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THÈSE

Pour obtenir le grade de

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Spécialité : **Sciences Economiques**

Arrêté ministériel : 7 Août 2006

Présentée par

Prudence DATO

Thèse dirigée par **Aude POMMERET**

préparée au sein du Laboratoire **IREGE**
et de l'Ecole Doctorale **SISEO**

La transition énergétique

Thèse soutenue publiquement le **09 Décembre 2016**,
devant le jury composé de :

M. Alain AYONG LE KAMA

Professeur, Université Paris Ouest Nanterre la Défense, Président

M. Patrice GEOFFRON

Professeur, Université Paris Dauphine, Rapporteur

Mme Katheline SCHUBERT

Professeur, Université Paris 1 Panthéon-Sorbonne, Rapporteur

M. Lucas BRETSCHGER

Professeur, ETH Zurich, Examineur

M. Rick VAN DER PLOEG

Professeur, Université de Oxford, Examineur

Mme Aude POMMERET

Professeur, Université Savoie Mont Blanc et CityU Hong Kong, Directrice de thèse



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UNIVERSITY OF GRENOBLE ALPES

DOCTORAL SCHOOL OF SISEO

LABORATORY OF IREGE

The energy transition

A DISSERTATION SUBMITTED

IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS

FOR THE DEGREE

DOCTOR OF ECONOMICS

Author:
Prudence DATO

Supervisor:
Professor Aude POMMERET

January 15, 2017

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The views expressed in this dissertation are those of the author and do not reflect the policy or position of the University Grenoble Alpes.

Abstract

The transition to renewable energy involves two kinds of environmental concerns. First, fossil fuels are exhaustible and second, their use generates negative externalities through irreversible environmental damage. Furthermore, there exist some possible synergies between energy efficiency measures and renewable energy adoption in the sense that the former reduces the energy demand so that the latter can begin to cut future greenhouse gases emissions. The main objective of this dissertation is to analyse the optimal energy transition under certain and uncertain occurrence of environmental catastrophe and to determine incentive-based instruments at the household level in order to boost the energy transition. The dissertation consists of four chapters.

The first two chapters of the dissertation focus on the optimal energy transition of a two-sector economy (energy and final goods) with exhaustible oil reserves, a renewable source of energy and a pollution threat. In the first chapter, the latter corresponds to a pollution threshold above which a part of the capital is lost. Given the baseline parameter values, we numerically show that the most profitable energy transition path may correspond to the one in which the economy starts using both resources, then crosses the pollution threshold and therefore loses a part of its capital. Ultimately, the economy keeps using both resources and never switches to sole adoption of clean energy. This result is in line with arguments supporting the idea that a complete transition to a low carbon economy is likely to be very slow. When additional investment in energy saving technologies is allowed, it favours a full transition to the sole use of renewable energy. It is then profitable to take advantage of these synergies by jointly promoting deployment of clean energy and providing incentives for investment in energy saving technologies. The second chapter considers that the pollution thresholds above which environmental catastrophes are expected to occur are uncertain and generates a loss of utility. Numerical solutions show that uncertainty of the occurrence of the catastrophe induces a precautionary behaviour, in the sense that it negatively affects the rate of the polluting resource extraction and drives the energy transition.

The third chapter is devoted to understand the behaviour of household regarding their decisions to simultaneously adopt renewable energy and to invest in energy efficiency. We first theoretically show that there exist interactions between the two decisions depending on a threshold on the pro-environmental index of the consumer. Second, we empirically show by using biprobit model that the two decisions are positively interrelated and cannot be estimated independently. Third, the paper investigates characteristics of the household that significantly 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 incentives policies to boost energy transition with respect to energy poverty, split incentives, economic and environmental motivations, etc.

The fourth chapter of the dissertation studies the efficient mix of investment in an intermittent renewable energy and energy storage. The novelty of our model accrues

from the flexibility it assigns to a household in feeding (resp. purchasing) electricity to (resp. from) the grid or store energy (or use stored energy) upon renewable energy installations. We study the consequences of demand side management by accounting for three levels of equipment in smart grids: (i) net metering, (ii) smart meters and (iii) energy storage. Additionally, we analyse the consequences of energy storage and smart meters for purchases of electricity from the grid and electricity consumption, the desirability of smart meter installation and the implications of curtailment measures in avoiding congestion. Our results indicate that electricity prices need to be carefully contemplated when the objective is to rely less on the grid through smart grid deployment.

Résumé

La transition vers les énergies renouvelables implique deux types de préoccupations environnementales. Tout d'abord, les combustibles fossiles sont épuisables et, deuxièmement, leur utilisation génère des externalités négatives à travers des dommages environnementaux irréversibles. En outre, il existe des possibilités de synergies entre les mesures d'efficacité énergétique et d'adoption de l'énergie renouvelable dans la mesure où les premières réduisent la demande d'énergie de sorte que la dernière puisse commencer à réduire les émissions futures de gaz à effet de serre. L'objectif principal de cette thèse est d'analyser la transition énergétique optimale dans des contextes de survenance certaine et incertaine d'une catastrophe environnementale et de déterminer les instruments incitatifs au niveau des ménages en vue de stimuler la transition énergétique. La thèse se compose de quatre chapitres.

Les deux premiers chapitres de la thèse se concentrent sur la transition énergétique optimale d'une économie à deux secteurs (énergie et bien final) avec des réserves pétrolières épuisables, une source d'énergie renouvelable et une menace de pollution. Dans le premier chapitre, celui-ci correspond à un seuil de pollution au-dessus duquel une partie du capital est perdue. Compte tenu des valeurs des paramètres de base, nous montrons numériquement que le chemin de transition énergétique le plus rentable peut correspondre à celui où l'économie commence à utiliser les ressources, puis franchit le seuil de pollution et perd une partie de son capital. En fin de compte, l'économie continue d'utiliser les ressources et ne passe jamais à l'adoption exclusive de l'énergie propre. Ce résultat est conforme aux arguments en faveur de l'idée selon laquelle une transition complète vers une économie sobre en carbone est susceptible d'être très lente. Lorsque des investissements supplémentaires dans les technologies d'économie d'énergie sont entrepris, ils favorisent une transition complète vers l'utilisation exclusive des énergies renouvelables. Il est alors avantageux de tirer parti de ces synergies en promouvant conjointement le déploiement de l'énergie propre et de fournir des incitations à investir dans les technologies d'économie d'énergie. Le deuxième chapitre considère que le seuil de pollution au-dessus duquel les catastrophes environnementales pourraient se produire est incertain et génère une perte d'utilité. Nous montrons numériquement que l'incertitude de la survenance de la catastrophe induit un comportement de précaution, en ce sens qu'elle affecte négativement la vitesse d'extraction des ressources polluantes.

Le troisième chapitre est consacré à comprendre le comportement des ménages en ce qui concerne leurs décisions d'adopter simultanément les énergies renouvelables et d'investir dans l'efficacité énergétique. Nous avons d'abord montré théoriquement qu'il existe des interactions entre les deux décisions en fonction d'un seuil sur l'indice pro-environnemental du consommateur. Deuxièmement, nous montrons empiriquement en utilisant le modèle biprobit que les deux décisions sont positivement liées entre elles et ne peuvent être estimées de manière indépendante. En troisième lieu, ce chapitre étudie les caractéristiques du ménage qui affectent de manière significative la probabilité conjointe d'adoption de l'énergie renouvelable et d'investissement dans l'efficacité énergétique et

la probabilité de ne rien entreprendre. Cette contribution peut servir à définir des politiques d'incitation pour booster la transition énergétique par rapport aux problèmes de la pauvreté énergétique, la discordance des intérêts ou "*split incentives*" entre le locataire et le propriétaire, les motivations économiques et environnementales, etc.

Le quatrième chapitre de la thèse étudie la combinaison efficace des investissements dans l'énergie intermittente renouvelable (i.e. panneaux solaires) et dans le stockage d'énergie. La nouveauté dans notre modèle concerne la flexibilité qu'il attribue au ménage en lui donnant la possibilité de fournir (resp. acheter) de l'électricité au réseau ou de stocker de l'énergie (ou utiliser l'énergie stockée) en plus des installations de production d'énergie renouvelable. De plus, nous analysons les conséquences de stockage d'énergie et d'adoption des compteurs intelligents sur les quantités achetées d'électricité provenant du réseau et sur la consommation d'électricité, l'opportunité d'installer les compteurs intelligents et les conséquences des mesures de restriction pour éviter la congestion du réseau. Nos résultats indiquent que le niveau du prix de l'électricité doit être soigneusement analysé si le but est de moins dépendre du réseau électrique à travers le déploiement de réseaux intelligents.

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List of Abbreviations

AIC:	Akaike information criterion
BIC:	Bayesian information criterion
Biprobit:	Bivariate probit
CCS:	Carbon Capture and Storage
CO₂-eq:	Carbon dioxide equivalent
COP21:	21st yearly session of the Conference of the Parties
EE:	Energy Efficiency
EPIC:	Environmental Policy and Individual Behaviour Change survey
EST:	Energy saving technology
FOC:	First order condition
GHG:	Greenhouse gases
Gtc:	Gigatonnes of carbon
GTM:	green tariff mechanism
GW:	Gigawatt
HH:	Household
IEA:	International Energy Agency
IPCC:	Intergovernmental Panel on Climate Change
IRENA:	International Renewable Energy Agency
kWh:	kilowatt-hour
LC:	Leontief conditions
MWh:	Megawatt-hours
NRE:	Non renewable energy
OECD:	Organisation for Economic Co-operation and Development
Ologit:	Ordered logit
PV:	Photovoltaics
RE:	Renewable Energy
RES:	Renewable Energy Source
RTP:	Real time prices
UNFCCC:	United National Framework Convention on Climate Change
VCM:	Voluntary contribution mechanism
WTP:	Willingness To Pay

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Chapter 0

Introduction

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0.1 Context

Gandhi's famous quote "the earth provides enough to satisfy every man's needs, but not every man's greed" (Nayyar, 1958) expresses the ultimate ability of humans to destroy natural processes. When no global limit on human behaviour and activities is set for satisfying basic needs (for example energy services), there is a risk that people will put more pressure on natural resources. In addition, polluting human activities are the source of environmental externalities such as air pollution, and damage to the atmosphere or to the ozone layer. This can affect the ecosystem in negative ways leading to environmental degradation or climate change. There has been growing public concern about climate change, which is amplifying extreme weather events such as severe flooding and droughts, violent wildfires and heat waves. Humankind has already experienced various catastrophes such as the New Madrid (USA) earthquakes in 1811-1812, the deadliest-ever Yellow River floods (China, 1931), hurricane Katrina (USA, 2005), the 2010 earthquake in Haiti, the 2011 Fukushima (Japan) nuclear disaster, the 2016 Fort McMurray Fire (Canada), among others. To avoid such catastrophic events, the international community agreed under the United National Framework Convention on Climate Change (UNFCCC) to a maximum level of warming. The Copenhagen accord in 2009 states that future global warming should be limited to below 2.0°C relative to the pre-industrial level (the 1850-1900 reference period). At the December 2015 Paris climate conference (COP21), 195 countries unanimously voted for the agreement confirming a goal of maintaining the increase in average temperature to 2°C below the pre-industrial average. The agreement intends to pursue efforts to limit this increase to 1.5°C. However, a limit of 1.5°C would require negative emissions. This presupposes a quick transition to renewable energy (RE) and energy efficiency (EE) and the adoption of biofuels combined with carbon capture and storage (CCS) technologies, in accordance with the Intergovernmental Panel on Climate Change (IPCC) mitigation pathways.

Greenhouse gas (GHG) emissions are mainly generated by human activities (IPCC, 2013) and are the primary cause of the global warming. The energy sector represents more than two-thirds of all anthropogenic GHG emissions and generates mostly CO_2 , which accounts for the largest share of global GHG emissions (Fig 6.1). This is a

consequence of world oil-dependence (Fig 6.2) and the fact that oil and coal are mostly responsible for CO₂ emissions (Fig 6.3). Even though the complete depletion of the stock of fossil fuels is an important issue as is climate change, there is evidence that the latter is predominant. For example, Bruckner et al. (2014) shows under some emission scenarios, that the estimate of total fossil fuel reserves and resources contain sufficient carbon above the CO₂ budget required to trigger an environmental catastrophe. There is also a large consensus that global GHG emissions will continue to increase over the next few decades if the economy relies on current climate change mitigation policies and corresponding green growth strategies. For example, global GHG emissions will increase by 25-90% (CO₂-eq) between 2000 and 2030, with a warming of about 0.2°C per decade (IPCC, 2007a). Thus, global warming is now evident and observable through increases in global average air and ocean temperatures, widespread melting of snow and ice, and a rising global average sea level. Many other natural systems are being affected, such as marine and freshwater systems, and agriculture and forestry, with massive consequences on humans health and their economic activities.

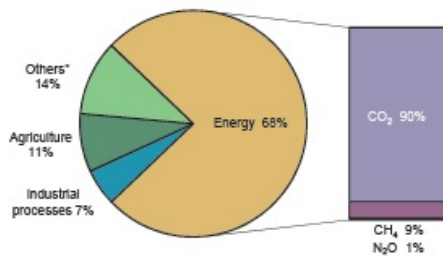


Figure 1: Shares of global anthropogenic GHG, 2010

Source: IEA, 2015a

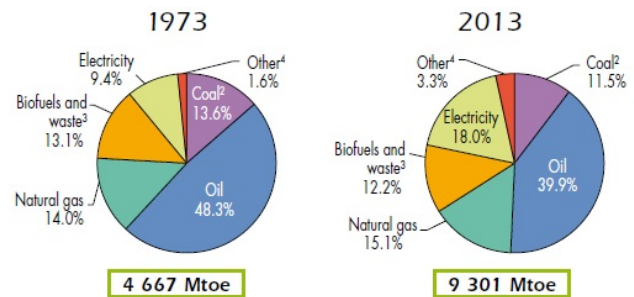


Figure 2: Fuel shares of total final consumption

Source: IEA, 2015e

Investments in renewable energy contribute to reducing CO₂ emissions and will help achieve the goal of limiting the increase in average temperature to 2°C . For example, under the REmap options ¹ the deployment of global modern renewable energy would

¹IRENA produced the REmap options approach to assess the gap between national renewable energy plans, additional renewable technology options in 2030 and the Sustainable Energy for All (SE4ALL) doubling objective. They first produced business-as-usual reference cases, which represent policies in place or under consideration. REmap options investigate additional technology options and illustrate the policy of doubling the share of renewables. They define the "realistic" potential for additional renewable

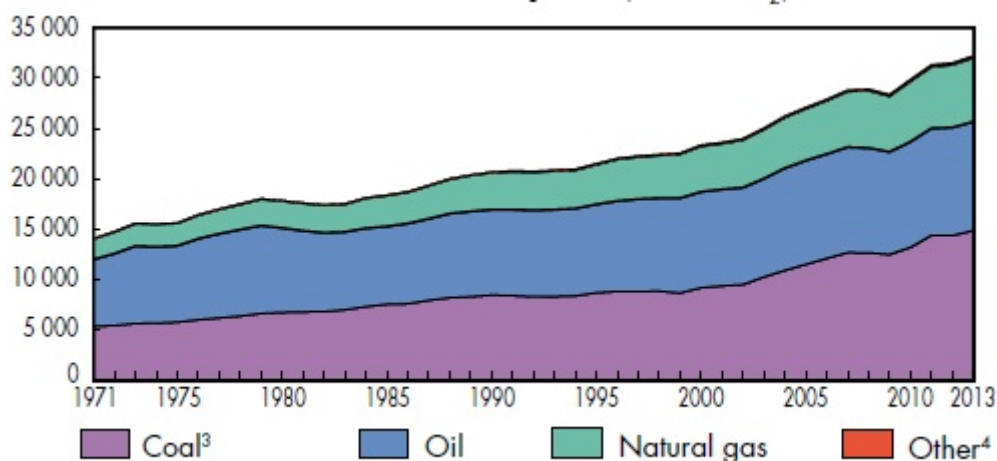


Figure 3: World CO₂ emissions from fuel combustion from 1971 to 2013 by fuel (Mtoe)

Source: [IEA, 2015e](#)

reach 119 exajoules per year (a share of 27%) and could also reduce world-wide annual CO₂ emissions by 8.6 Gt by 2030 ([IRENA, 2014](#)). Fortunately, statistics on investment in the production of RE have thus far shown a growing trend of 63-244 billion USD from 2006 to 2012 ([GEA, 2012](#)), which represented a 19% share of world final energy consumption in 2012 ([RENS21, 2014](#)). A recent report (Fig 6.4) indicates that global investments attained a new record of 285.9 billion USD in 2015, where wind and solar photovoltaics capacity accounted for 118GW, far above that of 2014 (i.e. 94GW). At the same time, the generation cost of RE continues to fall. For example, the global average levelised cost of electricity for crystalline silicon PV decreased from 143 USD per MWh in 2014 to 122 USD in 2015. However, this is not enough and the economy would need to put in more effort in order to achieve the Paris agreement. On top of this, renewable energy capacity is physically and technically limited ([De Castro et al., 2011, 2013](#)). Some recent studies show that the potential for global wind power ([De Castro et al., 2011](#)) and for global solar electric ([De Castro et al., 2013](#)) might even be lower than the current final consumption of energy by means of fossil fuels. So, if the economy intends to solely rely on clean sources of energy, it would require a reduction in energy demand. Therefore, it is crucial not only to drastically change the way energy is produced, but also to identify energy saving strategies.

energy technologies opportunities in each country.

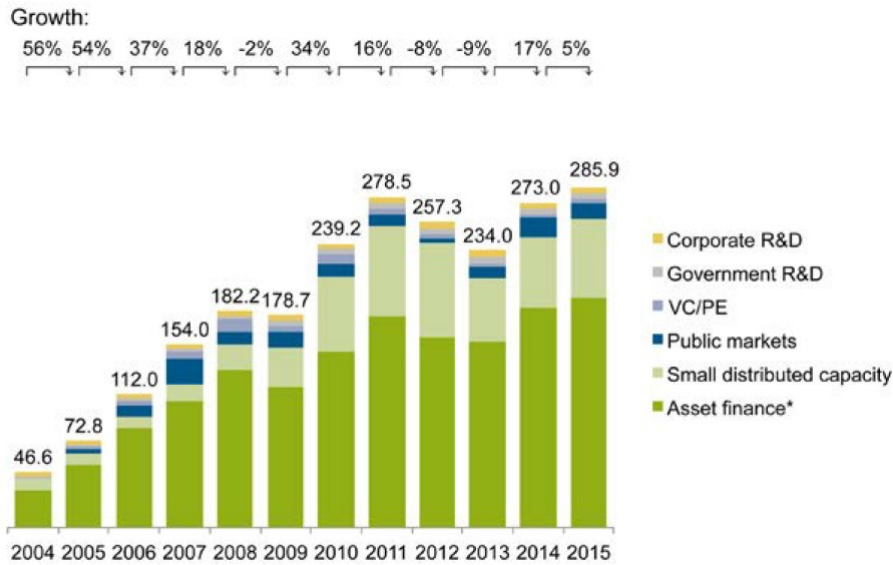


Figure 4: *Global new investment in renewable energy*

Source: [Frankfurt School-UNEP and Center/BNEF, 2016](#)

According to the Global Energy Assessment (GEA), about one-third of overall investment in the energy sector is efficiency-related, following the efficiency pathways ([GEA, 2012](#)). More precisely, investments worldwide in energy efficiency in buildings were estimated to be USD 81-99 billion in 2014, and play the largest role (almost 40%) in reducing GHG emissions from the energy sector over the period to 2050 ([IEA, 2015b](#)). Interestingly enough, there are 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. For example, in a net zero-energy building, energy demand is notably reduced due to efficiency gains so that the remaining energy needs are satisfied by means of renewable energy. In this sense, investing in energy efficiency would facilitate buildings to rely solely on the renewable energy sources. Notably, the report of [IRENA \(2014\)](#) indicates that emission savings from investments in renewable energy combined with energy-efficiency gains, would be sufficient to set the world on a path to preventing catastrophic climate change.

In this context, energy transition accounts for two main issues : (i) adoption of renewable energy and (ii) investment in energy efficiency. The former entails adopting clean energy

0.2. IRREVERSIBILITY AND UNCERTAINTY IN ENERGY TRANSITION AND ENVIRONMENTAL CATASTROPHE

sources as an alternative to polluting sources of energy, while the latter could help reduce overall energy consumption. Renewable energy generally refers to a type of energy which is produced by means of variable or intermittent resources. Those resources comprise wind (wind turbines), sunlight (solar panels), rain (hydro-power), waves (wave power), tides (tidal power), geothermal heat, and crops (biofuel). Regarding energy efficiency, there are two main types of energy conservation measures: efficiency investments and curtailments. The former necessitates monetary investments. This could include acquisition of new technologies or low-energy appliances such as top-rated energy-efficient appliances, low-energy light bulbs or energy-efficient windows. It could also include home renovation or installing energy efficient systems such as automated control systems, domotics or home automation. Curtailment refers to non-monetary investments that involve changes in behaviour, such as scheduling, turning off lights, cutting down on heating or on air conditioning and switching off standby mode (Thøgersen et al., 1995; Jansson et al., 2009).

Furthermore, there are specificities which influence optimal energy transition. Irreversibility and uncertainty are among them. Irreversibility can be related to investments or environmental catastrophe. The uncertainty may be about catastrophic events, future climate change regulations, efficiency of new technologies and future energy demand. In the following section, we describe the problem of irreversible environmental catastrophe and the uncertainty of its occurrence.

0.2 Irreversibility and uncertainty in energy transition and environmental catastrophe

In the early literature on natural resource economics, many authors considered the long run depletion of oil reserves (Dasgupta and Heal, 1974, 1979; Dasgupta and Stiglitz, 1981 and Krautkraemer, 1986) and the polluting features of oil (Nordhaus, 1994 and Tahvonen, 1996, 1997) separately. As the use of polluting energy resources generates pollution that accumulates over time, an ecological catastrophe may occur at some point in time. There is evidence that a large fraction of anthropogenic climate change resulting from

CO_2 emissions is irreversible on a multi-century to millennial time scale (Bruckner et al., 2014). As a consequence, global warming will induce severe degradation of rainforests (the Amazon for example) and their potential for carbon capture, a disintegration of the Greenland and Antarctic ice sheets with a multi-meter sea-level rise over centuries to millennia, and large-scale releases of methane from melting permafrost, substantially amplifying warming (World Bank, 2014). The irreversible decay of the ice sheet is estimated to occur when the global average temperature increase exceeds roughly $1.5^\circ C$ above the pre-industrial level (Robinson et al., 2012). The world will then continue to experience irreversible impacts of climate change even if it stops emissions from fossil-fuels.

Catastrophic events which could produce irreversible damage are variously considered in the literature. These include exhaustion of the natural regeneration capacity (Tahvonen and Withagen, 1996), irreversibility in the decision-making process (Pommeret and Prieur, 2009 and Ayong Le Kama et al., 2014) and a ceiling on the pollution stock (Lafforgue et al., 2009 and Chakravorty et al., 2012). For example, Tahvonen and Withagen (1996) distinguish two regions: a reversible and an irreversible pollution region. The assimilation capacity is strictly concave in the reversible region, while it becomes permanently exhausted in the irreversible region. They find that some equilibria are associated with irreversible pollution. Lafforgue et al. (2009) consider a constant rate of natural regeneration and assume that environmental damage depends on a pollution threshold. The damage is negligible when the economy stays below this threshold, otherwise the damage jumps to infinity. They suggest that sequestration policies should be implemented once the pollution ceiling is reached. Environmental damage resulting from pollution also display different features. Some authors consider the damage as income loss (Karp and Tsur, 2011 and Tsur and Withagen, 2013) or social welfare loss (Van der Ploeg and Withagen, 2012 and Prieur et al., 2013). Other authors focus on productive sectors: capital loss (Ikefuji and Horii, 2012), or destruction capacity (Golosov et al., 2014). Furthermore, some damage can be partly reversible at the expense of some restorative activities (Tsur and Zemel, 1996), or fully reversible once pollution stock falls below critical levels (Cropper, 1976).

The pollution catastrophe is an ecological regime switching problem that is related to the notion of irreversibility. To our knowledge, Tomiyama (1985) and Amit (1986) are the earliest contributors to the optimal control literature related to this type of optimal switching problem. Interestingly enough, these two authors reformulated the optimal switching problem as an optimal timing problem, therefore introducing the time of switch as an explicit decision variable. Further developments in this literature have mostly been concerned with deterministic settings. In a deterministic framework, Boucekkine et al. (2013) provide an optimal control approach that accounts for two different types of optimal switching problems. Boucekkine et al. (2012, 2013) apply this theory to the optimal management of exhaustible resources under ecological irreversibility and backstop adoption. They use optimality conditions such as the continuity of appropriate co-states and states variables, and that of the Hamiltonian.

Although there are pollution thresholds above which environmental catastrophes are expected to occur (Keller et al., 2008), such thresholds are not perfectly known (Gjerde et al., 1999). Anthropogenic perturbations of natural systems together with climate-related hazards drive the risk of climate change impacts, which increase with rising temperature. According to the IPCC (2014), "*Risks are considered key when there is a high probability that the hazard due to climate change will occur under circumstances where societies or social-ecological systems exposed are highly susceptible and have very limited capacities to cope or adapt and consequently potential consequences are severe.*". The report indicates that risks of global aggregate impacts (to both biodiversity and the overall economy) are moderate for additional warming between 1 – 2°C. Specifically, extensive biodiversity (ecosystem goods and services) loss results in high risks at around 3°C additional warming, while aggregate economic damage accelerate with increasing temperature. Furthermore, for sustained warming crossing certain tipping points, near-complete loss of the Greenland ice sheet would occur over a millennium or more, contributing up to a 7 m global mean sea level rise. Risks are differently evaluated and managed depending on the magnitude, irreversibility and the time available for strengthening adaptive capacities.

From the point of view of economic analysis, the management of environmental uncertainty together with irreversible decisions can be found in the real option literature. The term "option value" refers to any opportunity costs or benefits resulting from irreversibility and uncertainty (Pindyck, 2007). For example, adopting a policy today rather than waiting until tomorrow has a negative opportunity cost because of its sunk benefit. Pommeret and Schubert (2009) consider abatement technology as a real option in a general equilibrium setting, where the negative value of pollution alters both risk aversion and the inter-temporal elasticity of substitution. They find that increased 'greenness' of preferences and greater uncertainty induce earlier adoption. Then again, the question of an uncertain catastrophic environmental event goes back to Cropper (1976), using the example of a nuclear incident. Tsur and Zemel (1996) focuses on the potential depletion of a renewable resource. Both papers consider optimal control problems where catastrophe is a random event and the objective function is defined in terms of expectations. These expectations derive from a probability distribution function on the threshold value. In these frameworks, whenever the radioactive pollution (respectively the natural resource) stock exceeds (respectively falls below) a critical threshold, an event occurs which reduces society's utility to zero forever. Tsur and Zemel (1996) and Nævdal (2006) postulate that the event is partly reversible. When pollution reaches the unknown threshold, then an event occurs which substantially reduces the utility level. But, the economy can recover from its impact even if it implies bearing considerable costs (e.g., related to remediation). Ayong Le Kama et al. (2014) consider an ecological catastrophe involving irreversible degradation of regeneration capacity in particular. In the latter paper, uncertainty surrounding irreversible thresholds has strong repercussions on the optimal control of pollution because it generally induces more conservative behaviour. However, unintentional reaching of the threshold cannot be precluded, whereas the situation cannot be observed in the deterministic case. Environmental disasters can also occur repeatedly. Tsur and Zemel (1998) consider recurrent environmental catastrophes and finds that reversible events can induce more conservation (less pollution).

In addition to irreversible ecological switching, energy transition encompasses the switch

to renewable energy over a long process. In fact, energy policies employ scenarios that focus on adoption of renewable energy in order to drastically change the way energy is produced and to cut CO_2 emissions. This will help prevent the economy from facing severe environmental catastrophes. The implementation of energy transition policies requires multiple approaches that differ in many ways between countries. In Europe for example, Germany, the United Kingdom (UK) and France have taken the lead in implementing national policies to facilitate the energy transition with ambitious targets and policies (CERRE, 2015). But their strategies are different due to the difference in their energy mix (in large part nuclear for France, and coal for the UK and Germany). Furthermore, German energy transition policy (i.e. Energiewende) is a reference for energy transition worldwide due to its advanced stage of renewable penetration, high levels of energy efficiency and various policy efforts (World Energy Council, 2014). France has recently adopted legislation for its energy transition (Law N° 2015-992 with 215 articles), which is called "Energy Transition for Green Growth". It is designed to diversify the French energy mix and contribute to the global fight against climate change. France intends to reduce its final energy consumption by 50% by 2050 and its final energy consumption of fossil fuels by 30% by 2030 compared to 2012, and to bring the proportion of renewable energy to 23% of gross final energy consumption. Countries have their own unique characteristics and so need to optimally define their own energy transition paths for structural switching to a low carbon economy.

There is also a diverse set of policy mechanisms for regulating the transition to renewable energy. Several direct instruments (namely fiscal incentives such as grants and investment subsidies, renewable energy mandates, flexible grid access with net metering) and indirect instruments (environmental taxes to penalise the use of fossil fuels, for example) contribute to making the production of renewable energy more attractive. Quantity instruments (i.e. renewable portfolio standards and renewable energy credits) and price instruments (for example feed-in tariffs and auctions) also give incentives to enhance renewable energy deployment. Furthermore, different types of feed-in tariffs exist: fixed or premium, constant or declining over time, etc. However, after the optimal energy transition path has been defined with appropriate regulations, in the absence of incentive-based strategies,

there is no evidence that people will comply with these regulations. In the following section, we focus on the residential sector and describe household behaviour with respect to the adoption of renewable energy and investment in energy efficiency.

0.3 Household behaviour and energy transition

The residential sector has a substantial potential to cut overall energy demand because it represents an important share (23%) of world final energy demand (IEA, 2007) and it contributes 17% to global CO₂ emissions (IEA, 2015d). Furthermore, there is evidence that energy transition policies are mainly driven by political decisions, and therefore require public acceptance for their implementation. It is therefore important to better understand household behaviour regarding clean energy adoption and investment in energy efficiency, which are both important for a transition to a green economy. Although the two issues are separately investigated in the economics literature, the economy may benefit from possible synergies between energy efficiency measures and renewable energy adoption. In the following sections, we present the literature on demand for renewable energy (Section 6.3.1) and on investment in energy efficiency (Section 6.3.2). Section 6.3.3 is devoted to the possible interrelation between renewable energy and energy efficiency.

0.3.1 Renewable energy and household behaviour

Demand for green energy has gained a lot of attention in the literature due to the contribution of fossil fuel energy to world CO₂ emissions, which are primarily responsible for warming the atmosphere. Notably, in the residential sector, studies mainly focus on both real and hypothetical behaviour to explain the decision of the household to adopt a renewable energy device. The latter is based on stated-preference methods (contingent valuation, contingent behaviour or choice experiments, for example) in which preference and monetary values for renewable energy are estimated within a hypothetical market for renewable energy. For example, preference for renewable energy can be estimated by evaluating the willingness to adopt a renewable energy (Gerpott and Mahmudova, 2010; Ozaki, 2011; Zhai and Williams, 2012 and Sardianou and Genoudi, 2013), while evaluating the willingness to pay (WTP) to consume renewable energy can serve to

estimate the monetary values for renewable energy (Ek and Söderholm, 2008; Zorić and Hrovatin, 2012 and Liu et al., 2013). The estimation of preferences and monetary values for renewable energy can also be jointly carried out with stated-preference methods. The household first states its preference for renewable energy and then gives the maximum amount it is willing to pay to benefit from renewable energy (Krishnamurthy and Kriström, 2016 and Shi et al., 2013).

First, the willingness to adopt a renewable energy may be influenced by household characteristics and social norms. Regarding the influence of environmental attitudes of the consumer, Gerpott and Mahmudova (2010) and Ozaki (2011) find opposite results. The former demonstrates that environmental attitudes in Germany have a strong influence on the willingness of a consumer to adopt renewable energy using a Partial Least Squares analysis. While the latter uses correlation analysis to show that pro-environmental consumers do not necessarily adopt green electricity. This can be explained by the lack of strong social norms and personal relevance which affect the adoption of renewable energy, as well as the benefits and costs of the renewable energy. Social acceptance is latter investigated by Zhai and Williams (2012) who find a positive influence in a specific case of photovoltaics (PV). Additionally, financial incentives through taxes or subsidies are important to promote adoption of clean energy. In this sense, Sardanou and Genoudi (2013) suggest that in Greece, a tax deduction is the most effective financial policy measure to promote consumer acceptance of renewable energy in the residential sector.

Second, numerous studies have investigated the WTP to consume renewable energy. For example, Ek and Söderholm (2008) investigates norm-motivated and economic-motivated behaviour in the Swedish green electricity market. They show that variables such as cost of adoption, personal responsibility, perception of the benefit of adoption and social norms are the most important determinants of households choosing to pay a price premium for green electricity. Subsequently, Zorić and Hrovatin (2012) suggests that awareness-raising campaigns should follow green marketing targeting younger, well-educated and high-income households. Furthermore, household behaviour regarding

monetary valuation of renewable energy may differ between developed and developing countries. In a specific case of developing countries, [Liu et al. \(2013\)](#) investigates rural social acceptance for renewable energy adoption and finds that rural residents are generally favourable to renewable electricity development given its positive impacts on the environment.

Third, some studies have focused on both preference and the WTP for renewable energy. For example, [Krishnamurthy and Kriström \(2016\)](#) and [Shi et al. \(2013\)](#) focus on the willingness to accept and the WTP 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 \(2016\)](#) estimates a low WTP that corresponds to 11-12% of current electric bills and the ambiguous effect of income. Similarly, [Shi et al. \(2013\)](#) finds that economic variables are less important, while environmental concerns or attitudes consistently drives the decision to enter the hypothetical market of green electricity. They also demonstrate that participation in environmental organisations has a significant effect on the WTP to use only renewable energy.

The fact that the hypothetical approach relies on asking people to state their own preferences may lead to overstatement. This hypothetical bias is a source of enormous controversy. Alternatively, approaches based on actual behaviour employ surveys as opposed to hypothetical consumer behaviour. There are fewer studies in the literature investigating the actual behaviour of consumers towards renewable energy adoption. One of the advantages of a survey that focuses on the consumer behaviour is that it can help investigate how consumers actually react to different financing mechanisms for green electricity. For example, [Kotchen and Moore \(2007\)](#) considers the voluntary contribution mechanism (VCM) and the green tariff mechanism (GTM) to finance new generation capacity. They demonstrate 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 influencing early adoption of green electricity by Dutch residential users combining cognitive and economic approaches. They show that

in addition to economic variables, variables that are related to cognitive elements, basic knowledge and to past environmental behaviour strongly predict the probability of early adoption of green electricity. However, the fact that some studies focus only on green consumers (Young et al., 2010) constitutes the main limitation of surveys. Therefore, such studies can suffer from selection bias and the policy implications cannot be extended to consumers who do not adopt green behaviours. Furthermore, hypothetical and real approaches may give the same results for some key variables. For example, Roe et al. (2001) finds 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.

Variables that affect green energy demand in the residential sector may also affect the decision to invest in energy efficiency. In the following section we provide a review of the literature on factors influencing energy efficiency investment decisions in the residential sector.

0.3.2 Energy efficiency and household behaviour

Investments in energy efficiency also contribute to tackling climate change by reducing global energy demand. For example, 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). Furthermore, energy efficiency is a relatively cheap way to reduce GHG emissions in the short and medium term (Dietz et al., 2009 and Vandenberghe et al., 2007), while in the long term a complete transition to a low carbon economy is likely to be very slow (Fouquet, 2010). Therefore, the influence of household behaviour on their investment in energy efficiency has received a lot of attention in the economic literature. There is much evidence that economic factors are motivating energy efficiency (Howarth, 1997; Kempton and Neiman, 1986 and Steg, 2008) and can be helpful in designing appropriate taxes or subsidies to promote energy saving actions. For example, saving money or reducing energy bills 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 (between landlords

and tenants), 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 by supporting environmental actions through donation (Bindewald, 2013). For example, Wackernagel and Rees (1997) suggest that efficiency gains should be taxed away or otherwise removed from further economic circulation. Alternatively, the rebound effect can also be solved by pro-environmental motivation (Urban and Ščasný, 2012). But, there is no evidence in the literature regarding the influence of pro-environmental motivation on energy-saving actions at the household level. In the early literature, environmental concern did not have any effect on either energy consumption or energy-saving actions (Heslop et al., 1981). However, there has been growing concern about climate change in recent years (Capstick et al., 2015) and many studies show that environmental concerns have a significant impact on energy-saving actions (Barr et al., 2005 and Whitmarsh and O'Neill, 2010). A few studies still show limited effect (Carlsson-Kanyama et al., 2005 and Whillans and Dunn, 2015) or no effect (Steg, 2008) of pro-environmental motivation. Also, both economic and environmental concerns have different effects when energy conservation actions are considered separately.

In fact, the two main types of energy conservation actions are efficiency investments 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 involving changes in behaviour such as scheduling efforts, 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. \(1985\)](#) finds the opposite effect on non-monetary efficiency investments. Ultimately, both economic and environmental concerns may have ambiguous effects on energy-saving actions when considered as 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.

0.3.3 Interrelation between renewable energy and energy efficiency

The different variables that affect renewable energy adoption by households 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 the disparities between the effects 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 of renewable adoption and energy efficiency potentially produce biased results, because unobserved characteristics may exist that jointly determine the two decisions. For example, a household that is pro-environment can find it necessary to also invest in renewable energy (alternatively in energy efficiency) only if it has already invested in energy efficiency (alternatively in renewable energy). In this case, the household may rely on its environmental conscientiousness to combine the two investments. On the contrary, a household that already invests in energy efficiency (alternatively in renewable energy) may have limited financial capacity to also invest in renewable energy (alternatively in energy efficiency). Therefore, by jointly analysing the two possible decisions: (i) the adoption of renewable energy and (ii) investment in energy efficiency, one can capture the interrelation and the interaction between them. Such research could benefit policy design 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 study in the economics literature.

0.4 Smart grids and energy transition

The fact that many renewable sources of energy are inherently intermittent and unpredictable, makes their integration challenging. However, energy transition would lead to a significant change in the electricity grid in order to integrate clean and renewable sources for electricity generation. Therefore a new approach is required to efficiently manage the electricity grid, making full use of smart grid technologies for example. There are multiple definitions of smart-grids. According to the [IEA \(2011\)](#), "*A smart grid is an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users*". As described in Fig 6.5, the electricity system will then need to upgrade and to adapt to revolutionary new technologies in order to become smarter in many ways. Another definition of smart-grids comes from the [European Technology Platform \(2006\)](#), that developed the concept of smart grid in 2006 : "*A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it (generators, consumers and those that do both) in order to efficiently deliver sustainable, economic and secure electricity supplies*". Therefore, the main idea behind smart grids is the use of information technology to optimise energy production, distribution and consumption. This can contribute to cutting global CO_2 emissions and can be achieved by means of demand management, smart meters, energy efficiency, penetration of intermittent renewable energy, storage, micro-grids, etc. For example, [IEA \(2010\)](#) estimated that under the energy technology perspectives (ETP) BLUE Map scenario that smart grids offer the potential to achieve net annual emissions reductions of 0.7-2.1 Gt of CO_2 by 2050, including direct and indirect emission reductions. In this section, we focus on three levels of smart-grids: (1) possibility to feed into the electricity grid, (2) smart meters and (3) storage.

