Double Moral Hazard and the Energy Efficiency Gap

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April, 2015

Abstract

We investigate how moral hazard problems can cause sub-optimal investment in energy efficiency, a phenomenon known as the energy efficiency gap. We focus on contexts where both the seller and the buyer of an energy saving technology can take hidden actions. For instance, a home retrofit contractor may cut on the quality of installation to save costs, while the homeowner may increase her use of energy service when provided with higher energy efficiency. As a result, neither energy efficiency quality nor energy use are fully contractible. We formalize the double moral hazard problem and discuss how it can help rationalize the energy efficiency gap. We then compare two policy instruments: minimum quality standards and energy-savings insurance. Their relative efficiency depends on the balance between the monitoring costs associated with the former and the deadweight loss of the consumer's action induced by the latter. Calibrating the model to the U.S. retrofit industry, we find that at current market conditions, standards tend to outperform insurance. We also find that the welfare gains from undoing the double moral hazard are substantially larger than those from internalizing carbon dioxide externalities associated with underlying energy use.

JEL: D86,Q41

Keywords: Energy efficiency gap, moral hazard, energy-savings insurance, minimum quality standard, credence good, rebound effect.

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1. Introduction

The rationale for government interventions promoting energy efficiency has been debated for more than three decades. At the heart of the debate are empirical studies finding that people apply abnormally high discount rates to energy efficiency investment decisions (Hausman 1979; Train 1985). This suggests that some seemingly profitable investment opportunities are not undertaken.

The phenomenon, known as the energy efficiency gap, was first conceptualized by Jaffe and Stavins (1994). The authors emphasized the difference between market failure explanations of the gap (e.g., information asymmetries, technology spill-overs, energy price distortions), which could justify government intervention, and non-market failure explanations (e.g., consumer heterogeneity, costs and benefits of ancillary attributes), which do not. More recently, this dichotomy has been enriched with the concept of behavioral anomalies to account for the fact that consumers may value energy savings in a way that is inconsistent with perfect rationality (Gillingham and Palmer 2014; Allcott, Mullainathan, and Taubinsky 2014).[1]

In this paper, we aim to contribute to the energy efficiency gap debate by drawing attention to one market failure which, to our knowledge, has been overlooked in the related literature: moral hazard in the provision of quality in energy efficiency investments. For instance, the problem was not discussed in the most recent and exhaustive literature reviews on the energy efficiency gap (Gillingham, Newell, and Palmer 2009; Allcott and Greenstone 2012). We also shed light on little-discussed policy remedies such as energy-savings insurance and minimum quality standards for energy efficiency professionals.

Many energy efficiency technologies are considered to be credence goods, the performance of which is never completely known to the buyer (Darby and Karni 1973; Sorrell 2004). This characteristic is conducive to a variety of information problems, which have long been suspected to be the main source of market failures in energy efficiency markets (Howarth and Andersson 1993; Huntington, Schipper, and Sanstad 1994). This is especially true in the building sector. Technological complexity may complicate understanding of energy-saving opportunities. However, evaluations of energy audits find that consumers respond less to information provision than to price signals, suggesting that the knowledge gap is small (Palmer, Walls, Gordon, and Gerarden 2013; Frondel and Vance 2013; Murphy 2014b). Still, information may be understandable but asymmetrically shared. Several studies have

[1]The policy implications of these problems, in particular whether they warrant libertarian paternalistic interventions, is more debated among economists (Allcott 2014).

examined information asymmetries in rental housing, in which the landlord is supposedly more informed than the tenant about the energy efficiency performance of the dwelling. They find that a higher energy efficiency does not lead to a higher rent and that rented dwellings are less energy efficient than owner-occupied ones (Levinson and Niemann 2004; Davis 2012; Gillingham, Harding, and Rapson 2012; Burfurd, Gangadharan, and Nemes 2012; Myers 2013). Fewer studies have examined information asymmetries in home sales, in which the seller is supposedly more informed than the buyer about the energy efficiency performance of the dwelling. Research conducted in the Netherlands suggests that information conveyed by energy performance certificates tends to be capitalized into sale prices, but only weakly (Brounen and Kok 2011; Murphy 2014a).

The information asymmetries we consider here are related, but different in nature. Our motivational example consists of investments in building energy retrofit projects in which a contractor may cut on the quality of installation[2] to save costs, while the buyer may rebound, that is, increase her use of energy services when provided with higher energy efficiency. Both actions are unobservable to the other party. We refer to this problem as double moral hazard. Our focus is on the supply side of energy efficiency markets. We thus extend an analysis of information asymmetries so far confined to building sales and rental transactions.[3]

Our contribution is threefold. First, we formalize how moral hazard in the provision of quality leads to an energy efficiency gap. Second, we investigate policy solutions to this market failure. In the building sector, firms can offer energy-savings insurance (Mills 2003). We show that due to the unobservable consumer's response, a complete insurance contract is not optimal. We also examine professional certification in the form of minimum quality standards. Compared to insurance, such an instrument does not distort consumer incentives but incurs some monitoring costs. We suggest that these policies be part of the policy portfolio used to encourage energy efficiency, beside Pigouvian instruments (Allcott, Mullainathan, and Taubinsky 2014), energy efficiency subsidies (Ito 2013; Boomhower and Davis 2014), energy efficiency labels (Houde 2014), building codes (Aroonruengsawat, Auffhammer, and

[2]Such a quality shortfall may materialize as inefficient labor or capital input. For instance, an insulation contractor may omit to fill wall cavities before installing insulation panels and/or install insulation panels of a low grade.

[3]The hidden actions examined in our paper may propagate as hidden information in subsequent principal-agent relationships. That is, the contractor's failure can be internalized as the homeowner's by prospective homebuyers or renters, leading to non-capitalization of energy efficiency performance in home sale prices or rental contracts. We left this fruitful question of the articulation between moral hazard and capitalization problems for future research.

Sanstad 2012; Jacobsen and Kotchen 2011) and information provision (Jessoe and Rapson 2014). Our third contribution consists of developing sufficient statistics to assess the marginal welfare effect of different policy instruments and to quantify the size of the energy efficiency gap due to moral hazard. We illustrate the accuracy of the approach with sensitivity analysis on a stylized model of the U.S. insulation market calibrated using data from the U.S. 2009 Residential Energy Consumption Survey (RECS).

Our numerical simulations suggest that the social costs associated with moral hazard could be large. We find that for a broad set of parameters capturing different market environments, the deadweight loss from moral hazard is several times larger than the costs of quality audits. It is also approximately one order of magnitude larger than those from internalizing carbon dioxide externalities associated with natural gas use. Moral hazard problems lead to implied discount rates in the 15-35% range, instead of a 7% rate assumed in the absence of this market failure. A naive extrapolation of our results to the whole U.S. population of homeowners that use natural gas for space heating suggests that undoing moral hazard associated with insulation could save at least 11 billion cubic feet of natural gas and 0.6 million tons of CO_2 annually, hence yielding \$2.4 billion of present value benefits. Energy-savings insurance could close 75% of this gap and minimum quality standards could be even more welfare-improving.

The outline of the paper is as follows. Section 2 introduces the model. Section 3 examines energy-savings insurance, quality standards, and provides sufficient statistics of their marginal welfare effects. We then turn to the data. In section 4, we discuss how to establish causal evidence of moral hazard problems in the retrofit industry and present some indirect evidence from a unique dataset of random audits in France. In Section 5, we develop a stylized model of the U.S. home insulation market to compare policy impacts. Section 6 discusses sensitivity analysis and approximations of the deadweight loss. Section 7 concludes.

2. **Energy efficiency investments and double moral hazard**

Our model builds upon the double moral hazard model of Cooper and Ross (1985). Investments in energy retrofits for the residential sector, which involve hidden actions from both the homeowner and the contractor as we explain below, are considered as a canonical example. Other situations that give rise to one-sided moral hazard, for instance energy retrofits in the commercial and industrial sectors, can be viewed as special cases of this general model. They are occasionally discussed in the text.

2.1. **Setup**

A homeowner uses energy for space heating. This energy service s, measured in indoor temperature, provides her with value $V(s)$, multiplied by a taste parameter $\theta > 0$ representing heterogeneity across consumers in the valuation of energy service. The homeowner expects to pay energy bill $pE^0(s)$, where $E^0(\cdot)$ is the energy use and p the price of energy. The energy use may be a random variable influenced by idiosyncratic factors, such as weather conditions and the architectural characteristics of the house. For simplicity, we use a deterministic framework; utility is quasi-linear and there is no risk aversion. The homeowner sets the intertemporal energy service vector $\mathbf{s}^0_\theta$ so as to maximize utility $U^0(\theta, \mathbf{s})$ over an investment lifetime of l years, discounted at some rate r:

$$U^0(\theta, \mathbf{s}) \equiv \sum_{t=1}^{l} \left[\theta V_t(s_t) - p_t E^0_t(s_t)\right] (1+r)^{-t} \tag{1}$$

The homeowner can invest in retrofits to reduce her energy bill. In this setting, the homeowner is the principal and the contractor is the agent. Energy use after investment E is reported on homeowner's energy bill. Hence, it is common knowledge to both parties. Yet each one can take hidden actions $\mathbf{s}$ and q to influence it.

The homeowner chooses a stream of energy service $\mathbf{s}$. This action is unobserved to the contractor and a higher energy service will induce a higher energy use. Likewise, the contractor provides a certain quality q in installing an energy-efficient equipment. We assume that the quality q is unidimensional and can be measured as the number of hours worked by the contractor. Unlike other amenities, the impact of this action on the energy efficiency performance cannot be fully assessed by the homeowner. The only thing that is known to both parties is that a higher quality of installation lowers energy use.

The homeowner considers future discounted benefits with utility $U(\theta, \mathbf{s}, q)$, pays upfront cost for the retrofit ($T > 0$), and receives some fixed non-energy benefits net of the inconvenience costs generated by the investment (ϵ):

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

In what follows, we assume time invariance of energy price, technology and consumer value function. We remove t subscripts and consider vector $\mathbf{s}$ as a scalar s constant over time. We further simplify the notations with a discount factor Γ such that:

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

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:

$$\Pi(q) \equiv T - C(q) \tag{4}$$

The following assumptions hold (subscripts denote partial derivatives):

Assumption 1: Technology.
(i) At constant consumer 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: $E^0_s > 0$*,* $E_s > 0$ *and* $E_q < 0$
(iii) Energy savings exhibit decreasing returns: $-E^0_{ss} \leq 0$*,* $-E_{ss} \leq 0$ *and* $-E_{qq} \leq 0$
(iv) Contracting parties' actions are substitutes: $E_{qs} < 0$ *and* $E_s < E^0_s$
(v) Non-energy benefits are not sufficient to motivate investment: $\epsilon \leq C(q_{min})$

Assumption 2: Behavior and 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. *The industry is competitive with free entry:* $\Pi(q) = 0$*.*
Corollary: $T = C(q)$*.*

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., a house heated in a cold climate) rather than low (e.g., a house heated in a warm climate). 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. Their generality is discussed in Section 5.

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. Still, the assumption of perfect competition seems reasonable in the context studied here.[4]

2.2. **Social versus private optimum**

We will consider two equilibrium outcomes: a social (hereafter cooperative) optimum c and a private (hereafter non-cooperative) optimum nc. For any equilibrium situation $j \in \{c, nc\}$, the agreement between the homeowner and the contractor is a two-stage game that is solved backward. In the first stage, the homeowner of type θ invests if the net present value $NPV^j(\theta)$ of investment is positive, given her beliefs about her future optimal energy service s^j_θ and the optimal quality q^j_θ offered to her by the contractor:

$$NPV^j(\theta) \equiv U(\theta, s^j_\theta, q^j_\theta) - U_0(\theta, s^0_\theta) \geq 0 \tag{5}$$

In the second stage, both agents determine their own action given their belief about the other party's action. We focus hereafter on this second stage, for a participating consumer of type θ.

Under perfect information, the contract between the two parties 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^c_θ and q^c_θ that solve the first-order conditions for maximization[5] below will be such that their marginal benefit (in terms of value to the consumer and cost savings to the firm) equates their marginal effect on consumer's energy bill:

$$\forall t \quad \theta V' \leq pE_s \quad \text{with equality if} \quad s^c_\theta > s_{min} \tag{6}$$

[4]The home energy retrofit industry is indeed very fragmented. For instance, the heating, ventilation and air conditioning (HVAC) industry in California is characterized by small firms offering low wages, facing low barriers to entry and an annual turnover as high as 25% (Zabin, Lester, and Halpern-Finnerty 2011).

[5]Throughout the paper, the objective functions are well-behaved and the first-order conditions discussed are necessary and sufficient conditions for maximization.

$$C' \geq -pE_q\Gamma \quad \text{with equality if} \quad q_\theta^c > q_{min} \tag{7}$$

The cooperative optimum (s_θ^c, q_θ^c) 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:

$$\forall t \quad \frac{\mathrm{d}s_\theta^*}{\mathrm{d}q} = \frac{pE_{qs}}{\theta V'' - pE_{ss}} > 0 \tag{8}$$

$$\frac{\mathrm{d}q^*}{\mathrm{d}s} = \frac{-pE_{sq}}{C''/\Gamma + pE_{qq}} > 0 \tag{9}$$

Now if information is imperfect, 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 consumer, 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^{nc} that minimizes his cost:

$$\forall s \quad q^{nc}(s) = \underset{q \geq q_{min}}{\arg\min}\, C(q) = q_{min} \tag{10}$$

Proposition 1. *For a participating consumer of given type θ:*
(i) the private, non-cooperative equilibrium $(s_\theta^{nc}, q_\theta^{nc})$ exists and is unique
(ii) the social, cooperative equilibrium (s_θ^c, q_θ^c) exists and is unique if and only if:

$$\frac{\mathrm{d}q}{\mathrm{d}s_\theta^*} > \frac{\mathrm{d}q^*}{\mathrm{d}s} \tag{11}$$

proof: (i) The private 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 social 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.

