



FAERE

French Association
of Environmental and Resource Economists

Working papers

Investment in Energy Efficiency, Adoption
of Renewable Energy and Household
Behaviour: Evidence from OECD countries

Prudence Dato

WP 2017.05

Suggested citation:

P. Dato (2017). Investment in Energy Efficiency, Adoption of Renewable Energy and Household Behaviour: Evidence from OECD countries. *FAERE Working Paper, 2017.05*.

ISSN number: 2274-5556

www.faere.fr

Investment in Energy Efficiency, Adoption of Renewable Energy and Household Behaviour: Evidence from OECD countries*

Prudence Dato[†]

March 2, 2017

Abstract

There are possible synergies between the decision to invest in energy efficiency measures and to adopt renewable energy, in the sense that the former reduces energy demand so that the latter can further cut future greenhouse gas (GHG) emissions, and which has great potential in the residential sector. Much work has been done in the residential sector on demand for clean energy and on investment in energy efficiency, but to our knowledge there is no specific study that investigates the interaction between the two. This paper fills a gap in the literature, and first shows theoretically that there are interactions between the two decisions depending on the threshold of the cross effect related to the environmental motivation of the consumer. Second, the paper empirically shows that the two decisions are positively interrelated and cannot be estimated independently. As a result, univariate methods that estimate the decision to adopt renewable energy and investment in energy efficiency separately may produce inefficient results, because there may be unobserved characteristics that determine both decisions. Third, the paper investigates household characteristics that significantly affect the interaction between the two decisions using a generalised ordered logit model. Specifically, the paper provides evidence of factors that affect the joint probability of adopting renewable energy and investing in energy efficiency, and the probability of doing nothing. This contribution can serve to define incentive policies to advance the energy transition.

Keywords: *Energy efficiency, renewable energy, bivariate probit, generalised ordered logit.*

*I am grateful to my PhD supervisor A. Pommeret for her invaluable comments and helpful discussions on earlier drafts. I also thank an anonymous referee from the French Association of Environmental and Resource Economists (FAERE), M. Sabatier, D. Charlier, E. Lavaine, M. Drut and the participants at the FAERE conference (Toulouse), the EAERE conference (Zurich), the AFSE conference (Nancy), the IEPPEC conference (Amsterdam) and the CESAER seminar (Dijon) for their comments and suggestions. I am grateful to the OECD and to W. Oueslati for providing the EPIC data.

[†]IREGE, Savoie Mont Blanc University; 4, Chemin de Bellevue, BP 80439, 74944, Annecy-le-vieux CEDEX (France); Tel.: +33(0)4-50-09-24-40; fax: +33(0)4-50-09-24-39. E-mail address: prudence.dato@univ-savoie.fr.

1 Introduction

Most of the world’s electricity (60%) is consumed in residential and commercial buildings (IEA, 2008a). Specifically, residential buildings contribute 23% to global final energy demand (IEA, 2007) and 17% to world CO₂ emissions (OECD/IEA, 2015). Moreover, cooking, lighting, water heating, appliances and space heating in the residential sector account for 5%, 5%, 16%, 21% and 53%, respectively (IEA, 2008b). Therefore, there is great potential to reduce overall energy demand in the residential sector. In order to reduce the amount of energy used to get the same service, a household can decide to invest in energy efficient technology that results in saving energy. In 2014 for example, improvements in energy efficiency were driven by space heating efficiency improvements (e.g., following home renovation), water heating, lighting and appliances in residential buildings (IEA/OECD, 2014). Energy conservation actions can also be curtailments (Jansson et al., 2009), which refer to behaviour changes such as scheduling, turning off lights, cutting down on heating or air conditioning and switching off standby mode. By reducing its consumption of energy, a household contributes to reductions in future greenhouse gas (GHG) emissions. In one policy scenario of the International Energy Agency (IEA), 72% of the global decrease in CO₂ emissions between 2010 and 2020 will come from energy efficiency improvements (Knittel et al., 2014).

There are some possible synergies between energy efficiency measures and renewable energy adoption in the sense that the former reduces energy demand so that the latter can further cut future GHG emissions. A household can also invest in renewable energy by installing solar panels or wind turbines, which represented a share of 19% of world final energy consumption in 2012 (RENS21, 2014). This investment produces clean energy and contributes to reducing CO₂ emissions. For example, the deployment of renewable energy could reduce annual CO₂ emissions by 8.6 Gt by 2030 (IRENA, 2014). Additionally, the IRENA (2014) report states that such emissions savings, combined with energy-efficiency gains, would be sufficient to set the world on a path to prevent catastrophic climate change. Furthermore, Dato (2016) shows that it favours full transition to the sole use of renewable energy. Though investments in both energy efficiency and renewable energy are costly, they yield future gains that make them profitable after several years of use.

Thus, clean energy adoption and investment in energy efficiency are both important for a transition to a green economy. There is considerable literature on either demand for clean energy (Gerpott and Mahmudova, 2010; Sardianou and Genoudi, 2013; Zhai and Williams, 2012) or investment in energy efficiency (Dietz et al., 2009; Heslop et al., 1981; Howarth, 1997; Urban and Ščasný, 2012) in the residential sector. To our knowledge, there is no specific study that investigates household behaviour with respect to joint adoption of renewable energy and investment in energy efficiency; and the relationship between the two. This paper fills a gap in the literature and makes three contributions. First, we use a simple theoretical model to investigate the possible interactions between the decisions to invest in energy efficiency and in renewable energy. In this model, we assume that a household devotes its energy budget to buy non-clean energy and to un-

undertake investments in energy efficiency and in renewable energy, which contribute to a transition to a low carbon economy. The household gets some private or direct utility for using energy services (non-clean and renewable energy). The amount of the non-clean energy and that of the renewable energy which are used depend on the level of investment in energy efficiency. The household may also gain some additional environment-related satisfaction due to the contribution of the investments in energy efficiency and in renewable energy in reducing CO₂ emissions. This may depend on the cross effect of the two decisions. We show that there is a cross effect threshold below (resp. above) which investment decisions in energy efficiency and in renewable energy of the household are substitutes (resp. complements). As a consequence, there are interactions between the two decisions. Moreover, we show that the effect of the energy budget on this cross effect threshold depends on its effect on the marginal opportunity cost of undertaking the two investments.

The theoretical model is followed by empirical investigations of the interaction between the two decisions. We explore whether the decision to adopt renewable energy and to invest in energy efficiency in the residential sector are related. We use a bivariate probit (biprobit) model for the joint decision. Additionally, we investigate the determinants of the interaction between the two decisions by using generalised ordered logit model. Basically, we intend to explain why some households decide to invest both in energy efficiency and in renewable energy, while others decide to only invest in renewable energy or to only invest in energy efficiency, or to do nothing. The household that only adopts renewable energy or only reduces its energy consumption, contributes to the energy transition better than the household who does nothing, and less than the one who undertakes the two investments. For the two empirical investigations, we use the survey on Environmental Policy and Individual Behaviour Change (EPIC) from the Organisation for Economic Co-operation and Development (OECD). This survey was carried out in 2008 and 2011 across a total of fifteen countries and several areas (energy, food, transport, waste and water) and provides evidence on what affects household decision-making. Precisely, it provides information about socio-economic and environmental factors, attitudes and policy at the household level that can influence actual household decisions to invest in energy efficiency and to adopt renewable energy.

Second, the results of the biprobit model show that there is a positive interrelation between the decision of the household to invest in energy efficiency and to adopt renewable energy due to unobserved characteristics such as environmental motivations. In fact, environmental conscientiousness as a true environmental motivation is not observed and may lead to such a positive correlation, in the sense that a more pro-environmental household is more likely to invest in energy efficiency and in renewable energy. Thus, the bivariate probit model is more appropriate than separate univariate probit models. Moreover, the paper provides evidence about factors that affect the probability of adopting renewable energy and that of investing in energy efficiency. Notably, people living in poorer households are less likely to invest in energy efficiency and may end up using a high share of their income to pay for electricity. This is referred to as energy poverty in the literature. There is evidence of split incentives regarding decisions to invest in

energy efficiency and to invest in renewable energy. The fact that a household owns a residence increases its probability of undertaking investments in energy efficiency and in renewable energy. Regarding dwelling characteristics, we find that the type of dwelling and its size have a significant effect on the decision to invest in energy efficiency and no effect on the decision to adopt renewable energy. Also, environmental motivations and commitment have mixed effects on both investment in energy efficiency and adoption of renewable energy. Trust in researchers, scientists and experts has a positive effect on the two decisions.

Third, in the generalised ordered logit model we find that people living in wealthier households are more likely to jointly invest in energy efficiency and in renewable energy if they have already undertaken any of these investments, and if not, they are more likely to undertake one of the investments as well. In the same vein, tenants are less likely to combine the two investments due to split incentives. Also, a household that has already undertaken one of the investments and is living in a detached dwelling is more likely to make additional efforts to invest in the second, while size of the residence has no significant effect. This limitation can be overcome by environmental motivations. In this sense, people who have already undertaken one of the investments and for whom environmental issues are generally more important than non-environmental issues, are more likely to have an additional motivation to address barriers that could prevent them from fully contributing to the energy transition. Also, participation in charitable, environmental and local organisations has a positive effect, as does trust in scientists and local authorities.

The remainder of the paper is structured as follows. In section 2, we provide an empirical literature review on both adoption of renewable energy and investment in energy efficiency. In section 3, we present the theoretical predictions. Section 4 is devoted to the empirical analysis. We conclude in section 5.

2 Literature review

There is considerable literature on either demand for clean energy or investment in energy efficiency in the residential sector. In section 2.1, we provide some important studies on demand for clean energy and household behaviour while section 2.2 provides some analysis on household behaviour and the decision to invest in energy efficiency. To our knowledge, there is no specific investigation of the simultaneous decisions of renewable energy adoption and investment in energy efficiency at the household level. As the two decisions to adopt renewable energy and to invest in energy efficiency are taken by the same household in the residential sector and both are important in a transition to a green economy, an analysis of a joint decisions needs particular attention.

2.1 Clean energy demand and household behaviour

There is noteworthy literature on the demand for green energy, due to the importance of energy in the CO₂ emissions that bring about climate change. Notably, in the residential sector, studies primarily focus on real behaviour or hypothetical behaviour to explain the decision of the household regarding renewable energy. However, the two approaches often give different results (Cameron et al., 2002; Kotchen and Moore, 2007; Poe et al., 2002). The hypothetical behaviour based on stated-preference methods can rely on the willingness to adopt renewable energy (Gerpott and Mahmudova, 2010; Ozaki, 2011; Zhai and Williams, 2012 and Sardianou and Genoudi, 2013), on the willingness to pay for renewable energy (Ek and Söderholm, 2008; Zorić and Hrovatin, 2012 and Liu et al., 2013.) or on both decisions (Krishnamurthy and Kriström, 2014; and Shi et al., 2013).

Gerpott and Mahmudova (2010) find that environmental attitudes and social environment have a strong influence on the consumer and their propensity to adopt green electricity. On the contrary, Ozaki (2011) uses correlation analysis and finds that pro-environmental consumers do not necessarily adopt green electricity. A lack of strong social norms and personal relevance affect the adoption of renewable energy, as well as the value of the renewable energy (benefits and costs). In addition to environmental concern, Zhai and Williams (2012) investigate the influence of social acceptance, and show in a specific case of photovoltaics (PV) adoption that social acceptance also affects the adoption of renewable energy. Financial incentives through taxes or subsidies are also important to promote adoption of clean energy. Sardianou and Genoudi (2013) find that in Greece, a tax deduction is the most effective financial policy measure to promote consumer acceptance of renewable energy in the residential sector.