0.4.1 Feeding into the electricity grid

A low penetration of renewable energy in the electricity grid does not necessitate upgrading energy systems with smarter technologies. Even though electricity from wind and solar PV is intermittent, it is usually straightforward to manage the fluctuations

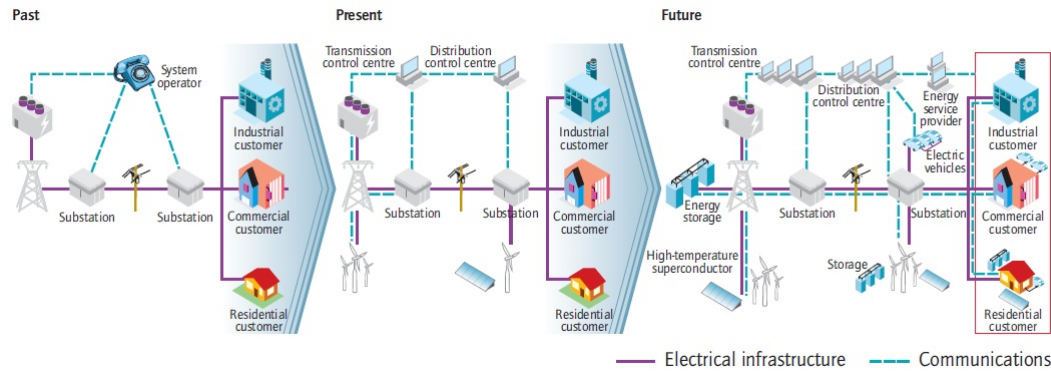


Figure 5: *Smarter electricity systems*

Source: [IEA, 2011](#)

when their contribution to total electricity is small. Selling to the grid can simply be achieved by net metering as long as this is not in conflict with legislation. This is allowed in European Union and in the U.S. while in Hong Kong and some African countries it is not. When wind and solar PV provide a much more important electricity, maintaining the reliability and the security of the energy systems become more challenging and may cause grid congestion. In this sense, giving households the possibility of feed excess electricity generation to the grid may require additional infrastructure. Although in many countries like the UK or Germany for example, it is already possible for households to provide renewable electricity to the grid, this may not become widespread.

The literature considering the penetration of renewables in the energy mix consists so far of two rather separate trends. On the one hand, macro-dynamic models à la Hotelling consider renewable energy as an abundant and steady flow available with certainty, but they ignore variability and intermittency and focus on the issue of cost (see for example [Hoel and Kverndokk, 1996](#) or [Tahvonen, 1997](#)). Another strand of literature studies the design of the electric mix (fossil fuels and renewables) when intermittency is taken into account (see [Ambec and Crampes, 2012, 2015](#)) or when storage takes care of peak electricity (see [Crampes and Moreaux, 2010](#)) or of excess nuclear production during periods of low demand ([Jackson, 1973](#)). A recent reference survey on the economics of solar electricity ([Baker et al., 2013](#)) emphasises the lack of economic analysis of a decentralised clean energy provision through renewable sources. Furthermore, [De Castro](#)

and Dutra (2013) show that the "public-goods" characteristics of reliability is likely to lead to an insufficient level of smart grid deployment. However, smart grids and electricity demand management has received much attention in the academic literature recently (see De Castro and Dutra, 2013 or Hall and Foxon, 2014 and Bigerna et al., 2016) and in the media (see The Economist, 2009 or The Telegraph, 2015a and The Telegraph, 2015b).

0.4.2 Smart meters

A smart meter is a type of smart-grid technology that allows for two-way communication between the utility and the consumer. Energy systems without smart meters lack transparency for consumers on the distribution side. Specifically, most people do not know how much electricity they are using until they are presented with a bill. Nor do most people know what proportion of their power is generated by nuclear, coal, gas or some form of renewable energy, or what emissions were produced in the process. Smart meter devices allow real-time pricing and also provide electricity price signals directly to smart appliances. Therefore, consumers become more reactive to peak load pricing and can make better decisions. For example, smart meters can enable consumers to use electricity only when it is available from renewables, and so favours high penetration of renewable electricity.

Smart meters are used relatively widely in Europe (e.g., Linky in France). However, Borenstein and Holland (2005) show that the expansion of electricity real time prices (RTP) is likely to harm customers who are already on RTP, but benefits customers who remain on flat rates. They also demonstrate that incremental changes in the use of RTP have impacts on the efficiency of the market that are not captured by those changing to RTP, an externality that implies that the incentive to switch to RTP will not in general be optimal. This suggests that, widespread use of smart meters may not always be beneficial to households and will necessitate investigating the socially optimal investment in smart meter devices. Also, the deployment of smart meters can contribute to an increase in the substitutability between electricity types at different periods. In this sense, households could have incentives to consume or store electricity when it is cheap to produce.

0.4.3 Storage

Energy storage systems can alleviate the reliability issue arising from intermittent sources of renewable electricity by decoupling the production and delivery of energy. There has been a growing interest in electric energy storage which is mostly dominated by pumped hydroelectric storage systems. Large-scale energy storage capacity is approximately 145 GW, mostly from pumped hydro (97%) (IEA, 2015c). Pumped-storage hydroelectricity is traditionally an engineering topic, with numerous papers in technical journals on the subject, while economists have not shown much interest (Forsund, 2015). For example, Crampes and Moreaux (2010) provide a simple framework to assess its efficiency and its optimal dispatch. They suggest that pumped storage systems should not be driven either by the electricity from thermal sources saved or by the cost saved at peak hours. In this sense, their economic driver is the net social gain from transferring social surplus from off peak to peak periods.

In addition to pumped storage system, many other energy storage systems are used worldwide. In an updated review, Beaudin et al. (2010) indicates that the challenge of the intermittency issue requires a different set of electric energy storage options. They characterise the different storage technologies which are: pumped hydro, compressed air energy, batteries, superconducting magnetic energy, hydrogen storage, flywheels, capacitors and super-capacitors. In a recent technology review on the place of energy storage in the energy transition, Gallo et al. (2016) also find that there is no energy storage technology that stands out in all technical characteristics simultaneously. Although electric energy storage technologies present many benefits with respect to management of the electricity grid with uncertain renewables, they may not become widespread as quickly as smart meters because they are expensive.

0.5 Organisation of the thesis

The transition to renewable energy involves two kinds of environmental concerns. First, fossil fuels are exhaustible and second, their use generates negative externalities through irreversible environmental damage. It then becomes crucial not only to decarbonise

energy systems, but also to find energy saving strategies in order to reduce global carbon emissions. Furthermore, there are some possible synergies between energy efficiency measures and renewable energy adoption in the sense that the former reduces the energy demand so that the latter can begin to cut future GHG emissions. The main objective of this dissertation is to analyse the optimal energy transition under the potential occurrence of an environmental catastrophe and to determine incentive-based strategies that can boost the energy transition. This dissertation consists of four chapters that independently present and discuss different aspects of energy transition. The first chapter focuses on the optimal energy transition involving decisions about both renewable energy adoption and investment in energy saving technologies, when there is a certain pollution threshold that triggers the occurrence of an environmental catastrophe. The second chapter investigates the optimal transition to renewable energy under uncertain occurrence of an environmental catastrophe. The third chapter is devoted to understanding household behaviour regarding energy transition. The fourth chapter explores the role of smart-grids in integrating intermittent renewable energy to facilitate the energy transition.

The first two chapters of the dissertation focus on the optimal energy transition of a two-sector economy (energy and final goods) with exhaustible oil reserves, a renewable source of energy and a pollution threat. In the first chapter, the latter corresponds to a certain pollution threshold above which an environmental and irreversible catastrophe occurs with the loss of part of the capital. The energy transition is driven by both the switching decision to cleaner energy sources and the pollution threshold effect. This chapter first proposes a general appraisal of optimal switching problems related to energy transition showing: (1) the possibility of a catastrophe due to accumulation of pollution; and (2) technological regimes with the adoption of renewable energy. To do that, we assume that the economy requires capital to produce clean energy that can be used as an input to produce a final good. We also assume complementarity between capital and energy as well as between clean and dirty energy. Second, given the baseline parameter values, we numerically show that the most profitable energy transition path may correspond to the one in which the economy starts using both resources, crosses the pollution threshold by losing a part of its capital and never adopts clean energy only.

This result is in line with arguments supporting the idea that a complete transition to a low carbon economy is likely to be very slow. Without innovations in the energy sector such as investment in energy efficiency, and because fossil fuels are needed to produce clean energy, it is more profitable to progressively reduce dependency on fossil fuels which is costless (except for the catastrophe, which occurs once), than to switch to sole use of a costly clean energy. Third, we extend the model to the adoption of energy saving technologies, which very few works deal with in the literature. Numerical results mainly show that this additional investment favours full transition to the sole use of renewable energy in the sense that it postpones environmental catastrophe, is welfare-improving and allows a complete energy transition. It is then profitable to take advantage of these synergies by jointly promoting deployment of clean energy and providing incentives for investment in energy saving technologies

The second chapter considers that the pollution thresholds above which environmental catastrophes are expected to occur are uncertain. The environmental event corresponds to flooding generated by climate change after which (i) only a quantity of capital and resources known ex-ante will be rescued and (ii) there is a direct loss of utility. This chapter first analyses the optimal energy transition as optimal switching problems involving two regime switches, one of them being uncertain. In this sense, we generalise from the model without uncertainty in the first chapter. It can be seen as a first attempt at an analytical representation of the energy transition under ecological risk. This new optimal control material is then applied to address the problem of optimal energy transition under ecological risk. For that purpose, we consider the same two-sector setting, where the economy produces energy and final goods. Energy initially comes from both oil and renewable energy sources (RES) but can eventually be produced using only RES if fossil fuels are exhausted. The use of oil by both the final goods sector and households has a potential negative impact on the environment through a stochastic critical pollution threshold above which a catastrophic event occurs. This event results in some loss of utility for households and in the destruction of a part of capital and fossil fuel reserves (the amounts rescued being known ex ante). We analytically solve the model for the steady state solutions using backward induction. Second, the probability of

damage occurrence and the optimal time to reach the economy only fuelled by renewable energy are obtained numerically. We demonstrate that there are numerical values that correspond to a higher pollution level at the steady state than that of the threshold level: the environmental catastrophe may happen. We also show situations in which the optimal energy transition path corresponds to three phases, starting with the use of both types of energy resources followed by the catastrophe, and finally by the use of RES only. Ultimately, higher hazard rates generate more cautious behaviour that negatively affects pollution, but the risk of damage still increases.

Following the suggestions of the first chapter regarding the importance of energy saving technologies in the full transition to renewable energy, the third chapter investigates at the household level, the two decisions to adopt renewable energy and to invest in energy efficiency. There are 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 substantially in the residential sector. Specifically, this chapter explores the influence of household behaviour on the energy transition through renewable energy adoption and investment in energy efficiency. In the residential sector, much work has been done either on demand for clean energy or on investment in energy efficiency, but to our knowledge there is no specific study that investigates the interaction between the two decisions. This chapter fills this gap in the literature and first theoretically shows that there are interactions (complementarity or substitution) between the two decisions depending on the threshold of the cross effect related to the environmental motivation of the consumer. We use a simple model in which a household devotes its energy budget to buy non-clean energy and to undertake investments in energy efficiency and in renewable energy, which contribute to a transition to a low carbon economy. The theoretical model is followed by empirical investigations of the interactions between the two decisions. We explore whether the decision of household to adopt renewable energy and that of investing in energy efficiency in residential sector are related. We use a bivariate probit (biprobit) model for the joint decision to show that the two decisions are positively interrelated and cannot be estimated independently. Additionally, we investigate the determinants of the interaction between

the two decisions by using a generalised ordered logit model. Essentially, 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. This contribution can serve to define incentive policies to boost energy transition with respect to energy poverty, split incentives, economic and environmental motivations, etc. 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).

A transition to renewable energy that depends on intermittent resources would generate another challenge: the reliability, safety and security of energy generation systems. Smart grid technologies provide solutions to deal with this new challenge and help promote the integration of renewable energy. In the fourth chapter of the dissertation, we study the efficient mix of investments in intermittent renewable energy (namely, solar panels) and energy storage, and evaluate the consequences of demand side management by accounting for three levels of equipment in smart grids: (i) net metering, (ii) smart meters and (iii) energy storage. The novelty of our model accrues from the flexibility it assigns to a household in feeding (or purchasing) electricity to (or from) the grid or to store energy (or use stored energy) upon renewable energy installations. Additionally, we analyse the consequences of energy storage and smart meters for purchase of electricity from the grid and electricity consumption, the desirability of smart meter installation and the implications of curtailment measures in avoiding congestion. The first result indicates that it is beneficial to install a smart meter enabling the household to benefit from electricity price variations when the expected electricity price is either sufficiently low or high. The second result is that the objective to rely less on the grid through the use of a smart meter cannot be attained unless the expected price is sufficiently high. Otherwise, the reliance on the grid will be higher leading to further emissions. This result points out that electricity price levels need to be carefully contemplated if the aim

is to depend less on the grid through smart grid deployment. Furthermore, we consider the congestion problem that can arise when there is too much in-feed to the grid. Our analysis demonstrates that curtailment measures to avoid congestion can discourage investment in renewable energy generation and energy storage capacity. When such investments are discouraged, our results indicate that, first, electricity generated and fed to the grid by the household will be curtailed at the higher end of the price schedule, second, the household will not necessarily purchase more electricity from the grid.

The dissertation is organised as follows.

Chapter 1: Energy transition under irreversibility: a two-sector approach

**Chapter 2: Energy transition under the risk of an environmental catastrophe:
a two-sector approach**

**Chapter 3: Investment in Energy Efficiency, Adoption of Renewable Energy
and Household Behaviour: Evidence from OECD countries**

Chapter 4: Intermittent renewable electricity generation with smartgrids

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Chapter 1

Energy transition under irreversibility: a two-sector approach 1

Abstract

This paper analyses the optimal energy transition of a two-sector economy (energy and final goods) under irreversible environmental catastrophe. First, it proposes a general appraisal of optimal switching problems related to energy transition showing: (i) the possibility of a catastrophe due to accumulation of pollution; and (ii) technological regimes with the adoption of renewable energy. Second, it numerically shows that for given baseline parameter values, the most profitable energy transition path may correspond to the one in which the economy starts using both resources, crosses the pollution threshold by losing a part of its capital, and never adopts only clean energy. Third, it extends the model to allow for additional investment in energy saving technologies. We then find that this additional investment favours full transition to the sole use of renewable energy. It is then profitable to take advantage of these synergies by jointly promoting deployment of clean energy and providing incentives for investment in energy saving technologies.

Keywords: *energy, irreversibility, pollution, switch.*

JEL Classification: *Q30, Q53, C61.*

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1.1 Introduction

In order to reduce global CO₂ emissions by 50 per cent from 2005 to 2050, some energy policies employ scenarios which focus on adoption of renewable energy (RE) sources and investment in energy saving technologies (EST). Despite growing investment in the production of RE (63 to 244 billion USD from 2006 to 2012 (GEA, 2012), fossil fuels, i.e. dirty energy sources are still mainly used (78.2%) throughout the world. Therefore it is crucial not only to drastically change the way energy is produced, but also to find energy saving strategies. According to the Global Energy Assessment (GEA), about one-third of overall investment in the energy sector is efficiency-related, following the efficiency pathways (GEA, 2012). This paper focuses on energy transition that involves decisions about both RE adoption and investment in EST. We analyse the optimal energy transition of a two-sector economy (energy and final goods) with exhaustible oil reserves, a renewable source of energy and a pollution threat.

Energy transition involves decisions about both RE adoption and investment in EST. The former concerns adopting clean energy sources as an alternative to polluting sources of energy, while the latter could help reduce overall energy consumption. In the early literature on natural resource economics, many authors adopted a different focus on the long run depletion of oil reserves and on the polluting feature of oil. Dasgupta and Heal (1974, 1979), Dasgupta and Stiglitz (1981) and Krautkraemer (1986) analyse the long run depletion of oil reserves, while Nordhaus (1994) and Tahvonen (1996, 1997) focus on the polluting aspects of oil. In this regard, one solution could be to adopt a backstop technology (a renewable resource for example) as a clean energy. More recently, several works (Acemoglu et al., 2014; Amigues et al., 2015 and Tsur and Zemel, 2003) focus on climate change as one of the important reasons for the transition to clean energy or to clean technologies. As the use of polluting energy resources generates pollution that accumulates over time, an ecological catastrophe may occur at some point in time. The catastrophic event will generate some irreversible damage² (Forster, 1975; Tahvonen and

²There are various types of irreversibility. It could be exhaustion of the natural regeneration capacity (Tsur and Withagen, 2013), an irreversibility in the decision process (Pommeret and Prieur, 2009 and Ayong Le Kama et al., 2014) or a ceiling on the pollution stock (Lafforgue et al., 2009 and Chakravorty et al., 2012).

Withagen, 1996; Ulph and Ulph, 1997; Pindyck, 2002; Pommeret and Prieur, 2009 and Ayong Le Kama et al., 2014). Damage can also be partly reversible (Tsur and Zemel, 1996 and Nævdal, 2006), or fully reversible (Kollenbach, 2015).

There is no consensus in the literature about how to model environmental damage resulting from pollution. Some authors consider the damage as income loss (Karp and Tsur, 2011 and Tsur and Withagen, 2013) or social welfare loss (Van der Ploeg and Withagen, 2012 and Prieur et al., 2013). Other authors focus on productive sectors: capital loss (Ikefuji and Horii, 2012); or destruction capacity (Golosov et al., 2014). The present paper assumes that the economy experiences a catastrophic event when the level of pollution is above a certain critical threshold. Therefore, the economy loses part of its productive stock of capital. Moreover, to support the simultaneous use of both resources, many authors assume a convexity of the production cost of renewable energy (Chakravorty et al., 1997 and Amigues et al., 2015) or an increasing extraction cost of fossil fuels (Tsur and Zemel, 2005 and Kollenbach, 2015). For example, Amigues et al. (2015) studies energy transition in a deterministic framework and consider adjustment costs over production capacity of renewable energy. They identify three energy regimes in a partial equilibrium setting with an intermediate regime of simultaneous use of both resources. In addition, several studies assume imperfect or perfect substitution between inputs. Alternatively, we consider the case of an economy with rigidities such that oil and RE sources are complementary, as in Pelli (2012). Moreover, we also assume that capital use and energy are complementary, as in Pindyck and Rotemberg (1983), Boucekkine and Pommeret (2004) or Díaz and Puch (2013).

In a deterministic framework, Boucekkine et al. (2013) provide first order optimality conditions in an optimal regime switching problem with threshold effects. These optimality conditions are the continuity of appropriate co-states and states variables, and that of the Hamiltonian. The present paper is mainly related to the application in that paper as it involves both the switching decision to cleaner energy sources and the pollution threshold effect as the main drivers of energy transition. However, the contribution of our paper is threefold. First, we use a two-sector approach in which the

economy requires capital to produce energy that can be used as inputs to produce a final good. We do not allow a natural regeneration capacity, instead we consider the irreversibility of pollution for a loss of capital. In the same vein, we do not account for direct pollution damage, but only the loss of productive capital due to the occurrence of a catastrophe. In contrast to this paper, we allow a simultaneous use of both resources (dirty and clean energy sources). More precisely, we assume that there is a complementarity between both resource use and capital in the production of final goods.

Given the baseline parameter values, we numerically show that the most profitable energy transition path may correspond to the one in which the economy starts using both resources, crosses the pollution threshold by losing a part of its capital and never adopts clean energy only. This result is in line with arguments supporting the idea that a complete transition to a low carbon economy is likely to be very slow. Without innovations in the energy sector such as investment in energy efficiency, and because fossil fuels are needed to produce clean energy, it is more profitable to progressively reduce dependency on fossil fuels which is costless (except for the catastrophe, which occurs once), than to switch to sole use of a costly clean energy. Sensitivity analysis shows that high productivity of capital and energy services in the final goods sector and of capital in producing clean energy postpones the occurrence of an environmental catastrophe. Therefore, public policy should promote innovation that helps increase the productivity of capital and energy services in final goods and energy sectors.

Third, we extend our model to the adoption of energy saving technologies, which very few works deal with ([Charlier et al., 2011](#); [De Groot et al., 2001](#) and [Acemoglu et al., 2014](#)). In order to fill the gap in the literature about the importance of EST in energy transition, we extend our model to allow for investment decisions in EST. More precisely, the economy may decide to invest in energy saving appliances or in energy efficient systems to reduce overall energy consumption. This investment is additional to that made in clean energy to help reach energy transition targets. Numerical results mainly show that this additional investment favours full transition to the sole use of renewable energy in the sense that it postpones environmental catastrophe, is welfare-improving and allows a

complete energy transition. It is then profitable to take advantage of these synergies by jointly promoting deployment of clean energy and providing incentives for investment in energy saving technologies. This is particularly important for developing countries which mostly rely on polluting energy resources and are the most vulnerable to climate change. The remainder of this paper is structured as follows: The model is presented in Section 2. We analyse the optimal energy transition path in Section 3. Section 4 extends the model to allow investment in EST. Conclusions are presented in Section 5.

1.2 Model

In this section, we present a model for transitory regimes (first and second regimes) in which both types of energy (dirty and clean) are used simultaneously, while production of dirty energy is cut out in the third and final regime (see section 1.3.1 for the definition of regimes). We consider a closed economy that produces energy and final goods in a general equilibrium setting. The economy uses a dirty source (exhaustible oil reserves) and a clean source (for example solar panels) to produce energy. Part of the energy is used as energy services by a representative consumer through a separable utility function. The other part is used as input in a Leontief production function to produce final goods. The use of dirty energy by both final goods sector and households has a negative impact on the environment. Above a certain pollution threshold, the economy experiences a catastrophic event and loses a part of its stock of capital. In the following sections, we describe the energy sector, the final goods sector, household utility and pollution threats, respectively.

1.2.1 Energy sector

Energy is an intermediate good that is produced using E_d , a non-renewable and dirty source, and E_c , a renewable and clean source. A representative consumer uses part E_C of the energy as energy services, while the other part E_Y is used as an input to produce final goods. Let us denote respectively E_{Cd} , E_{Cc} , E_{Yd} and E_{Yc} the parts of the dirty and the clean energy that households use and that the final goods sector uses. We assume that production of the dirty energy is costless. The stock S_t of the dirty energy source at

each time t is generated by the following dynamics:

$$\dot{S}_t = -E_{dt} \quad (1.1)$$

where E_{dt} is the rate of extraction of the dirty energy source.

The production of clean energy requires the use of capital. For example, to produce solar (or wind) energy, one needs to install solar panels (or wind turbines) in order to transform sunlight (wind) into electricity. Hence we assume a " η -to-one" transformation of K_{Et} , a part ϕ of capital K_t as follows:

$$E_{ct} = \eta K_{Et} = \eta \phi K_t \quad (1.2)$$

where η is the productivity of capital in the clean energy sector. Due to the high-efficiency energy conversion of clean technology such as solar panels, we assume that productivity is high and greater than one ($\eta > 1$).

In our model, pollution only comes from the use of dirty energy. The following energy market clearing conditions holds:

The dirty energy that the economy produces is fully consumed by households and as an input to produce final goods:

$$E_{dt} = E_{Ydt} + E_{Cdt}. \quad (1.3)$$

Total production of the clean energy is split between the final goods sector and household energy consumption:

$$E_{ct} = E_{Yct} + E_{Cct}. \quad (1.4)$$

Finally, the total energy used in the economy is from the dirty and clean energy sources:

$$E_{Yt} + E_{Ct} = E_{ct} + E_{dt}. \quad (1.5)$$

1.2.2 Pollution threat

The use of dirty energy source either by households or as an input to produce final goods generates greenhouse gas emissions. Pollution accumulates in the environment (atmosphere) according to the following process:

$$\dot{Z}_t = E_{dt}. \quad (1.6)$$

We do not account for the natural regeneration capacity of the environment as in [Van der Ploeg and Withagen \(2012, 2014\)](#). Admittedly, our pollution dynamics are quite restrictive. However, our assumption can be seen as the most pessimistic way to deal with the threat of pollution to justify the necessity of an energy transition. Moreover, though there are no formal statistics for natural assimilation, climate change experts usually report that half of the CO_2 emitted is currently removed from the atmosphere within a century ([IPCC, 2007b](#)). It may therefore have a very small effect on the path of fossil fuels. Relaxing this assumption would possibly delay a catastrophe, but will not affect an optimal transition that contains a regime after the catastrophe.

Ultimately the economy experiences a catastrophic event. When the level of pollution Z_t is above a certain critical threshold \bar{Z} , the economy loses once and for all a part θ of its capital stock when the catastrophe occurs. The stock of capital is then suddenly destroyed.

1.2.3 Final goods sector

In order to produce a final good Y_t , a part E_{Yt} of energy and a part $(1 - \phi)$ of capital (K_{Yt}) serve as inputs in a Leontief production function. The interpretation runs as follows: There exist operating costs where the amount depends on the energy requirements of the capital, such that for any capital use there is a corresponding energy requirement. Such complementarity is assumed in order to be consistent with several studies arguing that capital and energy are complements (see for example [Berndt and Wood, 1975](#); [Pindyck and Rotemberg, 1983](#); and more recently [Díaz and Puch, 2013](#)). The production function

is defined as:

$$Y_t = \min\{\alpha_2 K_{Yt}, \beta_2 E_{Yt}\}, \quad (1.7)$$

with

$$K_{Yt} = (1 - \phi)K_t. \quad (1.8)$$

For analytical convenience we also assume that use of both the dirty and clean resources is complementary. The clean and the dirty sources may not be complementary, and in reality two types of explanations can be provided. First, using an econometric approach, [Pelli \(2012\)](#) proves that there exists some complementarity between dirty sources of energy (oil, coal, gases) and clean ones (hydroelectric, biomass-wood and waste, geothermal, solar/photovoltaic, wind and nuclear). The implication is that production of energy using a clean source, for example solar panels, requires oil to build the solar panels. Second, the presence of rigidities in a macroeconomic view may also explain the complementarity between dirty and clean sources: for example, it is not easy to substitute between oil and the electricity provided by solar panels. Several studies assume imperfect substitution ([Michielsen, 2014](#)) or perfect substitution between energy sources ([Van der Ploeg and Withagen, 2012, 2014](#)). While the latter assumption is unrealistic and is an extreme case, the complementarity assumption is also an extreme case of imperfect substitution. Therefore, reality lies between these two extreme cases (perfect substitution and complementarity). Moreover, this assumption allows us to highlight the implication of complementarity between the two types of energy sources in the energy transition. Relaxing this assumption would introduce energy transition paths where fossil fuels are solely used in the first regime (see for example [Amigues et al., 2015](#)).

We define E_{Yt} as:

$$E_{Yt} = \min\left\{\frac{1}{\xi}E_{Ydt}, E_{Yct}\right\} \quad (1.9)$$

where ξ is the coefficient of the combination between the clean and the dirty sources of energy.

1.2.4 Households

We consider a representative household using energy services E_{Ct} and consuming a non-energy good C_t , excluding durable goods. We assume that utility can then be expressed over all goods as separable on energy services $u_t(E_{Ct})$ and on non-energy goods $u_t(C_t)$.^{3,4} Therefore, the gross utility U_t represents consumer preferences that are expressed by the discounted sum of instantaneous separable utility flows:

$$U_t = \int_{T_0}^{\infty} \left[\frac{C_t^{1-\delta}}{1-\delta} + \frac{E_{Ct}^{1-\delta}}{1-\delta} \right] e^{-\rho t} dt, \quad (1.10)$$

where ρ is the discount rate, δ is a positive coefficient of utility that is different from 1 and T_0 is time 0 with $T_0 = 0$.

Both the clean and the dirty energy sources are complementary for the same reasons as in the final goods sector⁵

$$E_{Ct} = \min\left\{\frac{1}{\xi}E_{Cdt}, E_{Cct}\right\} \quad (1.11)$$

where ξ is the part of the dirty energy used in the energy mix as defined in eq. (1.9).

Households own firms in both the energy and final goods sectors. They consume a part of the final goods production and invest the rest to produce clean energy and final goods:⁶

$$Y_t = C_t + \dot{K}_t, \quad (1.12)$$

³A non-separable utility function (Cobb-Douglas or Constant Elasticity of Substitution) would capture crossing effects arising from a strong relationship between the use of dirty energy, clean energy and the level of consumption. To avoid such effects, we focus on non-durable goods.

⁴An alternative model in which households consume final goods combined with home-based services produced from capital and energy consumption would lead to similar results in the sense that our definition of energy services (mainly clean energy) implicitly incorporates capital. However, we only consider investments in productive sectors (i.e. the final goods sector and the energy sector) for simplicity. As stated in footnote 3, such an alternative model would capture crossing effects arising from strong Leontief relationships.

⁵This is a strong assumption but it is consistent with the complementarity assumption considered in the final goods sector (see section 1.2.3). If there were an available technology in the final goods sector that allows for substitution between fossil fuel and renewable energy, this technology could be used by households as well.

⁶For simplicity and analytical tractability, we consider the particular case of no capital depreciation without loss of generality. The absence of capital depreciation, will simply induce a lower optimal level of investment.

with

$$K_t = K_{Et} + K_{Yt}. \quad (1.13)$$

In the following sections, we first analyse the optimal energy transition path. In Section 4, we provide the numerical results. Finally, we extend the model to the adoption of energy saving technologies in Section 5.

1.3 Optimal energy transition path

In this section, we analyse energy transition paths that include a catastrophic event and/or sole use of clean energy. Three regimes can occur. In the first one, energy is produced by both dirty and clean resources that are complementary, and the level of pollution is below the threshold. In the second regime, the catastrophe has occurred and both energy sources are used again, but pollution is above the threshold. The third regime is characterized by the sole use of the clean energy. We assume that time starts at $T_0 = 0$, T_1 is the date at which the second regime starts, while the third regime starts at date T_2 . T_1 and T_2 can take zero, strictly positive and infinite values. Crossing T_1 and T_2 defines nine energy transition paths. We first focus on the energy transition path that corresponds to strictly positive values for T_1 and T_2 ($T_1 > 0$, $T_2 > 0$), which we denote as the ‘central’ energy transition path because it is a succession of the three regimes. The second part of this section focuses on the remaining eight paths that we denote as ‘corner’ energy transition paths because there are specific cases. To solve for the corner energy transition paths, we simply need to set appropriate values (zero, infinite values for T_1 and T_2).

1.3.1 Central energy transition path

In this section, we analyse the central energy transition path that is a succession of regimes for which the regime switch corresponds to a change of model as follows: The economy starts by using both sources of energy (dirty and clean) and therefore pollutes. The economy accumulates pollution up to the threshold \bar{Z} (section 1.3.1). Once pollution exceeds this critical level \bar{Z} , the economy experiences a catastrophic event. Then, a part θ of capital is then suddenly destroyed, (section 1.3.1) but the economy still uses

both sources of energy. Once the economy switches to sole use of the clean energy, the production of dirty energy is cut out (section 1.3.1). We backward solve for the optimal general path starting from the third regime (sole use of clean energy) followed by the second regime and lastly by the first regime. We use the boundary conditions as in Boucekine et al. (2013) to find the optimal time at which the economy crosses the critical pollution threshold and turns to the sole use of clean energy. As it is not possible to obtain an analytical solution, we solve it numerically.

Third regime: Sole use of clean energy

During the third regime, the economy solely uses clean energy. Therefore, constraints (1.1) and (1.6) both become irrelevant and Eq. (1.9) and Eq. (1.11) drop and are replaced by $E_{Yt} = E_{Yct}$ and $E_{Ct} = E_{Cct}$, respectively. By combining Eq. (1.13) together with the Leontief conditions (LC, hereafter) applied to Eq. (1.7), Eq. (1.12) can be rewritten as (see the proof in Appendix A₁):

$$\dot{K}_t = \alpha_2(K_t - \frac{1}{\eta}E_{Yt} - \frac{1}{\eta}E_{Ct}) - C_t. \quad (1.14)$$

The social planner solves the following programme:

$$V_3 = \text{Max} \int_{T_2}^{\infty} \left(\frac{C_t^{1-\delta}}{1-\delta} + \frac{E_{Ct}^{1-\delta}}{1-\delta} \right) e^{-\rho(t-T_2)} dt$$

st Eq. (1.14),

where T_2 is the switching time to the third regime.

The corresponding Hamiltonian is defined as:

$$H_3 = \frac{C_t^{1-\delta}}{1-\delta} + \frac{E_{Ct}^{1-\delta}}{1-\delta} + \lambda_t \left[\alpha_2(K_t - \frac{1}{\eta}E_{Yt} - \frac{1}{\eta}E_{Ct}) - C_t \right],$$

with λ_t the co-state variable related to capital K .

The first order conditions (FOCs) with respect to C_t , E_{Ct} and K_t respectively give:

$$C_t^{-\delta} = \lambda_t \quad (1.15)$$

$$E_{Ct}^{-\delta} = \frac{\alpha_2}{\eta} \lambda_t \quad (1.16)$$

and

$$\frac{\dot{\lambda}_t}{\lambda_t} = \rho - \alpha_2, \quad (1.17)$$

where λ_t is the co-state variable associated with capital.

One can easily identify the consumption versus savings arbitrage condition in equations (1.15) and (1.16). It states that the marginal value of capital has to equal the marginal utility of consumption on the one hand, and the marginal utility of energy services on the other. Moreover, condition (1.17) implies a constant instantaneous return over capital.

Solving Eq. (1.14) using Eqs. (1.15)-(1.17), LC applied to Eq. (1.7) and the transversality condition (see the proof in Appendix A₂), we obtain:

$$K_t = -\frac{\Theta \delta}{\alpha_2 - \rho - \delta \Lambda} \lambda_{T_2}^{-\frac{1}{\delta}} e^{\frac{(\alpha_2 - \rho)}{\delta}(t - T_2)},$$

where $\Lambda = \frac{\alpha_2 \beta_2 \eta}{\alpha_2 + \beta_2 \eta}$, $\Theta = \frac{\alpha_2 \beta_2}{\alpha_2 + \beta_2 \eta} \left(\frac{\alpha_2}{\eta}\right)^{-\frac{1}{\delta}} + 1$ and λ_{T_2} , the marginal value of the capital at the switching time T_2 will be determined in Section 1.3.1 using boundary conditions.

We can easily deduce the value function V_3 during the third regime:

$$V_3 = -\frac{\delta [1 + (\frac{\alpha_2}{\eta})^{-\frac{1-\delta}{\delta}}] \lambda_{T_2}^{-\frac{1-\delta}{\delta}}}{(1-\delta)[\alpha_2(1-\delta) - \rho]}.$$

Second regime: Simultaneous use of dirty and clean energy, exhaustibility of the dirty source of energy

In the second regime, both the clean and dirty energy sources are still used after the catastrophe. Therefore, the economy faces an exhaustibility problem Eq. (1.1) while Eq. (1.6) is irrelevant. Applying LC to Eq. (1.7) and used together with Eq. (1.8), equation (1.12) can be rewritten as:

$$\dot{K}_t = \alpha_2(1 - \phi)K_t - C_t. \quad (1.18)$$

Using the LC from Eq. (1.9) and Eq. (1.11), and summing up the two, Eq. (1.1) becomes:

$$\dot{S}_t = -E_{dt} = -\xi(E_{Yt} + E_{Ct}). \quad (1.19)$$

The social planner solves the following programme:

$$V_2 = \text{Max} \int_{T_1}^{T_2} \left(\frac{C_t^{1-\delta}}{1-\delta} + \frac{E_{Ct}^{1-\delta}}{1-\delta} \right) e^{-\rho(t-T_1)} + V_3 * e^{-\rho T_2}$$

st Eq. (1.18) and Eq. (1.19) ,

where T_1 is the switching time to the second regime.

The corresponding Hamiltonian can be written as:

$$H_2 = \frac{C_t^{1-\delta}}{1-\delta} + \frac{E_{Ct}^{1-\delta}}{1-\delta} + \mu_t[\alpha_2(1 - \phi)K_t - C_t] - \nu_t \xi(E_{Yt} + E_{Ct}),$$

with μ and ν the co-state variables associated with the capital K and the stock of the dirty source of energy S_t , respectively.

Resolution of the capital accumulation equation Eq. (1.18) using the FOCs of the above programme gives (see proof in Appendix A₃):

$$K_t = -(\overline{K}_2 - K_{T_1}) * e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(t-T_1)} + \overline{K}_2,$$

where \overline{K}_2 is a constant and will be determined using boundary conditions in Section 2.3.3. Finally, using the fact that the dirty energy source is exhaustible and the fact that we have crossed the pollution threshold after a period of time T_1 , we get (see proof in Appendix A₄):

$$\nu_{T_1} = f(\nabla, \overline{K}_1, \overline{K}_2, T_1, T_2),$$

where ∇ is the set of parameters, \overline{K}_1 a constant and ν_{T_1} and K_{T_1} , the marginal value of the stock of the dirty source of energy and the level of capital at the switching time T_1

respectively, that will be determined by the boundary conditions in Section 1.3.1.

First regime: Simultaneous use of dirty and clean energy, pollution problem

At the beginning of the programme, the economy starts using both energy sources and faces a pollution problem Eq. (1.6). A catastrophic event may occur once the level of pollution reaches the critical threshold that results in loss of capital. We assume that dirty energy is abundant ($S_0 > \bar{Z}$) so that Eq. (1.1) is irrelevant. Therefore, the economy crosses the pollution threshold before complete depletion of the dirty energy source. From Eq. (1.19), equation (1.6) becomes:

$$\dot{Z}_t = -\dot{S}_t = \xi(E_{Yt} + E_{Ct}). \tag{1.20}$$

The social planner then solves:

$$V_1 = \text{Max} \int_0^{T_1} \left[\left(\frac{C_t^{1-\delta}}{1-\delta} + \frac{E_{Ct}^{1-\delta}}{1-\delta} \right) e^{-\rho t} \right] dt + V_2^* e^{-\rho T_1}$$

st Eq. (1.18) and Eq. (1.20),

which looks like the programme solved in the second regime (section 1.3.1) except for the sign of Eq. (1.20). We present the results of the first regime in Appendix A5.

Boundary conditions

We use three types of boundary conditions: (i) continuity of the co-state variable related to the capital μ_t ; (ii) continuity of K_t ; and (iii) the equality of the Hamiltonian at the switching time. The co-state variable ν_t associated with the pollution stock Z is not continuous at the switching time T_1 because Z_t is fixed to \bar{Z} . At the switching time T_2 , Z_t can be freely chosen and becomes continuous but it no longer exists during the third regime because clean energy is not polluting. The continuity of μ_t together with that of K_t helps to determine $\bar{K}_1, \bar{K}_2, K_{T_1}, K_{T_2}, \lambda_{T_2}, \nu_{T_0}$ and ν_{T_1} , respectively (The expressions and proof are available in the online appendix 1.8.2). We then simultaneously and numerically solve the equality of Hamiltonians at the switching time T_1 and T_2 to get T_1 and T_2 . Now, let us consider the corner energy transition paths before providing the numerical value function.

