamma \left(sE_s\eta_k^s - qE_q\eta_{1-k}^q \right)$$

The η terms are the elasticities of each parties' input to the insurance coverage. The elasticity of the rebound effect to insurance completeness, η_k^s , is positive. The elasticity of quality to insurance incompleteness, η_{1-k}^q , is negative. These elasticities are the key effects an econometrician would need to measure to evaluate the policy.⁴

Again, computation of the formula requires knowing the technology, namely the average marginal effects of inputs on energy use qE_q and sE_s . But interestingly, unlike the standard, the evaluator does not need to have information about cost $C(\cdot)$.

A4. Specification of the numerical model

A4.1. Demand side

The demand side is parameterized with the RECS data, using the following functional forms:

$$(39) \quad \theta \sim \text{Log-}\mathcal{N}(\mu, \sigma^2),$$

$$(40) \quad V(s) \equiv V_{max} \left(1 - e^{-\alpha(s-s_{min})}\right),$$

$$(41) \quad E^0(s) \equiv \beta(s - s_{min})^\gamma.$$

Parameterization proceeds in two steps. First, $V(\cdot)$ and $E^0(\cdot)$ are parameterized for a representative consumer of median type $\theta = 1$. Second, the distribution of θ is parameterized so as to fit the distribution of CDDs observed in the RECS data.

From the full RECS dataset, we select Floridian households owning and occupying their dwelling in 2009 and bearing the cost of electricity for air conditioning. Our working sample contains 503 observations and covers 53% of the Floridian households present in the full dataset. Complete summary statistics are provided in Table A1.

Recall that $r = 7\%$ and $l = 35$ years. The price of electricity p is set to \$0.1254/kWh, which is the median price paid for air conditioning in the RECS sample. The lower and upper bounds on cooling services are set to the minimum and maximum values found in the RECS sample: $s_{min} = 2,139$ CDD and $s_{max} = 5,246$ CDD.

The maximum comfort derived from air conditioning, V_{max} , is set to \$2,165. This value is obtained by assuming that the median homeowner (of annual income \$55,000 in the RECS sample) dedicates a maximum share of 3.9% (the 95th percentile of the RECS sample) of her income to air conditioning.

Parameters α , β and γ are calibrated so that (i) the optimal cooling service to the median homeowner is 3,672 CDD, the median of the RECS sample; given this input, (ii) the median homeowner's annual electricity use for air conditioning is 5,096 kilowatt.hour (kWh),

⁴With isoelastic functions, we have $\eta_{1-k}^q = -\eta_k^q$, hence $dW/dk = p\Gamma\eta_k^s(sE_s + qE_q)$.

the median of the RECS sample, and (iii) the price-elasticity of electricity use is -0.618 , according to recent estimates for the United States.⁵

Formally, the calibration system reads as follows:

$$(42) \quad \begin{cases} V'(3, 672) - pE_s^0(3, 672) = 0 \\ E^0(3, 672) = 5, 096 \\ \frac{dE^0(s^0(p))}{dp} \frac{p}{E^0(s^0(p))} = -0.618 \end{cases} \Leftrightarrow \begin{cases} V_{max}\alpha \exp(-\alpha(3, 672 - s_{min})) - p\gamma\beta(3, 672 - s_{min})^{\gamma-1} = 0 \\ \beta(3, 672 - s_{min})^\gamma = 5, 096 \\ \frac{\gamma}{1-\gamma - \frac{V_{max}\alpha^2 \exp(-\alpha(3, 672 - s_{min}))}{p\gamma\beta(3, 672 - s_{min})^{\gamma-2}}} = -0.618 \end{cases} \\ \Leftrightarrow \begin{cases} \alpha = 0.0011 \\ \beta = 2.0749 \\ \gamma = 1.0643 \end{cases}$$

Given these values, non-energy attributes δ (cf. Eq. 2) are calibrated so that the median homeowner is the marginal investor under asymmetric information:⁶ $NPV(\theta = 1, s_{\theta=1}^{AI}, q_{\theta=1}^{AI}) = 0$, which leads to $\delta = \$260$.