The following proposition states that the two equilibria will involve unambiguous locations:

Proposition 2. *Assuming condition (11) holds, a participating consumer of given type θ:*
(i) is offered a higher level of quality at the social optimum: $q_\theta^c \geq q_\theta^{nc}$
(ii) sets her energy service at a higher level at the social optimum: $s_\theta^c \geq s_\theta^{nc} > s_\theta^0$
(iii) faces a higher net present value at the social optimum: $NPV^c(\theta) \geq NPV^{nc}(\theta)$

proof: (i) For a given θ, $q_\theta^c \geq q_{min} = q_\theta^{nc}$. (ii) Since $s_\theta^*(\cdot)$ is increasing, $s_\theta^c = s_\theta^*(q_\theta^c) \geq s_\theta^*(q_\theta^{nc}) = s_\theta^{nc}$. For all s, $E_s^0 > E_s$ implies $U_s > U_s^0$. Therefore, assuming interior solutions: $U_s^0|_{s_\theta^0} = 0 = U_s|_{s_\theta^{nc}} > U_s^0|_{s_\theta^{nc}}$. Since U^0 is concave in s, U_s^0 is decreasing in s and $s_\theta^{nc} > s_\theta^0$. (iii) Comparing net present values $NPV^c(\cdot)$ and $NPV^{nc}(\cdot)$ is equivalent to comparing the utility functions after investment $U(\theta, s_\theta^c, q_\theta^c)$ and $U(\theta, s_\theta^{nc}, q_\theta^{nc})$. 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 in the social outcome: $NPV^c(\theta) \geq NPV^{nc}(\theta)$.

Recall from Assumption 1(ii) that q and s have an opposite effect on $E(s, q)$. Hence, if both inputs increase simultaneously, as is the case when the parties move from the private optimum to the social optimum, the decrease in energy use due to the increase in quality is partly offset by the increase in energy service. This phenomenon is known as the rebound effect. To the extreme, it can backfire, that is, be such that energy use increases after energy efficiency investments. This case cannot be ruled out from our analysis, as $E(s_\theta^c, q_\theta^c)$, $E(s_\theta^{nc}, q_\theta^{nc})$ and $E(s_\theta^0)$ cannot be compared unambiguously.

We shall now make a distinction between two types of backfire rebound effect, which will prove useful later in the analysis.

Definition 1: Investment backfire rebound effect. *An investment 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: Relative backfire rebound effect. *A relative backfire rebound effect occurs between two investment 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 $E(s^H, q^H) > E(s^L, q^L)$.*

2.3. **Consumer heterogeneity and aggregate welfare**

We now turn to a continuum of consumers of mass 1. Consumers are assumed to all live in a similar dwelling and only differ with respect to their preference for energy service θ. The higher the value of θ, the higher the demand for energy service, hence the higher the quality offered by a cooperative firm; in contrast, the quality offered by a non-cooperative firm remains at minimum. This proposition is demonstrated in Appendix A.

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

$$\frac{\mathrm{d}NPV^j}{\mathrm{d}\theta} = \left[V(s_\theta^j) - V(s_\theta^0)\right]\Gamma \tag{12}$$

As $V(\cdot)$ is increasing and $\forall\theta\ s_\theta^j > s_\theta^0$, the net present value of investment strictly increases with θ. Hence, if there exists a cutoff type θ_0^j such that $NPV^j(\theta_0^j) = 0$, it is unique. In what follows, we are interested in this most relevant case; alternative cases are discussed in Appendix B. Assuming that $F(\cdot)$ is the cumulative distribution function of θ, participation to investment N^j is given by:

$$N^j \equiv 1 - F(\theta_0^j) \tag{13}$$

Finally, aggregate social welfare is the sum of utility before investment for those consumers who do not invest ($\theta \in [0, \theta_0)$), plus the utility after investment for those who do invest ($\theta \geq \theta_0$):

$$W^j \equiv \int_0^{\theta_0^j} U^0(\theta, s_\theta^0)\mathrm{d}F(\theta) + \int_{\theta_0^j}^{+\infty} U(\theta, s_\theta^j, q_\theta^j)\mathrm{d}F(\theta) \tag{14}$$

Proposition 3. *Assuming that condition (11) is satisfied for all consumers with $\theta > 0$:*
(i) the social optimum entails higher participation than the private optimum: $N^c \geq N^{nc}$
(ii) the social optimum entails higher aggregate welfare than the private optimum: $W^c \geq W^{nc}$

proof: (i) Assume θ_0^c (respectively θ_0^{nc}) is the cutoff value of θ in the social (respectively private) optimum. Proposition (2iii) imposes the following inequality: $NPV^c(\theta_0^c) = 0 = NPV^{nc}(\theta_0^{nc}) \leq NPV^c(\theta_0^{nc})$. Since $NPV^j(\cdot)$ is increasing, $\theta_0^c \leq \theta_0^{nc}$. Hence, $N^c - N^{nc} =$

$\int_{\theta_0^c}^{\theta_0^{nc}} \mathrm{d}F(\theta) \geq 0$. (ii) $W^c - W^{nc} = \int_{\theta_0^c}^{\theta_0^{nc}} NPV^c(\theta)\mathrm{d}F(\theta) + \int_{\theta_0^{nc}}^{+\infty} [U(\theta, s_\theta^c, q_\theta^c) - U(\theta, s_\theta^{nc}, q_\theta^{nc})]\mathrm{d}F(\theta) \geq 0$.

This is a very general formalization of the energy efficiency gap: In the presence of moral hazard, investments in energy efficiency entail too low a quality of installation and too few homeowners participate. This result holds under very general assumptions of perfect rationality and risk-neutrality. Concretely, the homeowner does not have the technical skills to judge whether the retrofit has been properly completed, although she is aware that any defects will deter the energy performance of the investment. Anticipating that the contractor is aware of her limitations, she will expect him to save on installation costs and perform the job poorly. Any claim that he will provide the highest quality, enabling her to maximize energy savings, will be considered ”cheap talk” by the homeowner. The contractor will not deviate from these expectations and indeed complete the lowest possible quality job. Quality will be non-contractible and thus underprovided.

Appendix C discusses some comparative statics with respect to a composite indicator of all market and behavioral features: $\zeta \equiv p\Gamma(r, l)$. This indicator is very similar to the investment inefficiency parameter proposed by Allcott and Greenstone (2012). Any value of p, r or l that does not reflect perfect competition, perfect rationality or perfect information translates into a biased ζ. Comparative statics of ζ thus provides insight into the interaction between moral hazard and other market failures or behavioral anomalies.

3. Policies

In this section, we examine some regulatory and incentive-based instruments that can be used to address moral hazard in energy efficiency markets. We begin with the welfare analysis and then develop sufficient statistics that could guide future empirical work on the issue.

3.1. Energy-savings insurance

Insurance is the most common way of addressing moral hazard problems. In the energy field, energy-savings insurance and a variety of energy performance contracts have been offered for about twenty years in the commercial sector (Mills 2003), less frequently in the residential sector.[6] Such contracts typically have the contractor pay the consumer any shortfall in energy savings below a pre-agreed baseline. In our simple framework with no risk-aversion,

[6]GreenHomes 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.

insurance can be modeled as a contract in which the contractor bears a share k of the energy bill:

$$U(\theta, s, q) \equiv [\theta V(s) - (1-k)pE(s,q)]\,\Gamma - I + \epsilon \tag{15}$$

$$\Pi(q) \equiv I - C(q) - kpE(s,q)\Gamma \tag{16}$$

According to Assumption 3, the payment to the contractor is $I = C(q) + k\ pE(s,q)\Gamma$, where $kpE(s,q)\Gamma$ 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:

$$\forall t \quad \theta V' \leq (1-k)pE_s \quad \text{with equality if} \quad s_\theta^i(k) > s_{min} \tag{17}$$

$$C' \geq -kpE_q\Gamma \quad \text{with equality if} \quad q_\theta^i(k) > q_{min} \tag{18}$$

The optimal consumer's response is bounded above by a satiation value s_{max}.[7] By the Implicit Function Theorem, the insurance reaction functions $s_\theta^{**}(q,k)$ and $q^{**}(s,k)$ are both increasing in k:

$$\forall t \quad \frac{\mathrm{d}s_\theta^{**}}{\mathrm{d}k} = \frac{-pE_s}{\theta V'' - (1-k)pE_{ss}} > 0 \tag{19}$$

[7]Without satiation, full insurance ($k = 1$) would bring the marginal value of energy service in Equation 17 to zero, hence induce infinite energy service. Satiation could be introduced as the argument of the maximum of a parabolic utility function. Alternatively, in our 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.

$$\frac{\mathrm{d}q^{**}}{\mathrm{d}k} = \frac{-pE_q}{C''/\Gamma + kpE_{qq}} > 0 \tag{20}$$

The implementation of such a contract partly solves the moral hazard, as it induces the contractor to offer some quality (Equation 18). 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 consume more energy. The energy service in Equation 17 is consumed to the socially optimal level defined by Equation 6 when the consumer 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 $k \in (0, 1)$. We recover here the general result of Cooper and Ross (1985). For any insurance k, the agreement $(s^i_\theta(k), q^i_\theta(k))$ 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 social optimum is ambiguous.

Note that if consumer's types are imperfectly observable to the contractor, a screening issue arises. Consumers 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 $\hat{k}_\theta$ that sustains the Nash equilibrium to each type is determined cooperatively in the second stage of the game, so as to maximize joint surplus:

$$\forall\theta \quad \hat{k}_\theta = \underset{k\in[0,1]}{\arg\max}\, [U(\theta, s^i_\theta(k), q^i_\theta(k)) + \Pi(q^i_\theta(k))] \tag{21}$$

The first-order conditions for maximization in the second stage can be found in Appendix D. 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.

Note that if the consumer were not optimizing her energy service and consuming a constant level of it (e.g., a tenant who does not pay for her energy bill, or an employee in a commercial building), then the second moral hazard would not occur. The optimal insurance contract would feature full coverage and bring the parties to the social optimum. This can explain why contractors seem more willing to provide guarantee payments in the commercial sector than in the residential one.

3.2. **Minimum quality standard**

Various types of voluntary quality certifications can be found in the marketplace, most notably those provided by the Building Performance Institute (BPI) and the Residential Energy Services Network (RESNET) in the U.S. These programs typically ensure that professional workers and contracting companies are trained to the best practices and that their performance is regularly tested.

In our framework, a minimum quality standard translates into a perfectly enforced minimum labour requirement $\bar{q}$.[8] Yet such an instrument may cause two classic types of deadweight loss. First, compliance with the standard still needs to be monitored, which generates monitoring costs $M(\bar{q})$. These costs do not occur with energy-savings insurance, in which the object of the contract, namely energy use, is common knowledge. Second, minimum quality standards abstract from consumer heterogeneity. A minimum standard $\bar{q}$ can only be the optimal level of quality to one homeowner type, but it is suboptimal to all others (since, according to Proposition 1, the optimal quality is unique to each type θ). As a result, a uniform standard is strictly suboptimal over the population.

The optimal minimum standard will be set at a value $\bar{q}$ that maximizes the collective surplus, subject to the participation constraint:

$$\begin{aligned} &\underset{\bar{q}}{\text{Maximize}} \quad \left[\int_0^{\theta_0} U^0(\theta, s_\theta^0)\mathrm{d}F(\theta) + \int_{\theta_0}^{+\infty} \left[U(\theta, s_\theta^*(\bar{q}), \bar{q}) - M(\bar{q})\right]\mathrm{d}F(\theta)\right] \\ &\text{subject to} \quad NPV(\theta_0, s_{\theta_0}^*(\bar{q}), \bar{q}) - M(\bar{q}) \geq 0 \end{aligned} \tag{22}$$

As developed in Appendix D, the first-order condition for maximization will be:

$$\int_{\theta_0}^{+\infty} \left[\frac{\partial U(\theta, s_\theta^*(\bar{q}), \bar{q})}{\partial \bar{q}} - M'\right] \mathrm{d}F(\theta) = 0 \tag{23}$$

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.

[8] In practice, minimum quality standards could target materials used in retrofits and specific tasks.

3.3. **Intervention rules with interacting energy market failures**

As we have just seen, energy-savings insurance and quality standards can be used to address moral hazard problems. Both instruments are, however, second-best. Uniform quality standards cannot eliminate the gap, because of the heterogeneity in consumers' valuation of energy services and the monitoring costs. Energy-savings insurance is incomplete because moral hazard is bilateral.

Yet 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, discounted over the relevant time period with a discount factor Γ_x. For instance, p_x is positive for environmental or energy security externalities, and negative for average-cost energy pricing. Consumer utility before and after investment is now:

$$\begin{cases} U_x^0(\theta, s) \equiv U^0(\theta, s) - p_x E^0(s)\Gamma_x \\ U_x(\theta, s, q) \equiv U(\theta, s, q) - p_x E(s, q)\Gamma_x \end{cases} \tag{24}$$

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 14, respectively. The optimal actions that internalize external costs are denoted by superscript x.