1.3.2 Corner energy transition paths

We exclude four corner energy transition paths among a total of eight because they are infeasible. The corner energy transition path of $T_1 = 0$ combined with $T_2 > 0$, $T_2 = 0$ or $T_2 = \infty$ cannot occur because the economy cannot start above the pollution threshold without consuming the polluting energy. If the economy starts with the clean energy source, it will never cross the pollution threshold as it is not polluting. Thus, the corner energy transition path that corresponds to the case $T_2 = 0$ and $T_1 > 0$ is not possible. Finally, we consider the following corner energy transition paths: (i) One switch to the sole use of clean energy (section 1.3.2), (ii) One switch above the pollution threshold (section 1.3.2), (iii) No switch (section 1.3.2) and (iv) Starting with the clean energy (section 1.3.2). In this section we present only the four relevant energy transition paths⁷

One switch to the sole use of clean energy ($T_1 = \infty$)

This case is a corner energy transition path in which the economy never exceeds the critical pollution threshold and therefore only switches to sole adoption of the clean energy. The economy starts using both the dirty and clean resources that are complementary, and pollution is below the critical level. After some time T , it switches to sole use of the clean source of energy before the level of pollution crosses the pollution threshold. Therefore, the economy escapes the catastrophe forever. To obtain the switching time T , it is sufficient to set $T_1 = \infty$ and $T_2 = T$.

One switch above the pollution threshold ($T_2 = \infty$)

This case corresponds to the transition from the first regime to the second regime without the switch to the third regime. Again, the economy starts using both the dirty and clean sources of energy with a level of pollution that is below the threshold level. Then, the economy switches to the regime in which both energy sources are still used but, the level of pollution is now above its critical threshold and the economy never makes a

⁷Note that by assumption, the initial stock of the dirty source of energy S_0 is used in the first regime (\bar{Z}) and the remaining is used in the second regime ($S_0 - \bar{Z}$). Thus, any energy transition path that includes only the first regime or its combination with the third regime is characterized by S_{T_2} that goes to $S_0 - \bar{Z}$, while it goes to 0 for any energy transition path that includes both first and second regimes. When the energy transition path does not include either of the first two regimes, $S_{T_2} = S_0$.

full transition to the sole use of clean energy. To obtain the switching time T and the dynamics of variables, one needs to set $T_2=\infty$ and $T_1 = T$.

No switch ($T_1=\infty$ and $T_2=\infty$)

On the no-switch energy transition path, the economy always uses both the dirty and clean sources of energy. Moreover, it does not solely use clean energy and the level of pollution remains below its critical threshold forever. This energy transition path corresponds to the first regime and one does not need to use boundary conditions to obtain the switching time. It is sufficient to set $T_1=\infty$ and use the transversality conditions that give $\bar{K}_1 = 0$.

Starting with clean energy ($T_1=\infty$ and $T_2=0$)

On this energy transition path, the economy never uses the dirty source of energy and therefore does not pollute. The pollution threshold then becomes irrelevant. It corresponds to the third regime without any pollution threat. In this case, we need to set $T_1=\infty$ and $T_2=0$.

1.4 Numerical results and sensitivity analysis

In this section, we numerically solve for the switching times T_1 and T_2 , and calculate the value functions of the central energy transition path and that of each of the corner energy transition paths. We present the parameter values that are used to obtain the numerical results. We also provide the numerical value functions and the sensitivity analysis.

1.4.1 Numerical results

Due to lack of information about some parameters in our model, we can only provide numerical illustrations of our results. Therefore, we do not attempt to fully calibrate the model. As a consequence, the results hold only for the baseline values of the parameters. We also perform sensitivity analysis on parameters that are relevant to policy to assess the validity of the results. Parameter values have been chosen as follows: As in [Van der Ploeg and Withagen \(2014\)](#) we set the discount rate ρ at 0.014 and the inverse of the

elasticity of intertemporal substitution δ at 2. Moreover, we consider the pollution threshold $\bar{Z} = 1200$ gigatonne of carbon (*GtC*) as in [Prieur et al. \(2013\)](#), which relies on a calibration exercise developed by [Karp and Zhang \(2012\)](#). Other parameters are arbitrarily chosen in order to provide a numerical illustration (see online appendix [1.8.1](#) for more details).

With the baseline parameters, we first numerically solve for the optimal levels of T_1 and T_2 . Then, we derive the value functions of the central energy transition path and that of each of the corner energy transition paths, which we compare and select the one that gives the highest value function. The numerical results are summarised in [Table 1.1](#). We also provide graphical comparisons of the value functions of energy transition paths in [Figure 6.3](#).

Table 1.1: *The value functions of the energy transition paths*

Energy transition path	Value function
Central case ($T_1 = 28$; $T_2 = 100$)	-89.93
$T_1 = \infty$	-143.58
$T_2 = \infty$	-43.6568
$T_1 = \infty$; $T_2 = \infty$	-86.59
$T_1 = \infty$; $T_2 = 0$	-122.23

The most profitable energy transition path is the one that gives the highest value function to the social planner. Given our baseline parameters, it corresponds to the corner energy transition path in which $T_2 = \infty$. In such a case, the most profitable energy transition path can be described as follows: The economy starts using both sources of energy. Then, it crosses the pollution threshold and loses a part of its capital. Finally, the economy keeps using the dirty and clean energy and never switches to the sole adoption of clean energy in the long term. One could observe that the corner energy transition path that corresponds to $T_1 = \infty$ and $T_2 = \infty$ gives a value function that is higher than the one with cases $T_1 = \infty$; $T_1 = \infty$ and $T_2 = 0$ and the central case. This may be justified by the fact that the economy does not lose or gain enough by refraining from polluting more in order to never cross the pollution threshold. One can also observe that the central energy transition path is far from being the most profitable one. The numerical results with respect to the baseline parameters then show that there exist parameter values for which

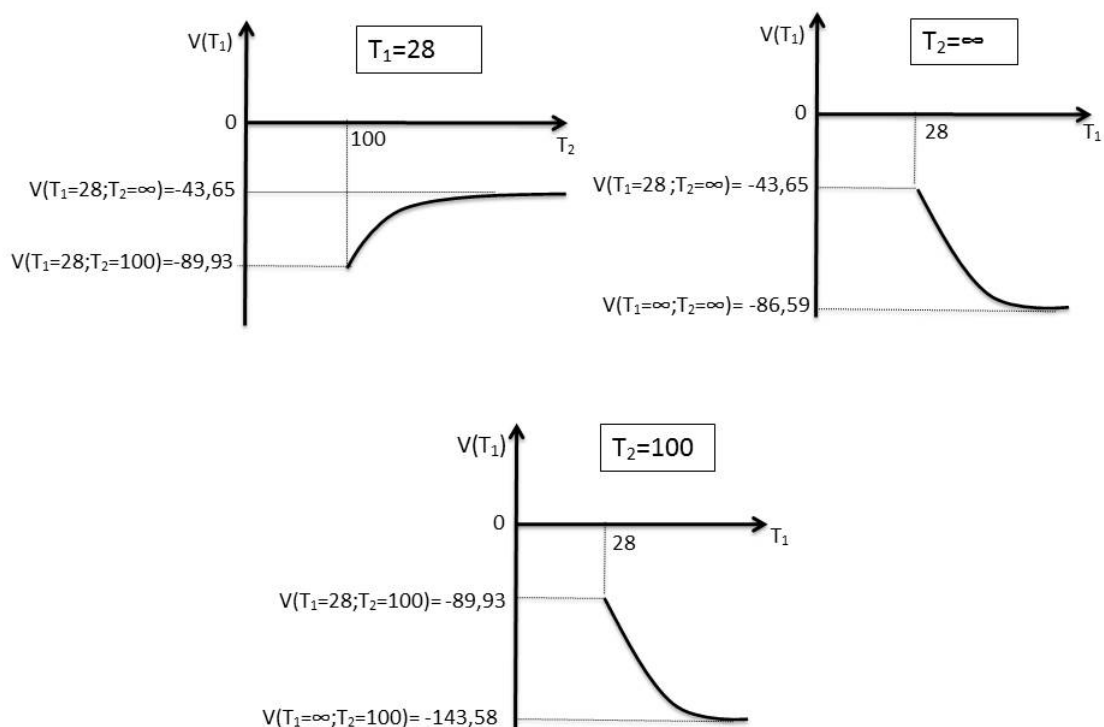


Figure 1.1: Comparison between value functions of the energy transition paths

it is less profitable for the economy to switch to the sole use of the clean source of energy.

1.4.2 Sensitivity analysis

As the baseline parameters rely mostly on values that are arbitrarily chosen, we devote this section to sensitivity analysis of parameters relevant to policy to assess the validity of the results. For each parameter, we chose two new values (one lower and one higher than the baseline value) which we compared with the result of the baseline value in order to isolate sensitivity to the value of the parameter. Specifically, for each new parameter value we calculated the switching times T_1 and T_2 and the value functions of the central and corner energy transition paths. Given these new values, we found that the corner energy transition path in which $T_1 > 0$ and $T_2=\infty$ still has the highest value function and so is the most profitable one (see Table 1.5 in the online appendix 1.8.3). We then

Table 1.2: *The sensitivity analysis on the occurrence of the catastrophe*

ρ	1.3%	1.4%	7%
T_1	33	28	5
θ	0.01	0.05	0.1
T_1	25	28	35
Z	600	1200	2000
T_1	10	28	68
η	1.05	1.5	2
T_1	26	28	34
α_2	0.00005	0.0001	0.0005
T_1	10	28	42
β_2	0.01	0.02	0.1
T_1	22	28	45
S_0	27000	28000	2800000
T_1	27.99	28	28.08

decided to focus only on the most profitable energy transition path and we present the sensitivity analysis with respect to the time T_1 at which the catastrophe occurs. The result of the sensitivity analysis is summarised in table 1.2.

The discount rate ρ negatively affects the time at which the catastrophe occurs. The implication of this result is that more impatient people (i.e. with a higher discount rate) extract more fossil fuel and will then cross the critical pollution threshold more quickly. This result is in line with the intergenerational equity issue that refers to fair intertemporal distribution of the endowment with natural assets such as fossil fuels. More impatient people do not care much about the future, over-exploit the dirty sources of energy today and then leave damage for future generations.

The occurrence of the catastrophe is positively affected by the size of the catastrophe (θ). In fact, if people know that the catastrophe will destroy a huge part of their stock of capital, they will fear the negative consequences of their dirty energy use more and will then reduce it. As a consequence, they could remain longer in the first regime before crossing the pollution threshold. This suggests that the economy that fears the negative consequences of climate change and the risk of ecological catastrophe is more favourable to the energy transition. In terms of policy implications, particular attention should be paid to innovations that help to reduce the use of energy, such as energy efficiency

investment at the household level. Also, there is a need to promote curtailment actions such as through behaviour change. This can be done through raising public awareness of the potential consequences of the use of fossil fuels such as climate change. As expected, a high pollution threshold (\bar{Z}) increases the time of the occurrence of the catastrophe. If the critical pollution threshold that could provoke the catastrophic event is high, the pollution problem will become less rigid. The economy will have more freedom to use the dirty source of energy and will therefore stay longer in the pre-event regime.

The productivity of capital (α_2) and energy services (β_2) in the final goods sector and that of capital in producing renewable energy (η) positively affect the occurrence of the catastrophe. High productivity in the final goods sector would require a low quantity of fossil fuels to produce the final goods that will be used for more investment and more consumption. Likewise, high productivity in the energy sector requires less capital to produce more renewable energy. As a consequence, the economy puts less pressure on the dirty source of energy, pollutes less and postpones the occurrence of the environmental catastrophe. Therefore, public policy should promote innovation that helps to increase the productivity of capital and energy services in productive sectors.

Finally, the initial stock of the dirty source of energy has only a slight positive effect on the occurrence of the catastrophe. In fact, the environmental catastrophe that occurs at the end of the first regime is a consequence of pollution that accumulates over time in the environment. The stock of the dirty source of energy does not matter much in the first regime as the economy will reach the pollution threshold level before the dirty source of energy is completely exhausted. Therefore, the pollution problem is dominant in the first regime while the exhaustibility problem of the dirty source of energy arrives later on during the second regime after the catastrophe has occurred.

1.5 Introducing investment in Energy Saving Technologies (EST)

Let us recall that E_{Yt} and E_{Ct} are energy services in the final goods sector and for households respectively. The final goods sector uses E_{Ydt} of the dirty source of energy and E_{Yct} of the clean source of energy, while households use E_{Cdt} of the dirty source of energy and E_{Cct} of the clean source of energy. At each period of time, in addition to consumption and investments in energy sector and final goods sector, the economy now invests a part of the final goods production q_t in energy saving technologies. We assume that q_t in energy saving technologies does not accumulate so that Eq.(1.12) becomes:

$$Y_t = C_t + \dot{K}_t + q_t$$

We assume that the investment q_t serves to reduce by $\varepsilon(q_t)$ units the resources that the economy needs in order to get the same energy services. Implicitly, it means that we do not account for a scale effect.⁸ The idea behind the no scale assumption is as follows: Suppose that $\varepsilon(q_t)$ is the maximum amount of energy that can be saved due to investment q_t in EST. Given this maximum level, investment in EST will be optimally undertaken with respect to energy use in order to avoid any waste. Let us assume that $\varepsilon(q_t)$ is an increasing function ($\varepsilon'(q_t) > 0$) and exhibits decreasing marginal returns ($\varepsilon''(q_t) < 0$) in the abatement investment. $\varepsilon(q_t)$ is increasing in the sense that the more the economy invests in EST, the more it reduces use of the energy resource to get a given energy service. Moreover, as $\varepsilon(q_t)$ is increasing, we assume that $\varepsilon(q_t)$ is concave in order to have a maximum for q_t . Also, we avoid a complete elimination of the use of energy resources so that it will require an infinite amount of investment to do so.

⁸One should also consider that the investment q_t induces a scale effect. The scale effect is characterized by an energy saving which is proportional to the amount of energy use. This would make the present model very complex and unsolvable because of the interaction that may appear between q_t and all the preceding control variables such as energy services.

1.5.1 Main analytical results

Due to the investment q_t in energy saving technologies, the dynamics of capital, the dirty source of energy and that of pollution are modified, while the household utility remains the same (see the proof in appendix B_1). Note that those dynamics do not change in terms of the extraction of energy resources, but only in terms of energy services. The same amount of energy resource provides more energy services when energy saving technologies are used. In comparison with the previous model, the social planner has to consider one additional control variable (investment q_t) to solve for the optimal energy transition.

The main change in the results is the fact that the level of capital at each period of time during the three regimes has an additional negative component. We therefore have chosen to present only the third regime (see the other regimes in Appendix B_2). For the third regime, all the previous FOCs remain the same. The main change comes from the FOC with respect to investment q_t :

$$\varepsilon'_Y(q_t) + \varepsilon'_C(q_t) = \frac{\eta}{\alpha_2}. \quad (1.21)$$

Equation (1.21) highlights the arbitrage condition between the reduction of resources as a gain from the energy saving technologies and the constant marginal cost of investment. The solution of Eq. (1.21) gives the optimal investment in energy saving technologies. Now, let us specify the energy saving $\varepsilon_i(q_t)$ as a class of power function $cq_t^{\sigma_i}$ where $i \in \{Y, C\}$ and c, σ_i are the parameters. Moreover, we set $c = 1$ and $\sigma_i \in [0, 1]$ in order to meet the required properties defined before.

Without loss of generality, let us assume that investment in EST yields the same productivity either at the household level or at the industry level such that $\sigma_1 = \sigma_2 = \sigma$. Thus, we get:

$$q^* = \left[\frac{\eta}{2\sigma\alpha_2} \right]^{\frac{1}{\sigma-1}}. \quad (1.22)$$

By replacing the optimal value of investment in EST Eq. (1.22) into the equation of

capital accumulation, we can solve the model as before to get the following expression of capital:

$$K_t = -\frac{\Theta\delta}{\alpha_2 - \rho - \delta\Lambda} \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t - T_2)} - \frac{\varpi}{\Lambda},$$

where $\varpi = \frac{2\Lambda}{\eta} \left(\frac{\eta}{2\sigma\alpha_2}\right)^{\frac{\sigma}{\sigma-1}} - \left(\frac{\eta}{2\sigma\alpha_2}\right)^{\frac{1}{\sigma-1}}$ and the remaining parameters are the same as the ones defined above.

In this new expression of capital, we have an additional component $-\frac{\varpi}{\Lambda}$ due to the investment in EST. This additional component is negative in the sense that it negatively affects the level of capital. In fact, the economy additionally uses a part of its income to invest in EST. This part could have been invested in a productive sector (final goods and energy) or consumed by households. Hence the share of income that goes to investment is reduced.

1.5.2 Empirical results and policy implications

As before, here we discuss corner energy transition paths which we compare to the central energy transition path to isolate the most profitable one. In order to make our numerical results comparable, we used the same set of baseline parameter values as before. Additionally, we set the productivity of investment in EST both at the household level and at industry level σ to 0.5. We numerically solved for the switching times T_1 and T_2 and calculated the value functions of the central energy transition path and that of each of the corner energy transition paths. We compared the value functions among them and identified the most profitable one which gives the highest value function. The numerical results are presented in the table below.

Table 1.3: *The values functions with EST*

Central case ($T_1 = 80$; $T_2 = 150$)	$T_1 = \infty$	$T_2 = \infty$	$T_1 = \infty$; $T_2 = \infty$	$T_1 = \infty$; $T_2 = 0$
-23.3194	-30.4469	-30.4528	-30.5553	-30.4329

The numerical results are threefold. First, investments in energy saving technologies increase the time at which the economy may experience the catastrophe and that of the

sole adoption of renewable energy. In fact, investments in energy saving technologies help to reduce the consumption of energy for the same quality of energy services and therefore help to reduce pressure on the stock of fossil fuels. As a result, pollution is reduced and the economy can remain longer in the first regime before the level of pollution crosses its critical threshold level. Second, investment in EST increases the welfare of the society. Although investment in EST reduces the share of the income that goes to investment in both the final goods sector and the clean energy production sector, it increases the welfare of the society. The gain from investment in EST overcomes its forgone utility.

Last but not least, investments in EST change the most profitable energy transition path which becomes the central energy transition path where there is a full transition to the sole use of clean energy. In that sense, it favours full energy transition. The implication is that saving energy reduces energy expenses and decreases the use of fossil fuel for energy services. There is then less of a need for fossil fuels during the first two regimes and the economy can remain in the regime longer. The economy becomes less energy intensive and the gain from energy expenses can be reallocated to increase investment in renewable energy and investment in EST. Then, switching to the sole use of clean sources of energy becomes more attractive. After the complete exhaustion of fossil fuels, the economy is energy efficient and can fully rely on renewable energy.

Note that the four corner energy transition paths give very similar welfare. This can be explained by the potential synergies that may exist between energy saving technologies and clean energy. As corner energy transition paths do not include the three regimes, they may not benefit much from these synergies. Additionally, we perform a sensitivity analysis using the same boundaries for the parameters as in Section 1.4.2 and find that this result is robust. This result is in line with the results of the scenario ‘Combined high renewables and efficiency’ from a 2006 European Commission Energy and Transport report (Directorate General for Energy and Transport) ⁹. The combination of renewable energy and energy efficiency policies results in lower energy requirements, allows for more growth of the renewable energy share for primary energy needs and also leads to a strong

⁹For more details see https://ec.europa.eu/energy/sites/ener/files/documents/ee_and_res_scenarios.pdf

decline in CO_2 emissions. Regarding policy implications, introducing EST policies will help to reduce pressure on fossil fuels and therefore postpone environmental catastrophe. This can be done through economic incentives for home renovation systems or energy efficient appliances for example. Interestingly, EST policy will also contribute to boost the full transition to clean energy. As investment in EST is welfare improving, it is then profitable for the economy to combine both adoption of clean energy and investments in energy saving technologies. Then, the economy will take advantage of the synergies that may arise from jointly promoting deployment of clean energy and providing incentives for investment in energy saving technologies.

1.6 Conclusion

This paper makes two main contributions. First, it analyses the optimal energy transition as optimal switching problems correspondent to the occurrence of environmental catastrophe and to the adoption of clean source of energy. We characterize two types of energy transition paths: (i) central energy transition path and (ii) corner energy transition paths. The boundary conditions serve to isolate the optimal energy transition path. We find that for given baseline parameter values and in the absence of any possibility to invest in energy saving technologies, the most profitable energy transition path may correspond to the one in which the economy starts using both resources, crosses the pollution threshold by losing a part of its capital, and never adopts only clean energy.

This result is in line with some arguments supporting the idea that a complete transition to a low carbon economy is likely to be very slow (Fouquet, 2010; Solomon and Krishna, 2011). Three explanations can be provided. First, electric power from other sources of energy is still used in all of the manufacturing processes for producing renewable energy. For example, producing solar panels has some indirect downstream energy requirements (Ayres, 2007). As the economy still needs fossil fuels to produce clean energy, it is more profitable to progressively reduce this costless dependence on fossil fuels (except for the

catastrophe that occurs once) than to switch to the sole use of a costly clean energy. Second, without innovations in the energy sector such as energy efficiency investment, the global demand of energy is expected to increase and the economy will become more energy intensive. In this sense, it may be less profitable to fully rely on a costly renewable energy. Third, some recent studies show that the potential of global wind power (De Castro et al., 2011) and that of global solar electric (De Castro et al., 2013) might be even lower than the current final consumption of energy by means of fossil fuels. Therefore, an immediate and complete transition to an economy that only relies on renewable sources of energy may not be profitable.

The second contribution of this paper is the extension of this model to the adoption of energy saving technologies. We mainly find that investment in energy saving technologies favours full energy transition. In this sense, it postpones environmental catastrophe, it is welfare improving and it allows a complete transition to sole use of clean energy. In terms of policy implications, we can say that without additional investment in energy saving technologies and due to the need for fossil fuels in the production of clean energy, it is more profitable to progressively reduce dependence on fossil fuels which are costless, than to switch to the sole use of a costly clean energy. Public policy should also promote innovation that helps increase the productivity of capital and energy services in productive sectors and saves both money and energy. As investment in energy saving technologies can encourage the energy transition, it is therefore profitable to take advantage of the synergies that may arise from jointly promoting clean energy and providing incentives for investment in energy saving technologies.

In this paper, we can give a general view of energy transition by considering optimal switching problems, but this has required other stringent assumptions such as the complementarity assumed between dirty and clean sources of energy in both intermediate and final consumption. This assumption does not allow us to focus on energy transition as a process of gradually substituting clean to dirty energy. An alternative would consist of incorporating intermediary phases of a gradual substitution between energy sources after the phase of complementarity between clean and dirty energy. This may change the

optimal energy transition path and therefore deserves further research. This paper can be extended to investigate factors that jointly favour the adoption of renewable energy and investments in energy saving technologies.

1.7 Appendix

1.7.1 Appendix A_0

–Table 1.4 here–

Table 1.4: *Variables and parameters*

E_{ij} , with $i = Y, C$ and $j = d, c$: The quantity of the energy type "j" that is used by i
Subscript Y refers to	: final goods sector
Subscript C refers to	: household
Subscript d refers to	: dirty energy
Subscript c refers to	: clean energy
Subscript t refers to	: time
S	: stock of the dirty source of energy
K_E	: capital that is used to produce the clean energy
K_Y	: capital that is used to produce final goods
K	: total level of capital
q	: investment in energy saving technologies
Z	: stock of pollution
C	: level of consumption of non-energy goods by households
$T_0 = 0$: beginning time of the first regime
T_1	: switching time to the second regime
T_2	: switching time to the third regime
Subscript T_0 refers to	: evaluation of the variable at $t = T_0$
Subscript T_1 refers to	: evaluation of the variable at $t = T_1$
Subscript T_2 refers to	: evaluation of the variable at $t = T_2$
η	: productivity of capital in the clean energy sector
ϕ	: part of capital that is used to produce clean energy
α_2	: productivity of capital in the final goods sector
β_2	: productivity of energy in the final goods sector
ξ	: part of dirty energy that is used in the energy mix
ρ	: discount rate
δ	: positive coefficient of the utility function
\bar{Z}	: pollution threshold above which the catastrophe occurs
θ	: part of capital that is loss due to the catastrophe
σ	: productivity of investment in energy saving technologies
S_0	: The initial stock of the dirty source of energy
K_0	: The initial stock of capital

1.7.2 Appendix A₁

Let us recall that the equation of capital accumulation is:

$$\dot{K}_t = Y_t - C_t. \quad (1.23)$$

We also know that: $Y_t = \min\{\alpha_2 K_{Yt}, \beta_2 E_{Yt}\}$, where, $K_t = K_{Et} + K_{Yt}$ and $E_{ct} = \eta K_{Et}$. $E_{ct} = \eta K_{Et}$ implies that $K_{Et} = \frac{E_{ct}}{\eta}$. Then,

$$K_{Yt} = K_t - K_{Et} = K_t - \frac{E_{ct}}{\eta}. \quad (1.24)$$

From Leontief conditions in the final goods sector, we have:

$$Y_t = \alpha_2 K_{Yt} = \beta_2 E_{Yt}. \quad (1.25)$$

During the third regime, only the clean source of energy is used so that we have the following equalities: $E_{Yct} = E_{Yt}$, and $E_{Cct} = E_{Ct}$. By summing up the above two expressions and plugging this into successive Eqs. (1.24), (1.25) and into Eq. (1.23) gives $\dot{K}_t = \alpha_2 K_t - \alpha_2 \frac{E_{Yt} + E_{Ct}}{\eta} - C_t$.

1.7.3 Appendix A₂

To determine the expression of capital in the third regime, we need to solve the following equation of capital accumulation for the capital K_t : $\dot{K}_t = \Lambda K_t - \Theta \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t - T_2)}$, where $\Lambda = \frac{\alpha_2 \beta_2 \eta}{\alpha_2 + \beta_2 \eta}$ and $\Theta = \frac{\alpha_2 \beta_2}{\alpha_2 + \beta_2 \eta} \left(\frac{\alpha_2}{\eta}\right)^{-\frac{1}{\delta}} + 1$. By making a change of variables $x_t = K_t e^{-\Lambda(t - T_2)}$ and using the following transversality conditions $\lim_{t \rightarrow \infty} \lambda_t K_t e^{-\rho(t - T_2)} = 0$, we get $K_t = -\frac{\Theta \delta}{\alpha_2 - \rho - \delta \Lambda} \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t - T_2)}$, for $\alpha_2(1 - \delta) < \rho$.

Finally, we need to impose the non-negativity condition on E_{Yt} so that:

$$E_{Yt} = \frac{\alpha_2}{\alpha_2 + \eta \beta_2} (\eta K_t - E_{Ct}) > 0 \Leftrightarrow -\frac{\Theta \delta \eta}{\alpha_2 - \rho - \delta \Lambda} - \left(\frac{\alpha_2}{\eta}\right)^{-\frac{1}{\delta}} > 0.$$

1.7.4 Appendix A₃

The expression of capital in the second regime is determined from FOCs as follows:

FOCs lead to: $\mu_t = \mu_{T_1} e^{(\rho - \alpha_2(1-\phi))(t-T_1)}$, $\nu_t = \nu_{T_1} e^{\rho(t-T_1)}$, $C_t = \mu_{T_1}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(t-T_1)}$ and $E_{Ct} = (\xi\nu_{T_1})^{-\frac{1}{\delta}} e^{-\frac{\rho}{\delta}(t-T_1)}$. Using the above expression of C, the equation of capital accumulation becomes: $\dot{K} - \alpha_2(1-\phi)K = -\mu_{T_1}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(t-T_1)}$. Using the same variable change as in Appendix B and taking K_t at $t=T_1$, gives:

$K_t = -(\overline{K_2} - K_{T_1}) * e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(t-T_1)} + \overline{K_2}$, where $\overline{K_2}$ is unknown and will be determined using boundary conditions in Section 2.3.3.

1.7.5 Appendix A₄

We assume that the dirty source of energy is exhaustible and that we have crossed the second regime after a period of time T_1 . Then, the initial stock of the dirty source of energy S_0 is equal to the sum of the part of the dirty source of energy that is used during the first regime which corresponds to the total amount of pollution \overline{Z} and the part of the dirty source of energy that the economy uses during the second regime. We have: $S_0 = \underbrace{\int_0^{T_1} \xi(E_{Yt} + E_{Ct})dt}_{\overline{Z}} + \int_{T_1}^{T_2} \xi(E_{Yt} + E_{Ct})dt$. This implies that: $S_0 - \overline{Z} = \int_{T_1}^{T_2} \xi(E_{Yt} + E_{Ct})dt = \frac{\xi\alpha_2}{\beta_2} \int_{T_1}^{T_2} K_t dt + \xi \int_{T_1}^{T_2} E_{Ct} dt$, with $S_0 > \overline{Z}$.

The above equation gives:

$$\frac{1}{\xi}(S_0 - \overline{Z}) = -(\xi\nu_{T_1})^{-\frac{1}{\delta}} * \frac{\delta}{\rho} \left[e^{-\frac{\rho}{\delta}(T_2-T_1)} - 1 \right] + \frac{\alpha_2(1-\phi)}{\beta_2} \overline{K_2} [(T_2 - T_1)] - \frac{\delta\alpha_2}{\beta_2(\alpha_2(1-\phi)-\rho)} * (\overline{K_2} - K_{T_1}) * \left[e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(T_2-T_1)} - 1 \right].$$

1.7.6 Appendix A₅

The level of capital at each time during the first regime is determined as follows:

FOCs give: $\mu_t = \mu_{T_0} e^{(\rho - \alpha_2(1-\phi))t}$, $\nu_t = \nu_{T_0} e^{\rho t}$, $C_t = \mu_{T_0}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t}$ and $E_{Ct} = (-\nu_{T_0}\xi)^{-\frac{1}{\delta}} e^{-\frac{\rho}{\delta}t}$. As before, we also replace the expression of C_t in the equation of capital accumulation to get: $\dot{K}_t - \alpha_2(1-\phi)K_t = -\mu_{T_0}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t}$. Solving the above equation and taking K_t at $t = 0$ give $K_t = -(\overline{K_1} - K_0)e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t} + \overline{K_1}$. Finally, at the end of the first regime, we cross the pollution threshold so that $\overline{Z} = \int_0^{T_1} \xi(E_{Yt} + E_{Ct})dt$.

This equation then implies that:

$$\nu_{T_0} = -\frac{1}{\xi} \left[\left(-\frac{\bar{Z}}{\xi} + \frac{\alpha_2(1-\phi)}{\beta_2} \bar{K}_1 * T_1 - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi)-\rho)} (\bar{K}_1 - K_0) [e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta}) * T_1} - 1] \right) * \frac{\rho}{\delta [e^{-\frac{\rho}{\delta} T_1} - 1]} \right]^{-\delta}$$

where ν_{T_0} and \bar{K}_1 are unknown and will be determined in Section 2.3.3 using boundary conditions.

1.7.7 Appendix B_1

Equations (1.12), (1.9) and (1.11) become respectively:

$$\dot{K}_t = Y_t - C_t - q_t, \quad (1.26)$$

$$\begin{cases} E_{Yt} = \min\{\frac{1}{\xi} E_{Ydt}, E_{Yct}\} + \varepsilon_Y(q_t), & t < T_2 \\ E_{Yt} = E_{Yct} + \varepsilon_Y(q_t), & t \geq T_2 \end{cases}$$

and

$$\begin{cases} E_{Ct} = \min\{\frac{1}{\xi} E_{Cdt}, E_{Cct}\} + \varepsilon_C(q_t), & t < T_2 \\ E_{Ct} = E_{Cct} + \varepsilon_C(q_t), & t \geq T_2. \end{cases}$$

where $t < T_2$ corresponds to the first two regimes, while $t \geq T_2$ denotes the third regime.

Also, equations (1.14), (1.19) and (1.20) become respectively:

$$\dot{K}_t = \alpha_2 K_t - \alpha_2 \frac{(E_{Yt} + E_{Ct}) - (\varepsilon_Y(q_t) + \varepsilon_C(q_t))}{\eta} - C_t - q_t.$$

$$\dot{S}_t = -E_{dt} = -\xi(E_{Yt} + E_{Ct}) + \xi(\varepsilon_Y(q_t) + \varepsilon_C(q_t))$$

and

$$\dot{Z}_t = E_{dt} = \xi(E_{Yt} + E_{Ct}) - \xi(\varepsilon_Y(q_t) + \varepsilon_C(q_t)).$$

1.7.8 Appendix B_2

Second regime

As before, the only change is the FOC with respect to q_t :

$$\varepsilon'_Y(q_t) + \varepsilon'_C(q_t) = \frac{\mu_t}{\xi\nu_t}. \quad (1.27)$$

Using the same specifications as before, the solution of Eq. (1.27) is :

$$q^* = \left[\frac{\mu_t}{2\sigma\xi\nu_t} \right]^{\frac{1}{\sigma-1}}. \quad (1.28)$$

The equation (1.28) helps to solve the model during the second regime as before. The expression of the capital during the second regime becomes:

$$K_t - \overline{K}_2 = -\mu_{T_1}^{-\frac{1}{\delta}} * \frac{\delta}{\alpha_2(1-\phi)(1-\delta) - \rho} e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}(t-T_1)} + \left[\frac{\mu_{T_1}}{2\sigma\xi\nu_{T_1}} \right]^{\frac{1}{\sigma-1}} \frac{\sigma-1}{\alpha_2(1-\phi)\sigma} e^{-\frac{\alpha_2(1-\phi)}{\sigma-1}(t-T_1)}.$$

We should also observe here that the level of capital at each period of time during the second regime has a second negative component. As the share of the income that goes to investment is reduced by investment in energy saving technologies, one should expect a decrease in capital.

As in the case without any investment in EST, all the dirty sources of energy are extracted during the first and the second regimes such that:

$$S_0 - \overline{Z} = \int_{T_1}^{T_2} \xi(E_{Yt} + E_{Ct} - \varepsilon_Y - \varepsilon_C) dt.$$

Solving the above equation, we get:

$$S_0 - \overline{Z} = \xi \frac{\alpha_2}{\beta_2} \overline{K}_2 [T_2 - T_1] + H_0 \left[e^{-\frac{\rho}{\delta}(T_2-T_1)} - 1 \right] \nu_{T_1}^{-\frac{1}{\delta}} + H_1 \left[e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}(T_2-T_1)} - 1 \right] \mu_{T_1}^{-\frac{1}{\delta}} + H_2 \left[e^{-\frac{\alpha_2(1-\phi)}{\sigma-1}(T_2-T_1)} - 1 \right] \left[\frac{\mu_{T_1}}{\nu_{T_1}} \right]^{\frac{1}{\sigma-1}} + H_3 \left[e^{-\frac{\alpha_2\sigma(1-\phi)}{\sigma-1}(T_2-T_1)} - 1 \right] \left[\frac{\mu_{T_1}}{\nu_{T_1}} \right]^{\frac{\sigma}{\sigma-1}} \quad (\mathbf{Eq A})$$

where $H_0 = -\xi \frac{\delta^{-1}}{\delta} \frac{\delta}{\rho}$, $H_1 = -\frac{\xi \delta^2 \alpha_2}{\beta_2 [\alpha_2(1-\phi)(1-\delta) - \rho] [\alpha_2(1-\phi) - \rho]}$, $H_2 = -\frac{\xi(\sigma-1)^2 \alpha_2}{\beta_2 (2\sigma\xi)^{\frac{1}{\sigma-1}} \sigma \alpha_2^2 (1-\phi)^2}$ and $H_3 = \frac{2\xi(\sigma-1)}{\alpha_2(1-\phi)\sigma(2\sigma\xi)^{\frac{\sigma}{\sigma-1}}}$.

First regime

As in the second regime the optimal investment in EST is:

$$q^* = \left[-\frac{\mu_t}{2\sigma\xi\nu_t} \right]^{\frac{1}{\sigma-1}}. \quad (1.29)$$

We then solve the equation of capital accumulation to get the following expression of capital during the first regime:

$$K_t - \bar{K}_1 = -\mu_{T_0}^{-\frac{1}{\delta}} \frac{\delta}{\alpha_2(1-\phi)(1-\delta) - \rho} e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} t} + \left[-\frac{\mu_{T_0}}{2\sigma\xi\nu_{T_0}} \right]^{\frac{1}{\sigma-1}} \frac{\sigma-1}{\sigma\alpha_2(1-\phi)} e^{-\frac{\alpha_2(1-\phi)}{\sigma-1} t}.$$

We still have an additional negative component of the capital due to investment in energy saving technologies.

At the end of the first regime, we cross the pollution threshold so that:

$$\bar{Z} = \int_0^{T_1} \xi(E_{Yt} + E_{Ct} - 2\varepsilon_t^*) dt.$$

By solving the above equation as before, we get the following expression:

$$\begin{aligned} \bar{Z} = & \xi \frac{\alpha_2}{\beta_2} \bar{K}_1 T_1 + H_0 \left[e^{-\frac{\rho}{\delta} T_1} - 1 \right] (-\nu_{T_0})^{-\frac{1}{\delta}} + H_1 \left[e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} T_1} - 1 \right] \mu_{T_0}^{-\frac{1}{\delta}} + \\ & H_4 \left[e^{-\frac{\alpha_2(1-\phi)}{\sigma-1} T_1} - 1 \right] \mu_{T_0}^{\frac{1}{\delta}} + H_3 \left[e^{-\frac{\alpha_2\sigma(1-\phi)}{\sigma-1} T_1} - 1 \right] \left[\frac{\mu_{T_0}}{\nu_{T_0}} \right]^{\frac{\sigma}{\sigma-1}}, \quad (\mathbf{Eq B}) \end{aligned}$$

where H_0 , H_1 and H_3 are the same as defined before and $H_4 = \frac{\xi\delta(\sigma-1)\alpha_2}{\beta_2\alpha_2((1-\phi)[\alpha_2(1-\phi)(1-\delta) - \rho]})$.

Boundary conditions

As in the case without any investments in EST, we apply some boundary conditions. Continuity of μ_t and continuity of K_t at the switching times T_1 and T_2 gives the following equation:

$$H_5 \mu_{T_0}^{-\frac{1}{\delta}} - \frac{\varpi}{\Lambda} = H_6 \mu_{T_0}^{-\frac{1}{\delta}} + H_7 \left[\frac{\mu_{T_0}}{2\sigma\xi\nu_{T_1}} \right]^{\frac{1}{\sigma-1}} + H_8 \left[\frac{-\mu_{T_0}}{2\sigma\xi\nu_{T_0}} \right]^{\frac{1}{\sigma-1}} + (1-\theta)K_0 \quad (\mathbf{Eq\ C}).$$

$$\text{Where } H_5 = -\frac{\Theta\delta}{\alpha_2 - \rho - \delta\Lambda} e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_2}, H_6 = \frac{\delta}{\alpha_2(1-\phi)(1-\delta)-\rho} \left[\theta e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_1} + (1-\phi) - e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_2} \right],$$

$$H_7 = \frac{\sigma-1}{\alpha_2\sigma(1-\phi)} \left[-e^{\frac{\rho-\alpha_2(1-\phi)}{\sigma-1}T_1} + e^{[\frac{\rho}{\sigma-1}T_1 - \frac{\alpha_2(1-\phi)}{\sigma-1}T_2]} \right] \text{ and } H_8 = \frac{(\sigma-1)(1-\theta)}{\alpha_2\sigma(1-\phi)} \left[-1 + e^{\frac{-\alpha_2(1-\phi)}{\sigma-1}T_1} \right].$$

Eq A, Eq B and Eq C express three different relationships between μ_{T_0} , ν_{T_0} and ν_{T_1} that we can simultaneously solve. Additionally, we simultaneously and numerically solve the equality of Hamiltonians at the switching time T_1 and T_2 to get T_1 and T_2 .

1.8 Online appendix

1.8.1 Parameter values

We consider an initial stock of the dirty source of energy S_0 to be equal to 28000 gigatonnes of carbon (*GtC*), and the value of the initial level of capital is set at 500. In the final goods sector, we set the parameter α_2 that is related to capital at 0.0001 and that of energy β_2 at 0.02 in the Leontief function. The factor of capital transformation into energy η is set at 1.5. This coefficient is higher than one so that one unit of capital produces more than one unit of clean energy. We also assume that to get one unit of energy services, the economy should provide 1.5 units of the dirty source of energy such that $\xi=1.5$. The part of capital that is lost due to the catastrophe θ is set at 0.05. Finally, we set $\phi=0.1$.