Finally, the distribution of CDDs observed in the RECS sample is fitted with a log-normal distribution of homeowners' types θ with parameters $\mu = 0$ and $\sigma = 0.5$ (see Figure A5).

A4.2. Supply side

The supply-side is parameterized with the GRU data, using the following functional forms:

$$(43) \quad E(s, q) \equiv \left(1 - G_{min} - (G_{max} - G_{min}) \left(1 - e^{-aq}\right)\right) E^0(s),$$

$$(44) \quad C(q) \equiv b + \frac{c}{2}q^2.$$

Recall that $G_{min} = 1\%$ and $G_{max} = 30\%$. Parameter a is calibrated so that the $q = 95\%$ quality input lowers electricity use by 20%, the 95th percentile of electricity savings estimated in the GRU program. With so-defined technology, the median savings estimated in the GRU

⁵Ros, A. (2015). An econometric assessment of electricity demand in the United States using panel data and the impact of retail competition on prices. Boston, MA: NERA Economic Consulting.

⁶Participation is therefore set to 50% under asymmetric information. In the RECS sample, 19 households have added insulation in the last two years, hence an annual fraction of investors of 1.9%. A participation of 100% in our model can be interpreted as an annual insulation rate of 3.8%. These rates are comparable to 2.9%, which would be the annual rate if investment occurred once every 35 years.

program, 10%, is obtained with a quality input of 35%.⁷ Parameters b and c are calibrated so that the $q = 35\%$ input is offered to the median homeowner under perfect information ($q_{\theta=1}^{PI}$) and the cost of this input matches the median cost estimated in the GRU program, \$650.

Formally, the calibration system reads as follows:

$$(45) \quad \begin{cases} E(\cdot, 95\%) = 80\% * E^0(\cdot) \\ E(\cdot, q_{\theta=1}^{PI}) = 90\% * E^0(\cdot) \\ C'(q_{\theta=1}^{PI}) = -p\Gamma(r, l)E_q(s_{\theta=1}^0, q_{\theta=1}^{PI}) \\ C(q_{\theta=1}^{PI}) = 650 \end{cases} \Leftrightarrow \begin{cases} 1 - G_{min} - (G_{max} - G_{min})(1 - e^{-a*95\%}) = 80\% \\ 1 - G_{min} - (G_{max} - G_{min})(1 - e^{-aq_{\theta=1}^{PI}}) = 90\% \\ cq_{\theta=1}^{PI} = p\Gamma(r, l)(G_{max} - G_{min})ae^{-aq_{\theta=1}^{PI}} * 5,096 \\ b + c(q_{\theta=1}^{PI})^2/2 = 650 \end{cases} \\ \Leftrightarrow \begin{cases} a = 1.0694 \\ q_{\theta=1}^{PI} = 35\% \\ b = 373 \\ c = 5,090 \end{cases}$$

⁷The average effect of hard-to-observe measures on total electricity use estimated in the GRU program is -3.13% , with standard deviation 1.68% . In parallel, the RECS data suggest that Floridian households dedicate 33% of their electricity use to air conditioning (see Table A1). We therefore assume that the median effect of retrofits on electricity use for air conditioning is $-3.13\%/33\% = -10\%$ and the 95th percentile effect is $(-3.13\% - 1.96 * 1.68\%)/33\% = -20\%$.