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 problems: $W_x^{c,x} \geq W_x^{nc,x}$
(ii) If no consumer is prone to an investment backfire rebound effect, then it is desirable to correct energy market failures. This holds whether or not moral hazard problems are addressed: $\forall \theta \; E(s_\theta^c, q_\theta^c) \leq E^0(s_\theta^0) \Rightarrow W_x^{c,x} \geq W_x^c$ *and* $E(s_\theta^{nc}, q_\theta^{nc}) \leq E^0(s_\theta^0) \Rightarrow W_x^{nc,x} \geq W_x^{nc}$
(iii) If consumers are prone to neither an investment nor a relative backfire rebound effect, then it is desirable to undo moral hazard problems. This holds even if energy market failures are not corrected: $\forall \theta \; E(s_\theta^c, q_\theta^c) \leq E(s_\theta^{nc}, q_\theta^{nc}) \leq E^0(s_\theta^0) \Rightarrow W_x^c \geq W_x^{nc}$

proof: See Appendix E.

As long as energy efficiency does not backfire, correcting energy market failures is desirable, regardless of whether or not the contracting parties overcome the moral hazard. Indeed, social welfare cannot be maximized if the parties do not account for the broader distortions associated with their actions.[9] 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.

3.4. **Sufficient statistics**

Deadweight loss from moral hazard on quality. We seek to approximate the deadweight loss associated with the quality shortfall caused by the moral hazard: $\Delta_q W \equiv W^c - W^{nc}$. 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 neglect changes in participation (see Appendix D). Similar envelope conditions allow us to also neglect the benefits from increased heating comfort. Rewriting Equation 23 with $M(\bar{q}) = 0$, the marginal benefits from a higher quality to participating homeowner are thus:

$$\frac{\mathrm{d}W}{\mathrm{d}\bar{q}} = p\Gamma E_q - C' \tag{25}$$

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

$$\overline{\Delta_q W} = -p\Delta_q E(s^{nc}, q)\Gamma - \Delta_q C(q) \tag{26}$$

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 (see Appendix G). Therefore, $\overline{\Delta_q W}$ provides a lower bound of the exact average deadweight loss: $\overline{\Delta_q W} \leq \Delta_q W$.

[9] In France, since September 2014, public subsidies for home energy retrofits are given only if the job is completed by a certified contractor. This ”eco-conditionnality” rule is an interesting way of addressing at the same time moral hazard and other problems, such as technology spillovers or energy-use externalities. Note however that subsidies are only a second-best solution to energy-use externalities (Giraudet and Quirion 2008).

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.

Marginal welfare effect of a quality standard. The marginal welfare effect of a quality standard is simply given by Equation 26, 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 $M(\cdot)$.

Marginal welfare effect of energy-savings insurance. The marginal effect of incremental insurance coverage k to the parties willing to engage in the contract is given by Equation 40 (Appendix D). It can be rewritten as follows:

$$\frac{\mathrm{d}W}{\mathrm{d}k} = p\Gamma\left(sE_s\eta_k^s - qE_q\eta_{1-k}^q\right) \tag{27}$$

The η terms are the elasticities of each parties' input to the insurance coverage. The elasticy 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. [10] These elasticities are the key effects an econometrician would need to measure to evaluate the policy.

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 $C(\cdot)$.

4. Moral hazard problems in building weatherization: Background

Home weatherization technologies involve a significant installation input. If completed poorly by professionals, installation can be the source of many defects. This includes, for instance, an improper connection of ducts in heating, ventilation and air conditioning (HVAC) systems, an imperfect filling of wall cavities before insulation installation or infiltrations around windowpanes. Such defects can typically not be detected at zero cost. A consumer has to

[10] With isoelastic functions, we have $\eta_{1-k}^q = -\eta_k^q$.

hire an expert to perform a blower door test or thermographic screening. Even if the consumer had the expertise to monitor the contractor completing the installation, doing it would incur some opportunity cost of time. Lastly, the defects may not manifest immediately but sometimes months or years after job completion.

While the problem is general to the building sector, it has specific implications when it comes to energy use. The building sector is believed to have the largest and most cost-effective potential for energy savings and carbon dioxide emissions reduction (Levine, Ürge-Vorsatz, Blok, Geng, Harvey, Lang, Levermore, Mongameli Mehlwana, Mirasgedis, Novikova, Rilling, and Yoshino 2007). Weatherization measures account for the bulk of this potential. According to a widely publicized although controversial[11] study by McKinsey & Co. (2009), improvements of building shells and HVAC systems could save 3 quadrillion end-use BTUs in the U.S. by 2020. Two-third of this amount would be achieved in existing homes. Yet this technical potential could remain partly untapped if moral hazard problems are important in the sector.

In this section, we discuss empirical evidence of the effects modeled in the previous section.

4.1. **Rebound effects**

Two sources of rebound effect were discussed in the model. A first source is the consumer's increased use of energy service after energy efficiency investment. Technically, this corresponds to the increasing slope of the consumer's reaction function. This type of rebound effect is well established in the literature. Hirst, White, and Goeltz (1985) provide early evidence from a retrofit program that households increased their indoor temperature settings after investment by almost 1°F on average. More recently, a meta-review on the rebound effect by Sorrell, Dimitropoulos, and Sommerville (2009) suggests that 10 to 30% of energy savings in space heating use are taken back after retrofit through increased comfort. Overall, backfire rebound effects seem to be unlikely (Gillingham, Kotchen, Rapson, and Wagner 2013; Borenstein 2013).

The other source of rebound effect in our model is induced by energy-savings insurance. Unlike the previous one, this one is a source of moral hazard. Technically, it corresponds to an upward shift of the consumer's reaction function. We are not aware of any estimation of the elasticity of the rebound effect to insurance coverage (i.e., η_k^s in Equation 27). Studies that estimate the effect of including heating bills in rents can nevertheless provide proxies. Using

[11] See Allcott and Greenstone (2012) for a constructive critique of the study.

the same dataset from the U.S. Department of Energy's Residential Energy Consumption Survey (RECS), Levinson and Niemann (2004) and Gillingham, Harding, and Rapson (2012) find that consumers who have heating bills included in rents, hence facing zero marginal cost for energy use, do use their heating system more intensively than those who bear the full cost.[12]

4.2. **Defective quality**

Empirical challenges. A consistent finding in the assessment of building energy retrofits is the discrepancy between predicted and realized energy savings (Metcalf and Hassett 1999). This has come to be known as the energy performance gap in the engineering literature (de Wilde 2014). For instance, in her assessment of Energy Upgrade California Home Retrofits, Brown (2012) finds predicted savings that exceed realized ones by a half. Several causes are usually put forward to explain that gap: uncertainty in building simulation (due to the complexity of ex ante building systems and the error associated with ex post measurement), which is usually assessed through sensitivity analysis of simulation models; occupancy effects; and defective quality. Compared to the other two problems, evidence of the latter is much more scarce and mostly anecdotal. For instance, as of 2008, only 15% of central air conditioning installations in existing dwellings were reported to meet satisfactory quality specifications in California (Messenger 2008). The impact of quality defects on energy use is even less known than their occurrence. Brown (2012) cites evidence that a 5% gap in insulation coverage can reduce the insulation effectiveness by 30%.

How can quality defects be properly identified? The ideal experiment would have exogenous variation in the level of observability of a particular type of retrofit and would allow one to compare the quality after retrofit for projects with low and high levels of observability. The change in quality induced by the exogenous variation in observability could then be attributed to moral hazard on the contractor's side. In this context, what would qualify as a valid exogenous variation in observability? Consider an intervention where a regulator implements random post-retrofit audits with and without announcing the audit in advance to the contractor and the homeowner. A simple prediction of our theory is that contractors will offer a better quality if they know that their work will be assessed after completion. The presence or absence of audit pre-announcement would thus introduce the variation required to test the presence of moral hazard.

[12]This is identified along two margins: the level of thermostat settings and the changes in thermostat settings. Interestingly, both studies find the latter margin to be more important.

Although several programs have generously subsidized pre-treatment energy audits, very few have considered post-treatment audits. To our knowledge, the data required to provide causal evidence of the existence of moral hazard in the retrofit market are thus nonexistent.

Suggestive evidence from France. Here we present summary statistics from a building audit program implemented in France to gain insight into the frequency and importance of the quality defects associated with energy saving technologies.

In 1978, France established the Decennial Liability, a mandatory insurance subscribed by building contractors to cover structural defects that may occur up to ten years after the construction of a building. The *Agence Qualité Construction* (AQC) was created by the French government to implement the legislation.

In 2010, the AQC set up a database, REX, focusing on thermal defects.[13] The REX database contains detailed information on defects in construction and renovation projects. Each project documented in REX is the outcome of a three-step audit conducted by an expert hired by the AQC. The first step consists of an interview with one or two project stakeholders. It is then followed by an on-site visit where the structural features of the building and energy-related technologies are carefully inspected. Finally, the expert assigned to a particular project shares his or her findings with other AQC experts, who may provide feedback.

Only buildings that met France's 'low-energy' requirements were considered under REX. These low-energy requirements cap the annual primary energy use of a building at 50 kWh per square meter. Since 2012, it is the building code standard for new constructions. From the pool of buildings that met these requirements, the AQC randomly selected more than 500 projects for an audit. The selection process was stratified by region, building end-use (single-family dwellings, multi-family dwellings and commercial buildings), type of project (construction and renovation), and the presence or absence of a label of performance.

For each building, defects were identified during the on-site visits, which occurred either during the project or up to two years after completion. The defects were characterized along several dimensions: severity, origin, nature. Severity was classified in three categories: minor, intermediate or major. Major defects are those for which an insurance claim was made. The other two levels are qualified to the discretion of the expert. No further information is provided as to how severity levels specifically impact the energy use of the building. Origin

[13] Prior to REX, data on thermal defects were not collected by the AQC as the Decennial Liability only covers structural defects.

refers to any part of the building the defect originated from. Even though experts have a specific training for recording thermal defects, they are able to and have to report any type of defect. We summarize origin into two categories: thermal (insulation, heating, hot water, ventilation) and structural (all other). Lastly, the nature of a defect refers to the stage of the project to which the failure was attributed. We summarize this information into four categories: design stage, execution stage, operation stage, and other.

As of March, 2015, the REX database contains detailed information on 2,712 defects collected on 554 audits. 19 audits had some information missing. We thus focus on 546 audits and 2,762 defects for which all the information was available. From this sample, 57% of the projects were new constructions and 43% were renovations of existing buildings. The buildings examined are evenly distributed across end-uses: commercial buildings (37%), single-family dwellings (34%) and multi-family dwellings (29%). From the 546 projects audited, only 81 have no defect. The median number of defect per building is 4. On average, each building experiences 5.1 defects of any type (standard deviation 4.9). Severity is minor in 70% of the cases, intermediate in 26% of the cases and major in 4% of the cases. Defects are mostly due to failures at the execution (37%) and operation stages (35%). Overall, thermal defects account for 43% of all defects. As Figure 1 shows, the severity and nature of defects in this category of origin is very similar to that of the full sample. Moreover, as Table 1 shows, the problem affects indistinctly all type of buildings.

Two important conclusions can be drawn. First, implementation of energy saving technologies is in most case imperfect. Virtually all projects, despite being selected to meet high performance requirements, experience at least several minor defects and one out of five experiences a major defect. Second, the defects mostly occur during and after the treatment. That is, at a stage of the project where the level of effort and due-diligence of a contractor ought to play an important role. It is thus likely that moral hazard contributes to the manifestation of quality defects in buildings.

5. A numerical illustration based on the US insulation market

We now go back to the model to illustrate the welfare implications of moral hazard problems and the relative advantages of policy instruments. We focus on natural gas use for space heating and investments in wall insulation in U.S. homes.

5.1. **Functional forms used in the simulations**

The homeowner sets temperature s, measured in Fahrenheit (°F), above a minimum comfort level s_{min}. The value $V(\cdot)$ that she derives from this energy service is bounded above by V_{max}, which corresponds to a maximum budget dedicated to space heating. The function is increasing and concave, and takes the following form:

$$V(s) \equiv V_{max}\left(1 - \mathrm{e}^{-\alpha(s-s_{min})}\right) \quad \text{with} \quad s_{min} \leq s \leq s_{max}, \tag{28}$$

where $\alpha > 0$ is a calibrated parameter.

The use of natural gas E^0, measured in thousand cubic feet of natural gas (MCF), increases with indoor temperature (at an increasing rate) with a constant calibrated elasticity $\gamma > 1$:

$$E^0(s) \equiv \beta(s - s_{min})^\gamma \quad \text{with} \quad s_{min} \leq s \leq s_{max}, \tag{29}$$

where parameter $\beta > 0$ is calibrated so as to convert Fahrenheit degrees into thousand cubic feet.

Investment in wall insulation of efficiency $G(q)$ lowers energy use as follows:

$$E(s, q) \equiv (1 - G(q))\, E^0(s). \tag{30}$$

Efficiency is increasing in the quality q offered by the contractor (at a decreasing rate), within two limits $0 < G_{min} < G_{max} < 1$:

$$G(q) \equiv G_{min} + (G_{max} - G_{min})\left(1 - \mathrm{e}^{-\omega(q-q_{min})}\right) \quad \text{with} \quad q_{min} \leq q \leq q_{max}, \tag{31}$$

where $\omega > 0$ is a calibrated parameter.

The contractor bears a fixed cost K, which corresponds to a minimum labor input q_{min}. As the contractor provides the homeowner with a higher quality, he needs to have installers work longer and mobilize higher skills, which results in higher wages. As a result, cost increases quadratically in the number of worker.hours q:

$$C(q) \equiv K + \rho(q - q_{min}) + \frac{\phi}{2}\,(q - q_{min})^2 \quad \text{with} \quad q_{min} \leq q \leq q_{max}, \tag{32}$$

where $\rho > 0$ and $\phi > 0$ are calibrated parameters.