1.8.2 Boundary conditions

1. Continuity of μ_t

- At $t = T_1$

$$\underbrace{\{(\bar{K}_1 - K_0) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta}\}^{-\delta} e^{(\rho - \alpha_2(1-\phi))T_1}}_{\text{First regime}} = \underbrace{\{(\bar{K}_2 - K_{T_1}) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta}\}^{-\delta}}_{\text{Second regime}}.$$

This implies that :

$$K_{T_1} = -(\bar{K}_1 - K_0) * e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} T_1} + \bar{K}_2 \quad (1.30)$$

- At $t = T_2$

$$\underbrace{\{(\bar{K}_2 - K_{T_1}) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta}\}^{-\delta} * e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} (T_2 - T_1)}}_{\text{Second regime}} = \underbrace{\{(-K_{T_2} * \frac{\alpha_2 - \rho - \delta\Lambda}{\Theta\delta})\}^{-\delta}}_{\text{Third regime}}.$$

That leads to:

$$K_{T_2} = (K_0 - \bar{K}_1) * \frac{\Theta[\alpha_2(1-\phi)(1-\delta) - \rho]}{\alpha_2 - \rho - \delta\Lambda} * e^{\frac{\alpha_2(1-\phi) - \rho}{\delta^2} [(1+\delta)T_1 - T_2]}. \quad (1.31)$$

2. Continuity of K_t

- At $t = T_1$

As part θ of capital is lost from the first to the second regime, we have: $\bar{K} = (1-\theta)\underline{K}$, with \bar{K} the capital in the second regime and \underline{K} the capital in the first regime.

K is continuous at T_1 so that:

$$\underbrace{-\bar{K}_2 + K_{T_1}}_{\text{Second regime}} = (1-\theta) \underbrace{[-(\bar{K}_1 - K_0)e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} T_1} + \bar{K}_1]}_{\text{First regime}}.$$

This gives:

$$K_{T_1} = (1-\theta) \left\{ (K_0 - \bar{K}_1) * e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} T_1} + \bar{K}_1 \right\}. \quad (1.32)$$

As Eqs. (1.30) and (1.32) are the same expression of K_{T_1} , we have the following equality:

Eq. (1.30)=Eq. (1.32) implies that:

$$-(\overline{K_1} - K_0) * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_1} + \overline{K_2} = (1 - \theta) \left\{ (K_0 - \overline{K_1}) * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_1} + \overline{K_1} \right\}.$$

This helps to deduce the expression of $\overline{K_2}$ as a function of $\overline{K_1}$:

$$\overline{K_2} = \theta(\overline{K_1} - K_0) * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_1} + (1 - \theta)\overline{K_1}. \quad (1.33)$$

- At $t = T_2$

From the second regime to the third, capital is not lost so that: $\overline{\overline{K}} = \overline{K}$, with \overline{K} the capital in the second regime and $\overline{\overline{K}}$ the capital in the third regime.

Continuity of capital implies that:

$$\underbrace{-(\overline{K_2} - K_{T_1}) * e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(T_2-T_1)} + \overline{K_2}}_{\text{Second regime}} = \underbrace{-\frac{\Theta\delta}{\alpha_2 - \rho - \delta\Lambda} \lambda_{T_2}^{-\frac{1}{\delta}}}_{\text{Third regime}}.$$

Using continuity of μ_t and Eq. (1.30) we have the following equality:

$$\lambda_{T_2} = \mu_{T_2} = \mu_{T_1} * e^{(\rho - \alpha_2(1-\phi))(T_2-T_1)} = \left\{ (\overline{K_2} - K_{T_1}) * \frac{\alpha_2(1-\phi)(1-\delta)-\rho}{\delta} \right\}^{-\delta} * e^{(\rho - \alpha_2(1-\phi))(T_2-T_1)}$$

$$\text{and } K_{T_1} - \overline{K_2} = -(\overline{K_1} - K_0) * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_1}.$$

From that, we get:

$$(\overline{K_1} - K_0) * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_1} * e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})(T_2-T_1)} + \overline{K_2} = -\frac{\Theta\delta}{\alpha_2 - \rho - \delta\Lambda} * (\overline{K_1} - K_0) * \frac{\alpha_2(1-\phi)(1-\delta)-\rho}{\delta} * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_1} * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}(T_2-T_1)}.$$

That gives:

$$\overline{K_2} = \left\{ \frac{\Theta[\alpha_2(1-\phi)(1-\delta) - \rho]}{\alpha_2 - \rho - \delta\Lambda} + 1 \right\} (K_0 - \overline{K_1}) * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_2}. \quad (1.34)$$

Eq. (1.33)=Eq. (1.34) leads to:

$$\overline{K_1} = \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \quad (1.35)$$

with $f(T_1, T_2) = \Gamma * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_2} - \theta e^{\frac{\alpha_2(1-\phi)-\rho}{\delta}T_1}$ and $\Gamma = -1 - \frac{\Theta[\alpha_2(1-\phi)(1-\delta)-\rho]}{\alpha_2 - \rho - \delta\Lambda}$.

$$\text{Eq. (1.35) in Eq. (1.34) leads: } \bar{K}_2 = -\Gamma \left\{ K_0 - \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right\} * e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} T_2}.$$

$$\text{Eq. (1.32) becomes: } K_{T_1} = (1 - \theta) * \left\{ K_0 - \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right\} * e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} T_1}.$$

$$\text{Eq. (1.31) becomes: } K_{T_2} = \left\{ K_0 - \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right\} * \frac{\Theta[\alpha_2(1-\phi)(1-\delta) - \rho]}{\alpha_2 - \rho - \delta \Lambda} * e^{\frac{\alpha_2(1-\phi) - \rho}{\delta^2} [(1+\delta)T_1 - T_2]}$$

$$\text{and } \lambda_{T_2} = \{ (\bar{K}_1 - K_0) * e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} T_1} * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta} \}^{-\delta} * e^{(\rho - \alpha_2(1-\phi))(T_2 - T_1)}$$

$$= \left\{ (-K_0 + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta} \right\}^{-\delta} * e^{(\rho - \alpha_2(1-\phi))T_2}.$$

Also, we have:

$$\nu_{T_0} = -\frac{1}{\xi} \left[\left(-\frac{\bar{Z}}{\xi} + \frac{\alpha_2(1-\phi)}{\beta_2} \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 * T_1 - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi) - \rho)} \left(\frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 - K_0 \right) \right) \left[e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} * T_1} - 1 \right] * \frac{\rho}{\delta [e^{-\frac{\rho}{\delta} T_1} - 1]} \right]^{-\delta}$$

and

$$\nu_{T_1} = \frac{1}{\xi} \left[\left(-\frac{S_0 + \bar{Z}}{\xi} + \frac{\alpha_2(1-\phi)}{\beta_2} \bar{K}_2 (T_2 - T_1) - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi) - \rho)} (\bar{K}_1 - K_0) e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} T_1} * \left[e^{\frac{\alpha_2(1-\phi) - \rho}{\delta} * (T_2 - T_1)} - 1 \right] \right) \frac{\rho}{\delta [e^{-\frac{\rho}{\delta} T_1} - 1]} \right]^{-\delta}.$$

3. Equality of the Hamiltonian

The last optimality condition is the equality of the Hamiltonian at the switching time T_1 and T_2 .

- At $t = T_1$: the equality is between the first and the second regime.

$$H_1(T_1^*) = H_2(T_1^*)$$

$$\Rightarrow \underbrace{\frac{E_C^{1-\delta}}{1-\delta} + \mu\alpha_2 K + \nu\xi(E_Y + E_C)}_{\text{First regime}} = \underbrace{\frac{E_C^{1-\delta}}{1-\delta} + \mu\alpha_2 K - \nu\xi(E_Y + E_C)}_{\text{second regime}}. \quad (1.36)$$

- At $t = T_2$: the equality is between the second and the third regime.

$$H_2(T_2^*) = H_3(T_2^*)$$

$$\Rightarrow \underbrace{\frac{E_C^{1-\delta}}{1-\delta} + \mu\alpha_2 K - \nu\xi(E_Y + E_C)}_{\text{Second regime}} = \underbrace{\frac{E_C^{1-\delta}}{1-\delta} + \lambda \left[\alpha_2 \left(K - \frac{1}{\eta} E_Y - \frac{1}{\eta} E_C \right) \right]}_{\text{Third regime}} \quad (1.37)$$

Solving simultaneously and numerically Eqs. (1.36) and (1.37), we can obtain T_1 and T_2 .

The expressions determined above are summarized as:

$$\begin{aligned}
 \bar{K}_1 &= \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0, \\
 \bar{K}_2 &= -\Gamma \left\{ K_0 - \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right\} * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta} T_2}, \\
 K_{T_1} &= (1 - \theta) * \left\{ K_0 - \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right\} * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta} T_1}, \\
 K_{T_2} &= \left\{ K_0 - \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right\} * \frac{\Theta[\alpha_2(1-\phi)(1-\delta) - \rho]}{\alpha_2 - \rho - \delta\Lambda} * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta^2} [(1+\delta)T_1 - T_2]}, \\
 \lambda_{T_2} &= \left\{ (-K_0 + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta} \right\}^{-\delta} * e^{(\rho - \alpha_2(1-\phi))T_2}, \\
 \nu_{T_0} &= -\frac{1}{\xi} \left[\left(-\frac{\bar{Z}}{\xi} + \frac{\alpha_2(1-\phi)}{\beta_2} \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 * T_1 \right. \right. \\
 &\quad \left. \left. - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi) - \rho)} \left(\frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 - K_0 \right) [e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta}) * T_1} - 1] \right) * \frac{\rho}{\delta [e^{-\frac{\rho}{\delta} T_1} - 1]} \right]^{-\delta}, \\
 \nu_{T_1} &= \frac{1}{\xi} \left[\left(\frac{-S_0 + \bar{Z}}{\xi} + \frac{\alpha_2(1-\phi)}{\beta_2} \bar{K}_2 (T_2 - T_1) \right. \right. \\
 &\quad \left. \left. - \frac{\alpha_2(1-\phi)\delta}{\beta_2(\alpha_2(1-\phi) - \rho)} (\bar{K}_1 - K_0) e^{\frac{\alpha_2(1-\phi)-\rho}{\delta} T_1} * [e^{\frac{\alpha_2(1-\phi)-\rho}{\delta} * (T_2 - T_1)} - 1] \right) \frac{\rho}{\delta [e^{-\frac{\rho}{\delta} T_1} - 1]} \right]^{-\delta}
 \end{aligned}$$

with $f(T_1, T_2) = \Gamma * e^{\frac{\alpha_2(1-\phi)-\rho}{\delta} T_2} - \theta e^{\frac{\alpha_2(1-\phi)-\rho}{\delta} T_1}$ and $\Gamma = -1 - \frac{\Theta[\alpha_2(1-\phi)(1-\delta) - \rho]}{\alpha_2 - \rho - \delta\Lambda}$.

4. Dynamics of variables

We used the above results to get an expression for state and control variables.

- First regime

$$\begin{aligned}
 K_t &= \left\{ K_0 - \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right\} * e^{(\frac{\alpha_2(1-\phi)-\rho}{\delta})t} + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} \\
 \mu_t &= \left\{ (-K_0 + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta} \right\}^{-\delta} * e^{(\rho - \alpha_2(1-\phi))t} \\
 \nu_t &= \nu_{T_0} e^{\rho t}
 \end{aligned}$$

$$C_t = \left\{ (-K_0 + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta} \right\} e^{(\frac{\alpha_2(1-\phi) - \rho}{\delta})t}$$

$$E_{Ct} = (-\nu_{T_0} \xi)^{-\frac{1}{\delta}} e^{-\frac{\rho}{\delta} t}$$

$$E_{Yt} = \frac{\alpha_2(1-\phi)}{\beta_2} \left[\left\{ K_0 - \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right\} * e^{(\frac{\alpha_2(1-\phi) - \rho}{\delta})t} + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0 \right].$$

- Second regime

$$\mu_{T_1} = \left\{ (-K_0 + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta} \right\}^{-\delta} * e^{(\rho - \alpha_2(1-\phi))T_1}$$

$$\mu_t = \left\{ (-K_0 + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta} \right\}^{-\delta} * e^{(\rho - \alpha_2(1-\phi))t}$$

$$\nu_t = \nu_{T_1} e^{\rho(t - T_1)}$$

$$K_t = -(\overline{K_1} - K_0) * e^{(\frac{\alpha_2(1-\phi) - \rho}{\delta})t} + \overline{K_2}$$

$$E_{Yt} = \frac{\alpha_2(1-\phi)}{\beta_2} \overline{K}_t$$

$$C_t = \mu_{T_1}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2(1-\phi) - \rho}{\delta})(t - T_1)}$$

$$E_{Ct} = (\nu_{T_1} \xi)^{-\frac{1}{\delta}} e^{-\frac{\rho}{\delta}(t - T_1)}.$$

- Third regime

$$\lambda_{T_2} = \left\{ (-K_0 + \frac{f(T_1, T_2)}{f(T_1, T_2) + \theta - 1} K_0) * \frac{\alpha_2(1-\phi)(1-\delta) - \rho}{\delta} \right\}^{-\delta} * e^{(\rho - \alpha_2(1-\phi))T_2}$$

$$K_t = -\frac{\Theta \delta}{\alpha_2 - \rho - \delta \Lambda} \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t - T_2)}$$

$$\lambda_t = \lambda_{T_2} e^{(\rho - \alpha_2)(t - T_2)}$$

$$C_t = \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t - T_2)}$$

$$E_{Ct} = \left(\frac{\alpha_2}{\eta} \right)^{-\frac{1}{\delta}} \lambda_{T_2}^{-\frac{1}{\delta}} e^{(\frac{\alpha_2 - \rho}{\delta})(t - T_2)}$$

$$E_{Yt} = \frac{\alpha_2}{\alpha_2 + \beta_2 \eta} (\eta \overline{K}_t - E_{Ct}).$$

1.8.3 Sensitivity analysis on the energy transition path

Table 1.5: *The sensitivity analysis on the energy transition paths*

	1.3%	1.4%	7%
ρ	1.3%	1.4%	7%
Central case	-100.86	-89.93	-19.77
$T_1=\infty$	-154.21	-143.58	-101.71
$T_2 = \infty$	-50.70	-43.66	-1.76
$T_1=\infty; T_2=\infty$	-104.01	-86.59	-2.75
$T_1=\infty; T_2=0$	-141.62	-122.23	-4.94
θ	0.01	0.05	0.1
Central case	-87.70	-89.93	-93.14
$T_1=\infty$	-143.58	-143.58	-143.58
$T_2 = \infty$	-42.11	-43.66	-45.79
$T_1=\infty; T_2=\infty$	-86.59	-86.59	-86.59
$T_1=\infty; T_2=0$	-122.23	-122.23	-122.23
Z	600	1200	2000
Central case	-86.66	-89.93	-99.33
$T_1=\infty$	-158.04	-143.58	-139.79
$T_2 = \infty$	-43.45	-43.66	-44.47
$T_1=\infty; T_2=\infty$	-546.80	-86.59	-61.20
$T_1=\infty; T_2=0$	-122.23	-122.23	-122.23
η	1.05	1.5	2
Central case	-89.51	-89.93	-91.34
$T_1=\infty$	-143.65	-143.58	-143.52
$T_2 = \infty$	-43.58	-43.66	-43.90
$T_1=\infty; T_2=\infty$	-86.59	-86.59	-86.59
$T_1=\infty; T_2=0$	-122.32	-122.23	-122.15
α_2	0.00005	0.0001	0.0005
Central case	-86.79	-89.93	-94.33
$T_1=\infty$	-142.87	-143.58	-210.69
$T_2 = \infty$	-43.64	-43.66	-44.14
$T_1=\infty; T_2=\infty$	-73.40	-86.59	-57.45
$T_1=\infty; T_2=0$	-122.61	-122.23	-117.90
β_2	0.01	0.2	0.1
Central case	-88.70	-89.93	-94.06
$T_1=\infty$	-146.69	-143.58	-142.09
$T_2 = \infty$	-43.52	-43.66	-44.31
$T_1=\infty; T_2=\infty$	-293.52	-86.59	-68.27
$T_1=\infty; T_2=0$	-122.23	-122.23	-122.23
S_0	27000	28000	2800000
Central case	-89.95	-89.93	-89.92
$T_1=\infty$	-143.58	-143.58	-143.58
$T_2 = \infty$	-43.68	-43.66	-42.87
$T_1=\infty; T_2=\infty$	-86.59	-86.59	-86.59
$T_1=\infty; T_2=0$	-122.23	-122.23	-122.23

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Chapter 2

Energy transition under the risk of an environmental catastrophe: a two-sector approach¹

Abstract

The transition to renewable energy involves two kinds of environmental concerns. First, fossil fuels are exhaustible and second, their use generates negative externalities through environmental damage. In particular, the pollution thresholds above which environmental catastrophes are expected to occur are uncertain. In this paper, we focus on the issue of optimal energy transition in a two-sector economy (energy sector and final good sector) with exhaustible oil reserves, renewable energy and a pollution threat. In order to model the energy transition under a risk of environmental damage, we consider that the economy currently uses both fossil fuels and renewable energy (RE), and that two changes in regime may occur. One change corresponds to the adoption of renewable energy as the sole source of energy and the other one refers to the pollution catastrophe. This catastrophic environmental event occurs when the stock of pollution reaches an uncertain threshold and generates a loss of utility. We solve the model numerically using the first order optimality conditions obtained analytically. We show that uncertainty of the occurrence of the catastrophe induces a precautionary behaviour, in the sense that it negatively affects the rate of the polluting resource extraction and drives the energy transition.

Keywords: *energy, pollution, irreversibility, catastrophe, switch, uncertainty.*

JEL Classification: *C61, D81, Q42, Q53.*

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2.1 Introduction

In recent years, investment in renewable energy sources (RES) have grown quickly, from 63 billion USD in 2006 to 244 billion USD in 2012 (Johansson et al., 2012). However, fossil fuels are still the main energy source (78.2%) used throughout the world. The transition to RES involves two kinds of environmental concerns. First, fossil fuels are exhaustible² and second, their use generates negative externalities through environmental damage³. Fossil fuels generated 84% of world greenhouse gas (GHG) emissions in 2009 (OECD, 2012). There are pollution thresholds above which environmental catastrophes are expected to occur (Keller et al., 2008). However, these thresholds are not perfectly known (Gjerde et al., 1999). Moreover, world energy demand is expected to grow as a result of demographic and economic development, in particular in large emerging countries that will represent 90% of the increase in world energy demand in 2035; at the same time, 20% of the world's population has no access to electricity (OECD, 2012). This suggests that we have to drastically change the way energy is produced. In this paper, we focus on the issue of optimal energy transition in a two-sector economy (energy sector and final good sector) with exhaustible oil reserves, RES and a pollution threat.

In order to model the energy transition under a risk of environmental damage, we consider that the economy currently uses both fossil fuels and RES, and that two changes in regime may occur. One change corresponds to the adoption of renewable energy (RE) as the sole source of energy following fossil fuel exhaustion and the other refers to the pollution catastrophe. Both RES adoption and pollution catastrophe are a type of regime switching that is related to the notion of irreversibility. When the pollution stock exceeds a certain threshold value, irreversible environmental damage occurs and when the stock is exhausted, production starts using only RES. This is in contrast to optimal regime switching problems à la Tomiyama (1985) and Amit (1986) under certainty or real option approaches as in Pommeret and Schubert (2009) under uncertainty, where the successive regimes are determined without external control or external constraints.

²There exists a vast literature on the long run depletion of oil reserves, starting with Dasgupta and Heal (1974, 1979), Dasgupta and Stiglitz (1981) and Krautkraemer (1998).

³Some literature also considers the polluting features of non-renewable resources (Nordhaus, 1994 and Tahvonen, 1996, 1997) or more recently Prieur et al. (2013).

Clearly enough, the two optimal switching problems, the ecological and the technological, will interact. Indeed, the risk of facing environmental catastrophe might decisively shape the decision whether or not to adopt 100% renewable energy. In a deterministic framework, [Boucekkine et al. \(2013\)](#) provides an optimal control approach that accounts for two different types of optimal switching problems. [Boucekkine et al. \(2013, 2012\)](#) apply this theory to the optimal management of exhaustible resources under ecological irreversibility and backstop adoption. In this paper, we use the same optimal control approach but the threshold value triggering the irreversible environmental event is uncertain and modelled as a catastrophe.

The question of a catastrophic environmental event goes back to [Cropper \(1976\)](#), using the example of a nuclear incident. [Tsur and Zemel \(1996\)](#) focuses on the potential depletion of a renewable resource. Both papers consider optimal control problems where catastrophe is a random event and the objective function is defined in terms of expectations. These expectations derive from a probability distribution function on the threshold value. In these frameworks, whenever the radioactive pollution (respectively the natural resource) stock exceeds (respectively falls below) a critical threshold, an event occurs which reduces society's utility to zero forever. [Tsur and Zemel \(1996\)](#) and [Nævdal \(2006\)](#) postulate that the event is partly reversible. When pollution reaches the unknown threshold, then an event occurs which substantially reduces the utility level. But, the economy can recover from its impact even if it implies bearing considerable costs (for instance related to remediation). [Ayong Le Kama et al. \(2014\)](#) considers the ecological catastrophe involving irreversible degradation of regeneration capacity in particular. In the latter paper, uncertainty surrounding irreversible thresholds has strong repercussions on the optimal control of pollution because it generally induces more conservative behaviour. However, we cannot preclude unintentional reaching of the threshold, whereas the situation cannot be observed in the deterministic case. Similarly, in this paper we consider that the catastrophic environmental event happens when the stock of pollution reaches an uncertain threshold. The environmental event corresponds to flooding generated by climate change after which (i) only a quantity of capital and resources known ex-ante will be rescued and (ii) there is a direct loss in utility.

This paper makes two contributions. First, it proposes a general appraisal of optimal switching problems involving two regime switches, one of them being uncertain. In this sense, we generalise Boucekkine et al. (2013, 2012). The second contribution is to apply this new optimal control material to address the problem of optimal energy transition under ecological risk. For that purpose, we consider a two-sector setting, where the economy produces energy and final goods. Energy initially comes from both oil and RES but can eventually be produced using only RES if fossil fuels are exhausted. Oil extraction is costless, while renewable energy requires capital. Part of the energy is used as energy services by consumers and the other is used as input for final goods production. Several studies on RE adoption assume imperfect or perfect substitution between inputs. On the contrary, we assume an economy with such rigidities that oil and RES are complementary, as in Pelli (2012). Moreover, we also assume that capital use and energy are complementary, as in Pindyck and Rotemberg (1983), Boucekkine and Pommeret (2004) or Díaz and Puch (2013). The use of oil by both the final goods sector and households has a potential negative impact on the environment through a stochastic critical pollution threshold above which a catastrophic event occurs. This event results in some loss of utility for households and in the destruction of a part of capital and fossil fuel reserves (the amounts rescued being known ex ante). We solve the model backward using the analytical first order optimality conditions. Numerical results show that the optimal energy transition path may correspond to three phases, starting with the use of both energy sources followed by the catastrophe, and finally by sole use of RES. It is therefore consistent with the view engineers⁴ now have on fossil fuel issues: the most immediate threat to society comes from climate change and not from exhaustibility (e.g., the often cited peak oil). It is also in line with a common pessimistic view of environmental policy inertia: an environmental catastrophe would help society adopt more renewables.

The remainder of this paper is structured as follows. The model is presented in section 2. We analyse the optimal energy transition in section 3. Section 4 is devoted to numerical

⁴See for example Amory Lovins' blog: <http://blog.rmi.org/> .

results and sensitivity analysis. We present conclusions in section 5.

2.2 Model

We consider a closed economy with two productive sectors. One of the sectors produces energy using oil, RES and capital as inputs or only RES and capital, depending on the regime. Notably, we account for the fact that generating energy using wind or sun requires essential equipment. The second sector produces final goods using energy and capital. Part of the energy is used in the form of energy services by a representative consumer. The other is used jointly with capital to produce final goods. Oil use generates GHG emissions that accumulates to create a pollution stock. The households' utility is impaired if this stock exceeds a stochastic critical threshold. In the following sections, we describe the energy sector, the pollution threat, the final good sector and household utility.

2.2.1 Energy sector

Energy has two main sources: oil E_s and RES E_x . Both the final goods sector and households use the energy. The former uses a part of it E_1 as an input to produce final goods, while the latter uses a part of the energy E_2 as energy services. E_{2s} , E_{2x} , E_{1s} and E_{1x} are the oil and RES uses of households and final goods sector respectively. We have the following energy market clearing conditions:

$$E_{st} = E_{1st} + E_{2st} \quad (2.1)$$

$$E_{xt} = E_{1xt} + E_{2xt} \quad (2.2)$$

We assume that extracting oil is costless and that the oil stock S_t exhibits the following dynamics:

$$dS_t = -E_{st}dt \quad (2.3)$$

with S_0 the initial stock of oil. Producing renewable energy requires the use of capital. We consider that the cost of solar or wind energy comes from the installations needed to transform the RES into electricity. For example, to produce solar (or wind) energy, one

needs to install solar panels (or wind turbines) in order to transform sunlight (wind) into electricity. Specifically, we assume a one-to-one transformation of a part of capital (K_1):

$$E_{xt} = K_{1t} \quad (2.4)$$

2.2.2 Pollution threat

Oil used to produce energy (that is in turn used directly by consumers or by final good producers) generates GHG emissions. Pollution accumulates according to the following process:

$$\dot{Z}_t = E_{st} - \alpha Z_t \quad (2.5)$$

where α is the rate of natural pollution assimilation. Pollution affects the economy only if the stock exceeds an uncertain threshold \bar{Z} above which flooding occurs and (i) households experience a loss of utility⁵ and (ii) the stock of capital and that of non-renewable energy (NRE) reach new (lower) levels that are known ex ante: capital and NRE that can be rescued are the one located sufficiently high relative to the sea level.⁶ A similar role for pollution can also be found in Zemel (2014). The catastrophic event may occur at any state of pollution with a probability distribution function that we define as $F(Z) = Pr(Z > \bar{Z})$ and a density function $f(Z) = \frac{dF(Z)}{dZ}$. From this definition, we take the hazard rate to be $\Gamma(Z) = \frac{f(Z)}{1-F(Z)}$. In order to account for the fact that the catastrophic event is more likely to occur given higher levels of pollution, we assume: $\Gamma'(Z) \geq 0$. We assume that the NRE source is abundant so that it cannot be exhausted before the pollution threshold is crossed: $\bar{Z} < S_0$.

2.2.3 Final good sector

In order to produce a final good Y , a part E_1 of energy and a part K_2 of capital serve as inputs in a Leontief production function. The interpretation runs as follows: there

⁵The specification of this loss is provided in subsection 2.4.

⁶This assumption simplifies the resolution substantially. Even if it eliminates some dynamic mechanisms, it does not affect those of most interest. In addition, it is not unrealistic for some regions like Hong Kong for instance where new industries are mostly offshore.

exist operating costs whose size depends on the energy requirements of capital, and to any capital use corresponds a given energy requirement. Such a complementarity is assumed in order to be consistent with several studies arguing that capital and energy are complements (see for instance [Berndt and Wood, 1975](#), [Pindyck and Rotemberg, 1983](#), or more recently [Díaz and Puch, 2013](#)). The production function is defined as:

$$Y_t = \min\{K_{2t}, E_{1t}\} \quad (2.6)$$

We distinguish the energy resource use before and after fossil fuels have been exhausted. Prior to their exhaustion, we assume that both oil and the renewable resource use are complementary. Two types of justification can be provided. First, [Pelli \(2012\)](#) proves using an econometric approach that there exists some complementarity between the dirty sources of energy (oil, coal, gases) and the clean ones (hydroelectric, biomass - wood and waste -, geothermal, solar/photovoltaic, wind and nuclear). The idea is that the production of energy using RES, for instance through solar panels, requires oil to build the solar panels. This is confirmed by [de Wit et al. \(2013\)](#) that conducts a meta analysis for all production factors including energy sources and show that there is no substitutability between them but rather some complementarity. Second, the presence of rigidity in a macroeconomic view may explain this complementarity between oil and RES as well since it is not that easy to substitute between oil and the electricity provided by solar panels. Therefore, this assumption allows us to highlight the implication of complementarity between the two types of energy sources in the energy transition. We define E_{1t} as:

$$E_{1t} = \min\{E_{1st}, E_{1xt}\} \quad (2.7)$$

Note that the complementarity assumption can also be viewed as an extreme case of imperfect substitution. Therefore, reality lies between these two extreme cases (perfect substitution and complementarity).

After fossil fuels exhaustion,⁷ a new technology allows producing the final good using only

⁷We assume that the new technology becomes available once fossil fuels have been exhausted. It is a way to account for the fact that fossil fuel producers prevent the innovation through lobbying.

RES, and the production function becomes:

$$Y_t = \min\{K_{2t}, E_{1xt}\} \quad (2.8)$$

The final good Y can be used as capital goods (for investment) or consumption goods: $Y_t = C_t + I_t$ where I_t is the total investment in capital used in both sectors at time t . Furthermore, we have $K_{1t} + K_{2t} = K_t$. In what follows, we abstract from any capital depreciation.

2.2.4 Households

We consider a representative household who consumes the energy good E_2 as energy services and the non-energy good C . Consumption of the final good and energy use are complementary. For the most part, households need energy to cook food, to use electronic appliances or to drive a car, so energy is complementary to final goods consumption in order to get utility or satisfaction. In the absence of environmental damage (ie. for a stock of pollution below the threshold \bar{Z}), the instantaneous utility function u_{wc} is then:

$$u_{wct} = \bar{C} \min\{C_t, E_{2t}\} \quad (2.9)$$

where u_{wc} is the instantaneous utility without catastrophe and $E_{2t} = \min\{E_{2st}, E_{2xt}\}$ accounts for the complementarity between oil and RES. Once the catastrophic environmental event has occurred, household utility is reduced. We assume that this reduction is a quadratic function of the basket composed of non-energy good C and energy good E_2 : the more the household consumes, the more it suffers. One can write a general instantaneous utility function u that is valid whatever the stock of pollution, using an indicative function 1_δ that is equal to 0 in the period before the occurrence of the catastrophic event and to 1 otherwise:

$$u(C_t, E_{2t}) = \bar{C} \min\{C_t, E_{2t}\} - 1_\delta \theta [\min\{C_t, E_{2t}\}]^2 \quad (2.10)$$

where θ is a scale parameter. Preferences are represented by the utility function U as the expected discounted sum of instantaneous utility flow u :

$$U = \int_0^{\infty} u(C_t, E_{2t})e^{-\rho t} dt \quad (2.11)$$

where ρ is the discount rate with $1 \leq \rho \leq 0$. Households own firms in both the energy and final goods sectors. Part of the final good production is used as investment in its own sector, part is used as investment in the energy sector and part is consumed. Investments in both sectors (final goods and energy goods) generate capital accumulation with no depreciation, and the market clearing condition is:

$$Y_t = C_t + \dot{K}_{1t} + \dot{K}_{2t} \quad (2.12)$$

In the following sections, we analyse the optimal energy transition path if a stochastic pollution threshold \bar{Z} exists.

2.3 Optimal energy transition path

In this section, we analyse the optimal energy transition and consider two types of regime switch: a chosen energy regime switch and an uncertain pollution threshold. Three regimes that correspond to the energy transition path may occur:

- First regime: energy is produced by both oil and the complementary renewable resource and pollution is below the threshold. At that time, the economy faces the risk of catastrophic events whose occurrence is uncertain but more likely when the economy experiences increasing pollution.
- Second regime: after the catastrophic event has occurred, the economy switches to the second regime in which both energy sources are still used but the critical pollution threshold has already been crossed. During this regime, the economy faces a flood generating a loss in utility and a reduction in the stock of capital and in the fossil fuels stock (rescued amounts are known ex ante).
- Third regime: fossil fuels have been exhausted and only renewable resources are

used in the third regime but the economy is still facing the negative consequences of the catastrophic event.

Note that the stochastic process of the threshold will be designed such that it will never be crossed if the only resource used is renewable. Therefore, it makes no sense to consider the chosen energy switch first and then the uncertain pollution threshold. However, corner cases may emerge for which either the switch and the threshold are merged or there are only two regimes. These corner solutions are extreme cases of our general resolution and do not require any particular analytical treatment.

We solve the model backward by starting the resolution from the third regime (only RE), followed by the second regime and finally the first regime. We use the optimal boundary conditions (continuity of (i) appropriate co-states, (ii) states variables and (iii) Hamiltonians across two regimes) as in [Boucekkine et al. \(2013\)](#), and the steady state in the first regime to find the optimal times to cross the pollution threshold and to fully adopt RE. As it is not possible to obtain analytical solutions for the switching times, we numerically solve for them.

2.3.1 Third regime

In the third regime, the economy uses only RES and faces the negative consequences of the catastrophic event. The economy enters the third regime at time T_2 which is known once the economy is in this regime. The social planner maximises the sum of discounted post event utility subject to the capital accumulation only. During this third regime, both pollution accumulation and fossil fuels dynamics are irrelevant as the economy has already crossed the critical pollution threshold (and is facing its negative consequences) and no fossil fuel is left .

By using the equality in Leontief production function referred to as the Leontief condition due to the interior solutions, the capital accumulation equation becomes $\dot{K}_t = K_{2t} - C_t$, since $Y_t = \min\{K_{2t}, E_{1t}\} = K_{2t} = E_{1xt}$. Moreover, we know that the capital is split between the final goods sector (K_{2t}) and energy sector (K_{1t}). The latter serves to produce the total energy (full renewable energy adoption) $K_{1t} = E_{1xt} + E_{2xt}$ such that $K_{2t} = K_t -$

$(E_{1xt} + E_{2xt})$. Then the equation of capital accumulation is: $\dot{K}_t = K_t - (E_{1xt} + E_{2xt}) - C_t$. The Leontief condition in the final goods sector implies that $E_{1xt} = \frac{1}{2}(K_t - E_{2xt})$ and the Leontief condition for consumers implies that $C_t = E_{2xt}$. Inserting the last two equalities into capital accumulation equation gives:

$$\dot{K}_t = \frac{1}{2}K_t - \frac{3}{2}C_t. \quad (2.13)$$

The program to be solved by the social planner:⁸

$$V_3 = \max_C \int_{T_2}^{\infty} (\bar{C}C - \theta C^2) e^{-\rho(t-T_2)} dt \quad (2.14)$$

s.t eq(2.13). The corresponding Hamiltonian is defined as

$$H_3 = \bar{C}C - \theta C^2 + \lambda \left(\frac{1}{2}K - \frac{3}{2}C \right)$$

with λ the co-state variable related to capital K . The first order conditions (FOCs) are

$$H_C = 0 \Rightarrow \bar{C} - 2\theta C = \frac{3}{2}\lambda \quad (2.15)$$

and

$$\frac{\dot{\lambda}}{\lambda} = \rho - \frac{1}{2} \quad (2.16)$$

Condition (2.15) highlights the traditional consumption/savings arbitrage. Condition (2.16) constrains the instantaneous return on capital to be constant over time. Furthermore, using equations (2.16) and (2.15) it is possible to solve for the expressions of λ_t and C_t as functions of time, T_2 and λ_{T_2} :

$$\lambda_t = \lambda_{T_2} e^{(\rho - \frac{1}{2})(t - T_2)}$$

and

$$C_t = \frac{\bar{C}}{2\theta} - \frac{3\lambda_{T_2}}{4\theta} e^{(\rho - \frac{1}{2})(t - T_2)}.$$

⁸Time subscripts have been omitted when unnecessary.

By inserting the expression of C_t in equation (2.13) and using the transversality condition, we can solve for capital K_t as well (see Appendix A1). We also obtain an expression for the value function (see Appendix A2):

$$K_t = \frac{3\bar{C}}{2\theta} + \frac{9\lambda_{T_2}}{8\theta(\rho-1)} e^{(\rho-\frac{1}{2})(t-T_2)} \Leftrightarrow \lambda_{T_2} = \left(K_{T_2} - \frac{3\bar{C}}{2\theta} \right) \frac{8\theta(\rho-1)}{9} \quad (2.17)$$

$$V_{3,T_2} = \frac{\bar{C}^2}{4\rho\theta} + \frac{1}{16(\rho-1)} \left[\left(K_{T_2} - \frac{3\bar{C}}{2\theta} \right) \frac{8\theta(\rho-1)}{9} \right]^2.$$

Therefore the value and trajectories in this regime are fully solved for given values of T_2 and K_{T_2} . We will solve for the optimal date to enter the third regime and the optimal capital at this date after having determined trajectories in the second regime.

2.3.2 Second regime

In the course of the second regime, both energy sources are still used, but the economy has already crossed the critical pollution threshold and is then facing environmental damage. The economy enters the second regime at time T_1 which is known once the economy is in this regime. The social planner maximizes the sum of discounted post event utilities until T_2 plus the discounted value function of the third regime, subject to both capital and NRE accumulation. Pollution accumulation is still irrelevant as the economy has already crossed the critical pollution threshold. The social planner knows that fossil fuels are exhausted at the end of this regime.

A difference with what happens in the third regime is that oil accumulation is relevant, as the economy is still using some oil after the catastrophic event has occurred. As in the third regime, the economy uses a part of capital K_1 to produce energy using RES as a part of the total energy capacity: $K_{1t} = E_{1xt} + E_{2xt}$. Due to the Leontief condition in the energy use $E_{1t} = \min\{E_{1st}, E_{1xt}\} = E_{1st} = E_{1xt}$ and $E_{2t} = \min\{E_{2st}, E_{2xt}\} = E_{2st} = E_{2xt}$. Equation (2.13) is therefore still valid for capital accumulation. The oil stock dynamics

equation $dS_t = -(E_{1st} + E_{2st})dt = -(E_{1t} + E_{2t})dt$ becomes (see Appendix A3):

$$dS_t = - \left(\frac{1}{2}K_t + \frac{1}{2}C_t \right) dt \quad (2.18)$$

The program to be solved by the social planner during the second regime is:

$$V_{2,T_1} = \max_C \int_{T_1}^{T_2} (\bar{C}C - \theta C^2) e^{-\rho(t-T_1)} dt + V_{3,T_2} e^{-\rho(T_2-T_1)} \quad (2.19)$$

s.t eq(2.13) and eq(2.18). The corresponding Hamiltonian can be written as:

$$H_2 = \bar{C}C - \theta C^2 + \lambda_1 \left(\frac{1}{2}K - \frac{3}{2}C \right) - \lambda_2 \left(\frac{1}{2}K + \frac{1}{2}C \right).$$

with λ_1 and λ_2 the co-state variables associated with the capital and oil stocks, respectively. The FOCs are:

$$H_C = 0 \Rightarrow \bar{C} - 2\theta C = \frac{3}{2}\lambda_1 + \frac{1}{2}\lambda_2 \quad (2.20)$$

$$\dot{\lambda}_1 = \left(\rho - \frac{1}{2} \right) \lambda_1 + \frac{1}{2}\lambda_2 \quad (2.21)$$

$$\frac{\dot{\lambda}_2}{\lambda_2} = \rho \quad (2.22)$$

Condition (2.20) is the usual consumption/savings arbitrage. It states that the marginal value of one more unit of consumption has to be balanced with the marginal losses of foregone investment and of the oil depletion that consumption implies. Contrary to what happens in the third regime, condition (2.21) states that the instantaneous return on capital is no longer constant over time and depends on the value of the oil stock relative to that of capital. This comes from the complementarity between capital and energy use in the production of final goods such that energy use can be expressed as a function of capital. Finally, condition (2.22) states that the oil value grows at a constant rate over time. It implies:

$$\lambda_2 = \lambda_{2,T_1} e^{\rho(t-T_1)} \quad (2.23)$$

Using equations (2.20), (2.21) and (2.23) helps solving for λ_{1t} and C_t (see Appendix A4) and K_t (see Appendix A5) as functions of $\lambda_{1.T_1}$ and $\lambda_{2.T_1}$. Now, let us apply the conditions that (i) oil is exhaustible, (ii) the economy completely depletes the initial stock of oil in the first two energy regimes and (iii) the dynamics of the resource stock is given by equation(2.18) to get:

$$S_{T_1} = \frac{1}{2} \int_{T_1}^{T_2} (K_t + C_t) dt.$$

The level of the NRE stock S_{T_1} is known as soon as the level of pollution reaches its threshold level \bar{Z} at T_1 . Therefore, by replacing K_t and C_t with their corresponding expressions, we get (see Appendix A6) an expression for the value of capital ($\lambda_{1.T_1}$) as a function of that of the oil stock ($\lambda_{2.T_1}$) at T_1 , the beginning of the second regime. Knowing S_{T_1} and K_{T_1} and T_1 at the beginning of the second regime, the only unknown variables in this regime are therefore T_2 and $\lambda_{1.T_1}$. We solve for them in the next subsection.