Many studies consider the willingness to pay for renewable energy. Ek and Söderholm (2008) investigate norm-motivated and economic-motivated behaviour in the Swedish green electricity market. They find that variables such as cost of adoption, personal responsibility, perception of the benefit of adoption and social norms to be the most important determinants of households choosing to pay a price premium for green electricity. Zorić and Hrovatin (2012) suggest that awareness-raising campaigns should follow green marketing, which should target younger, well-educated and high-income households. In a specific case of developing countries, Liu et al. (2013) investigate rural social acceptance of renewable energy adoption and find that rural residents are generally favourable to renewable electricity development given its positive impact on the environment. Krishnamurthy and Kriström (2014) and Shi et al. (2013) focus on the willingness to accept and the willingness to pay to use only renewable energy and their disparities across OECD countries. The former uses the 2011 EPIC-OECD survey while the latter uses the 2007 EPIC-OECD survey. Krishnamurthy and Kriström (2014) find a low willingness to pay (WTP) that corresponds to 11-12% of the current electric bill and income having an ambiguous effect. In the same way, Shi et al. (2013) find that economic variables are less important, while environmental concern or attitude consistently drives the decision to enter the hypothetical market of green electricity. They also find that participation in environmental organisations has significant effects on the WTP to use only renewable

energy.

There are fewer studies in the literature investigating the actual behaviour of consumers regarding renewable energy adoption, relying on real surveys instead of hypothetical consumer behaviour. A survey that relies on the real behaviour of consumers can help investigate how consumers actually react according to different financing mechanisms for green electricity. Roe et al. (2001) find that hypothetical analysis based on the WTP and hedonic analysis of actual price premiums charged for green electricity give similar values for key environmental attributes. Some studies only focus on green consumers (Young et al., 2010) and can suffer from selection bias, because policy recommendations could not be extended to consumers who do not adopt green behaviours. There are also disparities in the effect of different financing mechanisms for green electricity. For example, Kotchen and Moore (2007) consider a voluntary contribution mechanism (VCM) and a green tariff mechanism (GTM) to finance new generation capacity. They find that the two financing mechanisms are not equivalent when the constraint related to the level of contribution is binding. Arkesteijn and Oerlemans (2005) investigate factors that influence the early adoption of green electricity by Dutch residential users combining cognitive and economic approaches. They find that in addition to economic variables; cognitive variables and those related to basic knowledge and to actual environmental behaviour in the past strongly predict the probability of early adoption of green electricity.

Variables that affect green demand in the residential sector may also affect a household's decision to invest in energy efficiency. In the following section we describe some literature on factors influencing energy efficiency investment decisions in the residential sector.

2.2 Energy efficiency and household behaviour

There is a substantial literature on household behaviour and its effect on adoption of and investment in energy efficiency. Energy efficiency is a relatively cheap way to reduce GHG emissions in the short and medium term (Dietz et al., 2009; and Vandenberg et al., 2007), while in the long term a complete transition to a low carbon economy is likely to be very slow (Fouquet, 2010). There is a large amount of evidence that economic factors motivate energy efficiency (Howarth, 1997; Kempton and Neiman, 1986 and Steg, 2008) and can be helpful in designing appropriate taxes or subsidy mechanisms to promote energy saving. For example, saving money or energy bill reductions can be incentives to invest in energy efficiency. However, the potential gain from reducing energy use can be hindered by some problems such as split incentives, uncertainty about the gain, and the moral hazard problem that may prevent households from adopting or investing in an energy conservation system. Reducing energy use can also lead to reverse effects such as the rebound effect or the take-back effect (Greening et al., 2000; and Urban and Ščasný, 2012). The rebound effect can be solved by capturing efficiency gains for reinvestment in natural capital rehabilitation (Wackernagel and Rees, 1997) or in supporting environmental actions through donations (Bindewald, 2013). The rebound effect can also be solved by pro-environmental motivation Urban and Ščasný, 2012.

However, in the literature on energy-saving behaviour, there is no evidence of the effect of pro-environmental motivation on energy-saving actions at household level. The early literature found that environmental concern does not have any effect on either energy consumption or energy-saving actions (Heslop et al., 1981). On the other hand, there has been a growing concern about climate change in recent years (Capstick et al., 2015) and many recent studies find that environmental concerns have a significant effect of on energy-saving actions (Barr et al., 2005; and Whitmarsh and O’Neill, 2010). A few studies still find that pro-environmental motivation has a limited effect (Carlsson-Kanyama et al., 2005; and Whillans and Dunn, 2015) or no effect (Steg, 2008). Also, both economic and environmental concerns have different effects when we distinguish the actions of investing in energy efficiency.

The two main types of energy conservation actions are efficiency investment and curtailments (Jansson et al., 2009). The former involves the acquisition of new technologies, low-energy appliances (top-rated energy-efficient appliances, low-energy light bulbs, energy-efficient windows, etc.) or energy efficient systems (automated control systems, domotics or home automation), that require monetary investment. The latter refers to non-monetary investments in behaviour change such as scheduling, turning off lights, cutting down on heating or air conditioning and switching off standby mode. For example monetary efficiency investments that rely on external conditions (Urban and Ščasný, 2012) such as economic concerns, are less affected by internal motivations (Guagnano et al., 1995) such as pro-environmental motivations. Black et al. (1985) find the opposite effect on non-monetary efficiency investments. In the end, both economic and environmental concerns may have significant effects on energy-saving actions which are the outcome of both monetary and non-monetary investments. In addition to socio-economic and demographic factors, Urban and Ščasný (2012) investigate how environmental concern affects the adoption of monetary and non-monetary investments in energy efficiency in a multi-country setting using EPIC-OECD data. They find a positive and significant effect for pro-environmental motivation and a mixed effect for the other variables.

The different variables that affect household decisions about renewable energy adoption may have significant effects on energy efficiency investments as well. The fact that studies mostly focus on either renewable energy adoption or energy efficiency investment may explain empirical disparities in the effect of economic and environmental concerns. Interestingly enough, if the two decisions are interrelated, they cannot be estimated independently. In this case, univariate methods that separately estimate the two decisions on renewable adoption and energy efficiency potentially produce inefficient results, because there may be unobserved characteristics that determine the two decisions. For example, a household that is pro-environmental can find it necessary to also invest in renewable energy (resp. in energy efficiency) if it has already invested in energy efficiency (resp. renewable energy). In this case, the household may rely on its environmental conscientiousness to combine the two investments. In the same way, a household that already invests in energy efficiency (resp. renewable energy) may have limited financial capacity to also invest in renewable energy (resp energy efficiency). Therefore, by jointly

analysing the two possible decisions taken by the household on the adoption of renewable energy and investment in energy efficiency, one can capture the interrelation and the interaction between them. Such analysis holds potential for policy formulation, as adoption of renewable energy and investments in energy efficiency are both important in the future world energy market (Sheffield, 1997) and in the energy transition. To our knowledge, there is no such investigation in the economics literature and our study aims to fill this gap.

3 Theoretical predictions

In the following section, we develop a simple model to explore the possible interactions between the two decisions about investing in energy efficiency and in renewable energy at household level.

3.1 The model

As in Ekholm et al. (2010), let us assume that the consumption of energy can be separated from other consumption to form its own consumption problem, i.e. that the utility from energy is separable from other sources of utility and that the consumer has a specific energy budget which we denote R . This energy budget can be seen as the income that a household devotes to energy problems. It can also include a financial support or a "green grant" such as subsidies, government tax credits or interest-free eco-loans from a bank, that targets energy efficiency and renewable energy adoption.¹ We assume that a household devotes this energy budget to buy energy and also to undertake investments in energy efficiency and in renewable energy, which contribute to a transition to a low carbon economy.

During the first period ($t = 0$) investments in energy efficiency ee and in renewable energy re are undertaken at a cost k_1 and k_2 respectively. The rest of the energy budget is devoted to buy an amount d of energy provided from non-clean sources of energy at each period of time. We normalise the discounted unit price of this energy to one so that k_1 and k_2 can be interpreted as relative costs. The energy budget constraint of the household can be written as:

$$R = D + k_1 ee + k_2 re, \tag{1}$$

where $D = \sum_{t=0}^p d_t = d_t + d_{-t}$ is the total amount of non-clean energy over the whole period of time and d_{-t} is the amount of non-clean energy for the whole period except period t .

¹ In order to promote greener purchasing decisions, several countries have implemented policies providing financial support to households. According to OECD (2014) report, the Canadian ecoEnergy Retrofit-Homes programme helps home-owners to invest in energy-efficient upgrades such as insulation, upgrades or replacement of heating and cooling systems. Financial incentives such as tax credits or interest-free eco-loans are available in France as well to promote energy efficiency investments in the residential sector and investment in renewable energy.

For simplicity and to conform to cross-sectional data, we do not consider temporal effects of investments in energy efficiency and in renewable energy. Instead, we assume that the levels of the two investments are chosen at the first period. Therefore, we refrain from time-indexing the variables in the rest of the model. The energy budget constraint (1) expresses the limited investment capacity of the household. In fact, investment in energy efficiency is negatively related to investment in renewable energy for a given energy budget. This limited investment capacity may not favour a joint investment in both renewable energy and energy efficiency.

The household gets some satisfaction $u(E)$ from using energy services for fundamental needs such as cooking, lighting, electric home appliances, etc. We denote by E , the total amount of energy services, which is the sum of the clean energy (re) and the non-clean energy (d). The utility function $u(\cdot)$ is assumed to be increasing and concave ($u' > 0$ and $u'' < 0$). For simplicity, we assume that the two sources of electricity are perfect substitutes. Following Charlier et al. (2011), we assume that a household invests in energy efficiency in order to lower the cost of the energy in the future. Investing in energy efficiency helps the household to save energy during the following periods and therefore to enjoy energy services at a lower cost. In this sense, the level of the clean energy service and that of the non-clean energy service depends on the level of investment in energy efficiency (ee). Furthermore, the level of investment in renewable energy (re) and the amount of non-clean energy (d) that is required for a given energy service, depend negatively on the level of investment in energy efficiency: $\partial re / \partial ee < 0$ and $\partial d / \partial ee < 0$. The more the household invests in energy efficiency, the less it requires renewable energy and non-clean energy to get the same energy services. Even though a large number of papers (Greening et al., 2000 and Urban and Ščasný, 2012 for example) show that the potential gain from investing in energy efficiency can be hindered by energy rebound effect or the take-back effect, some studies find a solution to avoid this reverse effect (Wackernagel and Rees, 1997, Bindewald, 2013 and Urban and Ščasný, 2012). Consequently, we assume that these solutions are implemented so that the household cannot have such adverse behaviour.

In addition to personal or direct gain, investments in energy efficiency and in renewable energy help protect the environment by reducing global CO2 emissions. Hence, a household achieves additional environment-related satisfaction by investing in energy efficiency and renewable energy. Doni and Ricchiuti (2013) consider the sensitivity of consumers toward environmental improvements to be dependent on their degree of environmental awareness. Zhang et al. (2015) and Liu et al. (2012) explicitly model this sensitivity as consumer environmental awareness. This formulation is also close to that of a study by Ekholm et al. (2010) which consider that the consumer also gets some disutility from consuming an inconvenient fuel. As investments in energy efficiency and in renewable energy positively contribute to reductions in global CO2 emissions, the consumer gets some additional satisfaction by undertaking the two investments, depending on their pro-environmental motivation.

In the same vein, we assume that the household gets additional environment-related

satisfaction $v(re, ee)$, which captures the positive joint effect of the two decisions in reducing CO2 emissions. Therefore, it exhibits the following characteristics:

$$\frac{\partial v}{\partial re} > 0, \frac{\partial v}{\partial ee} > 0, \frac{\partial^2 v}{\partial ee \partial re} = \frac{\partial^2 v}{\partial re \partial ee} > 0 \quad \text{and} \quad \frac{\partial^2 v}{\partial re \partial re} = \frac{\partial^2 v}{\partial ee \partial ee} = 0.$$

The joint effect is defined as the cross derivative of the utility $v(re, ee)$. The marginal utility of investing in renewable energy (resp. energy efficiency) rises with investment in energy efficiency (resp. renewable energy). Therefore, this additional utility is high for the environmentally-friendly household that takes both decisions.