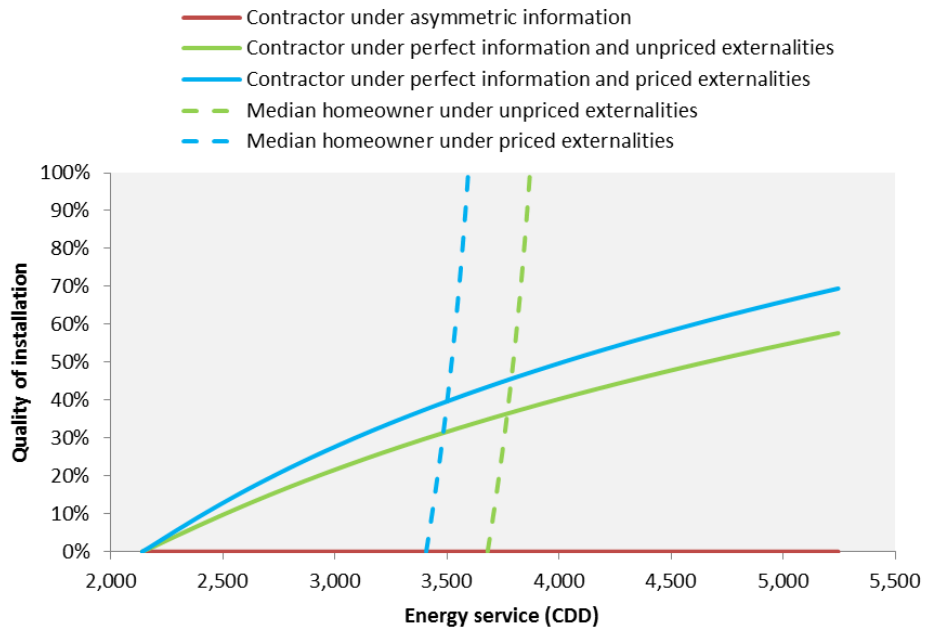


FIGURE A1. Reaction functions, with and without internalization of externalities

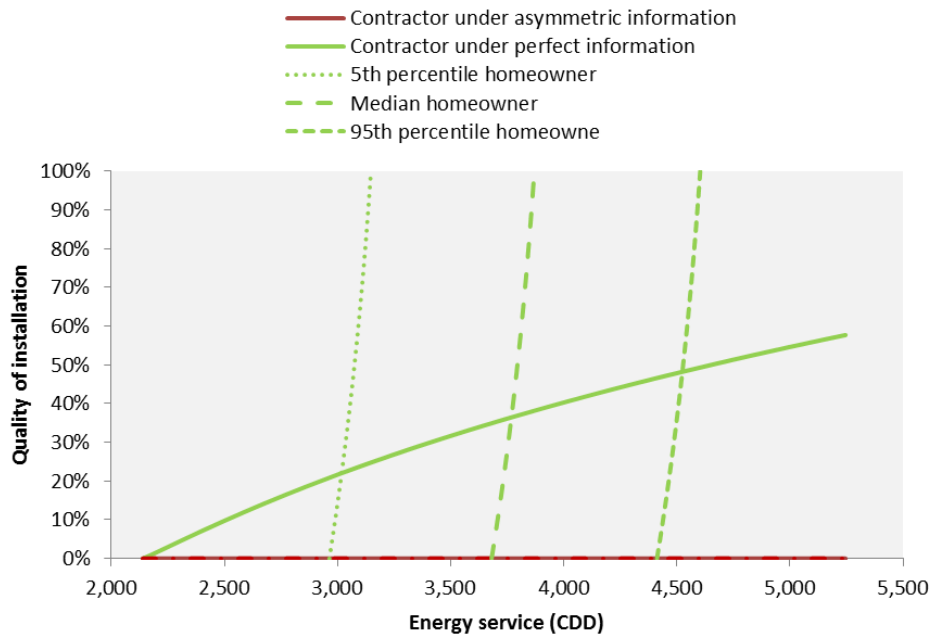


FIGURE A2. Reaction functions with heterogeneous homeowners, without externalities