2.3.3 Boundary conditions at $t = T_2$

Since the ecological catastrophe generates new levels for the stocks of resource and capital that are known, the state variables that are relevant for the second regime do not depend on the trajectories of the first regime. We can therefore unravel the problems before and after the pollution threshold is hit. Of course, the ecological catastrophe happens only with some probability, which restores a link between the three regimes. In particular, parameters that affect the value after the catastrophe will in turn affect the probability of catastrophe.

Following Boucekine et al. (2013), we use three types of boundary conditions at $t = T_2$: (i) continuity of λ_1 , the co-state variable associated with capital (ii) continuity of K and S (the latter has to be zero at T_2 ; note that this condition has already been used) and (iii) equality of the Hamiltonians at the switching time $t = T_2$. Note that the co-state variable λ_2 is associated with the oil stock whose level is constrained to be zero at $t = T_2$, and this co-state may therefore not be continuous at that time. This provides us with three conditions to solve for the three unknowns T_2 , $\lambda_{1.T_1}$ and K_2 . We can also derive (see Appendix 7) the expression of the value function in the second regime:

$$V_2 = f(K_{T_1}, S_{T_1})$$

where f is a polynomial with degree 2 in K_{T_1} .

2.3.4 First energy regime

The economy starts using both energy sources and the pollution level is under the critical pollution threshold. During this first period, the economy faces a risk of catastrophic events whose occurrence is uncertain. However, the catastrophe is more likely to happen if pollution is increasing. The social planner maximises the expected sum of discounted pre-event utility and the discounted value function of the second regime subject to capital and pollution accumulations. Pollution accumulation is a relevant constraint because of the risk of crossing the critical pollution threshold. It can be expressed as a function of the NRE accumulation that is similar to that prevailing in the second regime:

$$\dot{Z} = \dot{S} - \alpha Z = \frac{1}{2}K + \frac{1}{2}C - \alpha Z \quad (2.24)$$

As the NRE source is abundant (the economy will therefore cross the pollution threshold before the its complete depletion) and the level of NRE after the catastrophe is known ex ante, the NRE accumulation is irrelevant for the social planner decisions and does not need to be considered in the program. We first analyse the dynamics of an economy subject to a deterministic pollution threshold. This economy serves as a benchmark for the one subject to a stochastic pollution threshold.

Deterministic pollution threshold

The program to be solved by the social planner in the deterministic case is:

$$V_1^d = \max_C \int_0^{T_1} \bar{C} C e^{-\rho t} dt + V_2 e^{-\rho T_1} \quad (2.25)$$

s.t eq.(2.13) and (2.24)

The Hamiltonian can be written as:

$$H_1^d = \bar{C}C + \lambda_1 \left(\frac{1}{2}K - \frac{3}{2}C \right) + \lambda_2 \left(\frac{1}{2}K + \frac{1}{2}C - \alpha Z \right).$$

FOCs are given by:

$$\lambda_2 = -2\bar{C} + 3\lambda_1 \tag{2.26}$$

$$\dot{\lambda}_1 = \rho\lambda_1 - \frac{\lambda_1}{2} - \frac{\lambda_2}{2} \tag{2.27}$$

$$\dot{\lambda}_2 = \rho\lambda_2 + \alpha\lambda_2 \tag{2.28}$$

From (2.28), $\dot{\lambda}_2 = 0$ implies that $\rho + \alpha = 0$, which is impossible ($\rho > 0$ and $\alpha > 0$). It is therefore not possible to have a steady state. Since the program is fully linear with respect to both the control and state variables, only the co-state variables appear in the FOCs. This implies that the level of the control variables can be freely chosen. Thus, the maximum principle applied to our model with a certain pollution threshold fails to yield the optimal transition path from the first to the second regime.

Stochastic pollution threshold

The stochastic problem is very different from the deterministic one, as uncertainty serves to convexify the program. The social planner has to solve:⁹

$$V_1 = \text{Max} \int_0^\infty [\bar{C}C(1 - F_\tau(t)) + f_\tau(t)V_2(K_{T_1}, S_{T_1t})e^{-\rho t}]dt \tag{2.29}$$

s.t eq.(2.13) and (2.24)

⁹We assume successive regime switches because the occurrence of the catastrophe is uncertain. Without uncertainty, we could allow corner energy transition paths in which the economy can escape the catastrophe, start with the sole adoption of the renewable energy or never attend the pollution threshold that trigger the environmental catastrophe.

Let us first focus on the probability of remaining in the first regime $1 - F_\tau(t) = Pr(t < \tau)$ and on the probability of irreversibly crossing the pollution threshold $f_\tau(t) = \frac{dF_\tau(t)}{dt}$, where τ is the switching time to the second regime. The distribution of τ depends on that of pollution, so one can derive the distribution of τ from the pollution trajectories. As in [Ayong Le Kama et al. \(2014\)](#), we consider monotone trajectories for the pollution. We can then define the distribution of τ as:

$$1 - F_\tau(t) = Pr(t < \tau / \tau > 0) = Pr(Z(t) < \underline{Z}/Z_0 < \underline{Z}) = \frac{1 - F(Z(t))}{F(Z_0)}, f_\tau(t) = \frac{f(Z)\dot{Z}}{F(Z_0)}$$

From this point on we observe that $V_2(K_{T_1}, S_{T_1}) = \bar{V}_2$ since this value is fully determined by K_{T_1} and S_{T_1} , which are known. The Hamiltonian can then be written as:

$$H_1^s = \bar{C}C[1 - F(Z)] + f(Z)\left[\frac{1}{2}K + \frac{1}{2}C - \alpha Z\right]\bar{V}_2 + \lambda_1\left(\frac{1}{2}K - \frac{3}{2}C\right) + \lambda_2\left(\frac{1}{2}K + \frac{1}{2}C - \alpha Z\right).$$

FOCs are given by:

$$H_C^s = 0 \Rightarrow 3\lambda_1 - \lambda_2 = 2\bar{C}[1 - F(Z)] + f(Z)\bar{V}_2 \quad (2.30)$$

$$\dot{\lambda}_1 = \rho\lambda_1 - \frac{1}{2}f(Z)\bar{V}_2 - \frac{1}{2}\lambda_1 - \frac{1}{2}\lambda_2 \quad (2.31)$$

$$\dot{\lambda}_2 = (\rho + \alpha)\lambda_2 + \bar{C}Cf(Z) + \alpha f(Z)\bar{V}_2 - f'\left(\frac{1}{2}K + \frac{1}{2}C - \alpha Z\right)\bar{V}_2 \quad (2.32)$$

Considering the steady state (see Appendix A.8.)

$$\frac{\bar{C}}{\rho - 2}[2\rho - 1] + \frac{\Lambda(Z^*)}{\rho + \alpha}\left(\rho\bar{V}_2 - \frac{\alpha\bar{C}Z}{2}\right) = 0 \quad (2.33)$$

Moreover $C^* = \frac{\alpha}{2}Z^*$ and $K^* = \frac{3\alpha}{2}Z^*$.

Solving equation (2.33), we can derive the steady state level of pollution Z^* and determine those of capital, consumption and energy use. As it is not possible to obtain an analytical solution, we numerically solve for Z^* . Once Z^* is computed, we can derive the probability that Z^* is larger than the pollution threshold, i.e. the probability that the economy crosses

the pollution threshold.

2.4 Numerical results and sensitivity analysis

The concern here is to show that there are numerical values for the parameters of our model, that solve for the two final regimes in the first step, and for the steady state level of pollution in the second step. The ultimate objective is to compute the probability of reaching the pollution threshold. Once the numerical solution is derived, we perform a sensitivity analysis to identify the effects of parameters, including those describing uncertainty, on the probability of catastrophe.

2.4.1 Numerical results

To model the stochastic catastrophe, we consider a Weibull distribution. The hazard rate of this distribution is $\Lambda(Z) = k \frac{Z^{k-1}}{\delta^k}$ with $\delta > 0$. Moreover we assume $k > 1$ in order to have $\Lambda'(\cdot) > 0$. Baseline values for the parameters are:

Table 2.1: *Baseline parameters*

ρ	α	θ	\bar{C}	S_{T_1}	K_{T_1}	k	δ
0.005	0.03	0.07	9	5000	100	1.05	1000

Observe that there is no need to set values for S_0 and Z_0 . However we have assumed that $Z_0 \leq \bar{Z}$ and S_0 to be sufficiently large to be irrelevant for the first regime. The discount rate ρ is set as in [Tol \(2005\)](#). We assume that the natural regeneration rate of the environment is smaller than the value used by [Tahvonen \(1997\)](#). Other parameters are arbitrarily chosen in order to provide a numerical illustration. A sensitivity analysis will be conducted to appraise the validity of the results.

We first solve for regimes two and three in order to compute the value after the catastrophe, and the length of the second regime. We then turn to the computation of the first regime steady state and determine the probability of damage. For the baseline parameters we obtain a steady state level of pollution $Z^* = 3174$ that corresponds to

a 96.5 % probability of reaching the pollution threshold. Moreover, the length of the second regime is then $T_2 - T_1 = 40$ meaning that after the ecological catastrophe, the economy continues using NRE for 40 more years. Therefore it has proven possible to find parameter values (some realistic) leading to a very high probability of catastrophe, and a realistic time before the economy turns to only RE.

2.4.2 Sensitivity analysis

In this section, we perform a sensitivity analysis on the probability of damage and on the length of the second regime. For each parameter we compare damage probability and regime length with results obtained using the baseline values, in order to isolate the sensitivity to the parameter value (see Table 2.2).

The discount rate ρ positively affects the steady state level of pollution in the first regime. However, after a 60% decrease in ρ (i.e ρ becomes 0.002), the probability of occurrence remains very high, greater than 96%. This result seems intuitive in the sense that more impatient people consume more, pollute more and are willing to face a higher risk of environmental damage in the future. Moreover, the higher the discount, the longer it takes following the environmental catastrophe for NRE to be exhausted and for the RE to be used alone. Higher discounting reduces the value more in the final regime than in the second regime, which creates an incentive to switch later to that regime.

A higher regeneration rate reduces the steady state level of pollution therefore decreasing the probability of environmental damage. However, for a 10% regeneration rate, which is too high to be realistic, the probability of damage occurrence is still very high (greater than 80%). An increase in the regeneration capacity of the environment has two effects. First, less pollution is accumulated as the regeneration capacity of the environment increases. Second, as the environment becomes more efficient at regenerating, there is more incentive for people to increase their pollution by using more NRE. Numerical resolutions show that the first effect prevails. Of course the regeneration rate has no effect on what happens after the environmental catastrophe, hence on the length of the period before the third regime.

Table 2.2: Sensitivity analysis

ρ	0.002	0.003	0.004	0.005	0.0055
Z^*	3096.06	3122.08	3148	3173.8	3186.66
Pro	0.962223	0.9633	0.964342	0.965351	0.965843
$T_2 - T_1$	40.096	40.0984	40.1004	40.1023	40.1033
α	0.01	0.02	0.03	0.05	0.1
Z^*	7679.19	4297.83	3173.8	2277.57	1609.03
Pro	0.999797	0.990175	0.96535	0.906823	0.807519
$T_2 - T_1$	40.1023	40.1023	40.1023	40.1023	40.1023
θ	0.055	0.06	0.07	0.09	0.1
Z^*	3740.48	3520.07	3173.8	2712.06	2550.31
Pro	0.981602	0.976451	0.965351	0.942201	0.930923
$T_2 - T_1$	32.049	34.7334	40.1023	50.8401	56.209
S_{T1}	0.1	100	1000	5000	8000
Z^*	3183.48	3176.28	3173.8	3173.8	3173.8
Pro	0.965722	0.965446	0.965351	0.965351	0.965351
$T_2 - T_1$	0.00194619	1.37765	8.97695	40.1023	63.4316
K_{T1}	0.1	10	100	1000	1500
Z^*	3141.46	3145.67	3173.8	2446.67	1263.94
Pro	0.964081	0.964249	0.965351	0.922588	0.721638
$T_2 - T_1$	41.4078	41.2784	40.1023	28.3414	21.8079
k	1.01	1.05	1.2	1.5	3
Z^*	3273.93	3173.8	2919.8	2618.09	2219.37
Pro	0.963593	0.965351	0.973154	0.985537	0.999982
$T_2 - T_1$	40.1023	40.1023	40.1023	40.1023	40.1023
δ	200	500	1000	5000	10000
Z^*	2328.	2640.28	3173.8	7534.8	13016.1
Pro	0.999998	0.996781	0.965351	0.785228	0.732565
$T_2 - T_1$	40.1023	40.1023	40.1023	40.1023	40.1023

Reading: Pro is the probability of environmental damage occurrence.

Greater damage induces a lower steady state level of pollution and then a smaller probability of occurrence. However, for a nearly 50% greater damage parameter (i.e θ becomes 0.1), the probability of occurrence remains greater than 90%. If the damage from the environmental catastrophe is high, people fear the consequences of such a catastrophe more and have an incentive to pollute less. This damage parameter affects what happens during the regimes which occur after the environmental catastrophe as well. Greater damage delays the third regime. This is due to the fact that it reduces the value more in the third regime than in the second regime.

For low initial levels (smaller than 500), an increase in the availability of polluting resources at the beginning of regime two, S_{T_1} negatively affects the steady state level of pollution and then the probability of occurrence. Were S_{T_1} to be reduced to nearly 0 (namely 0.1), the probability of occurrence would then become slightly greater (0.9657) than for a stock equal to 5000. For a smaller S_{T_1} people fear to join the second regime more, which encourages less polluting behaviour in the first regime. Note however that, at least for our parameterisation, the sensitivity is very small, and for large enough values for the stock S_{T_1} (larger than 500) the probability of environmental damage becomes even fully insensitive to the NRE stock after the catastrophe. Consistent with intuition, the length of the second regime rises with the stock at the beginning of this regime. Additionally, as the stock of NRE at time T_1 tends toward zero, so does time before the third regime.

For low initial levels (smaller than 195), an increase in the availability of the stock of capital at the beginning of regime two, K_{T_1} , positively affects the steady state level of pollution, but the opposite effect appears for high initial levels of K_{T_1} . As a result, we obtained a non-monotonicity for the probability of damage occurrence as well. Also note that the larger the stock of capital when entering regime two, the more quickly the third regime is reached whatever the initial value of K_{T_1} . The mechanism for initially low K_{T_1} is as follows: a higher stock of capital after the damage occurs reduces the consequences of environmental damage, therefore increasing pollution and the risk of damage occurrence in the first period. But as K_{T_1} becomes very large it reduces the value from regime two while the value in regime three is nearly unaffected, because the time spent in regime two shrinks. This explains why reaching regime two becomes less attractive and the pollution (and risk of damage occurring) in period one decreases.

We can summarize the effect of the extent of an environmental catastrophe on fossil fuel exhaustion and RES adoption. The different features of the catastrophe affect the speed of RES adoption in different ways. This adoption occurs earlier either if the effect of the catastrophe on utility is smaller, or the rescued resource is smaller or the rescued capital is larger.

We now focus on the effect of uncertainty on the results. Only the first regime is affected by uncertainty, therefore the second regime duration $T_2 - T_1$ will stay the same whatever the values of the uncertainty parameters. For a higher k , the shape parameter of the Weibull distribution, the hazard rate $\Lambda(Z) = k \frac{Z^{k-1}}{\delta^k}$ becomes larger¹⁰ for a given Z ; as a result agents become more cautious regard to pollution (Z^* is smaller) but not enough to prevent the increase in probability of damage occurrence. For a nearly 50% increase in parameter k (i.e., k becomes 1.5), the risk of catastrophe is 98%. Damage occurrence becomes even certain for k larger than 3. Higher values of δ , the scale parameter of the Weibull distribution lead to smaller hazard rates for a given Z and less cautious behaviour with respect to pollution. But again, the direct effect of the distribution change prevails and a larger δ (therefore a smaller hazard rate) leads to a smaller probability of environmental damage occurrence. However any value for this parameter that is smaller than 150 results in certainty of damage occurring.

2.5 Conclusion

In the present paper, we analyse the optimal energy transition of a two-sector economy with exhaustible oil reserves, a renewable source of energy and a stochastic critical pollution threshold above which a catastrophic event (following flooding, for example) occurs. Three regimes appear that correspond to the optimal energy transition path. In the first, energy is produced by both oil and the renewable resource that are complementary, and pollution is below the threshold. At that time, the economy faces a risk of catastrophic events whose occurrence is uncertain but are more likely to occur with increasing pollution. After the catastrophic event has occurred, the economy switches to the second regime in which both energy sources are still used but it has already crossed the critical pollution threshold. During this second regime, the economy starts facing quadratic damage through a loss in utility. Only renewable resources are used in the third regime but the economy is still coping with the negative consequences

¹⁰provided $Z/\delta > exp(k)$.

of the catastrophic event. We analytically solve the model using backward induction. The probability of damage occurrence and the optimal time to reach the economy only fuelled by renewable energy are obtained numerically.

We demonstrate that there exist numerical values that correspond to a higher pollution level than that of the threshold level: the environmental catastrophe may happen. We also show situations in which the optimal energy transition path corresponds to three phases, starting with use of both types of energy resources followed by the catastrophe, and finally by the use of RES only. Finally, higher hazard rates generate more cautious behaviour that negatively affects pollution, but the risk of damage still increases. This work can be seen as a first attempt at an analytical representation of the energy transition. We could account for the risk of climatic damage and the exhaustibility of non-renewable resources, but this has required other stringent assumptions such as the complementarities assumed between capital and energy as well as between renewable and non-renewable energies, or the specification of the utility functions. The modelling of the renewable resource characteristics is also rather crude. In particular, the important issues of intermittency and therefore of storage are not addressed. Finally, the model should be extended to allow for the sole adoption of RES prior to fossil fuel exhaustion. However more numerical approaches should enable the study of a more general framework in future work.

2.6 Appendix

2.6.1 Appendix A1

To determine the expression of capital in the third regime, we need to replace the consumption expression given by the FOCs in the equation of capital accumulation (2.13) and use the transversality conditions and solve for capital K_t . The consumption expression $C_t = \frac{\bar{C}}{2\theta} - \frac{3\lambda T_2}{4\theta} e^{(\rho - \frac{1}{2})(t - T_2)}$ in (2.13) gives:

$$\dot{K}_t - \frac{1}{2}K_t = -3\frac{\bar{C}}{4\theta} + \frac{9\lambda T_2}{8\theta} e^{(\rho - \frac{1}{2})(t - T_2)}.$$

Changing of variables as follows: $x = K e^{-\frac{1}{2}(t - T_2)}$, implying that:

$$\begin{aligned}\dot{x}e^{\frac{1}{2}(t-T_2)} &= -3\frac{\bar{C}}{4\theta} + \frac{9\lambda_{T_2}}{8\theta}e^{(\rho-\frac{1}{2})(t-T_2)} \\ \Rightarrow \dot{x} &= -3\frac{\bar{C}}{4\theta}e^{-\frac{1}{2}(t-T_2)} + \frac{9\lambda_{T_2}}{8\theta}e^{(\rho-1)(t-T_2)}.\end{aligned}$$

The solution for the above differential equation in x is:

$$x_t = 3\frac{\bar{C}}{2\theta}e^{-\frac{1}{2}(t-T_2)} + \frac{9\lambda_{T_2}}{8\theta(\rho-1)}e^{(\rho-1)(t-T_2)} + \bar{x}$$

The solution for capital can be derived as:

$$K_t = \frac{3\bar{C}}{2\theta} + \frac{9\lambda_{T_2}}{8\theta(\rho-1)}e^{(\rho-\frac{1}{2})(t-T_2)} + \bar{x}e^{\frac{1}{2}(t-T_2)}$$

Using the transversality conditions to determine the value of \bar{x} :

$$\begin{aligned}\lim_{t \rightarrow \infty} K_t \lambda_t e^{-\rho(t-T_2)} &= \lim_{t \rightarrow \infty} K_t \lambda_{T_2} e^{-\frac{1}{2}(t-T_2)} = 0 \\ \Rightarrow \lim_{t \rightarrow \infty} \frac{3\bar{C}}{2\theta} \lambda_{T_2} e^{-\frac{1}{2}(t-T_2)} + \frac{9}{8\theta(\rho-1)} \lambda_{T_2}^2 e^{(\rho-1)(t-T_2)} + \bar{x} \lambda_{T_2} &= 0\end{aligned}$$

$\Leftrightarrow \bar{x} = 0$ with $\rho \leq 1$ and $\lambda_{T_2} \neq 0$.

Hence, the capital expression can be written as:

$$K_t = \frac{3\bar{C}}{2\theta} + \frac{9\lambda_{T_2}}{8\theta(\rho-1)}e^{(\rho-\frac{1}{2})(t-T_2)}$$

2.6.2 Appendix A2

To determine the value function of the third regime, we simply need to replace consumption in the value function and solve it.

Recalling that:

$$V_3 = \int_{T_2}^{\infty} (\bar{C}C - \theta C^2) e^{-\rho(t-T_2)} dt$$

The expression of C_t in the above expression gives:

$$V_3 = \int_{T_2}^{\infty} \left[\frac{\bar{C}^2}{4\theta} e^{-\rho(t-T_2)} - \frac{\lambda_{T_2}^2}{16\theta} e^{(\rho-1)(t-T_2)} \right] dt$$

$$\Rightarrow V_3 = -\frac{\bar{C}^2}{4\rho\theta} [e^{-\rho(t-T_2)}]_{T_2}^{\infty} - \frac{\lambda_{T_2}^2}{16\theta(\rho-1)} [e^{(\rho-1)(t-T_2)}]_{T_2}^{\infty}.$$

Which leads to:

$$V_3 = \frac{\bar{C}^2}{4\rho\theta} + \frac{\lambda_{T_2}^2}{16(\rho-1)}$$

2.6.3 Appendix A3

The concern here is to express the dynamics of NRE as a function of capital and consumption. As a result of the Leontief conditions in the production of final goods, we have: $Y = K_2 = E_1$. Also, the Leontief conditions in the modes of energy use imply that $E_{1t} = E_{1xt} = E_{1st}$ and $E_{2t} = E_{2xt} = E_{2st}$, that capital is invested to produce final goods and the RE: $K_t = K_{1t} + K_{2t} = K_{1t} + E_{2xt} + E_{1xt}$. Then, we deduce that $Y_t = K_{2t} = E_{1t} = K_t - E_{2t} - E_{1t}$, which implies that $E_{1t} = \frac{1}{2}(K_t - E_{2t})$.

By summing E_{1t} and E_{2t} , we get:

$$E_{1t} + E_{2t} = \frac{1}{2}(K_t - E_{2t}) + E_{2t} = \frac{1}{2}(K_t + E_{2t})$$

Finally, the Leontief conditions in the utility function gives $C_t = E_{2t}$ which we replace in the above equation to find that:

$$E_{1t} + E_{2t} = \frac{1}{2}(K_t + C_t)$$

Hence, the dynamics of NRE $dS_t = -(E_{1st} + E_{2st})dt = -(E_{1t} + E_{2t})dt$ become:

$$\frac{dS_t}{dt} = -\left(\frac{1}{2}K_t + \frac{1}{2}C_t\right)$$

2.6.4 Appendix A4

Capital value λ_{1t} in the second regime can be determined using the FOCs (2.23) and (2.21) (in the text). We have to solve the following differential equation for λ_{1t} :

$$\dot{\lambda}_{1t} - \left(\rho - \frac{1}{2}\right)\lambda_{1t} = \frac{\lambda_{2.T_1}}{2}e^{\rho(t-T_1)}.$$

By changing variables $x = \lambda_{1t}e^{-(\rho-\frac{1}{2})(t-T_1)}$, the above differential equation becomes:

$$\dot{x}_t = \frac{\lambda_{2.T_1}}{2}e^{\frac{1}{2}(t-T_1)}.$$

One can derive the solution as :

$$\lambda_{1t} = \lambda_{2.T_1}e^{\rho(t-T_1)} + \bar{x}e^{(\rho-\frac{1}{2})(t-T_1)}$$

To determine the unknown \bar{x} , we take the above expression at $t=T_1$:

$$\bar{x} = \lambda_{1.T_1} - \lambda_{2.T_1}$$

Hence,

$$\lambda_{1t} = \lambda_{2.T_1}e^{\rho(t-T_1)} + (\lambda_{1.T_1} - \lambda_{2.T_1})e^{(\rho-\frac{1}{2})(t-T_1)}$$

Using this equation as well as equations (2.20) and (2.23), we solve for C_t :

$$C_t = \frac{1}{2\theta}\bar{C} - \frac{3}{4\theta}\lambda_{2.T_1}e^{\rho(t-T_1)} - \frac{3}{4\theta}(\lambda_{1.T_1} - \lambda_{2.T_1})e^{(\rho-\frac{1}{2})(t-T_1)} - \frac{1}{4\theta}\lambda_{2.T_1}e^{\rho(t-T_1)}$$

2.6.5 Appendix A5

Using the consumption expression C_t in (2.13) to solve the equation of capital accumulation for K_t . The equation of capital accumulation (2.13) becomes:

$$\dot{K}_t - \frac{1}{2}K_t = -\frac{3}{2}\left[\frac{1}{2\theta}\bar{C} - \frac{3}{4\theta}\lambda_{2.T_1}e^{\rho(t-T_1)} - \frac{3}{4\theta}(\lambda_{1.T_1} - \lambda_{2.T_1})e^{(\rho-\frac{1}{2})(t-T_1)} - \frac{1}{4\theta}\lambda_{2.T_1}e^{\rho(t-T_1)}\right]$$

By changing variables as in **Appendix A1** and by taking the level of capital at $t=T_1$ (K_{T_1}) to determine the unknown \bar{x} , we get

$$K_t = \frac{3}{2\theta}\bar{C} + A_1(t)\lambda_{2.T_1} + A_2(t)\lambda_{1.T_1} + (K_{T_1} - \frac{3}{2\theta}\bar{C})e^{\frac{1}{2}(t-T_1)}$$

where

$$A_1(t) = \frac{12}{8\theta(\rho - \frac{1}{2})}e^{\rho(t-T_1)} - \frac{9}{8\theta(\rho - 1)}e^{(\rho-\frac{1}{2})(t-T_1)} + \frac{15 - 6\rho}{8\theta(\rho - 1)(2\rho - 1)}e^{\frac{1}{2}(t-T_1)}$$

and

$$A_2(t) = \frac{9}{8\theta(\rho - 1)}e^{(\rho-\frac{1}{2})(t-T_1)} - \frac{9}{8\theta(\rho - 1)}e^{\frac{1}{2}(t-T_1)}.$$

2.6.6 Appendix A6

Assuming that (i) oil is exhaustible, (ii) the economy completely depletes the initial stock of oil during the first two energy regimes and (iii) dynamics of the resource stock are given by equation(2.18) we get:

$$S_{T_1} = \frac{1}{2} \int_{T_1}^{T_2} (K_t + C_t)dt = \frac{1}{2} \int_{T_1}^{T_2} K_t dt + \frac{1}{2} \int_{T_1}^{T_2} C_t dt$$

Solving each part of the right hand side (RHS) of the above equation separately:

$$\chi_1 = \frac{1}{2} \int_{T_1}^{T_2} K_t dt$$

and

$$\chi_2 = \frac{1}{2} \int_{T_1}^{T_2} C_t dt.$$

We get

$$\chi_1 = \frac{1}{2} \int_{T_1}^{T_2} [\frac{3}{2\theta}\bar{C} + A_1(t)\lambda_{2.T_1} + A_2(t)\lambda_{1.T_1} + (K_{T_1} - \frac{3}{2\theta}\bar{C})e^{\frac{1}{2}(t-T_1)}]dt$$

$$\Rightarrow \chi_1 = \frac{1}{2}[D_0(\Delta) + D_1(\Delta)\lambda_{2.T_1} + D_2(\Delta)\lambda_{1.T_1}]$$

and

$$\begin{aligned}\chi_2 &= \frac{1}{2} \int_{T_1}^{T_2} \left[\frac{1}{2\theta} \bar{C} - \frac{3}{4\theta} \lambda_{2.T_1} e^{\rho(t-T_1)} - \frac{3}{4\theta} (\lambda_{1.T_1} - \lambda_{2.T_1}) e^{(\rho-\frac{1}{2})(t-T_1)} - \frac{1}{4\theta} \lambda_{2.T_1} e^{\rho(t-T_1)} \right] dt \\ &\Rightarrow \chi_2 = \frac{1}{2} [C_0(\Delta) + C_1(\Delta) \lambda_{2.T_1} + C_2(\Delta) \lambda_{1.T_1}]\end{aligned}$$

where

$$\Delta = T_2 - T_1,$$

$$D_0(\Delta) = \frac{3\bar{C}\Delta}{2\theta} + (2K_{T_1} - 3\frac{\bar{C}}{\theta})(e^{\frac{\Delta}{2}} - 1),$$

$$C_0(\Delta) = \frac{\bar{C}\Delta}{2\theta},$$

$$D_1(\Delta) = \frac{12}{8\theta\rho(\rho-\frac{1}{2})}(e^{\rho\Delta}-1) - \frac{9}{8\theta(\rho-1)(\rho-\frac{1}{2})}(e^{(\rho-\frac{1}{2})\Delta}-1) + \frac{15-6\rho}{4\theta(\rho-1)(2\rho-1)}(e^{\frac{1}{2}\Delta}-1),$$

$$C_1(\Delta) = -\frac{e^{\rho\Delta}}{\theta\rho} + \frac{1}{\theta\rho} + \frac{3}{4\theta(\rho-\frac{1}{2})}e^{(\rho-\frac{1}{2})\Delta} - \frac{3}{4\theta(\rho-\frac{1}{2})},$$

$$D_2(\Delta) = \frac{9}{8\theta(\rho-1)(\rho-\frac{1}{2})}(e^{(\rho-\frac{1}{2})\Delta}-1) - \frac{9}{4\theta(\rho-1)}(e^{\frac{1}{2}\Delta}-1),$$

and

$$C_2(\Delta) = -\frac{3}{4\theta(\rho-\frac{1}{2})}(e^{(\rho-\frac{1}{2})\Delta}-1)$$

Using the above expressions, we get:

$$S_{T_1} = \chi_1 + \chi_2 = \frac{1}{2} [D_0 + C_0 + (D_1 + C_1) \lambda_{2.T_1} + (D_2 + C_2) \lambda_{1.T_1}]$$

Hence,

$$W_1(\Delta)\lambda_{2.T_1} + W_2(\Delta)\lambda_{1.T_1} = 2S_{T_1} - 2\frac{\bar{C}}{\theta}\Delta - 2K_{T_1}(e^{\frac{1}{2}\Delta} - 1) + 3\frac{\bar{C}}{\theta}(e^{\frac{1}{2}\Delta} - 1) \quad (2.34)$$

where

$$W_1(\Delta) = D_1 + C_1$$

and

$$W_2(\Delta) = D_2 + C_2.$$

2.6.7 Appendix A7

First, the continuity of λ_1 at $t = T_2$ implies that (see Appendix A4):

$$\lambda_{T_2} = \lambda_{1.T_2} = \lambda_{2.T_1}e^{\rho\Delta} + (\lambda_{1.T_1} - \lambda_{2.T_1})e^{(\rho-\frac{1}{2})\Delta}$$

Then, we can rewrite the capital value at the beginning of the third regime (T_2) as:

$$K_{T_2} = \frac{3}{2\theta}\bar{C} + B_1(\Delta)\lambda_{2.T_1} + B_2(\Delta)\lambda_{1.T_1} \quad (2.35)$$

We now provide the expressions for $B_1(\Delta)$ and $B_2(\Delta)$ that appear in equation (2.35):

$$B_1(\Delta) = \frac{9}{8\theta(\rho-1)}e^{\rho\Delta}(1 - e^{-\frac{1}{2}\Delta})$$

$$B_2(\Delta) = -\frac{9}{8\theta(\rho-1)}e^{(\rho-\frac{1}{2})\Delta}$$

Taking the capital expression K_t in the second regime at $t = T_2$, we have:

$$K_{T_2} = \frac{3}{2\theta}\bar{C} + A_1(T_2)\lambda_{2.T_1} + A_2(T_2)\lambda_{1.T_1} + (K_{T_1} - \frac{3}{2\theta}\bar{C})e^{\frac{1}{2}\Delta}. \quad (2.36)$$

The continuity of capital at $t = T_2$ implies that the expressions for T_2 given in equations

(2.36) and (2.35) have to be equal. Hence,

$$Z_1\lambda_{2.T_1} + Z_2\lambda_{1.T_1} = K_{T_1}e^{\frac{1}{2}\Delta} - \frac{3}{2\theta}\bar{C}e^{\frac{1}{2}\Delta} \quad (2.37)$$

where, $Z_1(\Delta) = B_1(\Delta) - A_1$ and $Z_2(\Delta) = B_2(\Delta) - A_2$ with A_1 and A_2 that are known functions of the model parameters (see Appendix A5). Equation (2.37) expresses the relationship between the value of the capital ($\lambda_{1.T_1}$) and that of the NRE stock ($\lambda_{2.T_1}$) at the beginning of the second regime (T_1) according to the optimality conditions. To determine $\lambda_{1.T_1}$ and $\lambda_{2.T_1}$, one needs to solve equations simultaneously (2.34) and (2.37):

$$\begin{cases} W_1\lambda_{2.T_1} + W_2\lambda_{1.T_1} &= 2S_{T_1} - 2\frac{\bar{C}}{\theta}\Delta - 2K_{T_1}(e^{\frac{1}{2}\Delta} - 1) + 3\frac{\bar{C}}{\theta}(e^{\frac{1}{2}\Delta} - 1) \\ Z_1\lambda_{2.T_1} + Z_2\lambda_{1.T_1} &= K_{T_1}e^{\frac{1}{2}\Delta} - \frac{3}{2}\frac{\bar{C}}{\theta}e^{\frac{1}{2}\Delta} \end{cases}$$

Using the substitution method, the solution of the above system of two linear equations in $\lambda_{1.T_1}$ and $\lambda_{2.T_1}$ is:

$$\lambda_{1.T_1}^* = \frac{2S_{T_1}Z_1 - \frac{2\bar{C}}{\theta}\Delta Z_1 - 2K_{T_1}(e^{\frac{1}{2}\Delta} - 1)Z_1 + \frac{3\bar{C}}{\theta}(e^{\frac{1}{2}\Delta} - 1)Z_1 - Z_3W_1K_{T_1} + \frac{3}{2}\frac{\bar{C}}{\theta}Z_3W_1}{W_2Z_1 - W_1Z_2}$$

and

$$\lambda_{2.T_1}^* = \frac{1}{Z_1} \left[Z_3K_{T_1} - \frac{3}{2}\frac{\bar{C}}{\theta}Z_3 \right] - \frac{Z_2}{Z_1}\lambda_{1.T_1}^*$$

$\lambda_{2.T_1}^*$ and $\lambda_{1.T_1}^*$ are linear in K_{T_1} .

From that, we deduce the expression of the value function in the second regime V_2 .

Recalling that

$$V_2 = \text{Max} \int_{T_1}^{T_2} (\bar{C}C - \theta C^2)e^{-\rho(t-T_1)} dt + V_3e^{-\rho\Delta}$$

where

$$C_t = \frac{1}{2\theta}\bar{C} - \frac{3}{4\theta}\lambda_{2.T_1}e^{\rho(t-T_1)} - \frac{3}{4\theta}(\lambda_{1.T_1} - \lambda_{2.T_1})e^{(\rho-\frac{1}{2})(t-T_1)} - \frac{1}{4\theta}\lambda_{2.T_1}e^{\rho(t-T_1)}$$

and

$$V_3 = \frac{\bar{C}^2}{4\rho\theta} + \frac{1}{16(\rho-1)} \left[\left(K_{T_2} - \frac{3\bar{C}}{2\theta} \right) \frac{8\theta(\rho-1)}{9} \right]^2.$$

One can easily solve V_2 and get:

$$V_2 = \frac{\bar{C}^2}{4\rho\theta}(1-e^{-\rho\Delta}) + \frac{9}{16\theta} \frac{(\lambda_{1.T_1} - \lambda_{2.T_1})^2}{2(\rho - \frac{1}{2})} (1-e^{2(\rho-\frac{1}{2})\Delta}) + \frac{\lambda_{2.T_1}(\lambda_{1.T_1} - \lambda_{2.T_1})}{4\theta(2\rho - \frac{1}{2})} (1-e^{(2\rho-\frac{1}{2})\Delta}) + V_3 e^{-\rho\Delta}$$

As $\lambda_{2.T_1}^*$ and $\lambda_{1.T_1}^*$ are linear in K_{T_1} , we have:

$$V_2 = f(K_{T_1}, S_{T_1})$$

where f is a second degree polynomial in K_{T_1} .

2.6.8 Appendix A8

Combining equations (2.30) in (2.31) provides:

$$\dot{\lambda}_1 = (\rho - 2)\lambda_1 + \bar{C}[1 - F(Z)] \quad (2.38)$$

We now consider the steady state:

$\dot{\lambda}_1 = 0$ implies:

$$\lambda_1 = \frac{\bar{C}[1 - F(Z)]}{(2 - \rho)} \quad (2.39)$$

$\dot{\lambda}_2 = 0$ and $\dot{Z} = 0$ imply:

$$\lambda_2 = -\frac{\bar{C}Cf(Z) + \alpha f(Z)\bar{V}_2}{(\rho + \alpha)} \quad (2.40)$$

Combining equations (2.39) and (2.40) into (2.30) implies:

$$\frac{\bar{C}}{\rho - 2}[2\rho - 1] + \frac{\Lambda(Z)}{\rho + \alpha}[\rho\bar{V}_2 - \frac{\alpha\bar{C}Z}{2}] = 0 \quad (2.41)$$

Moreover $C = \frac{\alpha}{2}Z$ and $K = \frac{3\alpha}{2}Z$.

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Chapter 3

Investment in Energy Efficiency, Adoption of Renewable Energy and Household Behaviour: Evidence from OECD countries ¹

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 biased 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.*

JEL Classification: *Q42, Q21, C35, D11.*

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3.1 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 (IEA, 2015d). 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. 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 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.