Investments in energy efficiency and in renewable energy last for a finite horizon of time². Thus, the consumer cannot benefit infinitely from the two investments. We assume that the future gains from investment in energy efficiency and renewable energy are limited to p periods. The gross instantaneous utility of the household can be defined as:

$$U(ee, re, d) = u[re(ee) + d(ee)] + v(re, ee). \quad (2)$$

3.2 Optimal allocation

The household maximises the discounted sum of instantaneous utilities defined in eq.2 subject to the energy budget constraint eq.1 with respect to consumption of non-clean energy (d), investment in energy efficiency ee and investment in renewable energy re as follows:

$$\max_{d, ee, re} \sum_{t=0}^p \beta^t U(ee, re, d), \quad (3)$$

$$st \quad R = d + k_1 ee + k_2 re$$

where β is the discount factor. By replacing d from eq.1 into the objective function of the programme (9), the first order conditions with respect to ee and re give respectively:

$$re'u' + \frac{\partial v}{\partial ee} + \frac{\partial v}{\partial re} re' = k_2 re'u' + k_1 u' \quad (4)$$

and

$$\frac{\partial v}{\partial re} + u' = k_2 u' \quad (5)$$

Equations (4) and (5) are arbitrage conditions. Equation (4) states that the marginal gain of investing in energy efficiency should be equal to its opportunity cost, which is the marginal forgone utility. The marginal gain of investing in energy efficiency has two components: a direct marginal utility due to the amount of renewable energy that is saved ($re'u'$) and a marginal environment-related satisfaction which comes from both energy efficiency and the efficiency gain on the renewable energy ($\frac{\partial v}{\partial ee} + \frac{\partial v}{\partial re} re'$). The opportunity cost also has two components: the direct marginal forgone utility ($k_1 u'$) and the marginal forgone utility for not investing in renewable energy ($k_2 re'u'$). Similarly, equation (5) states that the marginal gain of investing in renewable energy ($\frac{\partial v}{\partial re} + u'$)

²Major renovations or refurbishment of residential buildings occur at 30-40 year intervals (Laustsen, 2008), while photovoltaic modules are usually guaranteed for a lifetime of 25 years (OECD/IEA, 2014).

should be compensated with the corresponding opportunity cost (k_2u').

Putting equation (5) into equation (4), gives the following equation that defines the household optimal allocation of investments in energy efficiency and in renewable energy:

$$k_1u' - \frac{\partial v}{\partial ee} = 0. \quad (6)$$

Equation (6) states that at the optimum, the direct marginal environment-related satisfaction of investing in energy efficiency is equal to its direct opportunity cost, after the indirect effects on renewable energy cancel each other. In order to determine if the two decisions are substitutes or complements, we focus on the effect of investment in energy efficiency on investment in renewable energy³. Primarily, we analyse the sign of the total derivative of investment in renewable energy with respect to investment in energy efficiency ($\frac{dre}{dee}$). A positive sign means that an increase in the investment in energy efficiency will increase investment in renewable energy so that the two decisions are substitutes.

Proposition 1: *There is a threshold on the joint effect below (resp. above) which investment decisions in energy efficiency and in renewable energy of the household are substitutes (resp. complements).*

The proof of proposition 1 is provided in appendix A. The threshold level of the joint effect is given by:

$$\overline{v_{eere}} = k_1(1 - k_2)u''.$$

After investment in energy efficiency has been undertaken, the household will additionally invest in renewable energy if the marginal opportunity cost (i.e. $k_1(1 - k_2)u''$) is lower than the corresponding marginal gain (i.e. the cross effect $\frac{\partial^2 v}{\partial ee \partial re}$). This can be explained by the fact that a less environmentally-friendly household is looking more for energy saving in order to reduce its energy bill than to contributing to a reduction in global emissions of CO₂, while a more environmentally-friendly household is getting additional satisfaction from protecting the environment. This result is consistent with the reasoning in Sun and Yang (2006): the household behaves as though it has two decisions ee and re which are divided into two different sets S_1 and S_2 depending on their function. S_1 refers to energy saving or economic motives while S_2 refers to environmental protection motives. Decisions in the same set are substitutes and decisions across the two sets are complements. In the same vein, the decisions of a household with a low pro-environmental index are mostly for economic motives (S_1) and are then substitutes. Whereas the decisions of a more environmentally-friendly household are complements,

³The definition of complementarity and substitutability in this paper is based on the direct effect because we aim to analyse the interactions between the two decisions of a household facing an energy budget constraint and costly investments in energy efficiency and in renewable energy. There are other complementary vs substitutability concepts such, price cross-elasticity, Fisher perfect complementarity, Edgeworth-Pareto complementarity (Samuelson, 1974).

because they are guided by both economic and high environmental motivations (S_1 and S_2).

Let us now focus on the effect of the energy budget on this threshold level of the joint effect $\overline{v_{eere}}$.

Proposition 2: *A household with a larger energy budget has a higher (resp. lower) threshold for the joint effect $\overline{v_{eere}}$, if the energy budget increases (resp. decreases) the marginal opportunity of the joint investments in energy efficiency and in renewable energy.*

We provide the proof for proposition 2 in appendix B. The implication of proposition 2 is as follows. If the energy budget has a positive effect on the marginal opportunity cost of investing in both energy efficiency and renewable energy, an increase in the energy budget will increase the possibilities for substitution between the two decisions. This is because the joint investments become more costly when the energy budget increases.

We will empirically test the above propositions in section 4 using a survey data from OECD countries. We primarily focus on the relationship between the household decision to invest in energy efficiency and in renewable energy. As the data does not provide information on the level of investment, we rather consider the adoption decision of the household regarding renewable energy and energy efficiency. Moreover, as the survey is based on self-reporting, we are not able to observe the cross-effect corresponding to true environment-related satisfaction. Thus, we assume that the cross-effect is part of the unobserved characteristics of the household. Moreover, information about the energy budget of the household were not provided. Therefore, proposition 2 cannot be directly tested. Alternatively, we consider the income as a proxy and examine its effect on the two decisions. Finally, we control for other characteristics of the household that can affect its decisions, which are not considered in the theoretical model. Those control variables are characteristics of the residence, environmental attitudes, perceptions, etc.

4 Empirical analysis

In this section, we first present the data and methods used. Second, we present the bivariate probit model (biprobit) to analyse the joint decision of renewable energy adoption and investment in energy efficiency. Third, we focus on the interaction between renewable energy adoption and investment in energy efficiency using the generalised ordered logit model.

4.1 Data and Methods

4.1.1 Data

We use the first two rounds of the large-scale household survey on Environmental Policy and Individual Behaviour Change (EPIC) conducted by the Organisation for Economic

Cooperation and Development (OECD). The two rounds focus on five thematic areas (energy, food, transport, waste and water) and aim at understanding household reactions to different environmental policies, the interactions of these policies and the role of household attitudes towards the environment (Serret and Brown, 2014). Information was collected on household characteristics (age, income, education), environmental attitudes (environmental concerns), and perceptions, etc., using an internet-based questionnaire.

The first round of the EPIC survey was carried out in January-February 2008 in ten OECD countries (Australia, Canada, France, Korea, Netherlands, Sweden, Czech Republic, Italy, Norway and Mexico.). The sample size was approximately 1,000 households in each country for a total of 10,251 households. In 2011, the same survey was carried out in the first six countries from 2008 and in five additional countries (Chile, Japan, Spain, Israel and Switzerland.). As in the first round, approximately 1,000 households were interviewed in each country for a total of 12,202 households. The sample size for the two rounds is 22,453 households. The dataset of the 2011 EPIC survey is richer than that of 2008 because it includes additional areas such as eco-innovation, knowledge, policy preferences and country-specific questions. Unfortunately, we could not use this additional information because we intend to use the two datasets to account for time variation. Therefore, we need to use the same type of information (variables) for household behaviour across the two survey rounds. As the same respondents cannot be identified in the EPIC survey from 2008 to 2011, we decide to pool the two datasets for the fifteen countries and to control for the effect of year. Note that efforts were made to avoid sample bias through stratification (age, gender, etc.) and quota sampling with large geographical coverage ⁴. Also, the two rounds are independent surveys and each represents a random sample from the population. Then, there is no correlation in the error terms within the observations of each survey.

We use data from the energy section (Part E) of the EPIC survey which we combine with socio-demographic characteristics (Part A), and attitudinal characteristics (Part B). Specifically, in the energy section we mainly focus on questions that concern the adoption of renewable energy (solar panels, wind turbines, hydro, etc.) and monetary investments in energy efficiency (Energy-efficiency-rated appliances, low-energy light bulbs, etc.). For a robustness check, we additionally consider non-monetary investments (switch off lights when leaving a room, cut down on heating or air conditioning, switch off appliances when not in use, switch off standby mode of appliances or electronic devices, etc.) that help reduce the consumption of energy as well. Both independent and dependent variables used in this paper are described in the following section (section 4.1.2).

4.1.2 Description of variables

Following the theoretical model, the dependent variables are related to investments in renewable energy and energy efficiency. As the data does not provide information on the level of investments, we consider the decisions of the household to adopt renewable

⁴For more details, see OECD (2011, 2014).

energy or to invest in energy efficiency. These two dependent variables are then constructed from questions related to renewable energy adoption and investments in energy efficiency. In the two survey rounds, a question was asked to identify households that installed renewable energy equipment in their current primary residence (solar panels for electricity or hot water and wind turbines) over the past ten years. Households could answer that they installed renewable energy items or that the residence was already equipped. As we are focusing on the decision to adopt renewable energy, we do not consider households whose residence was already equipped. We cross the information on the installation of renewable energy items with the source of electricity that the residence uses.

We also consider households stating that energy from the electricity provider is already from renewable energy sources (EPIC 2008) or that they have chosen the "renewable or green" energy tariff from their electricity provider (EPIC 2011), adopted renewable energy. Additionally, the 2011 survey provides a refinement giving some information on households using thermal solar panels for water heating, who are also considered as having adopted renewable energy. Although the investment decision in renewable energy and the decision to sign a contract with the electricity provider for a "renewable or green energy tariff" are fundamentally different, the two decisions can be interpreted as the decision to adopt renewable energy. To account for the fact that the two decisions are different, that is, the former decision requires financial investment and is irreversible while the latter decision is an electricity grid agreement which does not necessitate large investments and is reversible, we perform a robustness test that considers only investment decision in renewable energy (see Table 10).

The EPIC surveys provide information on monetary investment in energy efficiency such as: top-rated energy-efficient appliances, low-energy light bulbs, energy-efficient windows, thermal insulation of walls or roof, etc.). Households were asked whether or not they installed energy efficiency items over the past ten years in their current primary residence. As before, we only consider self-installed items as adoption of energy efficiency items to reduce the use of energy and not items that had already been installed. The EPIC surveys also provide information on behaviour changes to reduce the use of energy, that we call non-monetary investments in energy efficiency. Households were asked how often they adopt behaviours that could help reduce their energy use in their daily life, such as: cutting down on heating or air conditioning, switching off standby mode of appliances or electronic devices (TV, computer), air dry laundry rather than using a clothes dryer, etc. For a robustness check, we later include non-monetary investments in energy efficiency which we combine with monetary investments in energy efficiency. Whether the household invests in energy efficiency by using a part of its income or makes efforts to reduce its consumption of energy towards behaviour change, in the end the household reduces its consumption of energy.

Though the theoretical model does not include many household characteristics, we decide to control for them as they can also influence the decisions of households. However, there is no evidence in the literature about the importance of either socio-economic

and residential variables or attitudinal and perception variables in the decision of a household to adopt renewable energy or to invest in energy efficiency. Therefore, we include some variables that are available in the two EPIC datasets and can also be useful for policy recommendations in our independent variables. We consider three categories of characteristics. First, we use socio-economic and residential variables such as gender, age, household income, characteristics of the residence, etc. The size of the residence and the type of residence (detached or multi-occupancy) are used as proxies for the characteristics of the residence. Second, we consider perception, voting in elections, trust in and commitment to any local, charitable or environmental organisation as attitudinal variables. Third, some variables are also related to energy use: individual metering, peak price of electricity, factors that encourage reduction of energy consumption, etc. Note that we do not consider the energy consumption because it would necessitate that we control for different climate conditions (see for example Zhao and Magoulès, 2012). Collecting the weather data at the city level for all the countries that were included in the OECD-EPIC survey would be very challenging. Finally, we control for the year. The full description of the independent variables that are used and the summary statistics are presented in appendix C (table 14).