5.2. **Data and calibration**

Homeowners' characteristics are drawn from the U.S. Department of Energy's Residential Energy Consumption Survey (RECS) of 2009. We use information on indoor temperature, energy use, energy expenditure and income contained in the online database. We first extract a preliminary sample of 4,306 U.S. households who own and occupy their house and pay for natural gas for space heating. We then remove households who declare a winter daytime temperature below 60°F or above 80°F and thereby obtain a working sample of 4,266 households. This sample covers 35% of the complete dataset. Summary statistics are provided in Table 2.

In the reference scenario, we ignore potential behavioral anomalies and assume that homeowners discount future energy expenditures at a normal rate of 7%. They do it over the complete lifetime of an insulation project (35 years), thus assuming full capitalization of energy savings. To keep consistency with data, we use the price of natural gas derived from the RECS sample ($11.14/MCF), assuming away potential distortions in this market (Davis and Muehlegger 2010). All of these assumptions are subsequently relaxed in the sensitivity analysis. We consider environmental damages caused by carbon dioxide emissions associated with natural gas use and value them at $33/t$CO_2$.

Fewer data are available to parameterize the supply side of the insulation market. We use estimates from the engineering literature and informal discussions with practitioners. Our assumptions are detailed in Table 3.

In the RECS sample, the annual fraction of homeowners investing in insulation is 3.4%.[14] Our model is calibrated so that this rate is replicated in the private optimum and can be doubled at best. That is, participation among potential investors is set to 50% in the private optimum. A participation of 100% in the model can thus be interpreted as an annual insulation rate of 6.8% in the total population.

The calibration procedure leads to net non-energy benefits of $2,035. This means that attributes such as aesthetics or acoustic comfort yield benefits that exceed the hassle factor associated with insulation. Moreover, net non-energy benefits are necessary to induce the median homeowner to invest in insulation. All calibration targets are outlined in Table 4 and the calibration procedure is detailed in Appendix F.

[14] 6.8% of the population declare having insulation installed in the last two years (variable AGEINS=1). Note that the 3.4% rate is close to 2.9%, which would be the annual rate if investment occurred once every 35 years.

The temperature distribution found in the RECS sample is fitted with a log-normal distribution of homeowners' types with parameters $\mu = 0$ and $\sigma = 1$. Yet we do not intend to reproduce such a large heterogeneity, which may be partly driven by variables omitted in our model. Therefore, in the reference scenario, we assume a narrower distribution of homeowners' types with log-normal parameters $\mu = 0$ and $\sigma = 0.25$, from the 0.5th percentile ($\theta = 0.53$) to the 99.5th percentile ($\theta = 1.90$). The model fit is illustrated in Figure 2.

With these structural and numerical assumptions, the homeowner of type $\theta = 1$ is both the median of the distribution and the marginal participant in the private optimum. The model satisfies the necessary and sufficient conditions for existence and uniqueness of private and social equilibria (Proposition 1).

5.3. **Quantification of the energy efficiency gap**

Simulation results are illustrated in the figures and detailed in Table 5 for the median homeowner and Table 6 for the population average. In Figure 4, various equilibria are mapped in the framework proposed by Jaffe and Stavins[15] (1994), so as to visualize the trade-offs between economic efficiency and energy efficiency. Without internalization of energy-use externalities, the private optimum generates modest improvements in either welfare or energy efficiency, compared to the equilibrium before investment. In contrast, when the contractor cooperates to undo the moral hazard, both welfare and energy efficiency improvements become substantial. Average quality moves from 24 to 47 worker.hours (roughly a one workday gap), thus moving average energy efficiency from 3% to 27%. As a consequence, the average cost of quality increases from \$2,400 to \$2,830.[16] Lifetime discounted welfare net of environmental damages increases by \$1,723 (or \$1,249 if environmental damages are not accounted for). This number is several times larger than the cost of a home energy audit, estimated to be \$347 on average (Palmer, Walls, Gordon, and Gerarden 2013). Therefore, government intervention intended to undo the moral hazard could be welfare improving.[17].

[15]The authors have refined their conceptual diagram over the years. The version we specifically refer to first appeared in Jaffe, Newell, and Stavins (2004).

[16]If the supply side could perfectly price discriminate, the cost of quality would be equal to the sum of the zero-profit price and the homeowner's net present value. For the median homeowner, the cost of quality would be \$4,102, instead of \$2,830 under perfect competition.

[17]Undoing the moral hazard saves 0.4 tCO_2 annually. If home energy audits were sufficient to solve the moral hazard problem and achieve these savings, the lifetime discounted carbon dioxide cost-effectiveness of the instrument would be \$44/tCO_2.

Further improvements along both the energy efficiency and welfare dimensions can occur if environmental damages are internalized through a carbon price. In Jaffe and Stavins' words, the social optimum is then moved from the "Narrow economists' optimum" to the "True social optimum". The average welfare gains from undoing the moral hazard (\$1,723) are one order of magnitude larger than those from internalizing energy-use externalities (\$162). This result is quite general and does not necessitate sophisticated modeling. It reflects the difference between the marginal inefficiency due to moral hazard, namely the unit of energy that could have been cut by optimal investment (valued at energy price p = \$11.14/MCF), and the social cost of environmental damages (valued at p_{CO_2} = \$33/tCO_2 = \$1.69/MCF). Recall that here we assume away potential distortions in the price of natural gas, an assumption we then relax in sensitivity analysis.

The higher welfare level in the true social optimum is not general to the model, but due to the absence of backfire rebound effects in our calibration (see Proposition 4(iii)). Indeed, as reported in Table 4, the "investment" rebound effect is 31% in the private optimum and 34% in the social optimum. In addition, we find a "relative" rebound effect of 33%, meaning that 33% of energy efficiency gains are taken back when the economy moves from the private to the social optimum. These numbers are in the upper range of the estimates reported by Sorrell, Dimitropoulos, and Sommerville (2009) for space heating.

The moral hazard market failure can be restated as an average implied discount rate of 20%. This value is computed by solving and averaging the discount rate corresponding to each θ that matches the quality found in the social optimum with the net present value found in the private optimum, discounted at 7% by assumption.

Figure 3 illustrates, with the median homeowner, how equilibria are formed through reaction function intersections. The reaction functions are mildly upward sloping. The consumer's energy service varies by no more than 2 Degrees Fahrenheit with the quality of installation. Such a sensitivity is consistent with the values found in the literature (e.g., Hirst, White, and Goeltz (1985)). While the quality offered by the contractor is always at the minimum if he behaves non-cooperatively, it mildly increases with consumer's energy service if he behaves cooperatively. As predicted by Proposition 2, the social optimum implements both a higher quality and a higher energy service than the private optimum. The figure also pictures some comparative statics of the energy price. Pricing energy-use externalities shifts the consumer's reaction function inward and the contractor's upward (c.f., Equations 36 and 37). As discussed in Appendix C, the final location of the equilibrium – at a higher quality and a lower energy service – is not general but specific to model parameters.

5.4. **Comparison of policy instruments**

To isolate the ability of minimum quality standards and energy-savings insurance to specifically address moral hazard problems, we focus here on their welfare effects gross of environmental damages. More detailed results can be found in Tables 5 and 6.

If homeowner types were perfectly observable, the government would implement standards corresponding to each homeowner's optimal quality. Moreover, insuring contractors could design optimal contracts for every homeowner (Figure 7). On average, such contracts stipulate a coverage of 33% and close the energy efficiency gap by 77% along the welfare dimension. As illustrated in Figure 5, insurance shifts the reaction functions toward higher parties' actions (*c.f.* Equations 19 and 20). For the median homeowner, the resulting equilibrium entails a quality level that is intermediate between the social and private one and an energy service that is higher than in the social optimum. This positioning is contingent upon our calibration, not general to the model. Under full insurance, the contractor offers the socially optimal quality, but the marginal energy costs are zero. The homeowner thus consumes her maximum amount of energy service (s_{max}).

In practice, homeowners' types are unobservable. The insuring contractor cannot offer each homeowner her optimal contract, just like the government cannot implement as many standards as there are homeowner types. Rather, they both implement uniform instruments.

The optimal minimum quality standard is given by Equation 22. Let us assume first that monitoring a standard is costless. Increasing its stringency from 24 to 47 worker.hours increases both economic efficiency and energy efficiency (Figure 8). Further tightening increases energy efficiency but not economic efficiency: The standard becomes too stringent for most of the people. The optimal standard is very close to the quality that is optimal to the median homeowner (47.1 worker.hours). As shown in Figure 6, such a standard is too tight to the 5th percentile homeowner (type $\theta = 0.66$), who would have been better-off with a standard of 45.6 worker.hours. It is too loose to the 95th percentile homeowner (type $\theta = 1.51$), who would have been better-off with a standard of 48.4 hours. Therefore, there is a narrow quality range in which the standard can be set so that average welfare is very close to the social optimum.

A similar pattern is observed with uniform insurance. Increasing insurance coverage up to 30% increases both energy efficiency and economic efficiency (Figure 8). Between 30% and 40%, the optimal uniform insurance contract is very close to the situation where consumers are all offered their optimal contract. Again, welfare losses due to heterogeneity are negligible.

Energy efficiency then increases at the expense of economic efficiency up to a coverage of 60%, a situation discussed by Jaffe and Stavins as a ”Technologist’s optimum”. Beyond that point, energy efficiency starts decreasing too, until the curve hits the horizontal axis, for a coverage of $k = 100\%$, at the welfare level enjoyed before investment. That is, under full insurance, the total cost paid to the contractor is so high that no homeowner can be left with a positive net present value, hence none invests. Otherwise, indoor temperature would be set at corner $s_{max} = 80°F$, leading to an annual natural gas use of 79 MCF. This would imply a prohibitive lifetime discounted energy bill of $11,442, fully borne by the contractor and passed on to the homeowner as an insurance premium.

Overall, we find that the average welfare gain under the optimal standard is $290 greater than the gain obtained with optimal insurance (and $720 higher if environmental damages are accounted for). Unlike insurance, a standard entails monitoring costs, estimated for each realization at $347 from Palmer, Walls, Gordon, and Gerarden (2013). In practice, only a fraction of realizations can be randomly monitored, so this estimate is an upper bound of the true monitoring cost. When accounting for monitoring costs, the welfare difference between the standard and insurance becomes ambiguous. However, our assumption of insurance contracts running over 35 years certainly overestimates the welfare gains from insurance. Therefore, the superiority of minimum quality standards over energy-savings insurance seems to be a robust result.

6. Discussion

6.1. Sensitivity analysis

We first examine the sensitivity of the model to market barrier parameters: a larger heterogeneity in homeowners’ valuations, a lower initial insulation rate, higher insulation costs and a higher absolute valuation of energy service (Table 7, Figure 9). We find that compared to the reference scenario, absolute welfare levels vary by a large magnitude, but the deadweight loss from moral hazard is relatively stable [$1,085-1,260]. Moving from the private optimum to the social optimum increases welfare by 3-5%. Implied discount rates amount to 17-20%.

We then introduce market failures and behavioral anomalies, the comparative statics of which is formalized in Appendix C (Table 8, Figure 9). We model non-capitalization of energy savings by setting investment lifetime to 10 years, the typical period of residency in a dwelling. We also model undistorted natural gas price by removing the 49.7% markup above marginal cost estimated by Davis and Muehlegger (2010); the price is then $5.80/MCF.

Lastly, we model undervaluation of energy savings with a 20% discount rate. Compared to the reference scenario, introducing non-capitalization and undervaluation of energy savings decreases the absolute welfare level and increases the implied discount rate. Removing energy price distortions increases absolute welfare and lowers the implied discount rate. In addition, unlike market barriers, these alternative assumptions significantly reduce the deadweight loss from moral hazard, which amounts to $289-517 in absolute terms and 1-3% in relative terms.

If homeowners undervalue energy savings ($r = 20\%$) and ignore environmental damages, then they might not perceive optimal quality as beneficial: the welfare gains ($289) are below the upper bound of the monitoring cost ($347). This does not mean, however, that public intervention is not warranted. The situation with undistorted price of natural gas ($p = \$5.80$) is the closest to a market where no inefficiency other than moral hazard and carbon dioxide emission externalities occurs. In this most relevant context, the deadweight loss from moral hazard ($486, or $912 if environmental damages are accounted for) is still above the monitoring cost, though by a smaller margin than in our reference scenario. This strengthens the case for government intervention aimed at undoing the moral hazard.

Overall, the results of the sensitivity analysis suggest that the magnitude of the deadweight loss varies considerably with the investment lifetime, the energy price and the discount rate, but varies less with the parameters capturing market barriers.

6.2. **Approximation of the deadweight loss**

The net present value calculation, $\overline{\Delta_q W}$, which we proposed as a sufficient statistic of deadweight loss (cf. Equation 25), contains all the market and behavioural parameters p, r and l which were found most important in the sensitivity analysis. Moreover, Tables 7 and 8 (fourth row) show that it never underestimates the exact deadweight loss by more than 9% in absolute value across scenarios. This underlines the importance of having accurate estimates of the technology and its cost for future empirical research.

We now extrapolate our reference scenario to the U.S. population. Recall that the homeowners using natural gas for space heating covered 35% of the RECS dataset. Moreover, we confined our attention to 3.4% of that subpopulation (hence 1.2% of the complete dataset), the fraction of households investing in insulation annually. Applying these shares to a number of U.S. households of 115 million (U.S. Census Bureau value for 2008-2012), our analysis covered approximately 1.4 million households. On average, the moral hazard associated with insulation represents for each household a quality shortfall of one workday, a natural gas overuse of 8 MCF, 0.4 tons of CO_2 emissions and $1,723 of present value deadweight loss (net of environmental damages). At the population scale, undoing moral hazard could thus save 11 billion cubic feet of natural gas and 0.6 million tons of CO_2 annually, equivalent to $2.4 billion present value benefits.