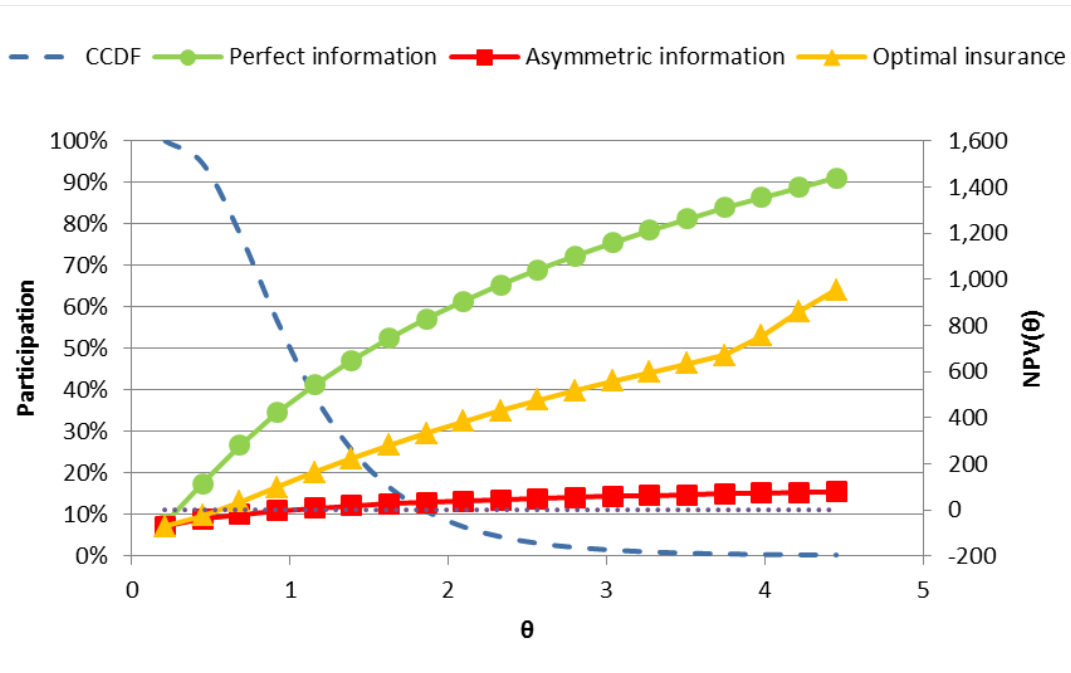


FIGURE A3. Net present value and participation, without externalities

Notes: The net present value of investment in insulation reads on the right vertical axis. The intersection of each curve with the zero horizontal axis determines the cutoff type θ_0 of the marginal participant in investment. For each cutoff type on the horizontal axis (from the 0.5th to 95.5th percentile of the θ distribution), participation across the population is determined by the value of the complementary cumulative distribution (CCDF) of θ , which reads on the left vertical axis.

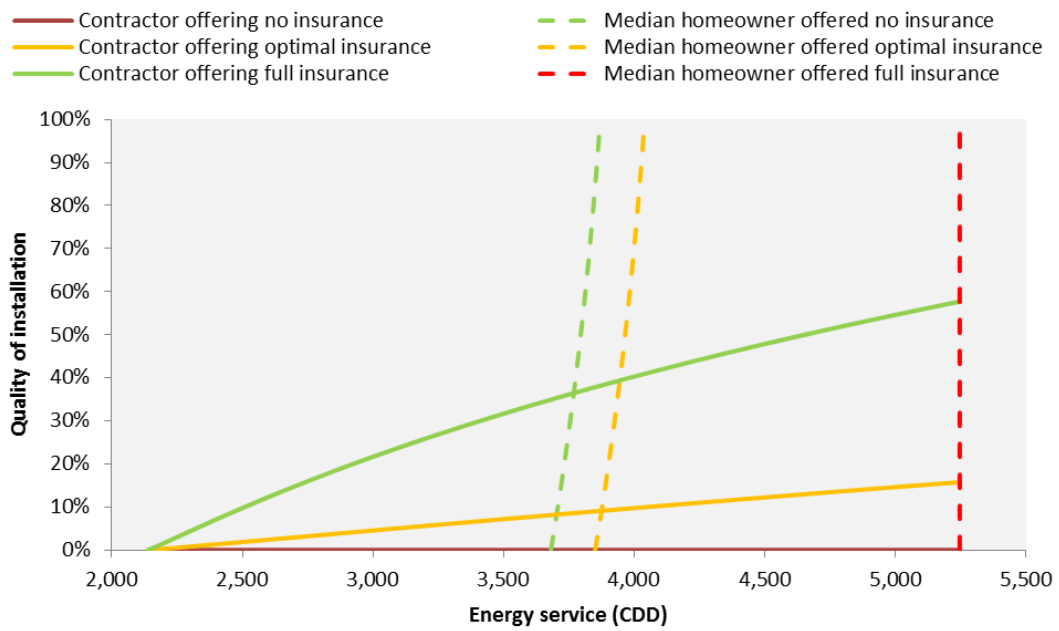


FIGURE A4. Reaction functions under different energy-savings insurance contracts, without externalities

Notes: The optimal insurance contract displayed here has a coverage of 17%.