4.1.3 Methods

The household faces two different decisions that contribute to energy transition. It can decide whether or not to invest in renewable energy. It can also decide whether or not to invest in energy efficiency. The household has two decisions that could be related, as shown in the proposition 1 of the theoretical model. As the survey was based on self-reporting, we are not able to observe the cross-effect corresponding to true environment-related satisfaction. The cross-effect is therefore assumed to be a part of the unobserved characteristics of the household. Although the two decisions do not directly depend on each other, their error terms may be correlated through unobserved characteristics. Following Cameron and Trivedi (2010), we first use a bivariate probit model that accounts for the joint decisions based on their correlation and provides more efficient estimators. Note that the probit model assumes that unobservable variables and residuals are normally distributed and independent of the explanatory variables. The general specification of the model is:

$$re^* = X' \beta_1 + \epsilon_1 \quad (7)$$

and

$$ee^* = X' \beta_2 + \epsilon_2, \quad (8)$$

where re^* and ee^* are latent variables (resp. investment in renewable energy and investment in energy efficiency), which determine the observed binary outcomes re (decision to adopt a renewable energy) and ee (decision to invest in an energy efficiency) such that $j = 1$ if $j^* > 0$ and $j = 0$ otherwise, with $j \in \{ee, re\}$. X denotes the vector of regressors (economic and residential variables, variables of perception, commitment and trust, energy use, etc.) that determine both re^* and ee^* . Moreover, the error terms ϵ_1 and ϵ_2 are assumed to be jointly normally distributed with means 0 and variances of 1.

In order to account for unobservable factors that may jointly motivate the two decisions, we allow for some correlation (ρ) between ϵ_1 and ϵ_2 . If there is a non-zero correlation between the two error terms then the bivariate Probit model will provide estimates with lower standard errors.

Additionally, we use the ordered probit/logit model to account for the interaction between the two decisions. Specifically, we focus on factors that affect the joint probability of adopting renewable energy and investing in energy efficiency and that of doing nothing. In fact, we intend to explain why some households decide to invest both in energy efficiency and in renewable energy, while others decide to only invest in renewable energy or to only invest in energy efficiency or to do nothing. Therefore, the household that only adopts renewable energy or only reduces its energy consumption (i.e $re = 1$ and $ee = 0$ or $re = 0$ and $ee = 1$) contributes more to the energy transition than the household who does nothing (i.e $re = 0$ and $ee = 0$) and less than the one who undertakes the two investments (i.e $re = 1$ and $ee = 1$) . In this case, the ordered probit/logit model is appropriate because the outcomes can be ranked and its general specification can be written as:

$$eere^* = X'\beta + \epsilon,$$

where there are thresholds values α_c such that $eere = c$ if $\alpha_{c-1} < eere^* < \alpha_c$, for $c = 1, 2, 3$. Moreover, $eere = 1$, $eere = 2$ and $eere = 3$ correspond respectively to no investments (i.e $re = 0$ and $ee = 0$), investment in either renewable energy or energy efficiency (i.e $re = 1$ and $ee = 0$ or $re = 0$ and $ee = 1$) and investments in both re and ee (i.e $re = 1$ and $ee = 1$). X denotes the vector of regressors that includes X_1 , X_2 and Z_1 and ϵ is standard normally (resp. logistically) distributed for ordered probit (resp. logit).

4.2 Joint decision of renewable energy adoption and investment in energy efficiency.

Table 1 below displays the cross repartition of the two decisions of renewable adoption and investment in energy efficiency.

Table 1: **Investment in energy efficiency by adoption of renewable energy**

| Investment in energy efficiency (EE) | Adoption of renewable energy (RE) | | Total |
|---|--|--------------|---------------|
| | no | yes | |
| no | 1,967 | 551 | 2,518 |
| yes | 10,423 | 5,878 | 16,301 |
| Total | 12,390 | 6,429 | 18,819 |

According to table 1, the majority of households in the sample (87%), invest in energy efficiency. Then, a large majority of households undertake monetary investments in energy efficiency. On the contrary, only 34% adopt renewable energy by installing their

own solar panels or wind turbines, or by subscribing to green energy from the electricity provider. Cross analysis shows that among those who invest in energy efficiency, only 36.06% of households additionally adopt renewable. Another 10.45% of households decide neither to adopt renewable energy, nor to invest in energy efficiency. Finally, very few households in the sample (3%) adopt renewable energy without investing in energy efficiency. So, there are good reasons to believe that the two decisions may be correlated. To verify this, we provide the correlation between the decision to adopt renewable energy and that of investing in energy efficiency.

Table 2: Cross-correlation table

| Variables | Adoption of renewable energy | Investment in energy efficiency |
|------------------|------------------------------|---------------------------------|
| Adoption of RE | 1.000 | |
| Investment in EE | 0.1018 (0.0000) | 1.000 |

()=significance level.

The correlation coefficient of 0.1018 is positive and different from zero (table 2). Following Cameron and Trivedi (2010), we use a bivariate probit model that accounts for the joint decisions based on their correlation and provides a more efficient estimator. First, we check whether the bivariate probit model is necessary. The result from the bivariate probit provides the test of the null hypothesis that the true correlation coefficient is equal to 0 and justifies the importance of using the bivariate probit model instead of estimating the two decisions separately. Our results reject the null hypothesis of the correlation coefficient at 1% ($\text{Prob} > \chi^2 = 0.0000$). Therefore, the bivariate probit model is more appropriate than separate univariate probit models because the two decisions are inter-related and cannot be estimated independently. As a result, univariate methods that separately estimate the two decisions about renewable adoption and energy efficiency potentially produce inefficient results, because there may be unobserved characteristics that jointly determine the two decisions. Second, we provide the results of the separate estimation for the probit models as a benchmark together with the results of the bivariate probit model in table 4. The two estimations do not give the same results as expected.

Third, we perform goodness of fit and prediction tests in order to evaluate how well the model fits the observations. We then compare the predicted probability with sample frequencies, and provide a summary in table 3. We find that the predicted probability is close to the frequency of the sample. Additionally, we compare predicted outcomes with actual outcomes and find that the percentage of correctly specified values, also referred to as the rate of prediction, is high (53.22 %).

We can now turn to the interpretation of the results of the bivariate probit model which focuses on the residential characteristics, the economic and environmental motivations, split incentive issues and perceptions, that can help in understanding the energy transition decisions of households.

The results show that there is a positive interrelation between the decision of the household to invest in energy efficiency and to adopt renewable energy, due to unobserved

Table 3: Comparison of predicted probabilities with sample frequencies

| Variable | Mean of Prob | Frequency |
|---------------|--------------|-----------|
| RE=1 | 0.40 | 0.34 |
| EE=1 | 0.89 | 0.87 |
| RE=0 and EE=0 | 0.08 | 0.11 |
| RE=0 and EE=1 | 0.51 | 0.56 |
| RE=1 and EE=0 | 0.03 | 0.02 |
| RE=1 and EE=1 | 0.38 | 0.31 |

characteristics such as environmental motivations. In fact, motivations are derived from self-reporting in which they were asked to rank the importance of many types of problems, including environmental issues. As a consequence, the true environmental motivation and the corresponding cross effect are not observed, and may lead to such a positive correlation. In this sense, a more pro-environmental household is more likely to invest in energy efficiency and in renewable energy.

Energy poverty

Household income has a positive and significant effect on the decision to invest in energy efficiency, while there is no significant effect on the decision to adopt renewable energy. People living in wealthier households are more likely to invest in energy efficiency, as found in Urban and Ščasný (2012). As investments in energy efficiency such as home renovation and energy saving technologies are costly, a high income household has a greater financial capacity to afford them and to benefit from reduction in their energy bill. So, people living in poorer households may end up using a large share of their income to pay for electricity, which is referred to as energy poverty (Bird and Hernández, 2012). Unexpectedly, income has no significant effect on the adoption of renewable energy in some countries as found in Shi et al. (2013), which is not consistent with the results in Zorić and Hrovatin (2012). This can be explained by the existence of various financial supports in some countries to promote renewable energy. On the other hand, financial supports for energy efficiency mainly target home renovation and are less directed at energy-efficient appliances or low-energy light bulbs for example. Additionally, households benefit from policy mechanisms such as feed-in tariffs, which allow them to sell their renewable energy at a guaranteed price, determined as closely as possible to the specific generation costs (Couture and Gagnon, 2010). This may give them an additional incentive to invest in renewable energy. Also, it is possible to buy green electricity directly from the electricity provider which may be profitable in the short term, and which could help households avoid costly investment to produce their own renewable energy. An interesting implication of the income effect is that investment in energy efficiency merits specific financial supports.

Split incentives

Ownership positively affects the adoption of renewable and investment in energy efficiency. The fact that a household owns a residence increases its probability of undertaking investments in energy efficiency and in renewable energy. This is logical in the sense that investment in renewable energy generation such as solar panels or wind turbines and in home renovation is mostly profitable after many years of use (30-40 years for home renovations and 25 years for photovoltaic modules). Such investments are therefore risky in the case of limited tenure. Although it is possible to move solar or wind installations, dismantling and re-installation are costly and may be very problematic. Therefore, without security of tenure a tenant will have less incentive to invest in renewable energy. This is commonly referred to as the 'split incentive' in the literature (Bird and Hernández, 2012), and is a barrier to energy efficiency. Our results are novel as they also show the presence of this barrier to renewable energy adoption.

Effects of dwelling characteristics

We find that the type of dwelling and its size have a significant effect on the decision to invest in energy efficiency and no effect on the decision to adopt renewable energy. A household living in a non-detached dwelling is less likely to invest to reduce its energy consumption. As shown in Santin et al. (2009), non-detached dwellings use less energy than detached dwellings. In this sense, households that live in non-detached dwellings and thus consume less electricity, have less incentive to reduce their energy consumption. Similarly, Sardianou (2008) find that dwelling size positively affects energy use. As suggested by our results, a household with a larger dwelling, thus consuming more electricity, has a greater incentive to reduce its electricity consumption, and is more likely to invest in energy efficiency. These results show that a household that consumes more electricity due to the characteristics of the residence, has greater incentive to invest in energy efficiency.

Environmental motivation

It is important to better understand how sensitive people are to energy-related issues and to understand their motivations in order to set appropriate incentives. It also aids in designing appropriate communication materials aimed at sensitising them to the energy transition. Specifically, knowing the opinions of householders can help target the specific environmental issues that would advance both the adoption of renewable energy and the reduction of energy use. The EPIC survey distinguishes between environmental problems as a general issue and specific environmental problems such as climate change, resource depletion, pollution, etc. The former is compared to other general issues such as unemployment, economic crisis, etc. Admittedly, this proxy for environmental motivation may not correspond to one's actual environmental conscientiousness, which is private information. Our results show that environmental motivations have a mixed effect on both investment in energy efficiency and adoption of renewable energy. That is to say, people who think that environmental issues are generally more important than

other issues (unemployment, economic crisis, etc.) are more likely to invest in renewable energy. This is consistent with results in Gerpott and Mahmudova (2010) and Zorić and Hrovatin (2012). Investments in renewable energy are mostly undertaken to reduce CO₂ emissions and probably less to save money. People for whom environmental issues are the priority and who are likely aware that renewable energy is a clean alternative and helps protect the environment, will have more motivation to overcome barriers to adopting renewable energy.