3.2 Literature review

There is considerable literature on either demand for clean energy or investment in energy efficiency in the residential sector. In section 3.2.1, we provide some important studies on demand for clean energy and household behaviour while section 3.2.2 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.

3.2.1 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, 2016; 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 (2016) 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 (2016) 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.

3.2.2 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 [Vandenbergh 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 biased 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.

3.3 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.

3.3.1 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.² 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. We normalise the 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:

$$R = d + k_1 ee + k_2 re. \tag{3.1}$$

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 (3.1) 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 $u(.)$ is assumed to be increasing and concave

²In 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.

($u' > 0$ 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.

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 time³. 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:

$$U(ee, re, d) = u [re(ee) + d(ee)] + v (re, ee). \quad (3.2)$$

3.3.2 Optimal allocation

The household maximises the discounted sum of instantaneous utilities defined in eq.3.2 subject to the energy budget constraint eq.3.1 with respect to consumption of non-clean energy (d), investment in energy efficiency ee and investment in renewable energy re as follows:

$$\begin{aligned} \max_{d, ee, re} \quad & \sum_{t=0}^p \beta^t U(ee, re, d) \\ \text{st} \quad & R = d + k_1 ee + k_2 re \end{aligned}, \quad (3.3)$$

where β is the discount factor. By replacing d from eq.3.1 into the objective function of the programme (3.7), the first order conditions with respect to ee and re give respectively:

$$re'u' + \frac{\partial v}{\partial ee} + \frac{\partial v}{\partial re} re' = k_2 re'u' + k_1 u' \quad (3.4)$$

and

$$\frac{\partial v}{\partial re} + u' = k_2 u' \quad (3.5)$$

Equations (3.4) and (3.5) are arbitrage conditions. Equation (3.4) 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

³Major 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).

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_1u') and the marginal forgone utility for not investing in renewable energy ($k_2re'u'$). Similarly, equation (3.5) states that the marginal gain of investing in renewable energy ($\frac{\partial v}{\partial re} + u'$) should be compensated with the corresponding opportunity cost (k_2u').

Putting equation (3.5) into equation (3.4), gives the following equation that defines the household optimal allocation of investments in energy efficiency and in renewable energy:

$$k_1u' - \frac{\partial v}{\partial ee} = 0. \quad (3.6)$$

Equation (3.6) 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 energy⁴. 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).*

⁴The 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).

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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, 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 3.4 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.

3.4 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.

3.4.1 Data and Methods

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 ⁵. 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

⁵For more details, see OECD (2011, 2014).

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 3.4.1).

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 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.

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. 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).

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 better 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:

$$re^* = X_1' \beta_1 + \epsilon_1$$

and

$$ee^* = X_1' \beta_1 + X_2' \beta_2 + Z_1' \beta_3 + \epsilon_2,$$

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_1 denotes the vector of regressors (economic and residential variables, variables of perception, commitment and trust, etc.) that determine both re^* and ee^* . X_2 denotes the vector of regressors that are only related to energy use (implicitly related to energy efficiency), while Z_1 are the vector of regressors (characteristics of residence) that directly affect ee^* but not re^* (exclusion variables). Moreover, the error terms ϵ_1 and ϵ_2 are assumed to be jointly normally distributed with means 0, variances of 1 and correlations of ρ .

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).

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

Table 3.1 below displays the cross repartition of the two decisions of renewable adoption and investment in energy efficiency.

Table 3.1: 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 3.2: *Cross-correlation table*

Variables	Adoption of renewable energy	Investment in energy efficiency
Adoption of RE	1.000	
Investment in EE	0.1018	1.000

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 validity of the residence characteristics as exclusion variables; the results are presented in table 3.3. We find that both residence size and living in a non-detached residence significantly affect the decision to invest in energy efficiency, and has no effect on the decision to invest in renewable energy. Second, 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 interrelated and cannot be estimated independently. As a result, univariate methods that separately estimate the two decisions about renewable adoption and energy efficiency potentially produce biased results, because there may be unobserved characteristics that jointly determine the two decisions. We then 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 3.5. The two estimations do not give the

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same results and confirm that the bivariate probit is more appropriate than the separate estimation of the two probit models.

Table 3.3: *Validity of exclusion variables*

	(Probit) EE	(Probit) RE
Living in a non-detached residence	-0.0726** (0.0364)	-0.0241 (0.0248)
Size of the residence	0.0645*** (0.0232)	-0.00598 (0.0166)
<i>N</i>	11198	16471

Standard errors in parentheses

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

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 3.4. 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 %).

Table 3.4: *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

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 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

3.4. EMPIRICAL ANALYSIS

Table 3.5: *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)		-0.0695* (0.0364)	
Size of the residence	0.0645*** (0.0232)		0.0657*** (0.0233)	
Household income	0.0267*** (0.00629)	0.00198 (0.00400)	0.0270*** (0.00630)	0.00231 (0.00509)
Owner	0.152*** (0.0383)	0.135*** (0.0243)	0.151*** (0.0383)	0.108*** (0.0322)
<i>Perception, commitment and trust</i>				
Environmental concerns (general issues)	-0.00711 (0.0105)	-0.0203*** (0.00683)	-0.00767 (0.0105)	-0.0250*** (0.00885)
Climate change	-0.0662** (0.0268)	0.0668*** (0.0194)	-0.0649** (0.0267)	0.0797*** (0.0245)
Resource depletion	0.0745** (0.0292)	-0.0302 (0.0215)	0.0747** (0.0292)	-0.0426 (0.0273)
Voting in local elections	0.0776** (0.0369)	0.0741*** (0.0245)	0.0788** (0.0369)	0.0296 (0.0325)
Commitment to charitable organisations	0.151*** (0.0413)	0.115*** (0.0250)	0.147*** (0.0412)	0.122*** (0.0319)
Commitment to environmental organisations	0.0575 (0.0486)	0.138*** (0.0312)	0.0565 (0.0486)	0.134*** (0.0389)
Commitment to local organisations	0.116** (0.0476)	0.0674** (0.0301)	0.115** (0.0475)	0.0918** (0.0370)
Trust in scientists	0.0541*** (0.0146)	0.0794*** (0.0116)	0.0549*** (0.0147)	0.0818*** (0.0146)
Trust in local authorities	0.00182 (0.0136)	0.0160 (0.0100)	0.00202 (0.0136)	0.0332*** (0.0124)
<i>Energy use</i>				
Energy costs before buying or renting a house	0.105*** (0.0367)	0.00902 (0.0239)	0.103*** (0.0367)	0.00844 (0.0308)
Individual metering	0.0831 (0.0860)		0.0700 (0.0856)	
Peak Tariff	0.0219 (0.0331)		0.0472 (0.0333)	
Label to reduce energy use	0.183*** (0.0562)		0.172*** (0.0561)	
rho			0.1618*** (0.0234)	
Log pseudolikelihood	-3680.8267	-9217.5155	-9183.1129	
Pseudo R2	0.0586	0.2295		
Observations	11198	18158	11198	

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

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 3.10 (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 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 3.11 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).

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, except for peak tariff which become significant at 10%. Also, there is only a slight difference in the coefficients

of these variables (see table 3.12 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.

3.4.3 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 3.6, 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 3.7). 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 3.7). Therefore, the parameters of the ordered logit change for different categories of the outcome (eere) and their interpretations are wrong. Following Williams (2006), we use a generalised ordered logit (gologit) method that offers an ordinal alternative in which the parallel-lines assumption is not violated.

Table 3.6: *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 3.7: *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 3.8. 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 3.8: *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 3.9. 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.

Table 3.9: *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.

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, 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 intergenerational 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 3.13) show that they are not altered.

3.5 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 biased 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 others 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.

3.6 Appendices

3.6.1 Appendix A

Proof of Proposition 1

The household solves the following programme.

$$\begin{aligned} \max_{d, ee, re} \quad & \sum_{t=0}^p \beta^t U(ee, re, d) \\ \text{st} \quad & R = d + k_1 ee + k_2 re \end{aligned} \quad (3.7)$$

and the optimal allocation is given by

$$k_1 u' - \frac{\partial v}{\partial ee} = 0. \quad (3.8)$$

We can derive an implicit function Q from Eq. (3.8) 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:

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

3.6.2 Appendix B

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

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

3.6.3 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

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Table 3.10: *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	-0.322*** (0.0501)	
Size of the residence	0.000470 (0.0317)	
Household income	-0.00237 (0.00855)	0.00314 (0.00469)
Ownership	0.109** (0.0501)	0.0799*** (0.0286)
<i>Perception, commitment and trust</i>		
Environmental concerns (general issues)	-0.0153 (0.0140)	-0.0269*** (0.00804)
Climate change issues	-0.0915*** (0.0351)	0.0944*** (0.0229)
Resource depletion issues	0.158*** (0.0382)	-0.0485* (0.0255)
Voting in local elections	0.118** (0.0490)	0.0414 (0.0296)
Commitment to charitable organisation	-0.00547 (0.0538)	0.122*** (0.0291)
Commitment to environmental organisation	-0.0845 (0.0629)	0.118*** (0.0359)
Commitment to local organisation	0.0967 (0.0639)	0.0781** (0.0344)
Trust in scientists	0.0796*** (0.0183)	0.0841*** (0.0136)
Trust in local authorities	-0.0155 (0.0177)	0.0217* (0.0117)
<i>Energy use</i>		
Energy costs before buying or renting a house	0.0253 (0.0490)	-0.00857 (0.0280)
Individual metering	0.0688 (0.109)	
Peak Tariff	0.0278 (0.0437)	
Label to reduce energy use	0.264*** (0.0707)	
rho	0.1779681*** (0.0308717)	
Log pseudolikelihood	-8464.4579	
Observations	13133	13133

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

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Table 3.11: *Robustness check: Estimation of Bivariate model with solar/wind energy and country effects*

Variables	With country effects		With country effects and so	
	EE	RE	EE	RE
<i>Residential and economic variables</i>				
Living in a non-detached residence	-0.0724*		-0.161***	
	(0.0421)		(0.0465)	
Size of the residence	0.0421*		0.0246	
	(0.0251)		(0.0274)	
Household income	0.0261***	0.0129**	0.0270***	0.00591
	(0.00661)	(0.00550)	(0.00712)	(0.00767)
Owner	0.138***	0.0421	0.191***	0.312***
	(0.0406)	(0.0350)	(0.0448)	(0.0557)
<i>Perception, commitment and trust</i>				
Environmental concerns (general issues)	-0.0281**	-0.0481***	-0.0185	-0.0208
	(0.0114)	(0.00957)	(0.0124)	(0.0131)
Climate change issues	-0.00538	0.0625**	0.00299	0.0351
	(0.0278)	(0.0253)	(0.0310)	(0.0344)
Resource depletion issues	0.0464	-0.00636	0.0440	-0.0421
	(0.0306)	(0.0282)	(0.0337)	(0.0373)
Voting in local elections	0.0448	0.0453	0.0337	-0.0320
	(0.0395)	(0.0358)	(0.0431)	(0.0490)
Commitment to charitable organisations	0.0785*	0.0903***	0.0909*	0.0170
	(0.0436)	(0.0340)	(0.0472)	(0.0473)
Commitment to environmental organisations	0.0764	0.190***	0.0722	0.279***
	(0.0514)	(0.0424)	(0.0570)	(0.0559)
Commitment to local organisations	0.113**	0.0865**	0.0727	0.162***
	(0.0502)	(0.0385)	(0.0537)	(0.0511)
Trust in scientists	0.0227	0.0331**	0.0283*	-0.0195
	(0.0157)	(0.0148)	(0.0172)	(0.0192)
Trust in local authorities	0.00308	0.0158	-0.00116	0.0545***
	(0.0144)	(0.0132)	(0.0157)	(0.0175)
<i>Energy use</i>				
Energy costs before buying or renting a house	0.103***	0.108***	0.145***	0.265***
	(0.0367)	(0.0329)	(0.0424)	(0.0434)
Individual metering	0.0700		0.194*	
	(0.0856)		(0.0991)	
Peak Tariff	0.0472		0.0115	
	(0.0333)		(0.0397)	
Label to reduce energy use	0.172***		0.211***	
	(0.0561)		(0.0651)	
rho	0.1585***		0.3459***	
	(0.0256)		(0.0387)	
Log pseudolikelihood	-8447.3955		-5876.8635	
Observations	11198		9410	

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

Table 3.12: *Robustness check: estimation with and without attitudinal variables*

	(With) EE	(Without) EE	(With) RE	(Without) RE
collective	-0.0695* (0.0364)	-0.0830** (0.0356)		
size_residence	0.0657*** (0.0233)	0.0798*** (0.0228)		
income	0.0270*** (0.00630)	0.0287*** (0.00609)	0.00231 (0.00509)	0.00618 (0.00499)
owner	0.151*** (0.0383)	0.165*** (0.0374)	0.108*** (0.0322)	0.112*** (0.0316)
exante	0.103*** (0.0367)	0.121*** (0.0359)	0.00844 (0.0308)	0.0266 (0.0299)
ind_metering	0.0700 (0.0856)	0.0768 (0.0836)		
peak	0.0472 (0.0333)	0.0576* (0.0326)		
est_label	0.172*** (0.0561)	0.192*** (0.0541)		
<i>N</i>	11198	11444		

Standard errors in parentheses

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

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Table 3.13: 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.

Chapter 4

Intermittent renewable electricity generation with smartgrids¹

Abstract

The aim of the paper is to analyse the efficient mix of investment in intermittent renewable energy and energy storage. The novelty of our model accrues from the flexibility it assigns to a household in feeding (resp. purchasing) electricity to (resp. from) the grid or store energy (or use stored energy) upon renewable energy installations. We study the consequences of demand side management by accounting for three levels of equipment in smart grids. The first level refers to the possibility to feed electricity to the grid that can simply be achieved by net metering. The second one concerns the installation of smart meters. The third level relates to energy storage. We analyse decisions concerning solar power and energy storage investments, and the consequences of energy storage and smart meters for electricity consumption and purchases of electricity from the grid. Additionally, we discuss the desirability of smart meter installation and study the implications of curtailment measures in avoiding congestion. Our results indicate that electricity prices need to be carefully contemplated when the objective is to rely less on the grid through smart grid deployment.

Keywords: *Renewable energy, Intermittency, Microgrid, Smartgrids, Energy Storage, Peak-shaving, Demand response.*

JEL Classification: *D24, D61, D81, Q41, Q42.*

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4.1 Introduction

Fighting climate change requires a considerable reduction in the use of fossil fuels. As electricity is expected to displace the use of fossil fuels in buildings, industries and for transportation in the near future, such a reduction can only be achieved through an energy transition towards clean and renewable sources for electricity generation. The decentralized electricity generation using renewables can also address outage problems arising in electricity congested countries like the US following market deregulation. Furthermore, they can enable developing countries to have better access to energy. This paper, accordingly, is about the integration of renewable electricity generation (e.g., solar and wind power). The fact that renewable sources of energy are inherently intermittent and unpredictable, however, makes their integration challenging. This suggests that one cannot ignore energy storage opportunities and demand management. We, therefore, study the optimal renewable energy investment decision for a household (HH) who can have access to the grid and to smart devices such as smart meters, batteries and so on.

So far the literature considering the penetration of renewables in the energy mix consists of two rather distinct fields. On the one hand, macro-dynamic models à la Hotelling consider renewable resources as abundant and having a certain steady flow. In this regard, these studies ignore variability and intermittency in renewable energy generation and focus on the cost of generation (see for instance [Hoel and Kverndokk, 1996](#) or [Tahvonen, 1997](#)). Another strand of literature studies the optimal energy source mix for electricity generation (fossil fuels and renewables) when intermittency is taken into account (see [Ambec and Crampes, 2012, 2015](#)), or when storage takes care of peak electricity (see [Crampes and Moreaux, 2010](#)) or excess nuclear energy production ([Jackson, 1973](#)). A recent reference survey on the economics of solar electricity ([Baker et al., 2013](#)) emphasizes the lack of economic analysis of a decentralized clean energy provision through renewable sources. We fill this gap by analysing a model that accounts for intermittency, energy storage and demand management.

Electricity demand management and smart grids have recently received a lot of attention in the academic literature (see [De Castro and Dutra, 2013](#) or [Hall and](#)

Foxon, 2014 and Bigerna et al., 2016) and in the media (see The Economist, 2009 or The Telegraph, 2015a and The Telegraph, 2015b). Without smart grids, the lack of transparency on the distribution side of the system is particularly apparent to consumers. Most people know neither the amount of electricity they are using (until they are presented with a bill) nor the proportion generated by nuclear, coal, gas and renewables, or the level of emissions produced in the process. Moreover, a smart grid will make it easier to co-ordinate the intermittent and dispersed sources of power, from rooftop solar panels or backyard wind-turbines, for example. Demand-side management policies, such as the installation of smart meters and energy storage devices, will be modeled as policies aiming at incentivizing agents to consume or store electricity when it is cheap. Therefore, such policies increase the substitutability between electricity at different period. In this paper, we account for three levels of equipment in smart grids. The first one refers to the possibility to sell to the grid, which can simply be achieved by net metering as long as this is not in conflict with the country's legislation.² The second one concerns the installation of smart meters, which are relatively widely used in Europe (e.g., Linky in France). Smart meters allow end-use consumers in electricity markets to monitor and change their electricity consumption in response to changes in the electricity price (Durmaz, 2016, Borenstein and Holland, 2005 and Joskow and Tirole, 2007). The third level relates to energy storage. Given the current storage technologies and costs, energy storage may not become widespread as quickly as smart meters.

The aim of the paper is to analyse the efficient mix of investments in intermittent renewable energy (namely, solar panels) and energy storage. The novelty of our model accrues from the flexibility it assigns to a HH in feeding (resp. purchasing) electricity to (resp. from) the grid or store energy (or use stored energy) upon renewable energy installations. Our first result indicates that it is beneficial to install a smart meter enabling the HH to benefit from electricity price variations when the expected electricity price is either sufficiently low or high. Our second result is that the objective to rely less on the grid through the use of a smart meter cannot be attained unless the expected price is sufficiently high. Otherwise, the reliance on the grid will be higher leading to

²While the European Union and the U.S. allow net metering, Hong Kong and some African countries do not.

further emissions. This result points out that the level of electricity prices needs to be carefully contemplated if the aim is to depend less on the electric grid. Furthermore, we consider the congestion problem that can arise when there is too much in-feeds to the grid. Our analysis demonstrates that curtailment measures to avoid congestion can discourage investment in renewable energy generating and energy storage capacities. When such investments are discouraged, our results indicate that , first, electricity generated and fed to the grid by the HH will be curtailed at the higher end of the price schedule, second, the HH will not necessarily purchase more electricity from the grid.

The remainder of this paper is structured as follows. The model is presented in Section 4.2. We analyze the optimal investments in solar panels and storage device in Section 4.3. We analyse in Section 4 the consequences of energy storage and smart meters for purchases of electricity from the grid and electricity consumption. In Section 5, we discuss the desirability of smart meter installation. Section 6 studies the implications of curtailment measures to avoid congestion. Finally, Section 7 concludes.

4.2 The model

We assume a two-period economy. During the first period, a HH invests K_1 (e.g., solar panels) to generate renewable energy (RE) whose total usage cost for the two periods is rK_1 .³ Once the RE investment is made, it serves to produce K_1 kilowatt-hour (kWh) of electricity in the first period. The RE generation during the second period, however, depends on the state of nature, which have two possible realizations. Let P_s denote the probability that there will be sun in the next period. Conversely, $P_n = 1 - P_s$ denotes the probability that the weather will be cloudy causing no solar power generation. Therefore, with probability P_s (or P_n), RE generation in the second period will be K_1 (or 0) kWh. In the first period, energy can be stored and transferred to the second period. Storing energy is costly due to the loss of energy during the restoration process. Denoting the amount of energy stored in the first period by S_1 , the available amount of energy that can be consumed in the second period will then be ϕS_1 . Here, $\phi < 1$ is the round-trip

³Jackson (1973); Gravelle (1976); Ambec and Crampes (2012, 2015) make a similar assumption.

efficiency parameter.⁴

In addition to storing energy to deal with the intermittent energy generation from the renewable resource, we assume that the micro-grid is connected to a central grid. Consider the following probability tree diagram, which illustrates the state dependent cost of purchases from the electric grid.

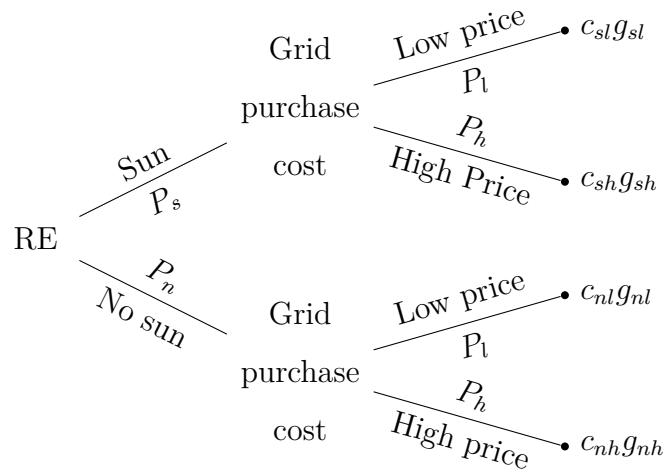


Figure 4.1: Central grid purchase costs

In the diagram, P_l denotes the probability of a low price on the grid, while $P_h = 1 - P_l$ is the probability of a high price. In the first period, the unit cost of electricity on the grid is c_1 . In the second period, however, the price on the grid will depend on the state. When there is sun and the price on the grid is low, the amount of expenditure made to purchase electricity will be $c_{sl}g_{sl}$, with g_{sl} the quantity of electricity and c_{sl} the unit cost. Similarly, when there is sun and the price on the grid is high, the total cost of purchasing electricity from the grid will be $c_{sh}g_{sh}$. The remaining entries on the diagram can be interpreted in a similar fashion.

At each period the HH has an instantaneous (gross) surplus over energy consumption.

⁴For simplicity, we assume that the usage cost of storage is accounted for through this parameter.

For $j = s, n$ and $i = l, h$ let $u(K_1 + g_1 - S_1)$ and $u(\mathbb{1}_s(j)K_1 + \phi S_1 + g_{ji})$, where

$$\mathbb{1}_s(j) = \begin{cases} 1, & \text{if } j = s \\ 0, & \text{otherwise,} \end{cases}$$

denote these surpluses in the first and second periods, respectively. It is assumed that $u' > 0$ and $u'' < 0$ where u' and u'' are the first- and second-order derivatives of the surplus function, respectively.

4.3 Optimal investment in solar panels and storage devices

4.3.1 With smart meter devices

In this section, we consider the optimal decisions of a HH in terms of solar panel and energy storage investments, and purchases from and sales to the electric grid. To do this we consider that the HH is equipped with a smart meter that connects the home to the grid for two-way exchanges of information and energy. In light of Figure 4.1 the benevolent planner solves the following programme:

$$\begin{aligned} \max_{\{K_1, S_1, g_1, g_{ij}\}} & u(K_1 + g_1 - S_1) - c_1 g_1 + \sum_j \sum_i P_j P_i [u(\mathbb{1}_s(j)K_1 + \phi S_1 + g_{ji}) - c_{ji} g_{ji}] - r K_1 \\ \text{s.t.} & K_1 \leq \bar{K}, S_1 \geq 0, K_1 \geq 0 \text{ and } S_1 \leq \bar{S}, \end{aligned}$$

where $j = s, n$ and $i = l, h$, and \bar{K} and \bar{S} are available capacities for solar panel and energy storage system installation, respectively. The Lagrangian function reads

$$\begin{aligned} \mathcal{L}(\cdot) &= u(K_1 + g_1 - S_1) - c_1 g_1 + \sum_j \sum_i P_j P_i [u(\mathbb{1}_s(j)K_1 + \phi S_1 + g_{ji}) - c_{ji} g_{ji}] - r K_1 \\ &+ \nu_1(\bar{K} - K_1) + \nu_2 S_1 + \nu_3 K_1 + \nu_4(\bar{S} - S_1). \end{aligned} \tag{4.1}$$

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We denote the optimal HH decisions by the ‘ g ’ superscript. The first order conditions with respect to K_1 , S_1 , g_1 and g_{ji} then yield

$$u'(K_1^g + g_1^g - S_1^g) + P_s \sum_i P_i u'(K_1^g + \phi S_1^g + g_{si}^g) - r = \nu_1 - \nu_3, \quad (4.2a)$$

$$\phi \sum_j \sum_i P_j P_i u'(\mathbb{1}_s(j)K_1^g + \phi S_1^g + g_{ji}^g) - u'(K_1^g + g_1^g - S_1^g) = \nu_4 - \nu_2, \quad (4.2b)$$

$$u'(K_1^g + g_1^g - S_1^g) = c_1, \quad (4.2c)$$

$$u'(\mathbb{1}_s(j)K_1^g + \phi S_1^g + g_{ji}^g) = c_{ji}, \quad (4.2d)$$

respectively. Plugging the first order necessary conditions for g_1^g and g_{ji}^g in Eqs. (4.2a) and (4.2b) gives

$$c_1 + P_s \sum_i P_i c_{si} - r = \nu_1 - \nu_3,$$

$$\phi \sum_j \sum_i P_j P_i c_{ji} - c_1 = \nu_4 - \nu_2.$$

The FOCs drop to the primitives of the model, that is, the prices. Different cases emerge depending on the cost of the solar panel installation relative to the cost of purchasing electricity from the central grid on the one hand, and the cost of storage (in terms of loss during the restoration process) relative to the price on the grid on the other hand. Here, we focus on the case where solar panels and storage are relatively cheap.⁵ Thus,

$$c_1 + P_s \sum_i P_i c_{si} - r > 0, \quad (4.3a)$$

$$\phi \sum_j \sum_i P_j P_i c_{ji} - c_1 > 0, \quad (4.3b)$$

and we have corner solutions, since, on the margin, the expected benefits from installing K_1 and S_1 are always higher. Consequently, $K_1^g = \bar{K}$ and $S_1^g = \bar{S}$. A similar analysis gives

$$\begin{aligned} g_1^g &> 0 && \text{if } c_1 < u'(\bar{K} - \bar{S}), \\ g_1^g &\leq 0 && \text{otherwise.} \end{aligned} \quad (4.4)$$

⁵We are convinced that this will be the case in a not-too-distant future. When solar panels and energy storage devices are sufficiently expensive such that they are not utilized, then our analysis can be deemed as less useful. Nevertheless, it is certainly possible to analyse the other cases and allow our study to be more exhaustive.

Furthermore, the way the grid will be used in the second period will depend on

$$\begin{aligned} g_{ji}^g &> 0 \quad \text{if } c_{ji} < u'(\mathbb{1}_s(j)\bar{K} + \phi\bar{S}), \\ g_{ji}^g &\leq 0 \quad \text{otherwise.} \end{aligned} \tag{4.5}$$

The optimal levels of the feed-ins to (or purchases from) the grid are then calculated as

$$\begin{aligned} g_1^g &= u'^{-1}(c_1) - \bar{K} + \bar{S}, \\ g_{ji}^g &= u'^{-1}(c_{ji}) - \mathbb{1}_s(j)\bar{K} - \phi\bar{S}. \end{aligned} \tag{4.6}$$

The optimality conditions given by Eqs. (4.4) and (4.5) dictate that the electricity will be purchased from (resp. sold to) the electric grid when it is sufficiently cheap (resp. expensive). In particular, given K_1^g , when the energy storage capacity is sufficiently high such that the marginal gross surplus is greater than the unit cost of electricity in the first period, electricity will be purchased and the other way around. A similar discussion follows for the second period. Different than the first period, however, previously stored energy (adjusted for the round-trip efficiency) will be used for consumption purposes leading a lower demand for grid electricity than otherwise. Notice also that the demand for the grid electricity will also depend on the meteorological shock, that is, whether there is sun or not.

No storage devices ($\bar{S} = 0$)

In the absence of energy storage, we consider the optimal decision of a HH in terms of solar panel installations and purchases from and sales to the electric grid. Without energy storage, the grid is the only backup possibility of the HH when it purchases electricity. We assume that the HH is still equipped with a smart meter allowing it to be exposed to a dynamic price schedule of electricity.

As the absence of energy storage is a limit case of the general case that we analysed earlier, we set $\bar{S} = 0$ and consider that Eq. (4.3a) holds. The HH, accordingly, still has an incentive to undertake investments in solar panels when the usage cost of the solar panels (i.e., r) is lower than their expected benefits, which is the sum of the avoided

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marginal cost of electricity in the first and the second periods (i.e., c_1 and $P_s \sum_i P_i c_{si}$, respectively). Thus, it is optimal to use all the available capacity to install the solar panels: $K_1^{gn} = \bar{K}$, where the superscript ‘ gn ’ denotes the limit case of no storage devices. For $\bar{S} = 0$, the conditions that describe the grid activity in the first and second periods are given by Eqs. (4.4) and (4.5). The optimal levels of the feed-ins (or purchases), accordingly, can be calculated from Eq. (4.6). The discussion regarding the grid activity is similar to the one for the general case, and therefore, is omitted.

4.3.2 No smart meter devices

This subsection is devoted to the optimal decisions of a HH who is not equipped with a smart meter device, and thus, cannot benefit from a dynamic pricing schedule during the second period. Consider a price tariff with c_1 and c_2 being the prices of electricity on the grid in the first and second periods, respectively. For $c_{ji} = c_2$, the HH solves the same program as in Section 4.3.1. Therefore, conditions that describe incentives to invest in solar panels and that of storage become

$$c_1 + P_s c_2 - r > 0 \text{ and} \tag{4.7a}$$

$$\phi c_2 - c_1 > 0, \text{ respectively.} \tag{4.7b}$$

Investment in solar panels is undertaken when its marginal benefit during the two periods ($c_1 + P_s c_2$) is bigger than its marginal cost (r). The HH then optimally installs solar panels given the available capacity \bar{K} . Thus, $K_1^o = \bar{K}$, where the superscript ‘ o ’ denotes the limit case of no smart meters. Similarly, the HH has incentives to store electricity in the first period when the avoided marginal cost of buying from the grid in the second period at a uniform price c_2 is higher than the marginal cost of storage (c_1/ϕ), that is, the opportunity cost of forgone electricity consumption in the first period adjusted for the storage loss. It is then optimal to store energy as much as possible so that $S_1^o = \bar{S}$. The way the grid electricity is used in the two periods is unchanged regarding Section 4.3.1. Namely, if the uniform price of electricity in the second period is low (resp. high), electricity will be purchased (resp. fed). The two conditions given by Eqs. (4.7a) and

(4.7b) together yield:

$$r - P_s c_2 < c_1 < \phi c_2.$$

A simultaneous solar electricity production and storage is conditioned by the price of the grid electricity in the first period that should neither be too high nor too low. In fact, if the first period electricity price is too low (resp. too high), it will prevent the HH from undertaking investment in solar energy (resp. energy storage).

4.4 Grid activity

In this section, we discuss the implications of the storage and smart meters for electricity consumption and the grid activity. Following the same parametric conditions that satisfy Eqs. (4.3a) and (4.3b), we first do a comparison between the cases with and without storage devices. This is then followed by a comparison between the cases with and without smart meters in the presence of storage devices.

4.4.1 Storage vs no storage

Recall that in the two cases (i.e., storage and no storage) and under the conditions given by Eqs. (4.3a) and (4.3b), it is always optimal to install the solar panels and the storage systems up to the available capacities: $K_1^{gn} = K_1^g = \bar{K}$ and $S_1^g = \bar{S}$. By using Eq. (4.2c) and taking $\bar{S} = 0$ for the limit case of no storage, the difference in the grid activity is given by

$$g_1^g - g_1^{gn} = \bar{S} > 0.$$

The equation above states that energy storage induces a higher activity in the grid in the first period. Given that the HH can store energy, it will purchase more electricity from the grid in the first period while keeping its first period electricity consumption the same.

The grid activity in the second period can similarly be calculated from Eq. (4.2d):

$$g_{ji}^g - g_{ji}^{gn} = -\phi \bar{S} < 0.$$

The negative difference states that storing energy will induce a relatively lower grid activity in the second period. The HH, accordingly, takes advantage of the availability of the storage device by storing energy up to the available capacity in the first period followed by its use in the second period. The storage device is, therefore, used as backup allowing for lower level of reliance on the electric grid in the second period.

The two above equations allow us to deduce that the expected total grid activity,

$$(g_1^g - g_1^{gn}) + \sum_j \sum_i P_j P_i (g_{ji}^g - g_{ji}^{gn}) = (1 - \phi) \bar{S} > 0,$$

will be higher when there is access to storage devices. This is because part of the additional grid electricity in the first period is lost due to storage ($\phi < 1$).

4.4.2 Smart meters vs no smart meters

Under the conditions given by Eqs. (4.3a) and (4.3b) and Eqs. (4.7a) and (4.7b), it is always optimal to install the solar panels and storage systems up to the available capacities: $K_1^g = K_1^o = \bar{K}$ and $S_1^g = S_1^o = \bar{S}$. The difference between the grid activities in the first period can be calculated from Eq. (4.2c) with ease:

$$g_1^g - g_1^o = 0.$$

During the first period, the grid activity is not affected by the use of smart meters. Nonetheless, this result can alter in the second period depending on the pricing program. Using Eq. (4.6) the difference between the expected grid activity when the prices are dynamic and when there is uniform pricing can be calculated as follows:

$$\sum_j \sum_i P_j P_i (g_{ji}^g - g_j^o) = \sum_j \sum_i P_j P_i u'^{-1}(c_{ji}) - u'^{-1}(c_2). \quad (4.8)$$

As is seen, the difference depends on the margin between the expected electricity consumption when the prices are dynamic and when they are not.⁶ Consequently, the

⁶Note that in the case of no access to smart meters, that is, when the price is uniform, the HH consumption is constant and, therefore, does not depend on the state of the weather.

availability of a smart meter induces high (resp. low) grid activity when the expected electricity consumption with dynamic pricing is higher (resp. lower) than the electricity consumption with uniform pricing. The result is that if the HH still consumes the same amount of electricity, having access to smart meter will not affect its grid activity. Conversely, given that both storage and solar panels are fully used, if the HH takes advantages of dynamic pricing and consumes more, it will need to compensate the additional electricity consumption by using the grid. The HH will, therefore, cause the grid activity to increase.

As Eq. (4.8) suggests, the difference between the grid activities in the two cases is affected by the prices in the two pricing schemes (c_{ji} and c_2). In addition, this also depends on whether the HH is prudent or not. Let $\mathbb{E} \stackrel{\text{def}}{=} \sum_j \sum_i P_j P_i$. We have the following proposition:

Proposition 1 *Let $c_{ji} \equiv \mu + x_{ji}$ where $\mu > 0$, $\mathbb{E}[x_{ji}] = 0$ and $\text{var}(x_{ji}) = \sigma^2$. Thus, μ and σ^2 correspond to the mean and variance of c_{ji} , respectively.*

- a- *If $c_2 = \mu$, there will be a higher activity on the grid when the HH is prudent and is equipped with a smart meter, that is, $\mathbb{E}[g_{ji}^g] - \mathbb{E}[g_j^o] > 0$ when $u''' > 0$.*
- b- *For a prudent HH, the expected grid activities in the dynamic and uniform cases can be the same only if the uniform price is strictly lower than μ . Let $\hat{c}_2 (< \mu)$ be the price such that $\mathbb{E}[g_{ji}^g] = \mathbb{E}[g_j^o]$. Then*

$$\begin{aligned} \mathbb{E}[g_{ji}^g] &> \mathbb{E}[g_j^o] && \text{if } c_2 > \hat{c}_2, \\ \mathbb{E}[g_{ji}^g] &\leq \mathbb{E}[g_j^o] && \text{otherwise.} \end{aligned} \tag{4.9}$$

Proof 1 *The proof of Proposition 1-a follows from Jensen's inequality. Furthermore, as $\mathbb{E}[u^{-1}(c_{ji})] - u^{-1}(\mu) > 0$ and $\partial u^{-1} / \partial c_2 < 0$, there exists a $\hat{c}_2 < \mu$, such that $\mathbb{E}[u^{-1}(c_{ji})] - u^{-1}(\hat{c}_2) = 0$. Consequently, if $c_2 \leq \hat{c}_2$, then $\mathbb{E}[u^{-1}(c_{ji})] - u^{-1}(\hat{c}_2) \leq 0$ and $\mathbb{E}[g_{ji}^g] - \mathbb{E}[g_j^o] \leq 0$, and vice versa. This proves Proposition 1-b.*

Figure 4.2 illustrates Proposition 1. If the objective is to rely less on the grid with a dynamic pricing schedule by using smart meters, then Proposition 1 demonstrates that

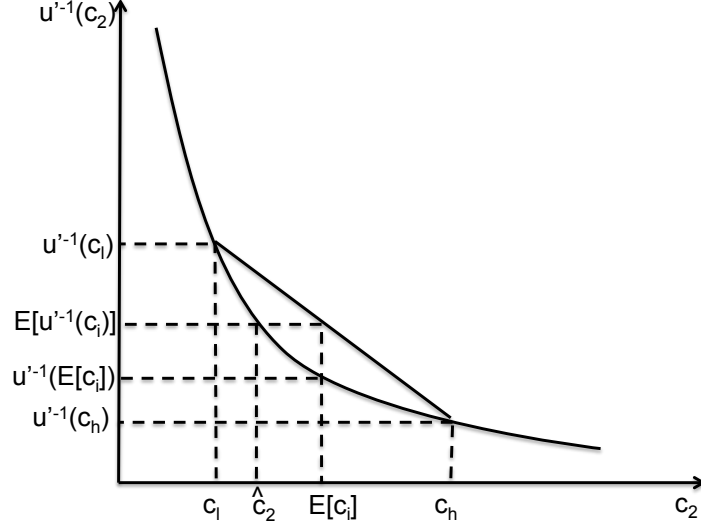


Figure 4.2: *Grid activity: smarter meter vs no smart meter. For illustration purposes, $c_{sl} = c_{nl} = c_l$ and $c_{sh} = c_{nh} = c_h$.*

such an objective cannot be attained unless the expected dynamic price is sufficiently high. In particular, when the expected price is equal to the uniform price, the grid activity is higher when the price schedule is dynamic. This indicates that the discrepancy between low and high prices in the dynamic price schedule needs to be carefully considered when the aim is to allow for a lower activity on the grid.

4.5 When to install smart meters?

In this section, we analyse the conditions under which it is optimal to install a smart meter. We have shown earlier in Sections 4.3.1 and 4.3.2 that a corner solution case dictates

$$c_1 + P_s \sum_i P_i c_{si} - r > 0 \quad \text{and}$$

$$\phi \sum_j \sum_i P_j P_i c_{ji} - c_1 > 0$$

for the prior, and

$$c_1 + P_s c_2 - r > 0 \quad \text{and}$$

$$\phi c_2 - c_1 > 0$$

for the latter. Thus for both the dynamic and uniform pricing cases, it is optimal to exhaust all of the investment possibilities for both the solar panels and energy storage systems.