6.3. Extensions

Considering risk-aversion would be a natural extension of the model. As a matter of fact, the performance of energy efficiency technologies depends on volatile factors, such as weather conditions or energy prices, to which consumers are likely to be adverse. Moreover, the home retrofit industry is made up of small industries that have little room to diversify risks (Lutzenhiser, 1994). In our model, risk-averse homeowners would expect higher energy expenditures than a certainty equivalent, hence demand less energy service. Risk-averse firms would respond with a lower quality in the social optimum. Overall, the introduction of risk-aversion on both sides of the market would reduce the size of the energy efficiency gap compared to a riskless situation.

Instead of assuming homogeneous firms that all fail to offer quality in equilibrium, we could assume heterogeneous firms. Within our informational structure, a fringe of firms may adopt reputation or signaling strategies and supply a better, or even optimal quality. Such private forces would reduce the size of the energy efficiency gap.

7. Conclusion

We examined how moral hazard problems can generate an energy efficiency gap, and how this information asymmetry may interact with other market failures. Taking home energy retrofits as an example, we show that if the quality of installation offered by a retrofit contractor is unobserved by the homeowner, then the contractor will cut it in equilibrium. This leads to a suboptimal level of energy efficiency along both the intensive and extensive margins: Actual quality underperforms engineering predictions and some consumers are discouraged from investing.

Numerical simulations calibrated to the U.S. home insulation market suggest that the potential welfare gains from undoing moral hazard are larger than the cost of quality audits. This holds for a large range of market environments, most notably when moral hazard is the only market failure in place. Therefore, undoing moral hazard is welfare-improving. The moral hazard problem induces an energy efficiency gap that is substantially larger than the one induced by energy-use externalities. We analytically establish and numerically illustrate that the deadweight loss associated with moral hazard can be closely approximated using only technological data. Extrapolating our results to the U.S. population of homeowners using natural gas for space heating, we find that increasing the quality of each insulation installation by one workday could save 11 billion cubic feet and 0.6 million tons of CO_2 each year, equivalent to $2.4 billion present value benefits.

Our analysis provides motivation for energy efficiency policies that would go beyond the internalization of energy-use externalities. This recommendation holds as long as consumers are not prone to a backfire rebound effect – a reasonable hypothesis (Sorrell 2009; Gillingham, Kotchen, Rapson, and Wagner 2013; Borenstein 2013). When addressing the moral hazard, the first-best outcome can only be attained to the extent that energy performance and consumer preferences can be made perfectly observable. Since no technology can meet that goal at an affordable cost yet, government intervention will only generate second-best outcomes: Minimum quality standards neglect consumer heterogeneity and incur some monitoring costs, while energy-savings insurance raise a second moral hazard. However, our numerical results suggest that the former can bring social welfare very close to its optimal level. Similarly, even with modest coverage, insurance contracts can deliver welfare gains that are economically important.

This insight is relatively new. While most investigations of the energy efficiency gap have focused on the role of possible undervaluation of energy savings by consumers (Gillingham, Newell, and Palmer 2009; Allcott and Greenstone 2012), ours underlines the importance of considering the behavior of the firms supplying energy efficiency. Moral hazard offers a simple explanation for the systematic overestimation of energy savings by engineering models and for the abnormally high discount rates rationalizing consumers' behavior. In practice, we provided suggestive evidence from France that defective quality is an issue in the building sector. Whether such defects result from contractors exploiting an informational rent now needs to be carefully identified empirically.

Acknowledgements

The authors started this research at the Precourt Energy Efficiency Center (PEEC), Stanford University. We thank PEEC for funding and James Sweeney for encouragements and comments. We are grateful to Tiger Adolf, Rick Diamond, Matt Golden, Evan Mills and Carol Zabin for early discussions that motivated this work. We thank Philippe Estinguoy and Martin Guer for providing the AQC REX data. We thank Frédéric Branger, Lawrence Goulder, Franck Lecocq, Marie-Laure Nauleau, Philippe Quirion, and Adrien Vogt-Schilb for comments on earlier drafts. Lastly, we thank participants to the various seminars and conferences where this paper was presented for their feedback.

Appendix A. Comparative statics with respect to consumer type θ

Applying the Implicit Function Theorem to Equation 6:

$$(33) \qquad \forall t \quad \frac{\mathrm{d}s_\theta^*}{\mathrm{d}\theta} = \frac{-V'}{\theta V'' - pE_{ss}} > 0$$

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

$$(34) \qquad \forall q,\ \forall \theta_1 > \theta_2 \quad s_{\theta_1}^*(q) > s_{\theta_2}^*(q)$$

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

Proposition 5. *If condition (11) is satisfied for two participating consumers 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) $q_{\theta_h}^{nc} = q_{\theta_l}^{nc} = q_{min}$
(ii) $s_{\theta_h}^{nc} \geq s_{\theta_l}^{nc}$
(iii) $s_{\theta_h}^{c} \geq s_{\theta_l}^{c}$
(iv) $q_{\theta_h}^{c} \geq q_{\theta_l}^{c}$.

proof: (i) is straightforward. (ii) Combined with (34), it implies: $s_{\theta_h}^{nc} = s_{\theta_h}^*(q_{\theta_h}^{nc}) \geq s_{\theta_l}^*(q_{\theta_l}^{nc}) = s_{\theta_l}^{nc}$. (iii) Likewise, (34) implies, for all s, $s_{\theta_h}^*(q^*(s)) \geq s_{\theta_l}^*(q^*(s))$. In particular, $s_{\theta_h}^c = s_{\theta_h}^*(q^*(s_{\theta_h}^c)) \geq s_{\theta_l}^*(q^*(s_{\theta_h}^c))$. 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 $s_{\theta_l}^*(q^*(\cdot))$: $\forall a > s_{\theta_l}^c,\ s_{\theta_l}^*(q^*(a)) - s_{\theta_l}^*(q^*(s_{\theta_l}^c)) < a - s_{\theta_l}^c \Leftrightarrow s_{\theta_l}^*(q^*(a)) < a$. Therefore, $s_{\theta_h}^c \geq s_{\theta_l}^c$. (iv) Lastly, since $g^*(\cdot)$ is increasing, $q_{\theta_h}^c = g^*(s_{\theta_h}^c) \geq g^*(s_{\theta_l}^c) = q_{\theta_l}^c$.

Appendix B. Participation to investment

For any equilibrium situation j, participation will depend on the limits of the net present value function, the sign of which is indeterminate:

$$\text{(35)} \qquad NPV^j(\theta) \equiv \underbrace{\left[\theta\left(V(s_\theta^j) - V(s_\theta^0)\right) - p\left(E(s_\theta^j, q_\theta^j) - E^0(s_\theta^0)\right)\right]}_{\geq 0} \Gamma \underbrace{-T + \epsilon}_{\leq 0}$$

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 Proposition 5, 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.

If $\lim_{\theta \to 0} NPV(\theta) \geq 0$ then all consumers participate. Participation is given by $N^j \equiv \int_0^{+\infty} \mathrm{d}F(\theta) = 1$.

If $\lim_{\theta \to 0} NPV(\theta) < 0$ and $\lim_{\theta \to +\infty} NPV(\theta) > 0$ then by Equation 12, there exists a unique cutoff type θ_0, as discussed in the text.

If $\lim_{\theta \to 0} NPV(\theta) < 0$ and $\lim_{\theta \to +\infty} NPV(\theta) \leq 0$ 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.

Appendix C. Comparative statics with respect to market and behavioral features

Recall that $\zeta \equiv p\Gamma(r, l)$. 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.

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:

$$\text{(36)} \qquad \forall t \quad \frac{\mathrm{d}s_\theta^*}{\mathrm{d}\zeta} = \frac{E_s}{\theta V''/\zeta - E_{ss}} < 0$$

$$\text{(37)} \qquad \frac{\mathrm{d}q^*}{\mathrm{d}\zeta} = \frac{-E_q}{C''/\zeta + E_{qq}} > 0$$

By the same reasoning as in Proposition 5, a higher ζ entails a higher energy service in private equilibrium. But optimal actions cannot be compared unambiguously in the private and social equilibria.

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

$$\frac{\mathrm{d}NPV^*}{\mathrm{d}\zeta} = -\left[E(s^*_\theta, q^*_\theta) - E^0(s^0_\theta)\right] \tag{38}$$

As long as energy efficiency investments decrease energy use for all consumers, the net present value is increasing in ζ. By the same type of reasoning as in Proposition 5, this leads to a higher participation and a higher average welfare. This conclusion is reversed if all consumers are subject to an investment backfire rebound effect, i.e., $\forall\theta\ E(s^*_\theta, q^*_\theta) > E^0(s^0_\theta)$. In this case, a higher ζ decreases participation and average welfare.

Appendix D. Optimal policies

Optimal insurance coverage. The first-order condition for finding the optimal insurance contract from Equation 21 is:

$$p\Gamma\left(\frac{\mathrm{d}s^{**}_\theta}{\mathrm{d}k}\left[\theta V' - pE_s\right] - \frac{\mathrm{d}q^{**}}{\mathrm{d}k}\left[\frac{C'}{\Gamma} + pE_q\right]\right) = 0 \tag{39}$$

Plugging in Equations 17 and 18 and further rearranging gives the equation that solves the optimal coverage $\hat{k}$:

$$\forall t \quad p\Gamma\left(kE_s\frac{\mathrm{d}s^{**}_\theta}{\mathrm{d}k} + (1-k)E_q\frac{\mathrm{d}q^{**}}{\mathrm{d}k}\right) = 0 \tag{40}$$

Optimal minimum quality standard. Assuming that the cutoff type exists and is unique, the constraint in Equation 22 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:

(41)
$$\frac{\mathrm{d}\theta_0}{\mathrm{d}\bar{q}}\Big(U^0(\theta_0(\bar{q}),s^0_\theta)-U(\theta_0(\bar{q}),s^*_\theta(\bar{q}),\bar{q})+M(\bar{q})\Big)+\int_{\theta_0(\bar{q})}^{+\infty}\left[\frac{\partial U(\theta,s^*_\theta(\bar{q}),\bar{q})}{\partial\bar{q}}-M'\right]\mathrm{d}F(\theta)=0$$

Recognizing that $U^0(\theta_0(\bar{q}),s^0_\theta)-U(\theta_0(\bar{q}),s^*_\theta(\bar{q}),\bar{q})=-NPV(\theta_0(\bar{q}),s^*_{\theta_0}(\bar{q}),\bar{q})$ and using the binding constraint leads to the result (Equation 23). In fact, since marginal participants are indifferent between investing and not investing, marginal changes in participation can be neglected.

Note that if participation to investment is nil without the standard, no standard will be welfare-improving. In contrast, if participation is full without the standard, the constraint will not be binding and the optimal standard will be defined by the following first-order condition:

(42)
$$\int_0^{+\infty}\left[\frac{\partial U(\theta,s^*_\theta(\bar{q}),\bar{q})}{\partial\bar{q}}-M'\right]\mathrm{d}F(\theta)=0$$

Appendix E. Proof of Proposition 4

We illustrate with energy-use externalities ($p_x>0$).

(i) For all θ, since $(s^{c,x}_\theta,q^{c,x}_\theta)$ maximizes U_x in the social setting, $U_x(\theta,s^{c,x}_\theta,q^{c,x}_\theta)\geq U_x(\theta,s,q)$ for all (s,q), and for $(s^{nc,x}_\theta,q^{nc,x}_\theta)$ in particular. Likewise, we have $U^0_x(\theta,s^{0,x}_\theta)\geq U^0_x(\theta,s^0_\theta)$. By Proposition 3, it follows that $W^{c,x}_x\geq W^{nc,x}_x$.

(ii) Again, for all θ, since $(s^{c,x}_\theta,q^{c,x}_\theta)$ maximizes U_x in the social setting, $U_x(\theta,s^{c,x}_\theta,q^{c,x}_\theta)\geq U_x(\theta,s^c_\theta,q^c_\theta)$. In addition, we have $NPV_x(\theta)=NPV(\theta)-p_x\Gamma_x[E(s,q)-E^0(s)]$. Assume θ^x_0 is the cutoff type in an equilibrium where both energy-use externalities and moral hazard are addressed, while θ_0 is the cut-off type in an equilibrium where only moral hazard problems are addressed. We have $NPV_x(\theta^x_0)=0=NPV(\theta_0)$. In the absence of an investment backfire rebound effect, we thus have $NPV_x(\theta^x_0)=0\leq NPV_x(\theta_0)$. Since NPV is increasing in θ, $\theta^x_0\leq\theta_0$, that is, participation is higher if externalities are internalized. The difference in aggregate welfare between the two equilibria is $\Delta W=\int_0^{\theta^x_0}\Delta U^0_x\mathrm{d}F(\theta)+\int_{\theta^x_0}^{\theta_0}[U_x(\theta,s^x_\theta,q^x_\theta)-U^0_x(\theta,s^0)]\mathrm{d}F(\theta)+\int_{\theta_0}^{+\infty}\Delta U_x\mathrm{d}F(\theta)$. The first and third integrands of the right-hand side are positive (see proof (i) just above). The second integrand is also positive, since $\forall\theta \geq \theta_0^x\ U_x(\theta, s_\theta^x, q_\theta^x) \geq U_x^0(\theta, s^{0x}) \geq U_x^0(\theta, s^0)$. Therefore, aggregate welfare is larger when externalities are internalized: $W_x^{c,x} \geq W_x^c$. The exact same reasoning leads to $W_x^{nc,x} \geq W_x^{nc}$. This is because since $(s_\theta^{nc,x}, q_\theta^{nc,x})$ maximizes U_x in the private setting, $U_x(\theta, s_\theta^{nc,x}, q_\theta^{nc,x})$ is greater than $U_x(\theta, s, q)$ for any other actions s and q determined in a private setting, e.g., $(s_\theta^{nc}, q_\theta^{nc})$.