In addition to reducing CO₂ emissions, investments in energy efficiency are also undertaken to save money. In fact, renewable energy adoption is mainly guided by environmental motives. For example, the cost of electricity generated from a residential PV system after subsidies is still higher than that generated from the power grid and those who adopt residential PV consider the environmental benefits to be the most important factor in their decision-making (Zhai and Williams, 2012). So, people who want to save money on their energy bill can be motivated to invest in energy efficiency, as can people who are pro-environmental. Therefore, environmental motivation does not have a significant effect on their decision to invest in energy efficiency. However, when it comes to comparing specific environmental issues, people who think the problem of climate change is the priority are more likely to invest in energy efficiency, while those who see the problem of resource depletion as the priority are less motivated to invest in energy efficiency. They may prefer alternative sources of energy which do not rely on depletable energy resources. These results confirm the importance of environmental concerns in a household's decision to adopt renewable energy, while climate change concerns lead investments in energy efficiency.

Commitment and trust

Another important issue is identifying the ways policies may affect how people behave. Commitment is important in the sense that it may help to identify households to target through organisations, events, etc. As in the case of general environmental issues, we find that commitment to environmental organizations (donation or physical participation) has no significant effect on the decision of households to invest in energy efficiency, while it has a positive effect on their decision to adopt renewable energy. Additionally, commitment to local and charitable organisations positively affects the two decisions. In fact, energy issues can be related to public goods and also treated as a local problem. Mostly, people participate in environmental organisations in order to protect the environment, which itself is a public good. As renewable energy is not polluting and then not negatively affecting the environment, it may offer more incentive to consume cleaner electricity. But this is not the case for investment in energy efficiency, which is guided by both the reduction of CO₂ emissions and saving money.

Moreover, an altruist who participates in a charitable organisation is more likely to be favourable to any types of investment such as in renewable energy or in energy efficiency that could help to reduce CO₂ emissions and which is beneficial for future generations. Some environmental problems related to energy use (such as air pollution) are also local

issues and so may be of great interest to local organisations. Trust in sources of information about the environmental impacts of products is another way to influence behaviour. We find that trust in researchers, scientists and experts has a positive effect on both decisions (renewable energy and energy efficiency), while trust in local or national authorities has a positive effect only on the adoption of renewable energy. As there is a large consensus among scientists regarding the negative consequences of using polluting energy sources as well as the importance of saving energy and adopting cleaner energy, people who trust scientists are more likely to invest in the two. These results mainly suggest that when households are committed to local and charitable organisations and when they also believe researchers, scientists and experts, they are favourable to the two decisions. Whereas commitment to environmental organisations only affect the decision to adopt renewable energy.

Energy-related issues

Additionally, we focus on some specific energy-related considerations. We find that people who take into account the cost of electricity before renting or buying a house are more likely to invest in energy efficiency, while there is no significant effect on the adoption of renewable energy. The intuition is that people who do not care much the cost of electricity before renting or buying a house may be less motivated to reduce their energy bill, and are therefore less likely to invest in energy efficiency. The fact that a household has access to differentiated peak and off-peak electricity rates does not significantly affect their decision to invest in energy efficiency. This can be explained by the fact that the dynamic pricing has some disadvantages, although it may help to reduce the energy bill. For example, scheduling energy use requires time and effort, and one cannot use electricity at the most convenient time. Surprisingly, paying according to the amount of electricity (for example through individual electricity metering) does not significantly affect a household's decision to invest in energy efficiency. Though investment in energy efficiency maybe more profitable if there is individual electricity metering which prevents free-riders, people may have motivations other than reducing their own energy bill.

Robustness check

In order to test whether the result of the financial capacity of the household influences its decision to invest in energy efficiency is robust, we extend energy efficiency to non-monetary investments, also called curtailments. In this sense, we now focus on energy conservation actions that can be both monetary and non-monetary investments. Almost 9% of our sample adopts curtailment behaviours and do not adopt monetary investments in energy efficiency. The results are presented in table 9 (see appendix C). We find that including non-monetary investments mostly affects results related to energy conservation. For the most part, size of residence, income, commitment to charitable and local organisations, and taking into account energy costs before buying or renting a house become non significant. In fact, most of these variables are related to the monetary

Table 4: Estimation of Probit and Bivariate probit Models

| Variables | Probit | | Biprobit | |
|---|------------------------|-------------------------|------------------------|-------------------------|
| | EE | RE | EE | RE |
| <i>Residential and economic variables</i> | | | | |
| Living in a non-detached residence | -0.0726** (0.0364) | -0.0458 (0.0284) | -0.0736** (0.0364) | -0.0550* (0.0310) |
| Size of the residence | 0.0645*** (0.0232) | -0.0161 (0.0187) | 0.0650*** (0.0233) | -0.00447 (0.0202) |
| Household income | 0.0267*** (0.00629) | 0.00406 (0.00487) | 0.0271*** (0.00630) | 0.00289 (0.00529) |
| Owner | 0.152*** (0.0383) | 0.0824*** (0.0300) | 0.151*** (0.0383) | 0.100*** (0.0335) |
| <i>Perception, commitment and trust</i> | | | | |
| Environmental concerns (general issues) | -0.00711 (0.0105) | -0.0261*** (0.00815) | -0.00746 (0.0105) | -0.0235*** (0.00896) |
| Climate change | -0.0662** (0.0268) | 0.0824*** (0.0232) | -0.0652** (0.0267) | 0.0709*** (0.0247) |
| Resource depletion | 0.0745** (0.0292) | -0.0353 (0.0259) | 0.0753*** (0.0292) | -0.0339 (0.0277) |
| Voting in local elections | 0.0776** (0.0369) | 0.0375 (0.0298) | 0.0789** (0.0369) | 0.0264 (0.0328) |
| Commitment to charitable organisations | 0.151*** (0.0413) | 0.133*** (0.0294) | 0.147*** (0.0412) | 0.133*** (0.0322) |
| Commitment to environmental organisations | 0.0575 (0.0486) | 0.151*** (0.0364) | 0.0584 (0.0486) | 0.168*** (0.0394) |
| Commitment to local organisations | 0.116** (0.0476) | 0.0862** (0.0347) | 0.116** (0.0475) | 0.0996*** (0.0373) |
| Trust in scientists | 0.0541*** (0.0146) | 0.0720*** (0.0138) | 0.0541*** (0.0147) | 0.0696*** (0.0148) |
| Trust in local authorities | 0.00182 (0.0136) | 0.0205* (0.0119) | 0.00167 (0.0136) | 0.0316** (0.0126) |
| <i>Energy use</i> | | | | |
| Energy costs before buying or renting a house | 0.105*** (0.0367) | 0.0226 (0.0283) | 0.104*** (0.0367) | 0.0348 (0.0311) |
| Individual metering | 0.0831 (0.0860) | 0.0724 (0.0711) | 0.0771 (0.0862) | 0.0994 (0.0787) |
| Peak Tariff | 0.0219 (0.0331) | -0.402*** (0.0262) | 0.0202 (0.0330) | -0.375*** (0.0286) |
| Label to reduce energy use | 0.183*** (0.0562) | 0.169*** (0.0539) | 0.184*** (0.0561) | 0.183*** (0.0582) |
| rho | | | 0.1660*** (0.0236) | |
| Log pseudolikelihood | -3680.8267 | -6524.2036 | -9077.8972 | |
| Pseudo R2 | 0.0586 | 0.2662 | | |
| Observations | 11198 | 18158 | 11198 | |

***1%, **5%, *10% and ()= robust std errors.

capacity of the household. The energy conservation decision of a household may not be affected by those variables as curtailment behaviours are not limited by financial capacity.

We also test whether the impact of income on the adoption of renewable energy changes if we control for the effect of country and if renewable energy adoption does not include buying green electricity. In fact, renewable energy incentive and financial support policies are not harmonised around the world. Each country has its own policy. Also, buying green electricity does not necessitate large investments such as production of solar or wind energy. For this reason, we only focus on adoption of renewable energy as an investment decision for wind turbines and solar panels. The results (see Table 10 in Appendix C) show that after controlling for country-specific effects, the effect of income on renewable energy adoption becomes significant. Moreover, when we also consider investment decisions related to wind and solar energy, we find that income does not significantly influence a household's decision to invest in renewable energy. These results reveal that a diversity of renewable energy policies may explain why income does not significantly influence renewable energy adoption. Households are also affected differently by their financial capacity with regard to their adoption decision (including green electricity) and investment decision (only wind or solar energy).

In most cases, only owners can undertake investments at home due to housing regulations. Therefore, tenants have limited possibilities to invest in renewable energy and in energy efficiency. Moreover, it is technically difficult to undertake these investments when living in a flat. Consequently, we check the robustness of our results excluding tenants and all households not living in detached or semi-detached residences. We find that the main results are not altered when excluding tenants and households living in a collective residence (see Table 11 in Appendix C). Further, in order to check the robustness of our results with respect to attitudinal characteristics such as perception, commitment and trust, we compare the results with and without attitudinal characteristics. We find that there is no change in the significance of the other variables and in the sign of the effects. Also, there is only a slight difference in the coefficients of these variables (see table 12 in appendix C). Finally, note that the results of all the above tests confirm that there is a significant and positive interrelation between the two decisions of the household (to adopt renewable energy and to invest in energy efficiency).

Five key points emerge from the results related to households deciding to adopt renewable energy and also to invest in energy efficiency. First, the results show that there is a positive interrelation between the decision of the household to invest in energy efficiency and that of adopting renewable energy. This is due to unobserved characteristics such as environmental motivation. Second, there is evidence of energy poverty related to energy efficiency investments. Third, problems related to split incentives appear to be a barrier to the adoption of renewable energy as well as to investments in energy efficiency. Fourth, the results confirm the importance of concern for the environment in the decision of a household to adopt renewable energy, while concern over climate change leads investments in energy efficiency. Finally, the results suggest that when households are committed to local and charitable organisations and when they also believe researchers,

scientists and experts, they are favourable to the two decisions. Whereas commitment to environmental organisations only affects the decision to adopt renewable energy.

4.3 Interaction between renewable energy adoption and investment in energy efficiency.

In this section, we are interested in the interaction between the decision to adopt renewable energy and to invest in energy efficiency. Essentially, we intend to explain why some households decide to invest in energy efficiency and also to invest in renewable energy, while others decide to only invest in renewable energy or to only invest in energy efficiency, or to do nothing. As a result, the household has four possible choices. It can decide (i) both to invest in energy efficiency and to invest in renewable energy, (ii) to only invest in renewable energy, (iii) to only invest in energy efficiency or (iv) to do nothing. In fact, it is difficult to rank the two decisions (only adoption of renewable energy or only reduction of energy consumption). Further, Table 1 shows that only a very few households (2%) adopt only renewable energy without investing in energy efficiency. Therefore, we combine the two outcomes. The implication is that the household that only adopts renewable energy or only reduces its energy consumption contributes to the energy transition more than the household who does nothing, and less than the one who jointly adopts renewable energy and invests in energy efficiency. The outcome variable can then take three different values: 3 for both adoption of renewable energy and investment in energy efficiency, 2 for adoption of renewable energy or investment in energy efficiency and 1 for none of these.

The ordered probit (oprobit) and ordered logit (ologit) methods are good candidates for estimation of our model. First, we base our choice on the Akaike information criterion (AIC), the Bayesian information criterion (BIC) and the log-likelihood criterion. As suggested by table 5, the ologit method is the best for our model because it has the lower AIC and BIC and the higher log-likelihood. Second, we test the significance of cut points cut1 and cut2 for the ologit and find that cut2 is significant and different from cut1 (table 6). So, the three categories should not be collapsed into two categories. Third, we perform the Brant test, which checks the assumptions of the parallel-lines. The Brant test shows that the assumptions of the parallel-lines model are violated (table 6). Therefore, the parameters of the ordered logit change for different categories of the outcome (eere) and their interpretations are wrong. Following Williams et al. (2006), we use a generalised ordered logit (gologit) method that offers an ordinal alternative in which the parallel-lines assumption is not violated.