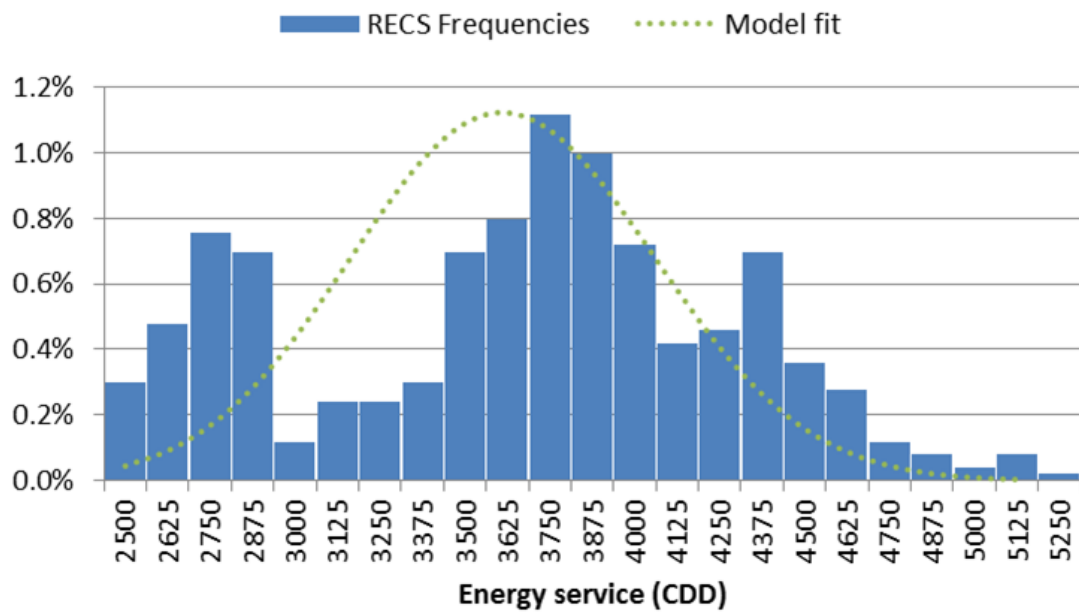


FIGURE A5. Model fit to the RECS data

Notes: The distribution of CDDs is calculated with the triangle method.

TABLE A1. Summary Statistics of the RECS Sample (503 observations)

	Unit	RECS entry	Mean	Standard deviation	Minimum	5th percentile	Median	95th percentile	Maximum
Cooling degree days in 2009, base temperature 65F	CDD	CDD65	3,584	643	2,139	2,573	3,672	4,528	5,246
Electricity usage for air conditioning, 2009	kWh	$\frac{BTUELCOL}{3.41214}$	5,967	4,380	473	2,013	5,096	12,651	60,993
Average price of electricity for air conditioning	\$/kWh	$\frac{DOLELCOL}{BTUELCOL/3.41214}$	0.1274	0.0123	0.0808	0.1101	0.1254	0.1499	0.1645
Gross household income, 2009	\$	MONEYPY	69,836	44,907	2,500	20,000	55,000	170,000	170,000
Income share dedicated to electricity for air conditioning		$\frac{DOLELCOL}{MONEYPY}$	1.6%	2.0%	0.1%	0.3%	1.1%	3.9%	26.3%
Share of total electricity used for air conditioning		$\frac{BTUELCOL}{BTUEL}$	34%	10%	11%	19%	33%	50%	62%

Notes: The figures used to parameterize the model are bolded. "Electricity cost for air conditioning" is measured in thousand BTU in RECS, here converted in kWh. "Gross household income" is measured with 24 income ranges; we identify each income range with its upper value and assume an average income of \$170,000 for the top category, which is consistent with U.S. Census Bureau 2009 data for owner-occupiers. The sample is further characterized with the following RECS entries: ELCOOL=1 (Electricity is used for air conditioning); PELAC=1 (Electricity used for air conditioning is paid by the household); KNOWRENT=1 (Housing unit is owned by someone in the household); REPORTABLE DOMAIN=17 (Florida).