The installation of the smart meter will be beneficial when the expected benefit (or the avoided cost) from its use is sufficiently high. This urges us to study the change in the difference between the two maximum value functions, that is, $V^g - V^o$, with respect to the uniform price (c_2) on the grid. Let r^g denote the cost of installing the smart meter. This leads us to the following proposition:

Proposition 2 *Let $c_{ji} \equiv \mu + x_{ji}$ where $\mu > 0$, $\mathbb{E}[x_{ji}] = 0$ and $\text{var}(x_{ji}) = \sigma^2$.*

- a- *If $\mu = c_2$, there exists two uniform prices \underline{c}_2 and \bar{c}_2 where $\underline{c}_2 \leq \bar{c}_2$ such that smart meters will be installed if and only if $c_2 \notin (\underline{c}_2, \bar{c}_2)$. The size of the interval $(\underline{c}_2, \bar{c}_2)$ increases with r^g .*
- b- *Given μ , if $V^g - r^g \geq \min_{\{c_2\}} V^o(c_2)$, then there exists two uniform prices \underline{c}_2 and \bar{c}_2 where $\underline{c}_2 < \bar{c}_2$ such that smart meters will be installed if and only if $c_2 \in (\underline{c}_2, \bar{c}_2)$.*

Proof 2 *Recall that the maximum value function for the dynamic pricing case upon the installation of the smart meter and the uniform price case are*

$$V^g = u(\bar{K} + g_1^g - \bar{S}) - c_1 g_1^g + \mathbb{E} \left[u(\mathbb{1}_s(j)\bar{K} + \phi\bar{S} + g_{ji}^g) - c_{ji} g_{ji}^g \right] - r\bar{K} \quad \text{and}$$

$$V^o = u(\bar{K} + g_1^o - \bar{S}) - c_1 g_1^o + \mathbb{E} \left[u(\mathbb{1}_s(j)\bar{K} + \phi\bar{S} + g_j^o) - c_2 g_j^o \right] - r\bar{K},$$

respectively.

It is optimal to install a smart meter if and only if the following is satisfied:

$$V^g - r^g \geq V^o \iff \mathbb{E} \left[u(\mathbb{1}_s(j)\bar{K} + \phi\bar{S} + g_{ji}^g) - c_{ji} g_{ji}^g \right] - r^g$$

$$\geq \mathbb{E} \left[u(\mathbb{1}_s(j)\bar{K} + \phi\bar{S} + g_j^o) - c_2 g_j^o \right]$$

Recall that the grid activities for the dynamic and uniform pricing cases in the second period were $g_{ji}^g(c_{ji}) = u'^{-1}(c_{ji}) - \mathbb{1}_s(j)\bar{K} - \phi\bar{S}$ and $g_j^o(c_2) = u'^{-1}(c_2) - \mathbb{1}_s(j)\bar{K} - \phi\bar{S}$, respectively. Let $f(c) \stackrel{\text{def}}{=} [u(u'^{-1}(c)) - c(u'^{-1}(c) - \mathbb{1}_s(j)\bar{K} - \phi\bar{S})]$. The previous inequality can be rewritten as follows:

$$V^g - r^g \geq V^o \iff \mathbb{E}[f(c_{ji})] - r^g \geq f(c_2)$$

The first derivative of $f(c)$ with respect to c is

$$\frac{\partial f}{\partial c} = -u'^{-1}(c) + \mathbb{1}_s(j)\bar{K} + \phi\bar{S} < 0 \quad (4.10)$$

The second derivative gives:

$$\frac{\partial^2 f}{\partial c^2} = -\frac{1}{u''(u'^{-1}(c))} > 0. \quad (4.11)$$

As f is convex, $V^g \geq V^o$. For $r^g > 0$, there exists $\underline{c}_2(r^g)$ and $\bar{c}_2(r^g)$ such that $V^g - r^g > V^o$ when $\mu \notin [\underline{c}_2(r^g), \bar{c}_2(r^g)]$. Note that for any r^g it is always possible to find a μ such that the slope of f is sufficiently steep to obtain $V^g - r^g > V^o$. This completes the proof for Proposition 2-a.

Considering Proposition 2-b, notice that

$$\begin{aligned} \frac{\partial V^o}{\partial c_2} &\leq 0 \quad \text{iff } c_2 \leq \tilde{c}_2 \quad \left(\text{i.e., } \mathbb{E}[g_j^o] \geq 0 \right), \\ \frac{\partial V^o}{\partial c_2} &> 0 \quad \text{otherwise,} \end{aligned}$$

with $\tilde{c}_2 \stackrel{\text{def}}{=} u'(P_s\bar{K} + \phi\bar{S})$, which is also the uniform price level for which the expected optimal grid activity is zero. When $V^g - r^g \geq \min_{\{c_2\}} V^o(c_2)$, $V^o(c_2)$ being convex, there exists \underline{c}_2 and \bar{c}_2 such that $V^o(\underline{c}_2) = V^o(\bar{c}_2) = V^g - r^g$ and $\underline{c}_2 \leq \tilde{c}_2 \leq \bar{c}_2$. Therefore, $V^g - r^g \geq V^o(c_2)$ if and only if $c_2 \in [\underline{c}_2, \bar{c}_2]$.

The intuition for the first part of Proposition 2 is the following. The net expected grid activity is zero ($\mathbb{E}[g_j^o] = 0$) and V^o attains its minimum level at \tilde{c}_2 . Thus, to the right (resp. left) of \tilde{c}_2 , the expected grid activity is positive (resp. negative). The vicinity \tilde{c}_2 also corresponds to the points where V^o is relatively flat. Given the probabilities and the convexity of the value function, this is also the value space where the additional expected value attained from the use of a smart meter device is relatively low for $\mu = c_2$. Consequently, the farther c_2 gets from \tilde{c}_2 , the more the HH will benefit from the differentiated prices.

Figure 4.3 illustrates an example in this regard. For the purpose of brevity, we restrict our attention to the positively sloped part of the V^o curve and take $x_{sl} = x_{nl} = x_l$ and $x_{sh} = x_{nh} = x_h$. The discussion for the negatively sloped part of V^o is symmetrical.

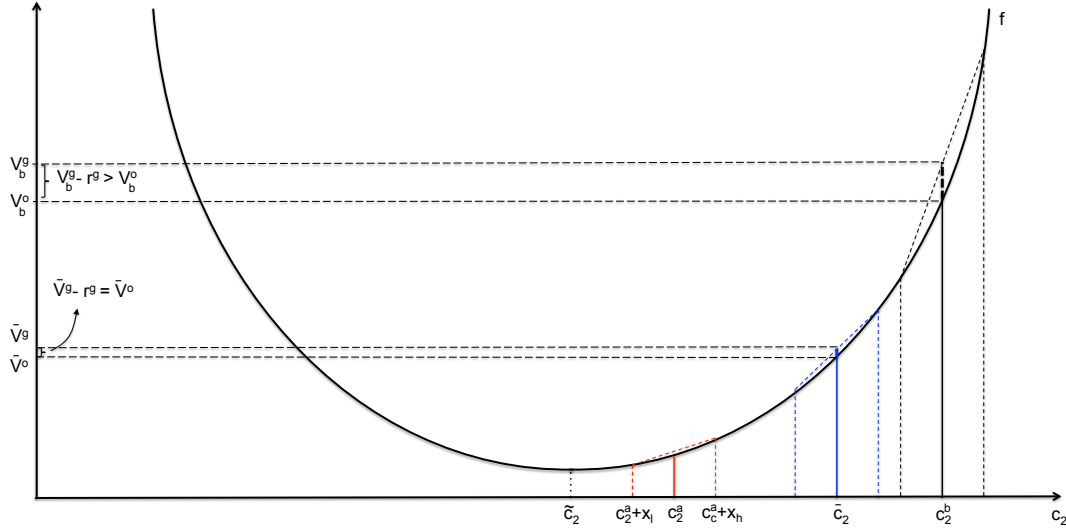


Figure 4.3: Smart meter investment decision ($\mu = c_2$)

As the figure shows, for a $\mu = c_2$ that is close to \tilde{c}_2 , the price variation does not lead to a big difference between the two value functions, V^g and V^o . Given the cost of the smart meter, r^g , this makes it suboptimal to invest. For a higher level of c_2 , the convexity of the curve induces a disproportionate change in the value function corresponding to the high and low prices. When $c_2 = \bar{c}_2$, we see that the HH is indifferent as to the installation of the smart meter ($\bar{V}_g - r^g = \bar{V}^o$). For higher values of c_2 , however, where the curve becomes steeper, the HH will benefit more and more from installing the device. It is evident from the figure that a higher cost of installation will necessitate the \bar{c}_2 to shift rightward leading to a larger wedge between the value function that corresponds to the high price and the one corresponding to the low price.

The intuition for the latter part of Proposition 2, where the expected price does not correspond to the uniform one, is the following. For a HH that is expected to purchase electricity from the grid in the absence of a smart meter device, that is, $c_2 < \tilde{c}_2$ and $\mathbb{E}[g_j^o] > 0$, a lower uniform prices translates into a higher welfare making it less attractive to install a smart meter. Alternatively, a rise in the uniform price increases the welfare of the HH when it is expected to feed the grid, $\mathbb{E}[g_j^o] < 0$. Thus, given μ , a higher uniform

prices makes it less attractive to install a smart meter.

Figure 4.4 illustrates the behavior of V^o , V^g , $\mathbb{E}[g_j^o]$ and $\mathbb{E}[g_{ji}^g]$ with respect to the uniform electricity price c_2 . The y-axis on the left shows the values for $V^g - r^g$ and V^o , while it does this for the expected grid activity when the price is uniform and dynamic, $E[g_j^o]$ and $\mathbb{E}[g_{ji}^g]$, respectively, and the expected price, $\mathbb{E}[c_{ji}]$, on the right. The x-axis designates the uniform prices.⁷ Notice that the curve representing $\mathbb{E}[g_j^o]$ takes on positive values the left of \bar{c}_2 and vice versa.

As is seen in the figure and as Proposition 2 indicates, the smart meter investment decision will not be optimal when the uniform price is sufficiently low (here, lower than \underline{c}_2). This is because the welfare of the HH, V^o , becomes higher than the welfare that would be obtained upon the installation of the smart meter, $V^g - r^g$. When the price is sufficiently high, that is, higher than \bar{c}_2 , the HH welfare becomes superior to the one upon the installation of the smart meter. Consequently, for a price between \underline{c}_2 and \bar{c}_2 , the smart meter will be installed. Notice that both \underline{c}_2 and \bar{c}_2 are functions of r^g , the installation cost of the smart meter device; that is, $\underline{c}_2(r^g)$ and $\bar{c}_2(r^g)$. In particular, while $\partial \underline{c}_2(r^g)/\partial r^g > 0$, $\partial \bar{c}_2(r^g)/\partial r^g < 0$. Thus, the interval that calls for the installation of the smart meter expands with a lower installation cost, and the other way around.⁸

The analysis up to here allows us to connect Proposition 2 with Proposition 1 and explicate the relationship between smart meter device installation decision and expected grid activity and consumption. This is presented in the following corollary:

Corollary 1

⁷In plotting the graph, we do not attempt to calibrate the model. The parameter values we use are $r = 0.03$; $\phi = 0.9$; $P_s = 2/3$; $P_l = 1/2$; $c_1 = 0.02$; $c_{sl} = 0.04$; $c_{sh} = 0.08$; $c_{nl} = 0.04$; $c_{nh} = 0.08$, $c_2 \in [0.025, 0.23]$, $\max(\bar{K}) = 2.1$, $\max(\bar{S}) = 1.9$ and $\gamma = 2$.

⁸For a HH that is not equipped with a smart meter, a rise in the uniform electricity price has different and opposite effects on the welfare some of which cancel each other in total. First, there is a negative effect (c_2/u''): an increase in the uniform price will reduce the total electricity consumption ($\partial u'^{-1}/\partial c_2 < 0$) resulting in a lower level of utility. Second, an increase in the uniform electricity price has two effects coming from the total cost of grid electricity: (i) a direct and negative effect due to the marginal increase in the price ($-\mathbb{E}[g_j^o]$) and (ii) an indirect and positive effect due to the marginal change in the grid electricity ($-c_2 \partial g_j^o / \partial c_2 = -c_2/u''$). The effect on the HH utility cancels with the marginal change in the grid electricity. Thus, the total effect depends negatively on the expected grid activity, $-\mathbb{E}[g_j^o]$. Therefore, smart meters installation becomes attractive as the uniform electricity price increases (resp., decreases) when the HH is expected to purchase from (resp., feed) the electric grid.

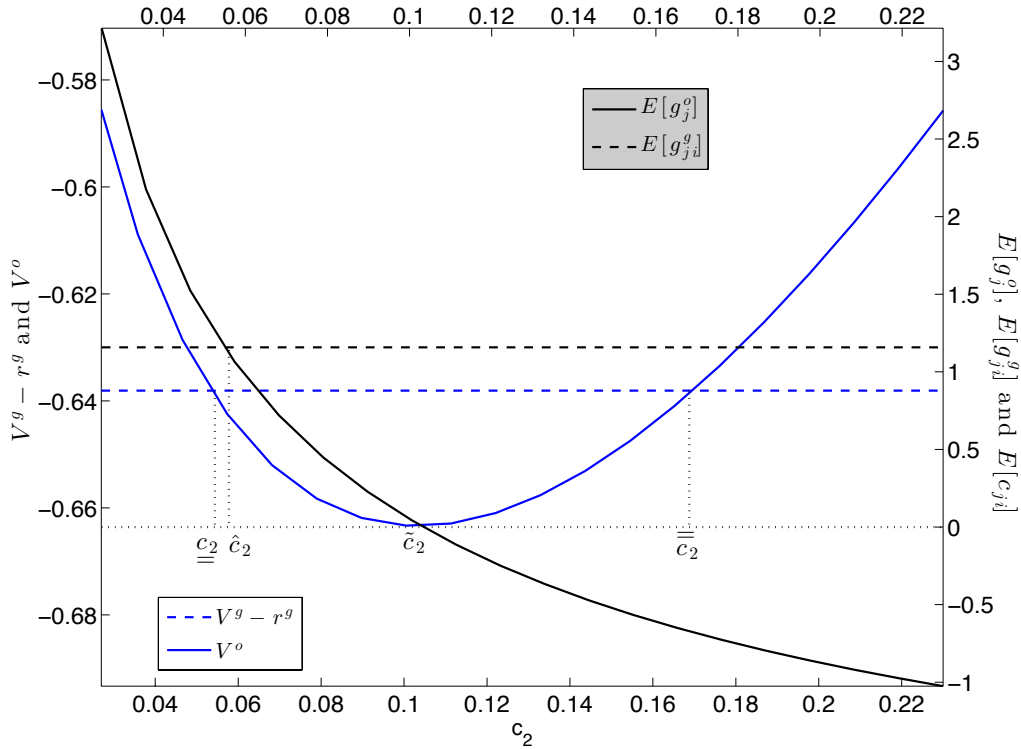


Figure 4.4: Smart meter investment decision ($\mu \neq c_2$)

- a- For $\mu = c_2$, if $c_2 \notin [\underline{c}_2, \bar{c}_2]$ it is optimal to install a smart meter leading to a higher grid activity (and consumption).
- b- Given μ , if $\underline{c}_2 \geq \hat{c}_2 < c_2 < \bar{c}_2$, it is optimal to install a smart meter leading to a higher grid activity (and consumption). If $\underline{c}_2 < c_2 < \hat{c}_2 \geq \bar{c}_2$, it is optimal to install a smart meter leading to a lower grid activity (and consumption).

Proof 3 Considering Corollary 1-a, optimal smart meter installation follows from Proposition 1-a and grid activity from Proposition 2-a. The difference in grid electricity consumption with and without a smart meter can be seen in Eq. (4.8).

Regarding Corollary 1-b, optimal smart meter installation follows from Proposition 1-b and grid activity from Proposition 2-b. The reader is referred to Eq. (4.9) for the difference in grid electricity consumption with and without a smart meter.

Corollary 1-a shows that smart meter installation leads to a higher level of expected grid activity and electricity consumption and, in turn, allow for a higher level of welfare.

When the expected dynamic price equals the uniform price and is sufficiently low (i.e., $\mu < \underline{c}_2$) such that it is optimal to install a smart meter, the HH is expected to purchase more electricity from the grid and consume more when equipped with a smart meter device. Conversely, when the expected dynamic price (which is still equal to the uniform price) is sufficiently high (i.e., $\mu > \bar{c}_2$) such that it is optimal to install a smart meter, the HH is expected to sell less electricity to the grid and, therefore, consume more when equipped with a smart meter device.

Corollary 1-b shows that smart meter installation can lead to a lower level of expected grid activity and electricity consumption, and yet, allow for a higher level of welfare. Consider the uniform price (\hat{c}_2) that equates the expected grid activity with that of the one with dynamic pricing. Assume that this case corresponds to the one where, on average, the HH purchases electricity from the grid (Figure 4.4 illustrates an example of this case). For a lower uniform price ($c_2 \in [\underline{c}_2, \hat{c}_2)$ to be precise) the grid purchase and electricity consumption will be higher on average. Conversely, the expected grid activity and electricity consumption in the uniform price case will be higher when the uniform price is bigger than \hat{c}_2 . Furthermore, when $\underline{c}_2 = \hat{c}_2$, the expected grid activity upon the installation of a smart meter device will always be higher.

Notice also that the $c_2 \in [\underline{c}_2, \hat{c}_2[$ has an inverse relationship with the installation cost, r^g . The lower is r^g , the smaller the values the uniform price can take such that it is optimal to install a smart meter. This would imply a relatively lower amount of electricity purchases upon installing the smart meter and, in turn, adopting a dynamic pricing schedule.

Consider now the case where the HH feeds electricity to the grid on average. As before, let \hat{c}_2 be the uniform price that equates the grid activity to the one with dynamic pricing. To the left of \hat{c}_2 , the expected sales of electricity to the grid will be higher and, in turn, electricity consumption will be lower for the dynamic pricing case. A uniform price higher than \hat{c}_2 , on the other hand, will lead to a lower expected sales to the grid and higher level of expected consumption. Accordingly, when $\bar{c}_2 = \hat{c}_2$, the expected grid

activity upon the installation of a smart meter device will always be lower.

The interval $c_2 \in]\hat{c}_2, \bar{c}_2]$ gets wider for a lower installation cost. The installation of the smart meter in the relevant domain, nevertheless, would lead to a smaller amount sales of electricity to the grid for lower electricity prices.

4.6 Congestion

This section focuses on the curtailment measures to avoid the congestion problem that arises when there is too much in-feeds to the grid. When selling to the grid is attractive, that is, $c_1 > u'(\bar{K} - \bar{S})$ or $c_{ji} > u'(\mathbb{1}_s(j)\bar{K} + \bar{S})$, and therefore, the HH can considerably feed in the grid, the distribution lines and transformers may become overloaded and reduce the quality of the electricity supply (Rui et al., 2014). There are a couple of mechanisms to avoid congestion. One current approach until grid expansion measures can be executed is the curtailment of the feed-ins of the distributed generators which leads to wastes in the RE generation (Jacobsen and Schröder, 2012, Luhmann et al., 2015).⁹

When curtailment occurs unexpectedly, the HH's investment decisions and grid activity are unaltered and, therefore, the program solved in Section 4.3 remains valid. The HH's welfare, however, is reduced by the value of the amount that is curtailed and in turn wasted. On the other hand, when the HH is aware of the curtailment measure, investment decisions and grid activity are affected. This, in turn, prevents the waste of the generated electricity and leads to a higher welfare compared to the case when the curtailment measure is taken unexpectedly. The welfare, nevertheless, is still lower than the one in the case where the HHs are not exposed to such measures.¹⁰

To demonstrate the impact of curtailment on optimal decisions when it is expected, we

⁹Price management is another approach to solve this problem (Bjørndal and Jörnsten, 2007). When the market price induce capacity problems, the price can be adjusted to reduce the level of the electricity transmission from the HHs to the grid.

¹⁰This is because in the latter case the HH problem is unconstrained.

consider a threshold \bar{g} ($\bar{g} \leq 0$) on the in-feeds. Accordingly, we impose $g_1 \geq \bar{g}$ and $g_{ji} \geq \bar{g}$. We are aware of the fact that in reality the curtailment does lead to a waste of generated electricity meaning that the HH does not perfectly account for the curtailment. However, the correct model will get closer to the one with perfect foresight as the HHs become more aware of the curtailment problem (that, in turn, would eventually lead to higher welfare). We, therefore, focus on the case where they are fully aware of this measure.

4.6.1 Optimal investment decisions

Curtailment imposes two additional constraints on feeding the grid in the HH decision programme: $g_1^m \geq \bar{g}$ and $g_{ji}^m \geq \bar{g}$. The two transmission constraints state that the grid activity should not exceed a negative threshold \bar{g} . Otherwise, the security and reliability of the grid would be disrupted. Let ‘ m ’ superscript denote the optimal value for the decision variables for the case where there is a threshold on feeding the grid. The FOCs with respect to g_1 and g_{ji} are

$$u'(K_1^m + g_1^m - S_1^m) - c_1 = -\nu_5, \quad (4.12a)$$

$$u'(\mathbb{1}_s(j)K_1^m + \phi S_1^m + g_{ji}^m) - c_{ji} = -\nu_{ji}, \quad (4.12b)$$

respectively. Here ν_5 and ν_{ji} are the multipliers associated with the constraints on feeding in the grid. Plugging Eqs. (4.12a) and (4.12b) into the FOCs wrt K_1 and S_1 yield

$$c_1 + P_s \sum_i P_i c_{si} - r = \nu_1 - \nu_3 + \nu_5 + P_s \sum_i P_i \nu_{si}, \quad (4.13a)$$

$$\phi \sum_j \sum_i P_j P_i c_{ji} - c_1 = \nu_4 - \nu_2 - \nu_5 + \phi \sum_j \sum_i P_j P_i \nu_{ji}. \quad (4.13b)$$

Furthermore, as in the previous section, we consider that Eq. (4.3a) holds.

In light of these equations, several scenarios can emerge. As an example it is possible to face a scenario where it is optimal to use all the storage capacity and yet install no solar panels. One can also consider a case in which it is optimal to fully use the total capacity for solar panels but store no energy. It is also possible to think of a scenario in which the solar panel investment and energy storage decisions take interior values. Figure

4.5 illustrates various cases for investment and grid purchase decisions by considering different electricity prices on the grid in the first period. Without attempting to calibrate the model, the parameter values we use are $r = 0.03$; $\phi = 0.75$; $P_s = 2/3$; $P_l = 1/2$; $c_1 \in [0.0117, 0.0232]$; $c_{sl} = 0.01$; $c_{sh} = 0.06$; $c_{nl} = 0.01$; $c_{nh} = 0.06$, $\max(\bar{K}) = 8$, $\max(\bar{S}) = 8$, $\bar{g} = -1$ and $\gamma = 2$.

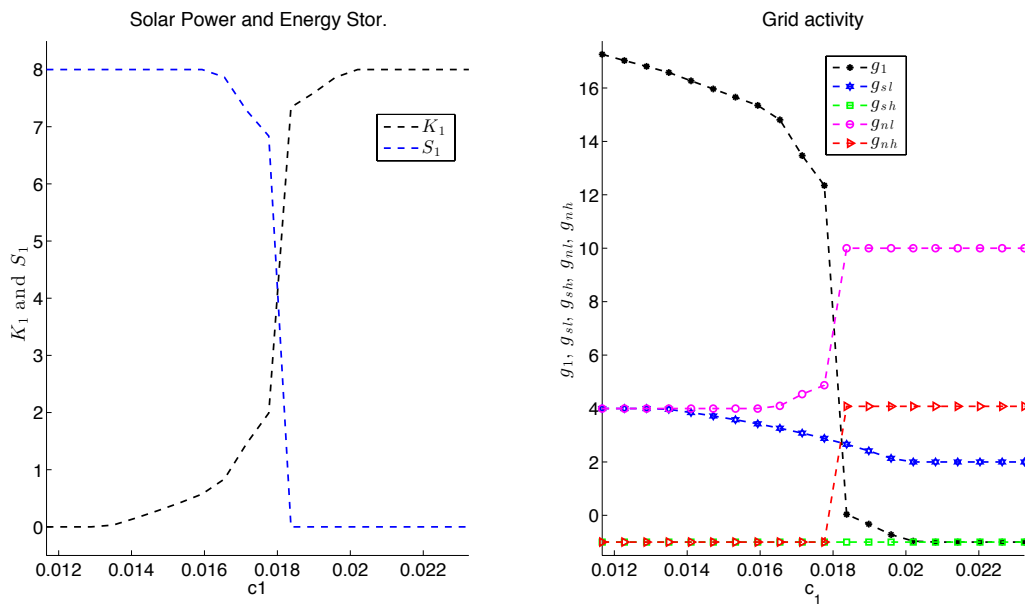


Figure 4.5: A case for interior solution

When the price on the grid in the first period is sufficiently low, the figure shows that it is optimal to store energy at the capacity by purchasing electricity only from the grid. In this case, there will be no investments for solar energy. When energy is stored at the capacity and the electricity price is high, it is seen that the electricity is fed in to the grid until the congestion threshold, \bar{g} , is met. For higher values for c_1 we see that both K_1 and S_1 take interior values. This regime changes when the price of electricity on the grid in the first period becomes sufficiently high. In this case, all capacity for the solar panels is exhausted. Yet, as the price on the grid becomes sufficiently high, storing energy becomes suboptimal.

Interior solution

We first focus on the case with interior solutions, that is, $\nu_1 = \nu_2 = \nu_3 = \nu_4 = \nu_5 = 0$. As it must always be true that

$$g_{nl}^m > g_{nh}^m > g_{sh}^m \text{ and } g_{nl}^m > g_{sl}^m > g_{sh}^m,$$

interiors solutions imply that $g_{sh}^m = g_{nh}^m = \bar{g}$.¹¹ From an analytical point of view, setting a limit on feeding the grid is equivalent to replacing two constraints, namely $K_1 \leq \bar{K}$ $S_1 \leq \bar{S}$, by two constraints on feeding the grid in the second period, that is $g_{sh}^m = g_{nh}^m = \bar{g}$.

The economic intuition as follows. If there is a limit for feeding the grid when there is sun and a high price on the electric grid, then there is no incentive to buy an infinite amount of solar panels. On the other hand, when there is no sun, the electricity price is high and feeding the grid is technically limited, then there is no incentive to have an infinite amount of storage capacity.

The optimal levels of S_1 and K_1 can be calculated as follows. Using interior solutions, Eqs. (4.13a) and (4.13b) read as

$$c_1 + P_s \sum_i P_i c_{si} - r = P_s P_h \nu_{sh}, \quad (4.14a)$$

$$\sum_j \sum_i P_j P_i c_{ji} - \frac{c_1}{\phi} = P_h \sum_j P_j \nu_{jh}. \quad (4.14b)$$

By replacing Eq. (4.12b) with ν_{ji} in Eqs. (4.14a) and (4.14b), the optimal levels of S_1 and K_1 can be calculated from the following system of equations:

$$c_1 + P_s(P_l c_{sl} + P_h u'(K_1^m + \phi S_1^m + \bar{g})) = r, \quad (4.15a)$$

$$P_n(P_l c_{nl} + P_h u'(\phi S_1^m + \bar{g})) + P_s(P_l c_{sl} + P_h u'(K_1^m + \phi S_1^m + \bar{g})) = c_1/\phi. \quad (4.15b)$$

The interpretation is as follows. Eq. (4.15a) shows that the marginal cost of solar panel

¹¹This is due to the fact that assuming $g_{sh} = \bar{g}$ only will lead to infinitely many solutions for S_1^m and K_1^m .

should equal, first, the avoided marginal cost of buying from the grid in the first period, second, avoided marginal cost of buying from the grid when there is sun and the price on the grid is low, and third, the marginal benefit of consuming energy generated by the HH, that is, $u'(K_1^m + \phi S_1^m + \bar{g})$, when there is sun and the price is high. On the other hand, Eq. (4.15b) indicates that the marginal cost of storage, c_1/ϕ , that is, the opportunity cost of forgone consumption in period 1 adjusted for the storage loss, should equal the expected avoided marginal cost of buying from the grid plus the expected marginal benefit of consuming energy generated by the HH.

The optimal levels for the number of solar panels and energy storage will be calculated from the following equations:

$$u'(\phi S_1^m + \bar{g}) = \frac{c_1/\phi - P_n P_l c_{nl} + c_1 - r}{P_n P_h}, \quad (4.16a)$$

$$u'(K_1^m + \phi S_1^m + \bar{g}) = \frac{r - c_1 - P_s P_l c_{sl}}{P_s P_h}. \quad (4.16b)$$

The grid activity is given by:

$$u'(K_1^m - S_1^m + g_1^m) = c_1,$$

$$g_{jh}^m = \bar{g},$$

$$u'(\mathbb{1}_s(j)K_1^m + \phi S_1^m + g_{jl}^m) = c_{jl}$$

Solar power constrained

When the solar power is constrained by the available physical capacity, and therefore, $K_1^m = \bar{K}$, the following conditions for the multipliers,

$$\nu_2 = \nu_3 = \nu_4 = \nu_5 = 0, \text{ and } \nu_1 > 0,$$

allow us to write (cf. Eqs. (4.13a) and (4.13a))

$$c_1 + P_s \sum_i P_i c_{si} - r = \nu_1 + P_s \sum_i P_i \nu_{si} > 0,$$

$$\phi \sum_j \sum_i P_j P_i c_{ji} - c_1 = \phi \sum_j \sum_i P_j P_i \nu_{ji} > 0.$$

A necessary condition for an interior solution is $g_{sh}^m = \bar{g}$. This is because, on the margin, the benefit from storing energy at the capacity will be lower than its cost in the first period, which would have been otherwise had the HH sold to the grid.¹² One way to circumvent this problem is to pick a lower level of energy storage and avoid consuming from the grid in the state when there is sun and the price is high.

Storage constrained

When energy storage is constrained by the available capacity for the device, and thus, $S_1^m = \bar{S}$, we have the following conditions for the multipliers:

$$\nu_1 = \nu_2 = \nu_3 = \nu_5 = 0, \text{ and } \nu_4 > 0.$$

Eqs. (4.13a) and (4.13a) then allow us to write

$$\begin{aligned} c_1 + P_s \sum_i P_i c_{si} - r &= P_s \sum_i P_i \nu_{si} > 0, \\ \phi \sum_j \sum_i P_j P_i c_{ji} - c_1 &= \nu_4 + \phi \sum_j \sum_i P_j P_i \nu_{ji} > 0. \end{aligned}$$

Similar to the previous subsection, a necessary condition for an interior solution is $g_{sh}^m = \bar{g}$. Otherwise, using a higher number of solar panels or consuming from the grid when there is sun and a high price on the electric grid will lead to a lower expected marginal return from solar power generation.

Solar power and storage constrained

When the installation of both the solar power and energy storage is constrained by the available physical capacity, and therefore, $K_1^m = \bar{K}$ and $S_1^m = \bar{S}$, we have the following conditions for the multipliers:

$$\nu_2 = \nu_3 = \nu_5 = 0, \nu_1 > 0 \text{ and } \nu_4 > 0.$$

¹²The optimal solution dictates $K_1^m = \bar{K}$ and $S_1^m = \bar{S}$ in the smart grid case so that some electricity can optimally be sold in both periods.

This leads us to

$$c_1 + P_s \sum_i P_i c_{si} - r = \nu_1 + P_s \sum_i P_i \nu_{si}, \quad (4.17a)$$

$$\phi \sum_j \sum_i P_j P_i c_{ji} - c_1 = \nu_4 + \phi \sum_j \sum_i P_j P_i \nu_{ji}. \quad (4.17b)$$

As a result, there is no restriction as to the use of the grid in the second period.

4.6.2 Electricity consumption and grid activity of unlimited feed-ins vs limited feed-ins

In this section we discuss the implications of unlimited and limited feed-ins (due to congestion problem) for electricity consumption and the grid activity. Following the same parametric conditions that satisfy Eqs. (4.3a) and (4.3b), we first do a comparison between the case with unlimited grid feed-ins and the case with limited feed-ins, which can lead to interior solutions for solar panel and energy storage device installations. This is then followed by specific cases of solar power constrained, storage constrained and solar power and storage constrained.

Interior solution

Recall that the interior solution under unlimited feeding the grid, constitutes

$$\nu_1 = \nu_2 = \nu_3 = \nu_4 = \nu_5 = 0.$$

and the superscripts ‘ g ’ and ‘ m ’ denote the optimal decisions in the unlimited and limited feeding the grid cases, respectively.

From Eqs. (4.12a) and (4.2c) we have

$$g_1^m - g_1^g = (\bar{K} - K_1^m) - (\bar{S} - S_1^m).$$

Furthermore, in the second period, using Eqs. (4.12b) and (4.2d), we get

$$g_{ji}^m - g_{ji}^g \geq \mathbb{1}_s(j)(\bar{K} - K_1^m) + \phi(\bar{S} - S_1^m) \geq 0$$

with the first inequality from the left being strict at least for g_{sh}^m and g_{nh}^m .¹³

These two equations allow us to deduce that

$$\begin{aligned} (g_1^m - g_1^g) + \sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g) &> (\bar{K} - K_1^m) - (\bar{S} - S_1^m) \\ &+ \sum_j \sum_i P_j P_i \left[\mathbb{1}_s(j)(\bar{K} - K_1^m) + \phi(\bar{S} - S_1^m) \right] \end{aligned} \quad (4.18)$$

As K_1^m and S_1^m are optimal, the above inequality can be rewritten as:

$$(g_1^m - g_1^g) + \sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g) > (1 + P_s)(\bar{K} - K_1^m) - (1 - \phi)(\bar{S} - S_1^m) \quad (4.19)$$

A sufficient condition for buying less from the grid when there is unlimited possibility of feeding the grid, is therefore¹⁴

$$\begin{aligned} (1 + P_s)(\bar{K} - K_1^m) &\geq (1 - \phi)(\bar{S} - S_1^m) \\ \left(\text{or } (1 + P_s)\bar{K} - (1 - \phi)\bar{S} \geq (1 + P_s)K_1^m - (1 - \phi)S_1^m \right) \end{aligned} \quad (4.20)$$

Consider the two periods. When the additional electricity that is expected to be generated by the solar panels exceeds that of the additional energy lost by the storage devices (that is, $(1 - \phi)(\bar{S} - S_1^m)$), there will be less purchase from the grid in the unlimited feeding the grid case.

When the net amount of electricity generated in the unlimited feeding the grid case (that is, $(1 + P_s)\bar{K} - (1 - \phi)\bar{S}$) is higher than it is for the case with limited feeding, then the HH will purchase a higher amount of electricity under the limited feed-in

¹³Otherwise, $g_{sh}^m - g_{sh}^g = 0$ and $g_{nh}^m - g_{nh}^g = 0$, which requires that $K_1^m = \bar{K}$ and $S_1^m = \bar{S}$. From Eqs. (4.16a) and (4.16b), one can see that the chance for the two equalities to hold simultaneously (or even individually) is extremely small, and therefore, negligible.

¹⁴Considering that $\nu_5 > 0$ and $g_1^m = \bar{g}$, Eq. (4.19) and the sufficient condition given by Eq. (4.20) will still be valid.

case. On the other hand, if the net amount of electricity generated in the unlimited feeding the grid case is lower, that is, when Eq. (4.20) is not satisfied, the result is ambiguous. This is mainly related to the fact that in the unlimited feeding the grid case, it is always optimal to store at the capacity when Eq. (4.3a) holds. Yet, when \bar{K} is sufficiently small, the necessary amount of energy that will be stored will be obtained from the grid. Even if there will be a lower amount of grid purchases in the second period, the first period purchase of electricity can be sufficiently high to cause a higher expected amount of purchase from the grid in the unlimited feeding the grid case.

Figure 4.6 illustrates the differences between the grid purchases for cases with unlimited feeding the grid and with limited feeding the grid. While the first graph from right demonstrates the total purchases from the grid, that is, $g_1^m - g_1^g + \sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g)$, the two figures from left demonstrate the grid purchases in the first and second periods, that is, $g_1^m - g_1^g$ and $\sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g)$, respectively. We are only interested with the qualitative pattern. Therefore, we do not attempt to calibrate the model. The parameter values we use are $r = 0.05$; $\phi = 0.49$; $P_s = 2/3$; $P_l = 1/2$; $c_1 = 0.03$; $c_{sl} = 0.02$; $c_{sh} = 0.3$; $c_{nl} = 0.02$; $c_{nh} = 0.3$, $\bar{g} = -0.5$, $\min(\bar{K}) = 2.46$, $\max(\bar{K}) = 4.46$, $\min(\bar{S}) = 0.17$, $\max(\bar{S}) = 2.17$. ($K_1^m = 2.46$ and $S_1^m = .17$.)

In particular, if the accessible solar panel capacity is low (e.g., $\bar{K} = 2.46$) and the accessible energy storage capacity is rather large (e.g., $\bar{S} = 2.17$), having the possibility to infinitely feed the grid will generate an adverse effect by causing more purchase from the grid. Figure 4.6 indicates that the difference between grid purchases for the cases with unlimited feeding the grid and with limited feeding the grid is the highest when the solar and storage capacities are low and high, respectively. Also, higher amount of solar panels and stored energy lead to lower amount of expected purchase from the grid.

Solar power and/or storage constrained

When the solar power is constrained by the available physical capacity, and therefore, $K_1^m = \bar{K}$, the difference between the expected total purchase of electricity in the unlimited

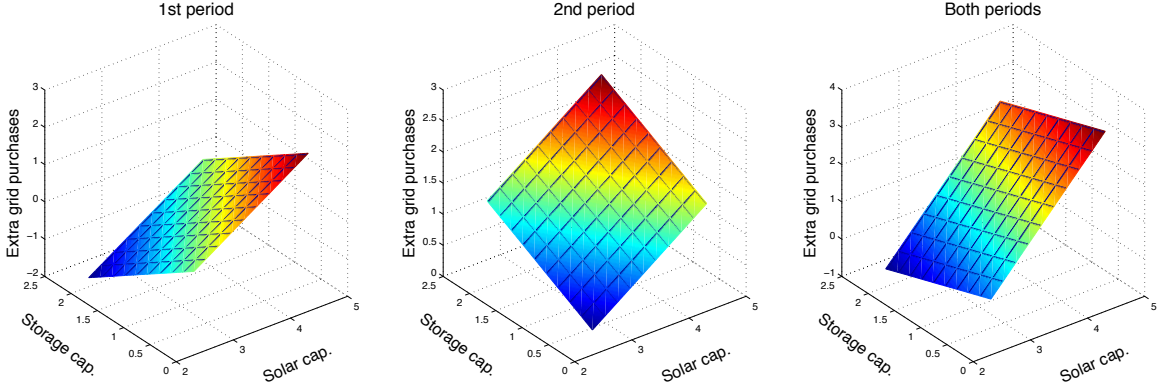


Figure 4.6: *Difference in purchases from the grid.*

feeding the grid and limited feeding the grid cases can be expressed as

$$(g_1^m - g_1^g) + \sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g) > -(1 - \phi)(\bar{S} - S_1^m), \quad (4.21)$$

As the RHS of Eq. (4.24) is negative, the result is ambiguous. On the other hand, when the solar power is constrained by the available physical capacity, and therefore, $S_1^m = \bar{S}$, the average level of grid purchases will be higher in the limited feeding the grid case. Lastly, the average level of grid purchases will be higher in the limited feeding the grid case when both the solar power and storage are constrained. For further details, see Appendix 4.8.

The following proposition summarizes the results thus far in this section:

Proposition 3

- a- *Curtailment measures can discourage investment in generating and storage capacities. In particular, different than the case with unlimited feed-ins, K_1 and S_1 can take interior values even when Eqs. (4.3a) and (4.3b) are satisfied.*
- b- *When investment are discouraged, electricity generated and fed by the HH to the grid will be curtailed at the higher end of the price schedule; that is, $g_{sh}^m = g_{nh}^m = \bar{g}$.*
- c- *When solar power and storage take interior values, the HH will not necessarily purchase more electricity from the grid.*

4.7 Conclusion

Climate change, congested electric grids in developed countries and lack of access to electricity in developing countries are problems that can be mitigated by further use of renewables (e.g., wind and solar power). The intermittent nature of renewables coupled with the non-reactive consumers to short-term fluctuations in electricity provision, nonetheless, suggest the implementation of new levels of equipment such as the possibility to sell to the grid, installation of smart meters and the use of energy storage.