Table 5: Statistics of ologit and oprobit

| Model | Obs | ll(null) | ll(model) | df | AIC | BIC |
|---------|-------|-----------|-----------|----|----------|----------|
| oprobit | 11198 | -10063.62 | -8376.696 | 32 | 16817.39 | 17051.74 |
| ologit | 11198 | -10063.62 | -8279.595 | 32 | 16623.19 | 16857.54 |

Table 6: Test on cut1 and cut2 and Brant test for ologit

| cut1=0 | cut2=0 | cut1-cut2=0 | Brant test (all) |
|-------------------|-------------|--------------|------------------|
| 0.2142035 | 4.029378*** | -3.815174*** | 418.91 *** |
| ***1%, **5%, *10% | | | |

Before going into details of the estimation results, we perform the goodness of fit and prediction tests in order to evaluate the fit of the gologit model. As before, the frequency of the sample is compared with the predicted probability summarised in table 7. We find that the two results are close. Also, the comparison of predicted outcomes with actual outcomes yields a high rate of prediction (69.05 %).

Table 7: Comparison of predicted probabilities with sample frequencies

| Variable | Mean of Pred Prob | Frequency |
|------------------------------|-------------------|-----------|
| RE=0 and EE=0 | 0.08 | 0.11 |
| RE=0 and EE=1; RE=1 and EE=0 | 0.54 | 0.58 |
| RE=1 and EE=1 | 0.38 | 0.31 |

The results of the gologit model are presented in table 8. The results show that the significance and the sign of the effects are the same for the two categories regarding household income, ownership, commitment to charitable and in local organisations, trust in scientists, taking into account energy costs before buying or renting a house, peak tariff and importance of label to reduce energy use.

Energy poverty, split incentives and environmental motivation

People living in wealthier households are more likely to jointly invest in energy efficiency and in renewable energy if they have undertaken any of these investments, and if not, they are also more likely to undertake one of the investments. Undertaking investments in both energy efficiency and renewable energy is costly. As argued before, people living in wealthier household have a greater financial capacity and are more likely to combine the two investments. Therefore, such investments are not affordable for poorer and vulnerable households, and this may limit their contribution to the energy transition. In the same vein, tenants are less likely to combine the two investments due to split incentives. This limitation can be overcome by environmental motivations. In this sense, people who have already undertaken one of the investments and for whom environmental issues are generally more important than non-environmental issues are more likely to have the additional motivation to overcome barriers that could prevent them from fully contributing to the energy transition.

Dwelling characteristics, attitudinal and energy-related effects

A household that has already undertaken one of the investments and who is living in a detached dwelling is more likely to make additional efforts to invest in the second,

Table 8: Generalised ordered logit (gologit) estimation

| Variables | Gologit | |
|---|-----------------------|-----------------------|
| | EERE=1 | EERE=2 |
| <i>Residential and economic variables</i> | | |
| Living in a non-detached residence | -0.115 (0.0806) | -0.103** (0.0520) |
| Size of the residence | 0.114** (0.0494) | 0.00739 (0.0343) |
| Household income | 0.0455*** (0.0143) | 0.0162* (0.00901) |
| Ownership | 0.265*** (0.0817) | 0.184*** (0.0564) |
| <i>Perception, commitment and trust</i> | | |
| Environmental concerns (general issues) | -0.0330 (0.0241) | -0.0365** (0.0150) |
| Climate change | -0.0663 (0.0545) | 0.102** (0.0422) |
| Resource depletion | 0.0886 (0.0600) | -0.0165 (0.0482) |
| Voting in local elections | 0.174** (0.0789) | 0.0698 (0.0549) |
| Commitment to charitable organisation | 0.308*** (0.0978) | 0.230*** (0.0539) |
| Commitment to environmental organisation | 0.157 (0.105) | 0.275*** (0.0676) |
| Commitment to local organisation | 0.308*** (0.113) | 0.178*** (0.0628) |
| Trust in scientists | 0.125*** (0.0308) | 0.121*** (0.0265) |
| Trust in local authorities | 0.0227 (0.0299) | 0.0402* (0.0224) |
| <i>Energy use</i> | | |
| Energy costs before buying or renting a house | 0.144* (0.0801) | 0.0946* (0.0525) |
| Individual metering | 0.334* (0.172) | 0.0507 (0.129) |
| Peak Tariff | -0.120* (0.0724) | -0.557*** (0.0483) |
| Label to reduce energy use | 0.364*** (0.111) | 0.375*** (0.104) |
| Pseudo R2 | 0.1955 | |
| Log pseudolikelihood | -8096.1711 | |
| Observations | 11198 | |

***1%, **5%, *10% and ()= robust std errors.

while residence size has no significant effect. We also find that participation in charitable, environmental and local organisations, and trust in scientists and local authorities have a positive effect. People who are involved in such organisations and have already undertaken one of the investments are more likely to understand the importance of the energy transition, which itself is related to environmental and local problems and inter-generational equity. Moreover, scientists or national or local authorities are the most suited to communicating about the energy transition. Therefore, people who trust them are more likely to invest in both energy efficiency and renewable energy. The results also show that people who take into account energy cost before renting or buying a house are more likely to combine investments in energy efficiency and renewable energy, and less likely to do nothing. However, this has no effect on the decision to adopt renewable energy, and a positive effect on the decision to invest in energy efficiency (biprobit). Contrary to the biprobit model, having access to dynamic pricing has a negative effect, while having individual metering positively affects the decision of the household if they have not undertaken any of the investments.

The results regarding the interaction between the two decisions suggest two main findings. First, the influence of income becomes less important in the decision of the household to go further when it has undertaken any of these investments. Second, barriers to the full contribution to the energy transition can be overcome by environmental motivations. Finally, we test whether removing the 2% of households who adopt renewable energy without investing in energy efficiency would affect our key results. The results (see appendix C, Table 13) show that they are not altered.

5 Conclusion

Investigating the interactions between household decisions related to investing in energy efficiency and adopting renewable energy is of great interest from policy perspective. This paper fills this gap in the literature and first uses a simple theoretical model to show that there are interactions between the two decisions depending on a cross effect which relies on environment-related satisfaction. Second, using a bivariate probit model the paper empirically shows that there is a positive interrelation between the decisions of the household to invest in energy efficiency and to adopt renewable energy, due to unobserved characteristics such as environmental motivations. As a result, univariate methods that separately estimate the two decisions potentially produce inefficient results. Moreover, the paper provides evidence about factors that affect the probability of adopting renewable energy and of investing in energy efficiency. Notably, people living in poorer households are less likely to invest in energy efficiency and may end up using a large share of their income to pay for electricity, and be in a situation of energy poverty. There is evidence of split incentives: ownership positively affects both the probability to invest in renewable and in energy efficiency.

The results also confirm the importance of environmental concerns in a household's decision to adopt renewable energy, while climate change concerns lead investments in

energy efficiency. Finally, the results suggest that when households are committed to local and charitable organisations and when they believe researchers, scientists and experts as well, they are favourable to the two decisions. However, commitment to environmental organisations only affects their decision to adopt renewable energy. Third, we use a generalised ordered logit model to account for the interaction between the two decisions. The results mainly suggest that (i) the influence of income becomes less important in the decision of the household to go further when it has undertaken any of these investments and (ii) barriers to full contribution to the energy transition can be overcome by environmental motivations.

With respect to policy, one should first consider the two decisions when designing incentive instruments for renewable energy adoption and for energy efficiency investment. Policies that rely on factors that jointly affect the two decisions would benefit from the synergies that may exist between them. For example, promoting a net zero-energy building by investing in both energy efficiency measures and renewable energy would facilitate reliance solely on renewable energy sources. Energy demand would therefore be markedly reduced due to efficiency gains, so that the remaining energy needs would be satisfied by means of renewable energy. Second, regulation of housing markets could help address split incentives by offering incentives to tenants to undertake investments in energy efficiency and in renewable energy as well. Financial support to reduce the costs of dismantling and re-installation of renewable energy equipment could provide incentives to tenants to undertake such investments as well. Third, policies targeting investment in energy efficiency need to be improved. In many countries, financial support for energy conservation systems are mainly profitable for wealthier households. Poorer households are financially limited, the requirement to invest before applying for reimbursement renders participation in financial support schemes unaffordable. Therefore, it is necessary to set green grants which should be interest-free eco-loans targeting only energy-poor households. Fourth, it may be of great interest to work with existing charitable, environmental and local organisations to communicate with their members on the importance of energy transition. They are predisposed to better understanding the crucial contribution of the energy transition in protecting the environment. Moreover, scientists or national or local authorities are the most suited to communicating about the energy transition. Therefore, they should be more involved in raising awareness and in publicising academic findings to a mainstream audience.

However, there are many other factors which we could not consider in this paper and that may limit tenants ability to install renewable energy equipment. For example, living in an apartment without a balcony, having limited space on the rooftop, etc. may limit the possibility of installing renewable energy equipment. Variables related to characteristics of the residence such as the age of the dwelling and the type of insulation could influence a household's decision of the to invest in energy efficiency. These variables are not provided in the EPIC survey and deserve further research.

References

- Arkesteijn, K. and L. Oerlemans (2005). The early adoption of green power by dutch households: An empirical exploration of factors influencing the early adoption of green electricity for domestic purposes. *Energy Policy* 33(2), 183–196.
- Barr, S., A. W. Gilg, and N. Ford (2005). The household energy gap: examining the divide between habitual-and purchase-related conservation behaviours. *Energy policy* 33(11), 1425–1444.
- Bindewald, E. (2013). Restore: An r of sustainability that can tame the "conundrum". Technical report, PeerJ PrePrints.
- Bird, S. and D. Hernández (2012). Policy options for the split incentive: Increasing energy efficiency for low-income renters. *Energy Policy* 48, 506–514.
- Black, J. S., P. C. Stern, and J. T. Elworth (1985). Personal and contextual influences on household energy adaptations. *Journal of applied psychology* 70(1), 3.
- Cameron, A. C. and P. K. Trivedi (2010). *Microeconometrics using stata*, Volume 2. Stata Press College Station, TX.
- Cameron, T. A., G. L. Poe, R. G. Ethier, and W. D. Schulze (2002). Alternative non-market value-elicitation methods: are the underlying preferences the same? *Journal of Environmental Economics and Management* 44(3), 391–425.
- Capstick, S., L. Whitmarsh, W. Poortinga, N. Pidgeon, and P. Upham (2015). International trends in public perceptions of climate change over the past quarter century. *Wiley Interdisciplinary Reviews: Climate Change* 6(1), 35–61.
- Carlsson-Kanyama, A., A.-L. Lindén, and B. Eriksson (2005). Residential energy behaviour: does generation matter? *International Journal of Consumer Studies* 29(3), 239–253.
- Charlier, D., A. Mosiño, and A. Pommeret (2011). Energy-saving technology adoption under uncertainty in the residential sector. *Annals of Economics and Statistics/Annales d'Économie et de Statistique*, 43–70.
- Couture, T. and Y. Gagnon (2010). An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy policy* 38(2), 955–965.
- Dato, P. (2016). Energy transition under irreversibility: A two-sector approach. *Environmental and Resource Economics*, Forthcoming, 1–24.
- Dietz, T., G. T. Gardner, J. Gilligan, P. C. Stern, and M. P. Vandenbergh (2009). Household actions can provide a behavioral wedge to rapidly reduce us carbon emissions. *Proceedings of the National Academy of Sciences* 106(44), 18452–18456.