A5. Additional Regression Results

TABLE A2. Day-of-the-Week Effect: Without Low Interest Loans (HTO),
Low-Income Grants (ETO) and Home Performance Projects (ETO)

Dep. Variable:	Monday	Tuesday	Wednesday	Thursday	Friday	Friday+WE
Log(Nat. Gas/month)	Effect	Effect	Effect	Effect	Effect	Effect
HTO=1	-0.0374** (0.0166)	-0.0420** (0.0175)	-0.0396** (0.0175)	-0.0493*** (0.0174)	-0.0616*** (0.0181)	-0.0615*** (0.0181)
ETO=1	-0.0537*** (0.0131)	-0.0587*** (0.0131)	-0.0545*** (0.0131)	-0.0659*** (0.0134)	-0.0566*** (0.0129)	-0.0565*** (0.0129)
HTO=1 X Monday	-0.0420 (0.0475)					
ETO=1 X Monday	-0.0224 (0.0250)					
HTO=1 X Tuesday		-0.0196 (0.0360)				
ETO=1 X Tuesday		0.00407 (0.0268)				
HTO=1 X Wednesday			-0.0315 (0.0339)			
ETO=1 X Wednesday			-0.0160 (0.0225)			
HTO=1 X Thursday				0.0194 (0.0352)		
ETO=1 X Thursday				0.0390* (0.0234)		
HTO=1 X Friday					0.0678** (0.0330)	
ETO=1 X Friday					-0.00647 (0.0273)	
HTO=1 X Friday + WE						0.0531* (0.0288)
ETO=1 X Friday + WE						-0.0696* (0.0376)
HTO=1 X WE	0.00264 (0.0419)	0.00728 (0.0426)	0.00491 (0.0427)	0.0145 (0.0426)	0.0267 (0.0429)	
ETO=1 X WE	-0.0572 (0.0424)	-0.0522 (0.0423)	-0.0563 (0.0425)	-0.0451 (0.0424)	-0.0544 (0.0423)	
Constant	7.271*** (0.00723)	7.271*** (0.00723)	7.271*** (0.00722)	7.271*** (0.00723)	7.271*** (0.00723)	7.271*** (0.00723)
Observations	382,935	382,935	382,935	382,935	382,935	382,935
R-squared	0.658	0.658	0.658	0.658	0.658	0.658
F- $H_0 : \eta_d = \phi_d$	0.133	0.278	0.146	0.216	3.009	3.858
Prob > F- H_0	0.716	0.598	0.702	0.642	0.0830	0.0496

Notes: Standard errors are clustered at the household level (* p<.10 ** p<.05 *** p<.01).

TABLE A3. Robustness of the Day-of-the-Week Effect w.r.t. Technology Classification

	Set of Technologies Included		Friday Effect:	Friday Effect:	Prob > F-
	HTO	ETO	HTO	ETO	$H_0 : \eta_F = \phi_F$
	HTO	ETO	η_F	ϕ_F	
Main	insl, duct, & loan	mxac, hiac, pool, wndw, leep, & hmpe	0.0718**	-0.00463	0.0547
Robust I	insl & duct	mxac, hiac, pool, & wndw	0.0678**	-0.00647	0.0830
Robust II	insl, duct, & loan	mxac, hiac, pool, & wndw	0.0718**	-0.00644	0.0621
Robust III	insl, duct, & loan	mxac, hiac, wndw, & hmpe	0.0717**	-0.0198	0.0345
Robust IV	insl, duct, & loan	mxac, hiac, & hmpe	0.0717**	-0.0209	0.0332
Robust V	insl, duct, & loan	mxac, & hiac	0.0717**	-0.0181	0.0504
Robust VI	insl & duct	mxac & hiac	0.0677**	-0.0181	0.0659
Robust VII	duct	mxac & hiac	0.113**	-0.0169	0.0207