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

Appendix F. Model calibration

Parameters α, β and γ (Section 5.1) are computed so as to allow the model to replicate calibration targets 1, 2 and 3 (Table 4). For $\theta = 1$ and $s^0 = 69°\text{F}$, this leads to:

(43)

$$\begin{cases} V'(s^0) - pE_s^0(s^0) = 0 \\ E^0(s^0) = 50 \\ \frac{\mathrm{d}E^0\left(s^0_{\theta=1}(p)\right)}{\mathrm{d}p}\frac{p}{E^0\left(s^0_{\theta=1}(p)\right)} = -0.4 \end{cases} \Leftrightarrow \begin{cases} V_{max}\alpha\exp\left(-\alpha(s^0 - s_{min})\right) - p\gamma\beta(s^0 - s_{min})^{\gamma-1} = 0 \\ \beta(s^0 - s_{min})^\gamma = 50 \\ \frac{\gamma}{1-\gamma-\frac{V_{max}\alpha^2\exp\left(-\alpha(s^0-s_{min})\right)}{p\gamma\beta(s^0-s_{min})^2}} = -0.4 \end{cases}$$

$$\Leftrightarrow \begin{cases} \alpha = 0.28 \\ \beta = 5.32 \\ \gamma = 1.02 \end{cases}$$

Note that if we assume linear technology ($\gamma = 1$), then the value of V_{max} that solves the system is \$2,719. This provides a lower bound for V_{max}, as V_{max} is increasing in γ:

$$\frac{\mathrm{d}V_{max}}{\mathrm{d}\gamma} = \frac{p\beta(s^0 - s_{min})^{\gamma-1}(1+\gamma\ln(s^0 - s_{min}))}{\alpha\exp\left(-\alpha(s^0 - s_{min})\right)} > 0 \tag{44}$$

Parameter ϵ, representing the non-energy benefits of insulation, is computed so as to allow the model to replicate calibration target 4. As the marginal investing homeowner has type $\theta = 1$, ϵ is such that $NPV(\theta = 1, s^{nc}_{\theta=1}, q^{nc}_{\theta=1}) = 0$, which leads to $\epsilon = \$2,035$.

Parameter ω is computed so as to allow the model to replicate calibration target 5:

$$G(q_{max}) = .99G_{max} \Leftrightarrow G_{min} + (G_{max} - G_{min})(1 - \omega(q_{max} - q_{min}) = .99G_{max} \Leftrightarrow \omega = .09 \tag{45}$$

Parameters ρ and ϕ are computed so as to allow the model to replicate calibration targets 6 and 7:

$$\begin{cases} C'(q_{min}) = 15 \\ C'(q_{max}) = 30 \end{cases} \Leftrightarrow \begin{cases} \rho = 15 \\ \rho + \phi(q_{max} - q_{min}) = 30 \end{cases} \Leftrightarrow \begin{cases} \rho = 15 \\ \phi = .16 \end{cases} \tag{46}$$

Appendix G. Derivation of the sufficient statistic

For a participating homeowner, the exact deadweight loss $\Delta_q W$ is:

$$W^c - W^{nc} = \sum_{t=1}^{l} \left[V(s^c) - V(s^{nc}) - p\left(E(s^c, q^c) - E(s^{nc}, q^{nc})\right)\right]\delta^t - \left[C(q^c) - C(q^{nc})\right] \tag{47}$$

We recognize that:

$$\Delta_q W = \overline{\Delta_q W} + \underbrace{\left[V(s^c) - V(s^{nc}) - p\left(E(s^c, q^c) - E(s^{nc}, q^c)\right)\right]}_{\geq 0}\Gamma \tag{48}$$

The term in brackets is positive because s^c maximizes the function $V(\cdot) - E(\cdot, q^c)$. Therefore, $\Delta_q W \leq \overline{\Delta_q W}$.

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Table 1. Projects and defects in the AQC REX sample

			Number of buildings	Number of defects	Number of defects, by severity and origin					
					Minor defects		Medium defects		Major defects	
					Structural	Thermal	Structural	Thermal	Structural	Thermal
Construction projects	Multi-family dwellings	Labeled	26	96	33	35	13	13	1	1
		Non-labeled	55	182	70	66	20	17	6	3
	Single-family dwellings	Labeled	19	83	23	45	3	10	2	0
		Non-labeled	58	221	52	102	12	45	5	5
	Commercial buildings	Labeled	28	116	46	44	15	8	3	0
		Non-labeled	55	336	164	88	48	25	8	3
Renovation projects	Multi-family dwellings	Labeled	50	245	98	47	39	47	9	5
		Non-labeled	23	129	53	27	15	32	2	0
	Single-family dwellings	Labeled	79	320	75	97	66	63	7	12
		Non-labeled	30	167	97	45	10	9	4	2
	Commercial buildings	Labeled	35	173	78	60	15	16	3	1
		Non-labeled	88	694	329	155	127	59	20	4
TOTAL			546	2762	1118	811	383	344	70	36

TABLE 2. Summary Statistics of the RECS Sample ($n = 4,266$)

	Unit	RECS Entry	Median	Mean	SD	Min	Max
Temperature when someone is home during the day (winter)	°F	TEMPHOME	69.0	69.3	3.4	60.0	80.0
Natural Gas cost for space heating, 2009	$	DOLNGSPH	562	624	386	33	3,591
Natural Gas usage for space heating, 2009	MCF	$\frac{\text{BTUNGSPH}}{1.023*10^{-3}}$	50.2	55.0	34.0	0.6	337.2
Price paid for natural gas for space heating	$/MCF	$\frac{\text{DOLNGSPH}*1.023}{\text{BTUNGSPH}*10^{3}}$	11.14	11.95	5.69	3.75	190.73
Gross household income, 2009	$	MONEYPY	65,000	78,928	50,727	2,500	170,000
Income share dedicated to natural gas for space heating		$\frac{\text{DOLNGSPH}}{\text{MONEYPY}}$	0.82%	1.54%	3.20%	0.02%	65.92%

Notes: "Natural gas cost for space heating" is measured in thousand BTU in RECS, here converted in MCF. "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.

Table 3. Model parameters

Parameter	Symbol	Value	Unit	Source
Minimum indoor temperature	s_{min}	60	°F	0.8th percentile of the RECS preliminary sample
Maximum indoor temperature	s_{max}	80	°F	99.9th percentile of the RECS preliminary sample
Minimum labour input	q_{min}	24	worker.hours	One workday = 24 worker.hours, e.g., three installers working 8 hours a day (Best guess)
Maximum labour input	q_{max}	72	worker.hours	Three workdays (Best guess)
Maximum valuation of energy service	V_{max}	2,816	$	The 95th percentile of the income share dedicated to space heating in the RECS sample is 4.3%. Applying this fraction to the median income of the sample ($65,000) leads to a maximum budget for space heating of $2,816.
Minimum energy efficiency of insulation	G_{min}	5%		(Best guess)
Maximum energy efficiency of insulation	G_{max}	30%		(Best guess)
Fixed cost of wall insulation	K	2,400	$	(Best guess)
Physical lifetime of insulation investment	l	35	years	(Best guess)
Discount rate	r	7%		Value recommended to assess private investment (U.S. OMB).
Price of natural gas	p	11.14	$/MCF	Median price of the RECS sample
Carbon price	p_{CO_2}	1.69	$/MCF	Equivalent to a social cost of carbon of $33/t$CO_2$ in 2010, which is the value recommended for impact analysis in the U.S. (White House, 2013)

Table 4. Calibration targets

Calibration target	Expression	Target value	Source
Optimal temperature before investment to the median homeowner	$s^0_{\theta=1}$	69°F	Median temperature of the RECS sample
Optimal annual energy use before investment to the median homeowner	$E^0(s^0_{\theta=1})$	50 MCF	Median annual natural gas use for space heating of the RECS sample
Price-elasticity of energy demand before investment to the median homeowner	See App.G	-0.4	Middle value of the [-0.03;-0.76] range found in the literature by Gillingham, Newell, and Palmer (2009) for short-term price-elasticities of natural gas use
Participation to insulation investment in the private optimum	See App.G	50%	See text (Section 4.3).
Energy savings at maximum quality level	$G(q_{max})$	$99\%G_{max}$	
Wage for insulation workers at minimum quality level	$C'(q_{min})$	$15/hour	According to the U.S. Bureau of Labour and Statistics, the median pay for insulation workers was $16.88/hour in 2010. According to Zabin, Lester, and Halpern-Finnerty (2011), the lower range of insulation wages in California is $10-15/hour
Wage for insulation workers at maximum quality level	$C'(q_{max})$	$30/hour	Upper range of the values reported by Zabin, Lester, and Halpern-Finnerty (2011) for California

Notes: Parameters α, β, γ, ω, ρ, ϕ and ϵ (Section 5.1) are calibrated so as to allow the model to replicate these targets. The procedure is detailed in Appendix F.

Table 5. Simulation results, median homeowner ($\theta = 1$)

		Uninternalized environmental damages				Internalized environmental damages			
Model output	Unit	Before investment	Private optimum	Social optimum	Optimal insurance	Before investment	Private optimum	Social optimum	Optimal insurance
Lifetime discounted welfare, gross	$	26,342	26,342	27,613	27,327	26,151	26,160	27,470	27,521
Lifetime discounted welfare, net of environmental damages	$	23,384	23,475	25,183	24,446	23,599	23,679	25,345	25,004
Homeowners' equilibrium temperature	°F	69.0	69.2	70.1	71.3	67.8	68.0	68.9	70.0
Annual natural gas use for space heating	MCF	50.0	48.5	41.1	48.7	43.1	42.0	35.9	42.6
Annual natural gas expenditure	$	557	540	458	543	481	467	400	474
Annual CO_2 emissions	tCO_2	2.6	2.5	2.1	2.5	2.2	2.1	1.8	2.2
Annual external cost of CO_2 emissions	$	85	82	69	82	73	71	61	72
Contractor's equilibrium quality	worker.hour		24.0	47.1	37.9		24.0	49.2	39.2
Energy efficiency of insulation			5%	27%	23%		5%	28%	24%
Rebound effect			39%	34%	89%		45%	39%	94%
Zero-profit insulation price	$		2,400	2,830	2,638		2,400	2,876	2,663
Homeowner's net present value	$		0	1,271	985		80	1,746	1,370
Wage for insulation workers	$/worker/hour		15.00	22.23	19.33		15.00	22.86	19.74
Insurance premium	$				2,317				2,641
Insurance optimal coverage					33%				31%

Notes: Adding "Zero-profit price of insulation" and "Homeowner's net present value" gives the insulation price that would be charged by a perfectly discriminating monopolist.

Table 6. Simulation results, averaged over the population of total mass 1

		Uninternalized environmental damages				Internalized environmental damages		
Model output	Unit	Before investment	Private optimum	Social optimum	Optimal insurance	Before investment	Private optimum	Social optimum
Lifetime discounted welfare, gross	$	27,488	27,503	28,760	28,474	27,297	27,321	28,617
Lifetime discounted welfare, net of environmental damages	$	24,531	24,596	26,330	25,594	24,745	24,814	26,493
Homeowners' equilibrium temperature	°F	69.0	69.2	70.1	71.3	67.8	68.0	68.9
Annual natural gas use for space heating	MCF	50.0	49.1	41.1	48.7	43.1	42.4	35.9
Annual natural gas expenditure	$	557	547	458	542	481	472	400
Annual CO_2 emissions	tCO_2	2.6	2.5	2.1	2.5	2.2	2.2	1.8
Annual external cost of CO_2 emissions	$	84	83	69	82	73	72	61
Contractor's equilibrium quality	worker.hour		24.0	47.1	37.8		24.0	49.1
Energy efficiency of insulation			2.5%	27.0%	23.0%		4.7%	27.5%
Rebound effect			31%	34%	89%		63%	39%
Cutoff type of the marginal participant			1.00	0.18	0.26		0.67	0.19
Participation rate			50%	100%	100%		94%	100%
Zero-profit insulation price	$		2,400	2,830	2,637		2,400	2,875
Homeowner's net present value	$		29	1,272	986		86	1,747
Wage for insulation workers	$/worker/hour		15.00	22.21	19.32		15.00	22.85
Insurance premium					2,317			
Insurance optimal coverage					33%			

Notes: ”Energy efficiency” is averaged over the whole population. The average over participants is obtained by dividing ”Energy Efficiency” by ”Participation rate”. Adding ”Zero profit price of insulation” and ”Homeowner's net present value” gives the insulation price that would be charged by a perfectly discriminating monopolist.