- Doni, N. and G. Ricchiuti (2013). Market equilibrium in the presence of green consumers and responsible firms: A comparative statics analysis. *Resource and Energy Economics* 35(3), 380–395.
- Ek, K. and P. Söderholm (2008). Norms and economic motivation in the swedish green electricity market. *Ecological Economics* 68(1), 169–182.
- Ekhholm, T., V. Krey, S. Pachauri, and K. Riahi (2010). Determinants of household energy consumption in india. *Energy Policy* 38(10), 5696–5707.
- Fouquet, R. (2010). The slow search for solutions: Lessons from historical energy transitions by sector and service. *Energy Policy* 38(11), 6586–6596.
- Gerpott, T. J. and I. Mahmudova (2010). Determinants of green electricity adoption among residential customers in germany. *International Journal of Consumer Studies* 34(4), 464–473.
- Greening, L. A., D. L. Greene, and C. Difiglio (2000). Energy efficiency and consumption—the rebound effect—a survey. *Energy policy* 28(6), 389–401.
- Guagnano, G. A., P. C. Stern, and T. Dietz (1995). Influences on attitude-behavior relationships a natural experiment with curbside recycling. *Environment and behavior* 27(5), 699–718.
- Heslop, L. A., L. Moran, and A. Cousineau (1981). "consciousness" in energy conservation behavior: An exploratory study. *Journal of Consumer Research*, 299–305.
- Howarth, R. B. (1997). Energy efficiency and economic growth. *Contemporary Economic Policy* 15(4), 1–9.
- IEA (2007). Statistics and balances, online statistics. Technical report, International Energy Agency (IEA) Publishing, www.iea.org/stats/index.asp.
- IEA (2008a). Energy technology perspectives, 2008: Scenarios & strategies to 2050: in support of the g8 plan of action. Technical report, International Energy Agency (IEA) Publishing.
- IEA (2008b). Worldwide trends in energy use and efficiency, key insights from the international energy agency (iea) indicator analysis. Technical report, OECD/IEA, 2008, Fig 4.3, page 46.
- IEA/OECD (2014). Energy efficiency market report. Technical report, IEA/OECD.
- IRENA (2014). Remap 2030: A renewable energy roadmap. Technical report, IRENA, Abu Dhabi. www.irena.org/remap.
- Jansson, J., A. Marell, and A. Nordlund (2009). Elucidating green consumers: A cluster analytic approach on proenvironmental purchase and curtailment behaviors. *Journal of Euromarketing* 18(4), 245–267.

- Kempton, W. and M. Neiman (1986). Energy efficiency: Perspectives on individual behavior.
- Knittel, C. R., M. Greenstone, and T. Carlos (2014). Understanding the economics of energy efficiency.
- Kotchen, M. J. and M. R. Moore (2007). Private provision of environmental public goods: Household participation in green-electricity programs. *Journal of Environmental Economics and Management* 53(1), 1–16.
- Krishnamurthy, C. K. B. and B. Kriström (2014). Determinants of the price-premium for green energy: Evidence from an oecd cross-section. *Environmental and Resource Economics*, 1–32.
- Laustsen, J. (2008). Energy efficiency requirements in building codes, energy efficiency policies for new buildings. *International Energy Agency (IEA)*, 477–488.
- Liu, W., C. Wang, and A. P. Mol (2013). Rural public acceptance of renewable energy deployment: The case of shandong in china. *Applied energy* 102, 1187–1196.
- Liu, Z. L., T. D. Anderson, and J. M. Cruz (2012). Consumer environmental awareness and competition in two-stage supply chains. *European Journal of Operational Research* 218(3), 602–613.
- OECD (2014). Greening household behaviour overview from the 2011 survey - revised edition. studies on environmental policy and household behaviour. Technical report, OECD Publishing.
- OECD/IEA (2014). Technology roadmap: Solar photovoltaic energy. Technical report, OECD/IEA.
- OECD/IEA (2015). Key trends in co2 emissions excerpt co2 emissions from fuel combustion 2015 edition - highlights. Technical report, OECD/IEA.
- Ozaki, R. (2011). Adopting sustainable innovation: what makes consumers sign up to green electricity? *Business Strategy and the Environment* 20(1), 1–17.
- Poe, G. L., J. E. Clark, D. Rondeau, and W. D. Schulze (2002). Provision point mechanisms and field validity tests of contingent valuation. *Environmental and Resource Economics* 23(1), 105–131.
- RENS21 (2014). Renewable 2014 global status report. Technical report, REN21 secretariat, Paris.
- Roe, B., M. F. Teisl, A. Levy, and M. Russell (2001). Us consumers’ willingness to pay for green electricity. *Energy policy* 29(11), 917–925.
- Samuelson, P. A. (1974). Complementarity: An essay on the 40th anniversary of the hicks-allen revolution in demand theory. *Journal of Economic literature* 12(4), 1255–1289.

- Santin, O. G., L. Itard, and H. Visscher (2009). The effect of occupancy and building characteristics on energy use for space and water heating in dutch residential stock. *Energy and buildings* 41(11), 1223–1232.
- Sardianou, E. (2008). Estimating space heating determinants: An analysis of greek households. *Energy and Buildings* 40(6), 1084–1093.
- Sardianou, E. and P. Genoudi (2013). Which factors affect the willingness of consumers to adopt renewable energies? *Renewable energy* 57, 1–4.
- Serret, Y. and Z. Brown (2014). Greening household behaviour: Overview of results from econometric analysis and policy implications. Technical report, OECD Publishing.
- Sheffield, J. (1997). The role of energy efficiency and renewable energies in the future world energy market. *Renewable energy* 10(2), 315–318.
- Shi, L., W. Zhou, and B. Kriström (2013). Residential demand for green electricity. *Environmental Economics* 4(1), 39–50.
- Steg, L. (2008). Promoting household energy conservation. *Energy policy* 36(12), 4449–4453.
- Sun, N. and Z. Yang (2006). Equilibria and indivisibilities: gross substitutes and complements. *Econometrica* 74(5), 1385–1402.
- Urban, J. and M. Ščasný (2012). Exploring domestic energy-saving: The role of environmental concern and background variables. *Energy policy* 47, 69–80.
- Vandenbergh, M. P., J. Barkenbus, and J. Gilligan (2007). Individual carbon emissions: The low-hanging fruit. *UCLA L. Rev.* 55, 1701.
- Wackernagel, M. and W. E. Rees (1997). Perceptual and structural barriers to investing in natural capital: Economics from an ecological footprint perspective. *Ecological economics* 20(1), 3–24.
- Whillans, A. V. and E. W. Dunn (2015). Thinking about time as money decreases environmental behavior. *Organizational Behavior and Human Decision Processes* 127, 44–52.
- Whitmarsh, L. and S. O’Neill (2010). Green identity, green living? the role of pro-environmental self-identity in determining consistency across diverse pro-environmental behaviours. *Journal of Environmental Psychology* 30(3), 305–314.
- Williams, R. et al. (2006). Generalized ordered logit/partial proportional odds models for ordinal dependent variables. *Stata Journal* 6(1), 58–82.
- Young, W., K. Hwang, S. McDonald, and C. J. Oates (2010). Sustainable consumption: green consumer behaviour when purchasing products. *Sustainable development* 18(1), 20–31.

- Zhai, P. and E. D. Williams (2012). Analyzing consumer acceptance of photovoltaics (pv) using fuzzy logic model. *Renewable Energy* 41, 350–357.
- Zhang, L., J. Wang, and J. You (2015). Consumer environmental awareness and channel coordination with two substitutable products. *European Journal of Operational Research* 241(1), 63–73.
- Zhao, H.-x. and F. Magoulès (2012). A review on the prediction of building energy consumption. *Renewable and Sustainable Energy Reviews* 16(6), 3586–3592.
- Zorić, J. and N. Hrovatin (2012). Household willingness to pay for green electricity in slovenia. *Energy Policy* 47, 180–187.

6 Appendices

6.1 Appendix A

Proof of Proposition 1

The household solves the following programme.

$$\begin{aligned} \max_{d, ee, re} \quad & \sum_{t=0}^p \beta^t U(ee, re, d) \\ \text{st} \quad & R = d + k_1 ee + k_2 re \end{aligned} \quad , \quad (9)$$

and the optimal allocation is given by

$$k_1 u' - \frac{\partial v}{\partial ee} = 0. \quad (10)$$

We can derive an implicit function Q from Eq. (10) defined as follows.

$$Q \equiv k_1 u' - \frac{\partial v}{\partial ee}.$$

We use this implicit function Q to derive the derivative of the optimal level of investment in renewable energy with respect to the optimal level of investment in energy efficiency. Taking total derivative of Q , we get:

$$\frac{\partial Q}{\partial re^*} dre^* + \frac{\partial Q}{\partial ee^*} dee^* = 0,$$

where

$$\frac{\partial Q}{\partial re^*} = k_1(1 - k_2)u'' - \frac{\partial^2 v}{\partial ee \partial re}$$

and

$$\frac{\partial Q}{\partial ee^*} = k_1 [(1 - k_2)re' - k_1] u'' > 0$$

We can then deduce that:

$$\frac{dre^*}{dee^*} = - \frac{\frac{\partial Q}{\partial ee^*}}{\frac{\partial Q}{\partial re^*}}.$$

The sign of $\frac{dre^*}{dee^*}$ depends on the sign of $\frac{\partial Q}{\partial re^*}$. We have the following condition:

$$\frac{dre^*}{dee^*} < 0 \iff \frac{\partial^2 v}{\partial ee \partial re} < \overline{v_{eeere}} = k_1(1 - k_2)u''.$$

6.2 Appendix B

The derivative of the threshold level of cross effect $\overline{v_{eeere}}$ with respect to the energy budget is given by:

$$\frac{\partial \overline{v_{eeere}}}{\partial R} = k_1(1 - k_2)u'''.$$

6.3 Appendix C

Table14: Description and summary of independent variables.

| Variables | Description | Mean |
|---|---|-------|
| Residential and Socio-demographic variables | | |
| Living in a non-detached residence (collective) | 1 for non-detached and 0 for detached | .43 |
| Size of the residence (size_residence) | 1-<50m ² ; 2-50-100; 3-100-200 ; 4->200 | 2.41 |
| Age of the respondent (age) | Continuous variable | 42.53 |
| Gender of the respondent (sex) | 0 for Female and 1 for Male | .49 |
| Employment status (employme) | 0 for not working and 1 for working | .63 |
| Household income (income) | 1 for usd 1- usd 24200....up to 10 for more than usd 127000 | 5.0 |
| Size of household (size_hh) | 1 for 1... up to 5 for 5+ | 2.86 |
| Ownership (owner) | 0 for no owner and 1 for owner | .64 |
| Urban or non-urban residence (urban) | 0 for not living in urban area and 1 for living in urban area | .70 |
| Duration of residence (duration) | 1 for less than 2 years... up to 4 for more than 15 years | 2.62 |
| Attitudinal variables | | |
| <i>Perception</i> | | |
| Environmental concerns (general issues) (env_conc) | 1 for most important... up to 6 for least | 3.52 |
| Air pollution (air_poll) | 1 for most important... up to 4 for least | 3.44 |
| Climate change (climate_) | 1 for most important... up to 4 for least | 3.35 |
| Resource depletion (resource) | 1 for most important... up to 4 for least | 3.46 |
| Waste generation (waste_ge) | 1 for most important... up to 4 for least | 3.33 |
| <i>Commitment and trust</i> | | |
| Voting in local elections (vote_loc) | 0 for no and 1 for yes | .70 |
| Commitment to charitable organisations (com_char) | 0 for no and 1 for yes | .24 |
| Commitment to environmental organisations (com_env) | 0 for no and 1 for yes | .14 |
| Commitment to local organisations (com_loca) | 0 for no and 1 for yes | .15 |
| Trust in scientists (trust_sc) | 1 for least trustworthy... up to 5 for most | 3.80 |
| Trust in local authorities (trust_lo) | 1 for least trustworthy... up to 5 for most | 2.68 |
| Trust in manufacturers (trust_ma) | 1 for least trustworthy... up to 5 for most | 2.34 |
| Trust in NGOs (trust_NG) | 1 for least trustworthy... up to 5 for most | 3.51 |
| Energy use and other variables | | |
| Individual metering (ind_mete) | 0 for no and 1 for yes | .95 |
| Peak Tariff (peak) | 0 for no and 1 for yes | .45 |
| Energy costs before buying or renting a house (exante) | 0 for no and 1 for yes | .29 |
| Importance of information to reduce energy use (est_info) | 0 for no and 1 for yes | .88 |
| Importance of environmental benefits to reduce energy (est_env) | 0 for no and 1 for yes | .88 |
| Importance of label to reduce energy use (est_labe) | 0 for no and 1 for yes | .88 |
| Importance of less expensive EE to reduce energy use (est_lexp) | 0 for no and 1 for yes | .89 |
| Year of the survey (year) | 0 for 2008 and 1 for 2011 | .54 |