Notes: This table only reports the estimates of the Friday effect for different grouping of HTO and ETO measures. Complete results are available from the authors upon request. Technology definition: Attic Insulation (insl); Duct Repair (duct); Low-Interest Loan (loan); Central A/C Super SEER (mxac); Central A/C High Efficiency (hiac); Pool Pump (pool); WindowLow-E (wndw); Low-Income Weatherization (leep); and Home Performance (hmpe).

TABLE A4. Day-of-the-week effects: All Energy Sources, Level

Dep. Variable:	Monday	Tuesday	Wednesday	Thursday	Friday	Friday+WE
kWh+Nat.	Effect	Effect	Effect	Effect	Effect	Effect
Gas/month						
HTO=1	-69.95*** (23.81)	-75.97*** (25.95)	-77.18*** (26.80)	-87.31*** (26.43)	-97.49*** (27.54)	-97.53*** (27.54)
ETO=1	-136.9*** (17.03)	-144.7*** (17.19)	-136.2*** (17.50)	-157.9*** (17.78)	-139.5*** (17.13)	-139.5*** (17.13)
HTO=1 X Monday	-60.49 (82.84)					
ETO=1 X Monday	-32.95 (38.10)					
HTO=1 X Tuesday		-28.57 (60.70)				
ETO=1 X Tuesday		8.559 (39.74)				
HTO=1 X Wednesday			-20.52 (50.96)			
ETO=1 X Wednesday			-32.16 (32.17)			
HTO=1 X Thursday				29.70 (54.29)		
ETO=1 X Thursday				71.47** (32.87)		
HTO=1 X Friday					73.21 (46.30)	
ETO=1 X Friday					-17.80 (39.50)	
HTO=1 X Friday + WE						90.72** (39.69)
ETO=1 X Friday + WE						-122.4** (53.12)
HTO=1 X WE	92.62** (46.72)	98.61** (48.68)	99.89** (49.44)	109.9** (49.11)	120.1** (49.93)	
ETO=1 X WE	-83.47 (66.94)	-75.68 (66.87)	-84.06 (67.16)	-62.62 (67.13)	-80.97 (66.88)	
Constant	1,563*** (10.59)	1,563*** (10.60)	1,563*** (10.59)	1,564*** (10.59)	1,563*** (10.59)	1,563*** (10.59)
Observations	497,025	497,025	497,025	497,025	497,025	497,025
R-squared	0.686	0.686	0.686	0.686	0.686	0.686
F- H_0 : $\eta_d = \phi_d$	0.0913	0.262	0.0373	0.433	2.240	6.027
Prob > F- H_0	0.763	0.609	0.847	0.511	0.135	0.0141

Notes: Standard errors are clustered at the household level (* p<.10 ** p<.05 *** p<.01).

TABLE A5. Day-of-the-week effects: Exclude 6 months before and after the installation