Table 7. Sensitivity to market barrier parameters

			Reference	Large homeowner heterogeneity	Low initial insulation rate	High cost of insulation	High valuation of energy service
				σ=1	initial rate=3.5%	FC=\$3000, $C'(q_{min})$=\$20, $C'(q_{max})$=\$50	V_{max}=\$4000
Implied discount rate			20%	17%	18%	17%	20%
Exact deadweight loss	$		1,258	1,239	1,206	1,085	1,260
Proxy of deadweight loss	$		1,158	1,158	1,158	997	1,158
Appproximation			-7.9%	-6.5%	-3.9%	-8.1%	-8.1%
Lifetime discounted welfare, gross	$	Before inv.	27,488	48,901	27,488	27,488	43,100
		Private	27,503	48,957	27,489	27,503	43,115
		Social	28,760	50,195	28,694	28,587	44,375
Lifetime discounted welfare, net of environmental damages	$	Before inv.	24,531	45,943	24,531	24,531	40,140
		Private	24,596	46,065	24,535	24,596	40,205
		Social	26,330	47,776	26,264	26,129	41,940
Annual natural gas use for space heating	MCF	Before inv.	50.0	50.0	50.0	50.0	50.0
		Private	49.1	48.9	49.9	49.1	49.2
		Social	41.1	40.9	41.1	41.6	41.2
Homeowner's equilibrium temperature	°F	Before inv.	69.0	68.3	69.0	69.0	69.0
		Private	69.2	68.5	69.2	69.2	69.1
		Social	70.1	69.4	70.1	70.0	69.9
Contractor's equilibrium quality	worker.hour	Private	24.0	24.0	24.0	24.0	24.0
		Social	47.1	46.9	47.1	43.1	47.1
Energy efficiency of insulation		Private	2.5%	2.4%	0.2%	2.5%	2.5%
		Social	27.0%	25.7%	27.0%	25.7%	27.0%
Rebound effect		Private	31.1%	6.7%	17.0%	31.1%	31.7%
		Social	34.0%	29.1%	34.0%	34.3%	34.4%
Cutoff type of the marginal participant		Private	1.00	1.03	1.58	1.00	1.00
		Social	0.18	0.18	0.19	0.20	0.15
Participation rate		Private	50.0%	48.8%	3.4%	50.0%	50.0%
		Social	100.0%	95.7%	100.0%	100.0%	100.0%
Zero-profit insulation price	$	Private	2,400	2,400	2,400	3,000	2,400
		Social	2,830	2,827	2,830	3,495	2,830
Homeowner's net present value	$	Private	29	114	14	29	29
		Social	1,272	1,352	1,206	1,099	1,275
Wage for insulation workers	$/worker/hour	Private	15.00	15.00	15.00	20.00	15.00
		Social	22.21	22.16	22.21	31.92	22.22
Calibrated non-energy benefits	$		2,036	2,032	1,970	2,636	2,036

TABLE 8. Sensitivity to market failure and behavioral anomaly parameters

			Reference	Non-capitalization of energy savings	Undistorted price of natural gas	Undervaluation of energy savings
				l=10 years	p=\$5.80/MCF	r=20%
Implied discount rate			20%	26%	15%	35%
Exact deadweight loss	$		1,258	517	486	289
Proxy of deadweight loss	$		1,158	473	443	263
Appproximation			-7.9%	-8.6%	-9.0%	-9.1%
Lifetime discounted welfare, gross	$	Before inv.	27,488	14,911	32,158	10,597
		Private	27,503	14,919	32,165	10,603
		Social	28,760	15,436	32,652	10,892
Lifetime discounted welfare, net of environmental damages	$	Before inv.	24,531	11,954	29,196	7,640
		Private	24,596	12,013	29,253	7,696
		Social	26,330	12,962	30,165	8,380
Annual natural gas use for space heating	MCF	Before inv.	50.0	50.0	50.1	50.0
		Private	49.1	49.1	49.2	49.1
		Social	41.1	41.8	42.0	42.5
Homeowner's equilibrium temperature	°F	Before inv.	69.0	69.0	69.0	69.0
		Private	69.2	69.2	69.1	69.2
		Social	70.1	70.0	69.7	69.9
Contractor's equilibrium quality	worker.hour	Private	24.0	24.0	24.0	24.0
		Social	47.1	41.3	40.9	38.0
Energy efficiency of insulation		Private	2.5%	2.5%	2.5%	2.5%
		Social	27.0%	24.9%	24.7%	23.1%
Rebound effect		Private	31.1%	31.1%	32.2%	31.1%
		Social	34.0%	34.4%	35.0%	34.8%
Cutoff type of the marginal participant		Private	1.00	1.00	1.00	1.00
		Social	0.18	0.23	0.20	0.28
Participation rate		Private	50.0%	50.0%	50.0%	50.0%
		Social	100.0%	100.0%	100.0%	100.0%
Zero-profit insulation price	$	Private	2,400	2,400	2,400	2,400
		Social	2,830	2,706	2,698	2,641
Homeowner's net present value	$	Private	29	16	15	11
		Social	1,272	525	494	295
Wage for insulation workers	$/worker/hour	Private	15.00	15.00	15.00	15.00
		Social	22.21	20.39	20.28	19.38
Calibrated non-energy benefits	$		2,036	2,202	2,210	2,260

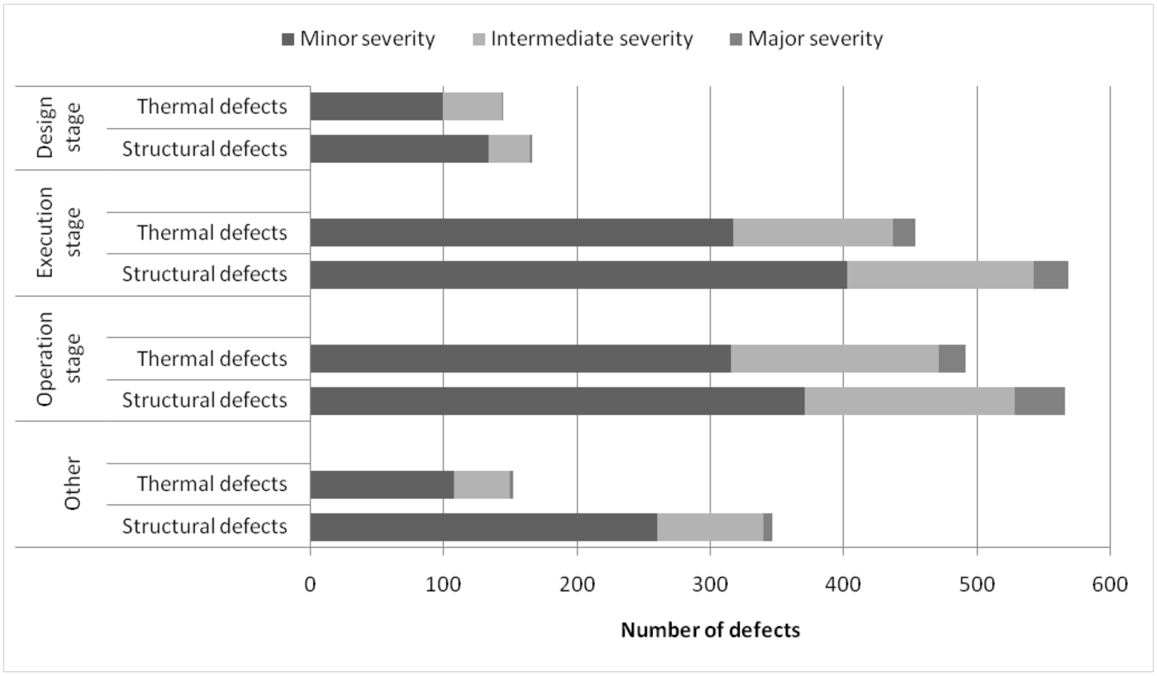

Figure 1. **Defects in the AQC REX sample.** Overall, 2,762 defects were observed through 546 audits. They are displayed here by severity, origin and nature.

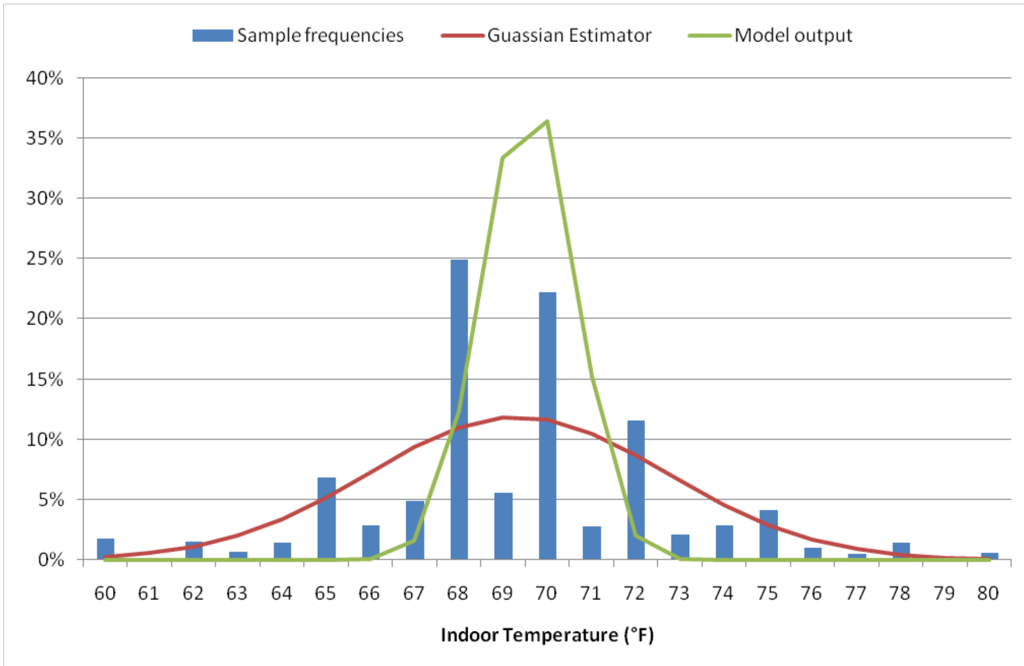

FIGURE 2. **Model fit to RECS sample data.** The Gaussian estimator is the normal distribution of temperature with parameters $\mu = 69.3$ and $\sigma = 3.4$, the mean and standard deviation of the RECS sample (Table 2). The model output is the probability distribution function of s^0_θ, calculated with the triangle method and assuming a log-normal distribution of θ with parameters $\mu = 0$ and $\sigma = 0.25$.

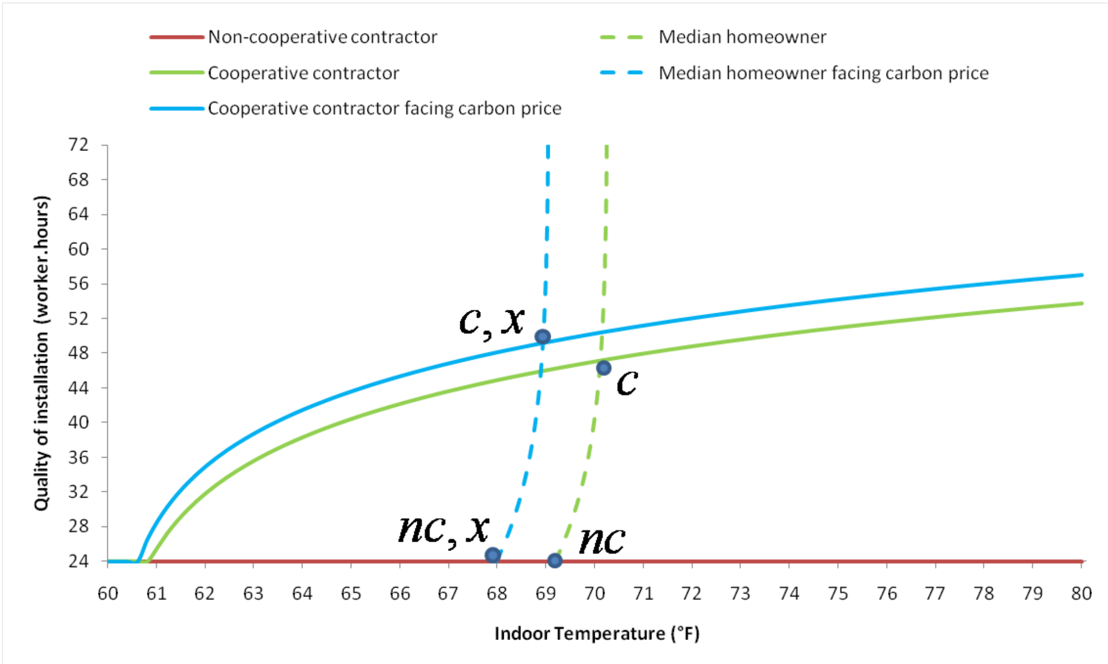

FIGURE 3. **Reaction functions, with a homeowner of median type $\theta = 1$.** (c) refers to the social optimum, (nc) to the private optimum and (c, x) and (nc, x) to the same optima in the presence of a carbon price of \$33/tCO_2.

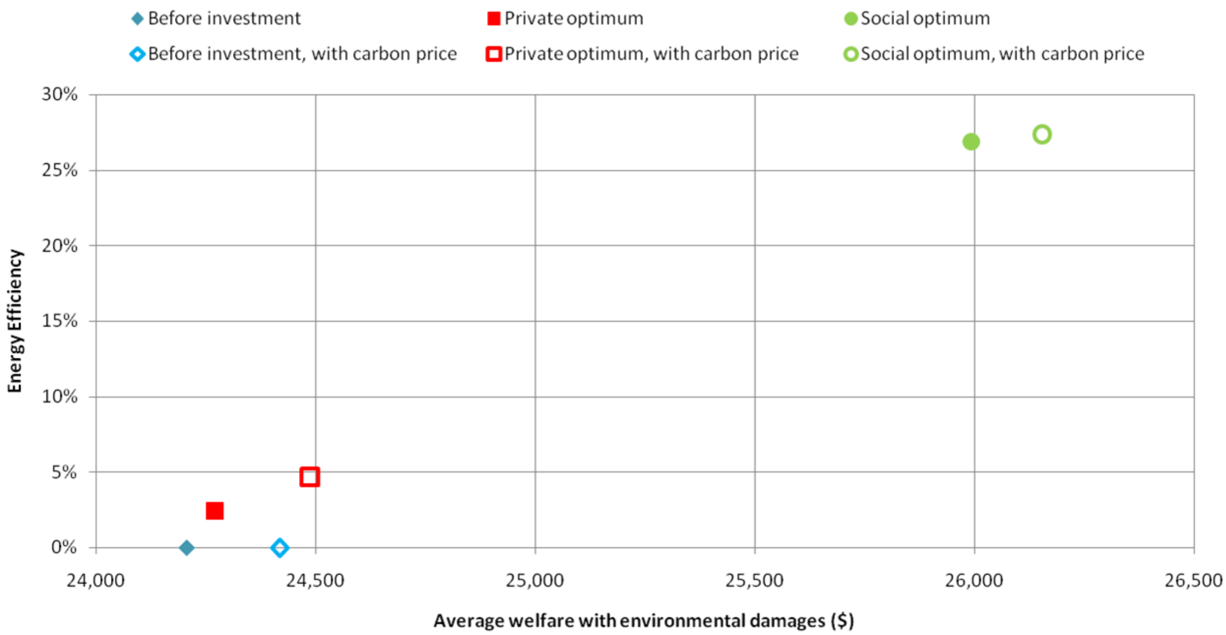

FIGURE 4. **The energy efficiency gap.** The horizontal axis represents average lifetime discounted welfare, net of environmental damages valued at $33/t$CO_2$. The vertical axis represents average energy efficiency (with the value 0% attributed to non-participating homeowners).