Table 9: Robustness check: Estimation of Bivariate probit with both monetary and non-monetary investments in energy efficiency

| Variables | Biprobit | |
|---|--------------------------------|-------------------------|
| | EE2 | RE |
| <i>Residential and economic variables</i> | | |
| Living in a non-detached residence | -0.325*** (0.0501) | -0.0468* (0.0284) |
| Size of the residence | -0.00116 (0.0318) | -0.0159 (0.0187) |
| Household income | -0.00223 (0.00855) | 0.00429 (0.00488) |
| Ownership | 0.110** (0.0501) | 0.0809*** (0.0300) |
| <i>Perception, commitment and trust</i> | | |
| Environmental concerns (general issues) | -0.0151 (0.0141) | -0.0264*** (0.00815) |
| Climate change issues | -0.0919*** (0.0351) | 0.0823*** (0.0232) |
| Resource depletion issues | 0.159*** (0.0382) | -0.0369 (0.0259) |
| Voting in local elections | 0.118** (0.0491) | 0.0379 (0.0298) |
| Commitment to charitable organisation | -0.00537 (0.0538) | 0.133*** (0.0294) |
| Commitment to environmental organisation | -0.0826 (0.0629) | 0.150*** (0.0364) |
| Commitment to local organisation | 0.0973 (0.0639) | 0.0864** (0.0347) |
| Trust in scientists | 0.0787*** (0.0183) | 0.0724*** (0.0138) |
| Trust in local authorities | -0.0159 (0.0177) | 0.0208* (0.0119) |
| <i>Energy use</i> | | |
| Energy costs before buying or renting a house | 0.0272 (0.0490) | 0.0213 (0.0283) |
| Individual metering | 0.0748 (0.110) | 0.0730 (0.0712) |
| Peak Tariff | -0.00400 (0.0437) | -0.404*** (0.0262) |
| Label to reduce energy use | 0.276*** (0.0708) | 0.168*** (0.0539) |
| rho | 0.1876459 1*** (0.0312183) | |
| Log pseudolikelihood | -8321.7626 | |
| Observations | 13133 | 13133 |

***1%, **5%, *10% and ()= robust std errors.

Table 10: Robustness check: Estimation of Bivariate model with solar/wind energy and country effects

| Variables | With country effects | | With country effects | |
|---|-----------------------------|-------------------------|------------------------------|-------------------------|
| | EE | RE | EE | RE |
| <i>Residential and economic variables</i> | | | | |
| Living in a non-detached residence | -0.0774* (0.0422) | -0.0793** (0.0375) | -0.175*** (0.0468) | -0.172*** (0.0468) |
| Size of the residence | 0.0405 (0.0251) | -0.0236 (0.0217) | 0.0316 (0.0274) | 0.0316 (0.0274) |
| Household income | 0.0263*** (0.00661) | 0.0157*** (0.00572) | 0.0266*** (0.00712) | -0.0266*** (0.00712) |
| Owner | 0.138*** (0.0406) | 0.0410 (0.0364) | 0.185*** (0.0449) | 0.185*** (0.0449) |
| <i>Perception, commitment and trust</i> | | | | |
| Environmental concerns (general issues) | -0.0278** (0.0114) | -0.0466*** (0.00964) | -0.0184 (0.0124) | -0.0184 (0.0124) |
| Climate change issues | -0.00584 (0.0278) | 0.0542** (0.0255) | 0.00281 (0.0310) | 0.00281 (0.0310) |
| Resource depletion issues | 0.0463 (0.0306) | -0.00680 (0.0284) | 0.0434 (0.0337) | -0.0434 (0.0337) |
| Voting in local elections | 0.0443 (0.0395) | 0.0353 (0.0359) | 0.0335 (0.0431) | -0.0335 (0.0431) |
| Commitment to charitable organisations | 0.0788* (0.0436) | 0.0996*** (0.0342) | 0.0898* (0.0472) | 0.0898* (0.0472) |
| Commitment to environmental organisations | 0.0773 (0.0513) | 0.207*** (0.0426) | 0.0713 (0.0570) | 0.207*** (0.0570) |
| Commitment to local organisations | 0.113** (0.0502) | 0.0934** (0.0386) | 0.0726 (0.0537) | 0.113** (0.0537) |
| Trust in scientists | 0.0224 (0.0157) | 0.0266* (0.0150) | 0.0284* (0.0172) | -0.0284* (0.0172) |
| Trust in local authorities | 0.00296 (0.0144) | 0.0154 (0.0133) | -0.00112 (0.0157) | 0.00112 (0.0157) |
| <i>Energy use</i> | | | | |
| Energy costs before buying or renting a house | 0.118*** (0.0387) | 0.120*** (0.0331) | 0.142*** (0.0424) | 0.142*** (0.0424) |
| Individual metering | 0.170* (0.0903) | 0.0653 (0.0856) | 0.188* (0.0993) | -0.188* (0.0993) |
| Peak Tariff | 0.0256 (0.0364) | -0.237*** (0.0317) | 0.0263 (0.0397) | 0.237*** (0.0397) |
| Label to reduce energy use | 0.203*** (0.0590) | 0.258*** (0.0580) | 0.218*** (0.0652) | 0.218*** (0.0652) |
| rho | 0.1604704 *** (0.025715) | | 0.4134992 *** (0.0471648) | |
| Log pseudolikelihood | -8396.4141 | | -5207.4594 | |
| Observations | 11198 | | 9410 | |

***1%, **5%, *10% and ()= robust std errors.

Table 11: Robustness check: Estimation of Bivariate model excluding tenants and households living in a collective residence

| Variables | Excluding tenants | | Excluding collective house | |
|---|-----------------------|-----------------------|----------------------------|-----------------------|
| | EE | RE | EE | RE |
| <i>Residential and economic variables</i> | | | | |
| Living in a non-detached residence | -0.0743 (0.0456) | -0.0007 (0.0364) | | |
| Size of the residence | 0.0585** (0.0286) | 0.0259 (0.0230) | 0.0968*** (0.0286) | 0.00405 (0.0227) |
| Household income | 0.0341*** (0.0074) | 0.0061 (0.0059) | 0.0308*** (0.00817) | 0.00774 (0.00647) |
| Owner | | | 0.166*** (0.0561) | 0.0291 (0.0460) |
| <i>Perception, commitment and trust</i> | | | | |
| Environmental concerns (general issues) | -0.0146 (0.0130) | -0.0213** (0.0104) | -0.00309 (0.0144) | -0.0289** (0.0114) |
| Climate change issues | -0.0745** (0.0331) | 0.0778*** (0.0287) | -0.0922** (0.0366) | 0.0707** (0.0306) |
| Resource depletion issues | 0.106*** (0.0370) | -0.0313 (0.0321) | 0.119*** (0.0399) | -0.00876 (0.0344) |
| Voting in local elections | 0.0965** (0.0482) | 0.0733* (0.0401) | 0.0583 (0.0521) | 0.0555 (0.0426) |
| Commitment to charitable organisations | 0.156*** (0.0507) | 0.118*** (0.0370) | 0.159*** (0.0567) | 0.101** (0.0400) |
| Commitment to environmental organisations | 0.0429 (0.0587) | 0.175*** (0.0452) | 0.116* (0.0683) | 0.169*** (0.0486) |
| Commitment to local organisations | 0.114** (0.0560) | 0.0939** (0.0416) | 0.105* (0.0604) | 0.0914** (0.0437) |
| Trust in scientists | 0.0712*** (0.0184) | 0.0710*** (0.0172) | 0.0668*** (0.0199) | 0.0795*** (0.0184) |
| Trust in local authorities | 0.0152 (0.0170) | 0.0240 (0.0146) | -0.00379 (0.0186) | 0.0406** (0.0158) |
| <i>Energy use</i> | | | | |
| Energy costs before buying or renting a house | 0.108** (0.0452) | -0.00404 (0.0358) | 0.0963* (0.0493) | 0.0237 (0.0384) |
| Individual metering | 0.0416 (0.126) | 0.00299 (0.108) | 0.136 (0.130) | -0.0703 (0.113) |
| Peak Tariff | -0.0190 (0.0409) | -0.374*** (0.0329) | 0.0218 (0.0442) | -0.394*** (0.0349) |
| Label to reduce energy use | 0.132* (0.0705) | 0.171*** (0.0663) | 0.154** (0.0754) | 0.148** (0.0715) |
| rho | | 0.1543*** (0.0285) | 0.1872*** (0.0311) | |
| Log pseudolikelihood | | -6401.8768 | -5424.1275 | |
| Observations | | 8036 | 6721 | |

***1%, **5%, *10% and ()= robust std errors.

Table 12: Robustness check: estimation with and without attitudinal variables

| | (With) EE | (Without) EE | (With) RE | (Without) RE |
|----------------|------------------------|------------------------|-----------------------|-----------------------|
| collective | -0.0736** (0.0364) | -0.0869* (0.0356) | -0.0550* (0.0310) | -0.0477 (0.0304) |
| size_residence | 0.0650*** (0.0233) | 0.0801*** (0.0228) | -0.00447 (0.0202) | 0.0117 (0.0199) |
| income | 0.0271*** (0.00630) | 0.0287*** (0.00609) | 0.00289 (0.00529) | 0.00579 (0.00519) |
| owner | 0.151*** (0.0383) | 0.164*** (0.0374) | 0.100*** (0.0335) | 0.0995** (0.0329) |
| exante | 0.104*** (0.0367) | 0.123*** (0.0359) | 0.0348 (0.0311) | 0.0519 (0.0303) |
| ind_metering | 0.0771 (0.0862) | 0.0838 (0.0844) | 0.0994 (0.0787) | 0.0832 (0.0776) |
| peak | 0.0202 (0.0330) | 0.0281 (0.0324) | -0.375*** (0.0286) | -0.370*** (0.0281) |
| est_label | 0.184*** (0.0561) | 0.207*** (0.0542) | 0.183*** (0.0582) | 0.216*** (0.0575) |
| <i>N</i> | 11198 | 11444 | | |

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 13: Robustness check of the gologit estimation without the 2% of RE=1 and EE=0

| Variables | Gologit | |
|---|-----------------------|------------------------|
| | EERE=1 | EERE=2 |
| <i>Residential and economic variables</i> | | |
| Living in a non-detached residence | -0.123 (0.0806) | -0.0943* (0.0534) |
| Size of the residence | 0.120** (0.0499) | -0.00378 (0.0353) |
| Household income | 0.0485*** (0.0143) | 0.0115 (0.00925) |
| Ownership | 0.270*** (0.0817) | 0.155*** (0.0577) |
| <i>Perception, commitment and trust</i> | | |
| Environmental concerns (general issues) | -0.0326 (0.0240) | -0.0435*** (0.0154) |
| Climate change issues | -0.0679 (0.0542) | 0.125*** (0.0434) |
| Resource depletion issues | 0.0916 (0.0602) | -0.0370 (0.0497) |
| Voting in local elections | 0.173** (0.0792) | 0.0712 (0.0565) |
| Commitment to charitable organisations | 0.308*** (0.0977) | 0.216*** (0.0556) |
| Commitment to environmental organisations | 0.153 (0.105) | 0.297*** (0.0687) |
| Commitment to local organisations | 0.307*** (0.113) | 0.187*** (0.0648) |
| Trust in scientists | 0.124*** (0.0308) | 0.122*** (0.0270) |
| Trust in local authorities | 0.0250 (0.0300) | 0.0457** (0.0228) |
| <i>Energy use</i> | | |
| Energy costs before buying or renting a house | 0.159** (0.0799) | 0.0724 (0.0540) |
| Individual metering | 0.304* (0.172) | 0.111 (0.133) |
| Peak Tariff | -0.109 (0.0722) | -0.647*** (0.0497) |
| Label to reduce energy use | 0.361*** (0.111) | 0.391*** (0.107) |
| Pseudo R2 | 0.2153 | |
| Log pseudolikelihood | -7742.3275 | |
| Observations | 10869 | |

***1%, **5%, *10% and ()= robust std errors.