Dep. Variable:	Monday	Tuesday	Wednesday	Thursday	Friday	Friday+WE
kWh+Nat.	Effect	Effect	Effect	Effect	Effect	Effect
Gas/month						
HTO=1	-0.0444** (0.0173)	-0.0499*** (0.0184)	-0.0486*** (0.0186)	-0.0608*** (0.0184)	-0.0713*** (0.0188)	-0.0712*** (0.0188)
ETO=1	-0.0670*** (0.0132)	-0.0721*** (0.0132)	-0.0668*** (0.0133)	-0.0776*** (0.0133)	-0.0689*** (0.0131)	-0.0688*** (0.0131)
HTO=1 X Monday	-0.0559 (0.0504)					
ETO=1 X Monday	-0.0182 (0.0222)					
HTO=1 X Tuesday		-0.0263 (0.0354)				
ETO=1 X Tuesday		0.00804 (0.0231)				
HTO=1 X Wednesday			-0.0298 (0.0323)			
ETO=1 X Wednesday			-0.0171 (0.0203)			
HTO=1 X Thursday				0.0301 (0.0350)		
ETO=1 X Thursday				0.0340 (0.0216)		
HTO=1 X Friday					0.0750** (0.0336)	
ETO=1 X Friday					-0.00812 (0.0251)	
HTO=1 X Friday + WE						0.0567* (0.0289)
ETO=1 X Friday + WE						-0.0759** (0.0364)
HTO=1 X WE	-0.00189 (0.0410)	0.00359 (0.0419)	0.00248 (0.0421)	0.0145 (0.0420)	0.0250 (0.0421)	
ETO=1 X WE	-0.0602 (0.0400)	-0.0552 (0.0400)	-0.0604 (0.0401)	-0.0498 (0.0400)	-0.0585 (0.0399)	
Constant	7.281*** (0.00687)	7.281*** (0.00686)	7.281*** (0.00686)	7.281*** (0.00687)	7.281*** (0.00686)	7.281*** (0.00686)
Observations	460,692	460,692	460,692	460,692	460,692	460,692
R-squared	0.656	0.656	0.656	0.656	0.656	0.656
F- $H_0 : \eta_d = \phi_d$	0.468	0.660	0.111	0.00927	3.925	4.582
Prob > F- H_0	0.494	0.417	0.739	0.923	0.0477	0.0324

Notes: Standard errors are clustered at the household level (* $p < .10$ ** $p < .05$ *** $p < .01$).

TABLE A6. Day-of-the-week effects: Natural Gas Only

Dep. Variable: Log(Nat. Gas/month)	Monday Effect	Tuesday Effect	Wednesday Effect	Thursday Effect	Friday Effect	Friday+WE Effect
HTO=1	-0.0966*** (0.0216)	-0.0827*** (0.0219)	-0.0781*** (0.0225)	-0.0952*** (0.0211)	-0.0857*** (0.0215)	-0.0856*** (0.0215)
ETO=1	-0.0437*** (0.0147)	-0.0519*** (0.0146)	-0.0461*** (0.0149)	-0.0535*** (0.0147)	-0.0467*** (0.0149)	-0.0466*** (0.0149)
HTO=1 X Monday	0.0494 (0.0454)					
ETO=1 X Monday	-0.0240 (0.0290)					
HTO=1 X Tuesday		-0.0269 (0.0431)				
ETO=1 X Tuesday		0.0172 (0.0293)				
HTO=1 X Wednesday			-0.0454 (0.0384)			
ETO=1 X Wednesday			-0.0105 (0.0265)			
HTO=1 X Thursday				0.0378 (0.0493)		
ETO=1 X Thursday				0.0254 (0.0299)		
HTO=1 X Friday					-0.00907 (0.0463)	
ETO=1 X Friday					-0.00825 (0.0267)	
HTO=1 X Friday + WE						-0.0360 (0.0383)
ETO=1 X Friday + WE						0.00423 (0.0456)
HTO=1 X WE	-0.0826 (0.0534)	-0.0967* (0.0535)	-0.101* (0.0538)	-0.0843 (0.0532)	-0.0936* (0.0533)	
ETO=1 X WE	-0.123** (0.0491)	-0.115** (0.0491)	-0.121** (0.0492)	-0.114** (0.0491)	-0.120** (0.0492)	
Constant	3.005*** (0.0101)	3.005*** (0.0101)	3.005*** (0.0101)	3.005*** (0.0101)	3.005*** (0.0101)	3.005*** (0.0101)
Observations	298,599	298,599	298,599	298,599	298,599	298,599
R-squared	0.791	0.791	0.791	0.791	0.791	0.791
F- $H_0 : \eta_d = \phi_d$	1.856	0.717	0.558	0.0464	0.000235	0.250
Prob > F- H_0	0.173	0.397	0.455	0.829	0.988	0.617

Notes: Standard errors are clustered at the household level (* $p < .10$ ** $p < .05$ *** $p < .01$).