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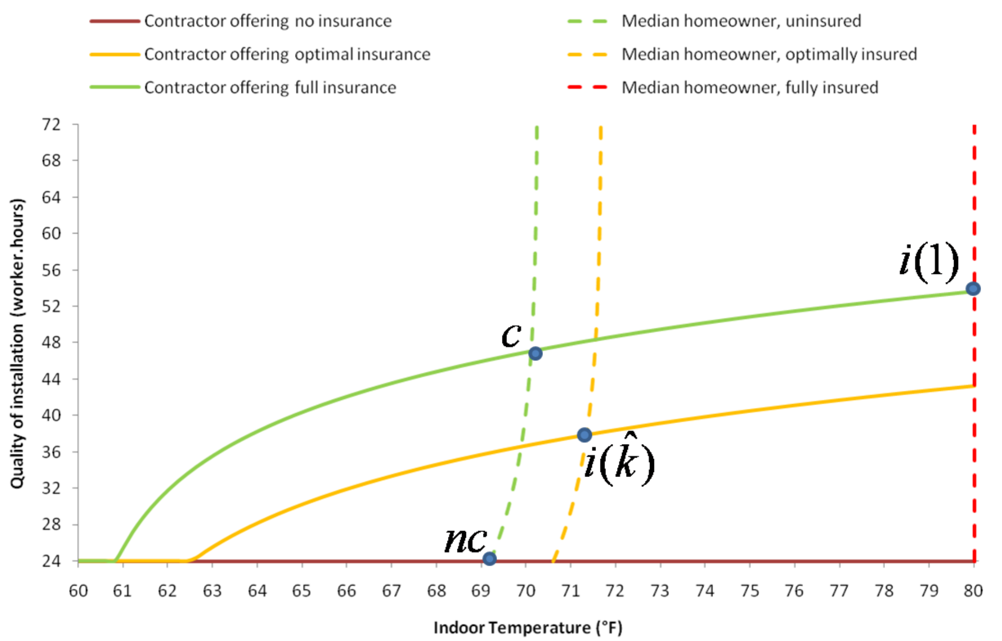

FIGURE 5. **Reaction functions under energy-savings insurance, with a homeowner of median type $\theta = 1$.** (c) refers to the social optimum, (nc) to the private optimum, $(i(\hat{k}))$ to the equilibrium induced by insurance with optimal coverage $\hat{k}$ and $(i(1))$ to the full insurance equilibrium.

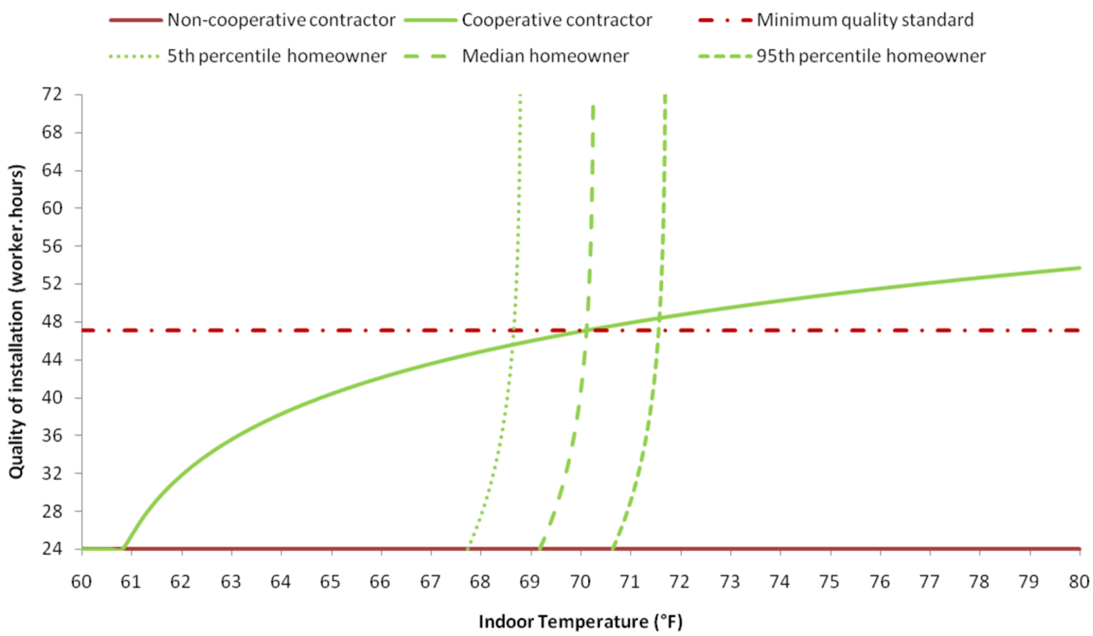

Figure 6. **Reaction functions with a minimum quality standard.** The standard is optimal to the median homeowner ($\theta = 1$), but suboptimal to all others. For instance, it is too tight to the 5th percentile of the homeowners' distribution ($\theta = 0.66$) and too loose to the 95th percentile ($\theta = 1.51$).

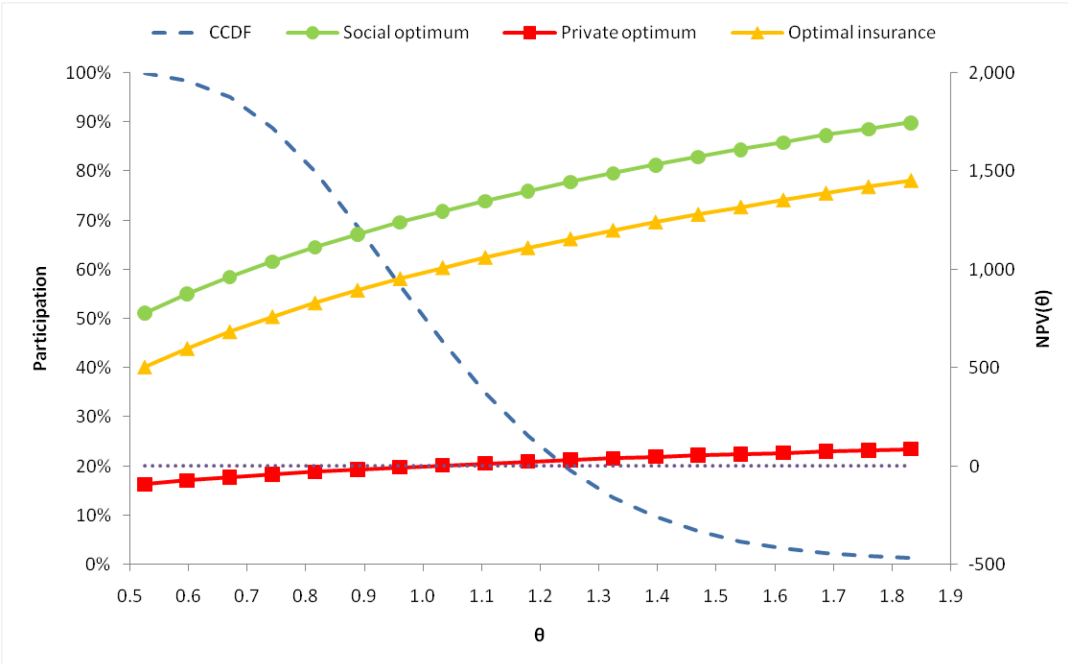

FIGURE 7. **Net present value and participation with respect to homeowner's type θ.** The net present value (gross of environmental damages) of investment in insulation reads on the right vertical axis. The intersection of each curve with the zero horizontal axis determines the cutoff type θ_0 of the 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.

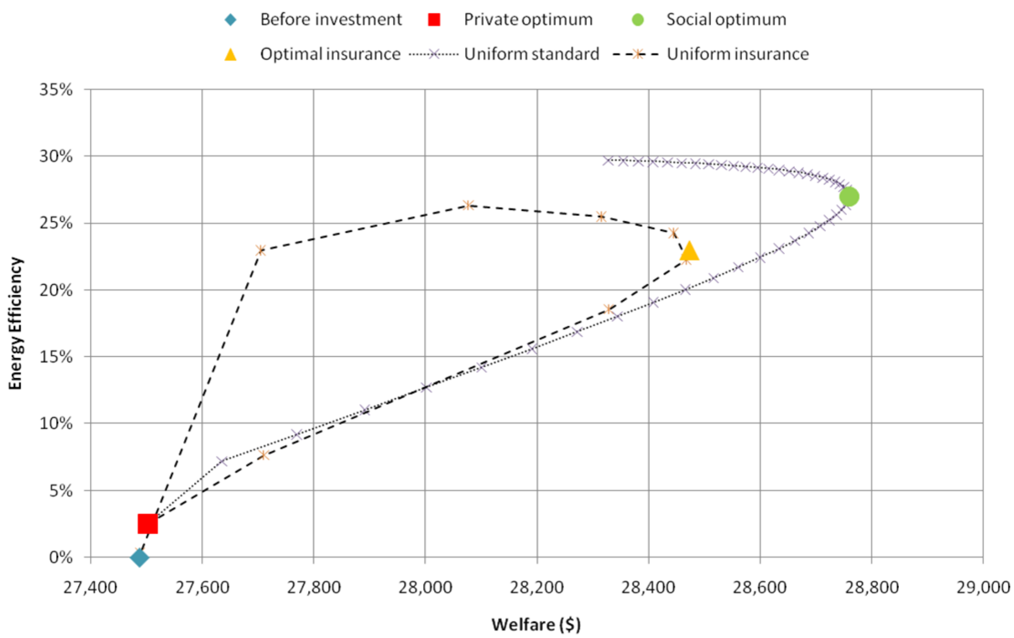

FIGURE 8. **Economic and energy efficiency of policy instruments.** The welfare displayed on the horizontal axis is the average lifetime discounted welfare gross of environmental damages. Each mark of the uniform standard parametric curve represents an additional worker.hour of labour requirement, from q_{min} to q_{max}. The stringency of the standard increases counter-clockwise. Each mark of the uniform insurance curve represents an incremental 10% of insurance coverage, from 0 to 100%. Insurance coverage increases counter-clockwise.

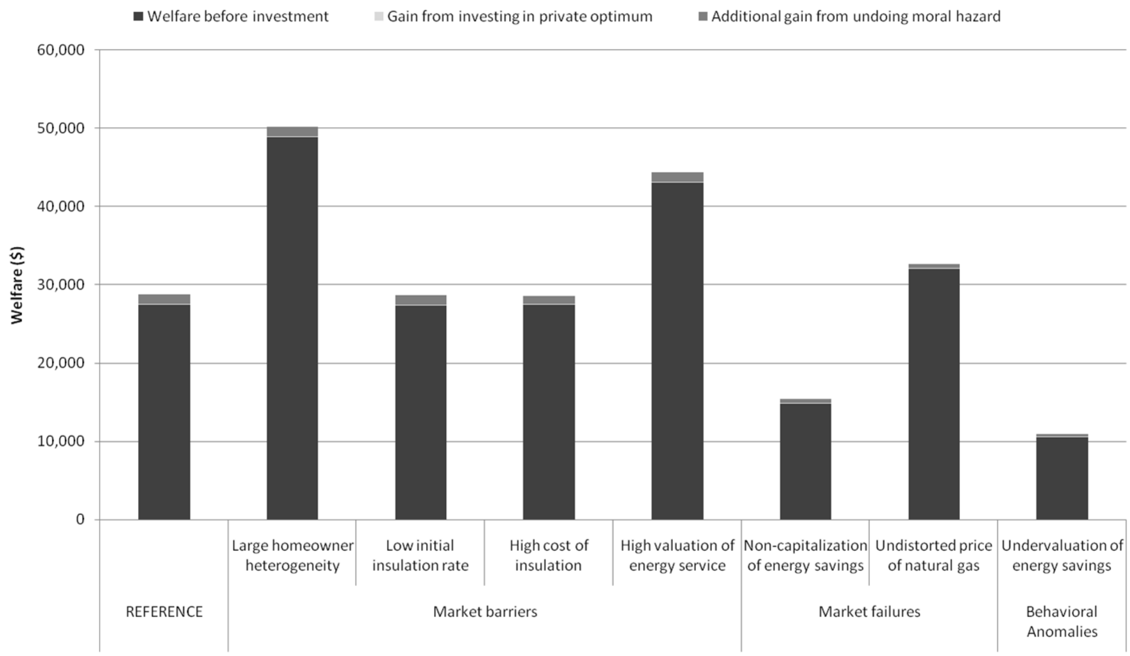

FIGURE 9. **Sensitivity analysis.** The welfare displayed on the vertical axis is the average lifetime discounted welfare gross of environmental damages. Scenario assumptions are detailed in Tables 7 and 8 .