In this paper, we analyze the optimal investments in solar panels and storage device in this regard and evaluate the consequences of energy storage and smart meters for purchases of electricity from the grid and electricity consumption. We additionally discuss the desirability of smart meter installation and study the implications of curtailment measures to avoid congestion. Our first result indicates that it is beneficial to install a smart meter enabling the HH to benefit from electricity price variations when the expected electricity price is either sufficiently low or high. Our second result is that the objective to rely less on the grid through the use of a smart meter cannot be attained unless the expected price is sufficiently high. Otherwise, the reliance on the grid will be higher leading to further emissions. This indicates that electricity prices need to be carefully contemplated when the objective is to rely less on the grid through smart grid deployment. We also consider a congestion problem that can arise due to too much in-feeds to the grid. Our analysis demonstrates that curtailment measures to avoid congestion can discourage investment in renewable energy generating and energy storage capacities. When such investments are discouraged, our results indicate that, first, electricity generated and fed to the grid by the HH will be curtailed at the higher end of the price schedule, and second, the HH will not necessarily purchase more electricity from the grid.

More could be done within our framework. We could appraise the suitability of smartgrids in case there is a black-out risk as encountered both in developed countries like the US and developing countries like India. In addition, we could explore cases where solar panels or storage investments are so expensive that related investments are only beneficial when complemented with additional smartgrids. Finally our results could serve as a

basis to design environmental policies such as subsidies either for microgrids or smartgrids.

Appendices

4.8 Electricity consumption and grid activity: unlimited vs limited feed-ins

Solar power constrained

When the solar power is constrained by the available physical capacity, and therefore, $K_1^m = \bar{K}$, we have the following conditions for the multipliers:

$$\nu_2 = \nu_3 = \nu_4 = \nu_5 = 0, \text{ and } \nu_1 > 0.$$

Looking at the first period, an interior solution for g_1 implies

$$u'(\bar{K} + g_1^m - S_1^m) = u'(\bar{K} + g_1^g - \bar{S}). \quad (4.22)$$

As the marginal utility is decreasing with consumption, that is, $u'' < 0$, $g_1^m < g_1^g$. A higher level of energy storage, accordingly, will lead to a higher level of grid purchase in the case with unlimited feeding the grid in the first period:

$$g_1^m - g_1^g = -(\bar{S} - S_1^m) < 0.$$

In the second period, the expected difference between grid purchases in the smart meter and smart grid cases is

$$\sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g) \geq \phi(\bar{S} - S_1^m) > 0. \quad (4.23)$$

This indicates that the expected purchase in the unlimited feeding the grid case will be higher in the second period.

Summing up the two inequalities, the difference between the expected total purchase of

electricity in the unlimited feeding the grid and limited feeding the grid cases can be expressed as

$$(g_1^m - g_1^g) + \sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g) > -(1 - \phi)(\bar{S} - S_1^m), \quad (4.24)$$

As the RHS of Eq. (4.24) is negative, the inequality given by Eq. (4.24) is no more a sufficient condition to buy less from the grid with unlimited feeding the grid. The intuition is as follows: as the parametric condition dictates that it is optimal to store at the maximum capacity, the grid purchases in the first period can be sufficiently high to cause a higher level of purchase from the grid in the unlimited feeding the grid case.

Figure 4.7 shows the differences between the grid purchases for cases with unlimited feeding the grid and limited feeding the grid when $K_1^m = \bar{K}$. While the first two graphs from left demonstrate the purchases from the grid in the first and the second period, respectively, the last figure demonstrates the expected sum of the grid purchases in the two periods. Namely, the three figures from left to right demonstrate $g_1^m - g_1^g$, $\sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g)$ and $g_1^m - g_1^g + \sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g)$, respectively. We are only interested with the qualitative pattern, and thus, we do not attempt to calibrate the model. The parameter values that we employ are $r = 0.05$; $\phi = 0.49$; $P_s = 2/3$; $P_l = 1/2$; $c_1 = 0.030$; $c_{sl} = 0.02$; $c_{sh} = 0.3$; $c_{nl} = 0.02$; $c_{nh} = 0.3$; $\bar{g} = -0.5$, $\bar{K} = 2.45$, $\min(\bar{S}) = 0.15$, $\max(\bar{S}) = 2.15$. ($K_1^m = 2.45$ and $S_1^m = 0.15$.)

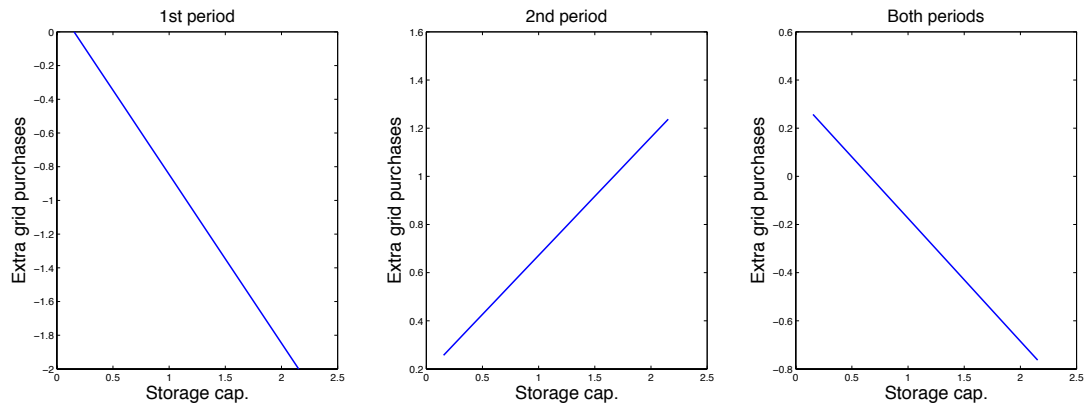


Figure 4.7: Difference in purchases from the grid ($K_1^m = \bar{K}$).

4.8. ELECTRICITY CONSUMPTION AND GRID ACTIVITY: UNLIMITED VS LIMITED FEED-INS

In line with our intuition above, the last figure show that lower values of energy storage capacity, low storage capacity will allow for a higher grid activity with limited feeding the grid. Nevertheless, with higher storage capacities, which allow for larger amounts of energy to be stored in the first period (see Fig. 4.7a), the total amount of energy purchased from the grid increases. This happens even if the grid purchases are lower in the second period with unlimited feeding the grid.

Storage constrained

When the solar power is constrained by the available physical capacity, and therefore, $S_1^m = \bar{S}$, we have the following conditions for the multipliers:

$$\nu_1 = \nu_2 = \nu_3 = \nu_5 = 0, \text{ and } \nu_4 > 0.$$

From Eq. (4.19), the difference between the purchase of electricity in the limited feeding the grid and unlimited feeding the grid cases can be expressed as

$$(g_1^m - g_1^g) + \sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g) > (1 + P_s)(\bar{K} - K_1^m), \quad (4.25)$$

As $\bar{K} > K_1^m$, the LHS is strictly positive. Therefore, the average level of grid purchases will be higher in the limited feeding the grid case.

Solar power and storage constrained

Recall that we have the following conditions for the multipliers when the installation of both the solar power and energy storage is constrained by the available physical capacity, and therefore, that is, $K_1^m = \bar{K}$ and $S_1^m = \bar{S}$:

$$\nu_2 = \nu_3 = \nu_5 = 0, \nu_1 > 0 \text{ and } \nu_4 > 0.$$

The difference between the purchase of electricity in the unlimited feeding the grid and limited feeding the grid cases can now be expressed as

$$(g_1^m - g_1^g) + \sum_j \sum_i P_j P_i (g_{ji}^m - g_{ji}^g) > 0, \quad (4.26)$$

Therefore, the average level of grid purchases will be higher in the limited feeding the grid case.

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Chapter 5

Conclusion

In this dissertation, we analysed the optimal energy transition under the occurrence of an environmental catastrophe and determined incentive-based strategies that can encourage the energy transition. In the context of growing energy demand and the contribution of fossil fuels to global warming, it becomes crucial not only to decarbonise electricity generation, but also to find energy saving strategies. In this regard, we developed four chapters that discuss different issues related to the energy transition. In the first chapter, we studied the optimal energy transition involving decisions about both renewable energy adoption and investment in energy saving technologies, when there is a deterministic pollution threshold that triggers the occurrence of an environmental catastrophe. We have characterised two types of energy transition paths: (1) a central energy transition path and (2) corner energy transition paths. The boundary conditions serve to isolate the optimal energy transition path. We used given baseline parameter values to show that in the absence of any possibility of investing in energy saving technologies, it is not profitable to adopt only clean energy. As a result, a complete transition to a low carbon economy is likely to be very slow ([Fouquet, 2010](#); [Solomon and Krishna, 2011](#)).

Three explanations for this can be provided. First, electric power from other sources of energy is still used in all of the manufacturing processes for producing renewable energy. For example, producing solar panels has certain indirect downstream energy requirements ([Ayres, 2007](#)). As the economy still needs fossil fuels to produce clean energy, it is more profitable to progressively reduce this costless dependence on fossil fuels

(except for the catastrophe that occurs once) than to switch to the sole use of a costly clean energy. Second, without innovation in the energy sector such as energy efficiency investment, the global demand for energy is expected to increase and the economy will become more energy intensive. In this sense, it may be less profitable to fully rely on a costly renewable energy. Third, some recent studies show that the potential for global wind power (De Castro et al., 2011) and for global solar electric (De Castro et al., 2013) might be even lower than the current final consumption of energy by means of fossil fuels. Therefore, an immediate and complete transition to an economy that only relies on renewable sources of energy may not be physically and technically feasible without energy saving measures. We then extend this model to allow for the adoption of energy saving technologies. We mainly find that investment in energy saving technologies favours full energy transition. Consequently, it postpones environmental catastrophe, it is welfare improving and allows a complete transition to the sole use of clean energy.

The second chapter investigated the optimal transition to renewable energy under uncertain occurrence of an environmental catastrophe. We analytically solved the model for the steady state solution to identify the optimal energy transition path. This is followed by numerical solving that relies on given baseline parameters values, and we obtained the probability of damage occurrence and the optimal time to reach the economy that uses only renewable energy. Given the baseline parameter values, we have demonstrated that the environmental catastrophe may happen, and we have exhibited the corresponding optimal energy transition path which consists of three phases. The economy starts using both types of energy resources, then experiences the environmental catastrophe, and is ultimately fuelled by renewable energy sources only. We have also shown that uncertainty of the occurrence of the catastrophe induces precautionary behaviour, in the sense that it negatively affects the rate of the polluting resource extraction and drives the energy transition. This work can be seen as a first attempt at an analytical representation of the energy transition under ecological risk.

Following the suggestion from the first chapter of coupling investments in renewable energy and energy saving technologies, the third chapter has been devoted to better

understanding household behaviour regarding energy transition. We have theoretically shown that there are interactions between the two decisions depending on a cross effect which relies on environmental-related satisfaction. Then, we empirically investigated the interactions between the two decisions. More precisely, we used a bivariate probit model to show 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. We provided evidence on 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 greater share of their income to pay for electricity and be in a situation of energy poverty. There is evidence of split incentives: home ownership positively affects the two probabilities to invest in renewable energy and in energy efficiency. The results also confirm the importance of environmental concerns (as a general issue) in the decision of the household to adopt renewable energy, while climate change concerns (as a specific issue) lead investments in energy efficiency. On top of that, 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 both decisions. The commitment of households to environmental organisations only affects their decision to adopt renewable energy. Furthermore, we used a generalised ordered logit model to account for the interaction between the two decisions. The results have mainly suggested that (i) the influence of income becomes less important in the decision of the household to go further once it has undertaken any of these investments and (ii) the barriers that hinder the household to fully contribute to the energy transition can be overcome by environmental motivations.

In the fourth chapter, we explored the role of smart-grids in integrating intermittent renewable energy to facilitate the energy transition. The intermittent nature of renewables coupled with the non-reactivity of consumers to short term fluctuations in electricity provision, suggest the implementation of new technologies such as the possibility to sell to the grid, installation of smart meters and the use of energy storage. In this regard, we have analysed the optimal investment in solar panels and storage devices and evaluated

the consequences of energy storage and smart meters for purchase of electricity from the grid and electricity consumption. We have additionally discussed the desirability of smart meter installation and have studied the implications of curtailment measures to avoid congestion. This chapter indicates that it is optimal to install a smart meter device when the expected electricity price is either sufficiently low or high. The chapter also suggests that there will be higher reliance on the grid leading to further emissions, unless the expected price is sufficiently high. This indicates that electricity prices need to be carefully contemplated when the objective is to rely less on the grid through smart grid deployment. Congestion problems can arise when electricity provision to the grid is attractive, leading to overloaded distribution lines and transformers and reducing the quality of the electricity supply. Our analysis has considered this congestion problem and has demonstrated that curtailment measures to avoid congestion can discourage investment in renewable energy generation and energy storage capacities. Consequently, electricity generated and fed to the grid by the household will be curtailed at the higher end of the price schedule, and the household will not necessarily rely more on the grid.

Several policy implications can be derived from the results that have been suggested by the four chapters. The first chapter has recommended that without additional investment in energy saving technologies and due to the need for fossil fuels in the production of clean energy, it is more profitable to progressively reduce dependence on fossil fuels which are costless, than to switch to the sole use of a costly clean energy. Public policy should then promote innovation that helps increase the productivity of capital and energy services in productive sectors and save both money and energy. As investment in energy saving technologies can encourage the energy transition, it is therefore profitable to take advantage of the synergies that may arise from jointly promoting clean energy and providing incentives for investment in energy saving technologies.

The second chapter has demonstrated that uncertainty plays an important role in the energy transition in the sense that it induces a precautionary behaviour. This suggests that when people fear the negative consequences of climate change, the occurrence of which is uncertain, they are more favourable to the energy transition.

The third chapter has investigated the interrelation between the decisions of households to adopt renewable energy and to invest in energy efficiency and has revealed that their interrelation is positive. One should then 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 buildings to rely only on renewable energy sources. Energy demand is then notably reduced due to efficiency gains so that the remaining energy needs can be satisfied by means of renewable energy.

Certain energy issues have been pointed out in the third chapter: (i) split incentives problems, (ii) energy poverty and (iii) motivating factors. To solve these issues, the following policies can be envisaged. First, regulation of housing markets could help solve split incentives in order to give incentives to tenants to undertake investments in energy efficiency and in renewable energy as well. Financial support to reduce the costs of dismantling existing equipment and re-installing renewable energy equipment could give incentives to tenants to undertake such investments as well.

Second, policies targeting investments in energy efficiency need to be improved. In many countries, financial support for energy conservation systems are mainly profitable for wealthier households. As a household needs to first invest before applying for the reimbursement, poorer households are financially limited and investments are not affordable for them. Therefore, it is necessary to offer green grants which should be interest-free eco-loans targeting only energy-poor households.

Third, it may be of great interest to take advantage of existing charitable, local and environmental organisations to communicate with their members about the importance of energy transition. These members are highly predisposed to better understanding the crucial contribution of the energy transition in protecting the environment. Moreover,

scientists and national or local authorities are the best suited to communicate about the energy transition. Therefore, they should also be more involved in raising awareness, and academic findings should be communicated more widely to make the topics more popular.

Finally, our results on smart-grids could serve as a basis to design environmental policies such as subsidies either for micro-grids or smart-grids. They indicate that the design of the dynamic pricing scheme should be such that the expected electricity price is sufficiently high. This will induce less reliance on the electricity grid through the use of a smart meter, which in turn would lead to less emissions. They also suggest that curtailment measures can be used to deal with the congestion problem as an alternative to the price management approach.

In the first two chapters, we give a general view of energy transition with the risk of climatic damage and the exhaustibility of non-renewable resources by considering optimal switching problems, but this has required other stringent assumptions such as the complementarity between dirty and clean sources of energy in both intermediate and final consumption. This assumption does not allow a focus on energy transition as a process of gradually substituting clean for dirty energy. An alternative would consist of incorporating intermediary phases of a gradual substitution between energy sources, after the phase of complementarity between clean and dirty energy. This may change the optimal energy transition path and therefore necessitate further research. Furthermore, there are many other factors which we could not consider in the investigation of the influence of household behaviour on the energy transition. For example, living in an apartment without a balcony, limited rooftop space, etc. may limit the possibility of installing renewable energy equipment. Also variables related to the characteristics of the residence such as the age of the dwelling, the type of insulation could influence the decision of the household to invest in energy efficiency. But, these variables are not provided in the EPIC survey and would require further research with a new database. Regarding the smart-grid study, we could appraise the suitability of smart-grids in the event there is a black-out risk, as encountered both in developed countries like the US and developing countries like India. In addition, we could explore cases where solar panels or

storage investments are so expensive that related investments are only beneficial when complemented with additional smart-grids.

Environmental issues, namely energy issues, are becoming crucial due to the growing concern about climate change. Although this dissertation provides some insights about energy transition, there is more to investigate as energy transition has many challenges. Therefore, our plan for future research is as follows.

First, the focus on energy transition questions the importance of pro-environmental behaviour in adopting renewable energy and investing in energy efficiency. However, people behave in environmentally-friendly ways regarding energy consumption, transport, water, waste, etc. For example, one can be very environmentally-friendly in adopting renewable energy or adopting curtailment behaviours but not at all environmentally-friendly in the choice of transport. It is therefore important to address the environmental behaviour in multiple dimensions and construct the relationship that may exist between them. Furthermore, one can calculate a summary index to synthesise the behaviour of people in environmental sectors. For empirical investigations, we will use the EPIC data that provides information on how people behave in five sectors: energy, transport, waste, water and food. This information will enable the construction of an index of pro-environmental behaviour. Furthermore, we will study the influence of these characteristics on pro-environmental behaviour by making use of additional information on socio-economics, dwelling and attitudinal characteristics.

Second, we intend to use the index of pro-environmental behaviour together with others factors to empirically study the WTP to use only renewable energy using a pseudo-panel approach. In fact, in the third chapter we have examined the household preference for renewable energy. Additionally, it may be of great interest for policies to evaluate the WTP to consume renewable energy as an estimate of the monetary value of renewable energy. Furthermore, standard panel data are multi-dimensional data and rich sets of information collected from the same units over time, which accounts for both dynamic (times series) and static (cross section) dimensions. Unfortunately, the EPIC data that

we intend to use is cross-sectional data and repeated over time from different households. To overcome this issue, pseudo-panel data is often used as an alternative to the standard panel data. It will consist of creating cohorts on the basis of shared characteristics from the repeated cross-section of the EPIC survey (2008, 2011). Such characteristics need to be time-invariant, and one should also consider the trade-off between the number of cohorts and their size. I can then construct the cohort mean of each variable that will be used for estimation. This empirical study will help to understand the level at which renewable energy is affordable for households by taking into account both dynamic and static dimensions.

Third, following the first and second chapters, other research will be devoted to improving the energy transition model by considering the transition to renewable energy as a process of gradually substituting dirty for clean sources of energy. This can be done by considering substitution as an intermediary phase that precedes the full energy transition. Particular attention will be given to fiscal instruments such as subsidies and carbon taxes that promote investments in renewable energy and in energy saving technologies. This will help explore the implementation of the more profitable energy transition path.

Fourth, we envisage using the model that we have developed in the fourth chapter to explore the consequences of regulation on the deployment of smart-grids and micro-grids and to conduct experiments to better understand household behaviour in this regard. First, we will consider the decentralisation of the efficient mix of investments in renewable energy and energy storage through competitive market mechanisms. The consequences of quantity and price instruments will be both assessed. For example, we will explore the implications of different types of feed-in tariffs (fixed or premium, constant or declining over time), renewable portfolio standards, renewable energy credits, auctions, etc. Second, we will conduct field (or lab) experiments to test the theoretical results. Specifically, we will test the consequences for electricity consumption under real conditions and grid activity of assigning flexibility to households in investing in solar panels or using the electricity grid and a storage device as a backup.

Chapter 6

Résumé élargi

6.1 Contexte

La célèbre citation de Gandhi « il y a assez de tout dans le monde pour satisfaire aux besoins de l'homme, mais pas assez pour assouvir son avidité » ([Nayyar, 1958](#)) exprime bien la capacité de l'homme à détruire les processus naturels. Si aucune limite globale n'est fixée sur le comportement des humains et les activités qui leur permettent de satisfaire aux besoins de base (les services d'énergie par exemple), il est à craindre qu'ils mettent plus de pression sur les ressources naturelles. En outre, les activités humaines basées sur des ressources polluantes produisent des externalités environnementales telles que la pollution de l'air et des dommages à l'atmosphère ou à la couche d'ozone. Cela peut affecter négativement l'écosystème et peut donc conduire à la dégradation de l'environnement ou au changement climatique. Il y a actuellement une véritable prise de conscience du changement climatique défini comme un dérèglement du climat qui amplifie les phénomènes météorologiques extrêmes tels que les inondations, les sécheresses, les incendies violents et les vagues de chaleur.

L'humanité a déjà connu plusieurs catastrophes similaires comme les tremblements de terre de New Madrid en 1811-1812 aux Etats-Unis, les inondations les plus meurtrières de la rivière Jaune en Chine en 1931, l'ouragan Katrina aux Etats-Unis en 2005, le tremblement de terre en Haïti en 2010, la catastrophe nucléaire de Fukushima au Japon en 2011, et plus récemment le vaste incendie du Fort McMurray au Canada en 2016, entre autres. Dans le but d'éviter ou de limiter la survenance de tels événements catastrophiques, la communauté internationale a convenu en vertu de la Convention-Cadre des Nations Unies sur les changements climatiques (CCNUCC) d'un niveau maximum de réchauffement. L'accord de Copenhague en 2009 stipule que le réchauffement de la planète devrait être limité à moins de 2°C par rapport à son niveau pré-industriel (i.e. la période de 1850 à 1900). Récemment, lors de la conférence sur le climat de Paris (COP21) en décembre 2015, 195 pays ont voté à l'unanimité un accord appelé l'Accord de Paris. Cet accord a confirmé l'objectif de maintenir l'augmentation de la température moyenne à 2°C en dessous de la moyenne pré-industrielle. L'accord entend aussi poursuivre les efforts pour limiter cette augmentation à 1,5°C. Toutefois, selon le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC), pour

atteindre cette limite de 1,5°C, il faudrait envisager des émissions négatives. Ce qui suppose non seulement une transition rapide vers les Énergies Renouvelables (ER) et l'Efficacité Énergétique (EE), mais aussi l'adoption des biocarburants combinés avec des technologies de Capture et de Stockage du Carbone (CSC).

En effet, les activités humaines génèrent principalement des Gaz à Effet de Serre (GES) (IPCC, 2013) et sont la cause principale du réchauffement climatique. Le secteur de l'énergie produit plus des deux tiers de toutes les émissions de GES d'origine anthropique et génère principalement du CO_2 représentant la plus grande part des émissions mondiales de GES (Fig 6.1). Ceci peut s'expliquer par la forte dépendance du monde au pétrole (Fig 6.2) et par le fait que le pétrole et le charbon sont les principales sources d'émissions de CO_2 (Fig 6.3). Même si l'épuisement total des stocks de combustibles fossiles demeure une question importante de même que le changement climatique, il semblerait que ce dernier soit prédominant. Par exemple, Bruckner et al. (2014) montrent que le niveau total estimé des réserves et des ressources de combustibles fossiles contient suffisamment de carbone au-dessus du budget de CO_2 pouvant conduire à une catastrophe environnementale. Il existe aussi un large consensus sur le fait que les émissions mondiales de GES continueront d'augmenter au cours des prochaines décennies si l'économie repose sur les politiques actuelles d'atténuation des changements climatiques et des stratégies de croissance verte correspondantes. Selon l'IPCC (2007a), les émissions mondiales de GES augmenteront de 25 à 90% (CO₂-équivalent) entre 2000 et 2030 avec un réchauffement d'environ 0.2°C par décennie. Ainsi, le réchauffement climatique est maintenant une évidence et est observable dans le monde entier à travers l'augmentation des températures moyennes de l'air et de l'océan, la fonte généralisée des glaciers et l'élévation du niveau moyen des océans. De nombreux autres systèmes naturels sont affectés tels que les systèmes marins et d'eau douce, l'agriculture et la sylviculture avec des conséquences considérables sur la santé humaine et sur les activités économiques.

Pour réduire les conséquences du changement climatique il faudrait investir, entre autres, dans les énergies renouvelables. Ces investissements contribueront à réduire les émissions de CO₂ et permettront d'atteindre l'objectif de limitation de l'augmentation

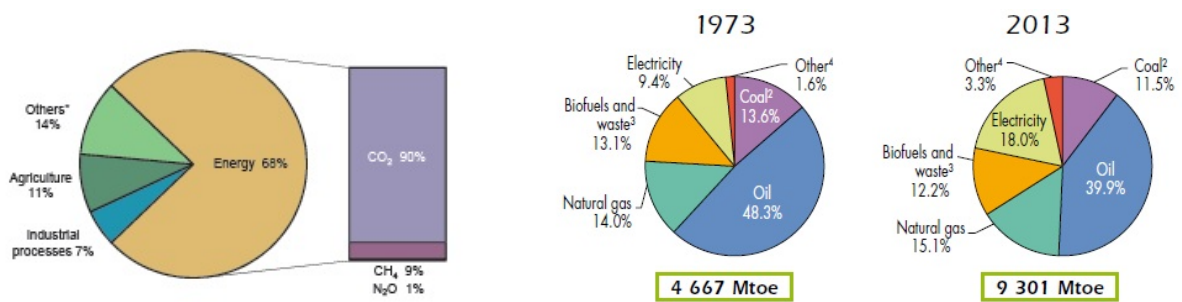


Figure 6.1: Les parts de GES anthropiques, **Figure 6.2:** Les parts des carburants dans la consommation finale totale

Source: IEA, 2015a

Source: IEA, 2015e

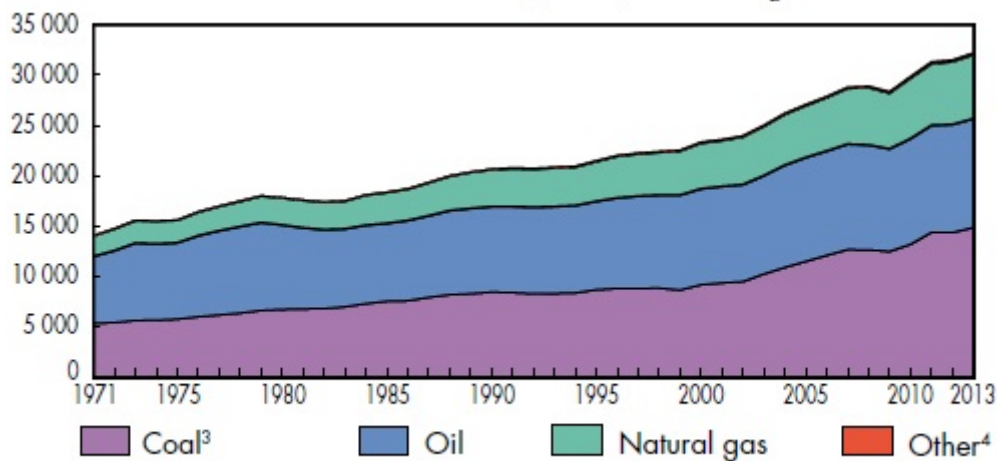


Figure 6.3: Les émissions mondiales de CO₂ provenant de la combustion de carburant de 1971 à 2013 par type de carburant (Mtoe)

Source: IEA, 2015e

de la température moyenne à 2°C. Selon les options de REmap¹, le déploiement de l'énergie renouvelable moderne mondiale atteindrait 119 exajoules par an (une part de 27 % de la production totale énergétique) et peut réduire les émissions annuelles de CO₂ à l'échelle mondiale de 8,6 gigatonnes d'ici 2030 (IRENA, 2014). De plus, les

¹L'Agence internationale de l'énergie renouvelable (IRENA) produit l'approche des options de REmap pour évaluer l'écart entre les plans nationaux de promotion d'énergie renouvelable, d'autres options de technologies d'énergies renouvelables en 2030 et le double objectif du programme d'énergie durable pour tous (SE4ALL). Ils ont d'abord produit des cas de référence de *statu quo*, qui représentent des politiques mises en place ou à l'étude. Les options REmap étudient les options technologiques supplémentaires et illustrent la politique qui vise à doubler la part des énergies renouvelables. Elles définissent le potentiel « réaliste » des opportunités additionnelles de déploiement de technologies d'énergies renouvelables dans chaque pays.

statistiques sur les investissements dans la production de l'énergie renouvelable ont montré jusqu'à présent une tendance à la hausse de 63 à 244 milliards de dollars entre 2006 et 2012 (GEA, 2012), ce qui représente une part de 19 % de la consommation finale mondiale d'énergie en 2012 (RENS21, 2014). Un rapport récent (Fig 6.4) indique que les investissements mondiaux ont atteint un nouveau record de 285,9 milliards de dollars en 2015, avec une capacité de 118GW pour l'éolienne et l'énergie solaire photovoltaïque, une capacité bien au-dessus de celle de 2014 (i.e. 94GW). Dans le même temps, les coûts de production des énergies renouvelables continuent de baisser. Par exemple, le coût global moyen de l'électricité produite avec la technologie photovoltaïque de type silicium cristallin passe de 143 de dollars US par MWh en 2014 à 122 de dollars US en 2015. Cependant, cela n'est pas suffisant et les économies auront besoin de faire davantage d'efforts afin de parvenir à l'accord de Paris. En plus de cela, le potentiel de la capacité d'énergie renouvelable est physiquement et techniquement limité (De Castro et al., 2011, 2013). Des études récentes montrent que le potentiel de l'énergie éolienne (De Castro et al., 2011) et celui de l'énergie solaire (De Castro et al., 2013) pourrait être encore plus faible que la consommation finale actuelle de l'énergie au moyen de combustibles fossiles. Par conséquent, si l'objectif est de se fonder uniquement sur les sources d'énergie propre, il faudrait que les économies réduisent la tendance à la hausse de la demande d'énergie. Il est donc essentiel non seulement de changer radicalement la façon dont l'énergie est produite, mais aussi de trouver des stratégies d'économie d'énergie.

Selon le Global Energy Assessment (GEA), environ un tiers de l'investissement global dans le secteur de l'énergie est lié à l'efficacité (GEA, 2012). Plus précisément, les investissements mondiaux liés à l'efficacité énergétique dans les bâtiments sont estimés à 81-99 milliards de dollars US en 2014 et constitueront le poste le plus important (près de 40 %) dans la réduction des émissions de GES du secteur de l'énergie à l'horizon 2050 (IEA, 2015b). Il est aussi intéressant de noter qu'il existe des possibilités de synergies entre l'efficacité énergétique et l'adoption de l'énergie renouvelable dans la mesure où la première réduit la demande d'énergie de sorte que la dernière puisse réduire davantage les émissions futures de GES. Par exemple, dans une maison à consommation énergétique nette zéro, la demande d'énergie est réduite en raison notamment des gains

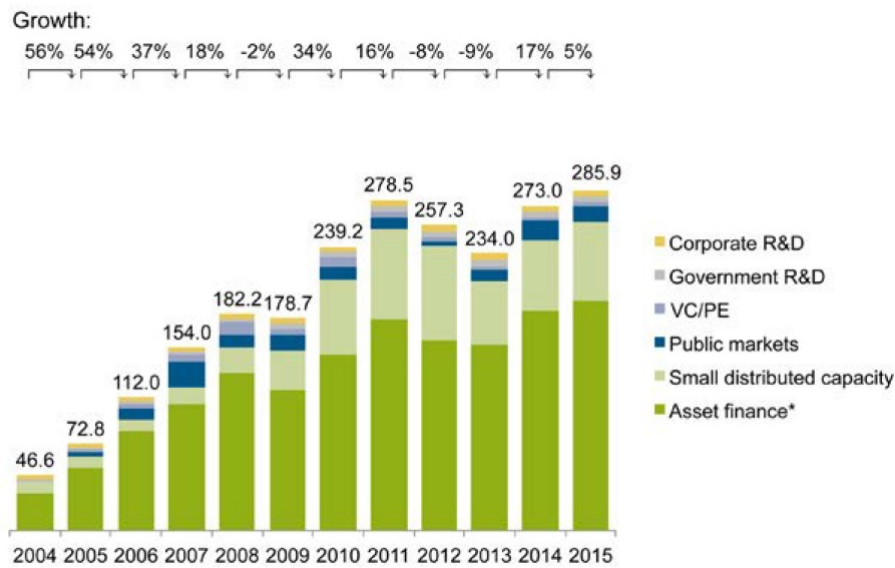


Figure 6.4: *Nouvel investissement mondial dans les énergies renouvelables*

Source: [Frankfurt School-UNEP and Center/BNEF, 2016](#)

d'efficacité permettant de combler les besoins en énergie restants au moyen d'énergies renouvelables. Dans ce sens, l'investissement dans l'efficacité énergétique faciliterait l'utilisation exclusive des sources d'énergies renouvelables dans les bâtiments. Le rapport de l'[IRENA \(2014\)](#) indique que les économies d'émissions provenant des investissements dans les énergies renouvelables et des gains d'efficacité énergétique, seraient suffisantes pour mettre le monde sur un chemin pouvant l'aider à éviter un changement climatique catastrophique.

Dans ce contexte, la transition énergétique tient compte de deux préoccupations principales : (i) l'adoption des énergies renouvelables et (ii) l'investissement dans l'efficacité énergétique. La première question concerne l'adoption de sources d'énergie propre comme une alternative aux sources d'énergie polluante. Quant à la deuxième, elle pourrait contribuer à réduire la consommation globale d'énergie. L'énergie renouvelable fait généralement référence à un type d'énergie qui est produite au moyen de ressources variables ou intermittentes. Ces ressources comprennent le vent (les éoliens), les radiations solaires (l'énergie solaire), la pluie (l'hydro-électricité), les vagues (énergie houlomotrice), les marées (énergie marémotrice), la chaleur géothermique ou aérothermique, les cultures

6.2. IRRÉVERSIBILITÉ ET INCERTITUDE DANS LA TRANSITION ÉNERGÉTIQUE ET CATASTROPHE ENVIRONNEMENTALE

agricoles (biocarburants), etc. En ce qui concerne l'efficacité énergétique, il existe deux principaux types d'actions pouvant permettre de réduire la consommation finale d'énergie : les investissements en matière d'efficacité et les changements d'habitudes. La première option nécessite des investissements monétaires. Il peut s'agir d'une acquisition de nouvelles technologies ou des appareils à faible consommation d'énergie tels que les appareils électroménagers ou des ampoules électriques à faible consommation d'énergie ou des fenêtres écoénergétiques. Il peut aussi s'agir de la rénovation de maisons ou des systèmes écoénergétiques tels que les systèmes de contrôle automatisés ou la domotique. Les changements d'habitudes, quant à eux, ne nécessitent pas d'investissements monétaires. Il peut s'agir des efforts de planification de consommation énergétique, d'éteindre les lumières en cas d'absence prolongée, de réduire l'utilisation du chauffage ou de la climatisation et de mettre les appareils électriques systématiquement en mode veille en cas d'une non utilisation (Thøgersen et al., 1995; Jansson et al., 2009).

Dans le même temps, il existe certains facteurs qui peuvent influencer sur la transition énergétique optimale. Parmi ceux-ci, on peut citer l'irréversibilité et l'incertitude. La notion d'irréversibilité peut être liée à des investissements ou à une catastrophe environnementale. Quant à l'incertitude, elle peut concerner la survenance d'événements catastrophiques, les futures régulations liées aux changements climatiques, l'efficacité des nouvelles technologies et la future demande d'énergie. Dans la section suivante, nous décrivons les problèmes de catastrophe écologique irréversible et sa survenance incertaine.

6.2 Irréversibilité et incertitude dans la transition énergétique et catastrophe environnementale

Dans les premiers travaux concernant l'économie des ressources naturelles, de nombreux auteurs ont considéré séparément le problème d'épuisement des réserves de pétrole (Dasgupta et Heal, 1974, 1979 ; Dasgupta et Stiglitz, 1981 et Krautkraemer, 1986) et le caractère polluant du pétrole (Nordhaus, 1994 et Tahvonen, 1996, 1997). Etant donné que l'utilisation des ressources énergétiques polluantes génère de la pollution qui s'accumule au fil du temps, il est à craindre qu'à un moment donné une catastrophe

écologique survient. Il est prouvé qu'une grande partie des changements climatiques anthropiques résultant des émissions de CO_2 est irréversible sur plusieurs siècles voir plusieurs millénaires (Bruckner et al., 2014). Par conséquent, le réchauffement climatique va entraîner une grave dégradation des forêts tropicales (l'Amazonie par exemple) et de leur potentiel de capture du carbone, une désintégration des calottes glaciaires du Groenland et de l'Antarctique. Ce qui conduira à l'élévation du niveau marin sur plusieurs mètres au cours des siècles, voire des millénaires, et aux rejets à grande échelle de méthane à partir de la fonte du pergélisol, amplifiant ainsi sensiblement le réchauffement climatique (World Bank, 2014). Il est estimé que le déclin irréversible de la calotte glaciaire se produira lorsque l'augmentation de la température moyenne mondiale dépassera environ $1.5^\circ C$ au dessus du niveau pré-industriel (Robinson et al., 2012). Dans ces conditions, le monde va continuer de subir les conséquences irréversibles du changement climatique, même si on arrive à supprimer les sources de pollution d'origine fossile.

L'événement catastrophique générant des dommages irréversibles est diversement considéré dans la littérature. Il pourrait s'agir de l'épuisement de la capacité de régénération naturelle (Tahvonen et Withagen, 1996), de l'irréversibilité dans le processus de décision (Pommeret et Prieur, 2009 et Ayong Le Kama et al., 2014) ou d'un plafond sur le stock de pollution (Lafforgue et al., 2009 et Chakravorty et al., 2012). Tahvonen et Withagen (1996) distinguent deux types de région : une région réversible et une zone de pollution irréversible. La capacité d'assimilation est strictement concave dans la région réversible, alors qu'elle est épuisée dans la région irréversible. Ils trouvent certains équilibres associés à la région de pollution irréversible. Lafforgue et al. (2009) considèrent plutôt un taux constant de régénération naturelle et supposent que les dommages environnementaux dépendent d'un seuil de pollution. Le dommage est négligeable lorsque l'économie reste en dessous de ce seuil alors que le dommage fait un bond et devient infini dans le cas contraire. Ils suggèrent que les politiques de séquestration de carbone devraient être mises en œuvre une fois que le plafond de la pollution est atteint. Les dommages environnementaux induits par la pollution peuvent également prendre des formes différentes. Certains auteurs considèrent ces dommages

comme une perte de revenu (Karp et Tsur, 2011 et Tsur et Withagen, 2013) ou comme une perte du bien-être social (Van der Ploeg et Withagen, 2012 et [Prieur et al., 2013](#)). D'autres auteurs se concentrent sur les secteurs productifs et considèrent les dommages comme une perte de capital (Ikefuji et Horii, 2012) ou comme une destruction de capacité ([Golosov et al., 2014](#)). En outre, certains dommages peuvent être partiellement réversibles au détriment de certaines activités de traitement (Tsur et Zemel, 1996), ou totalement réversibles une fois que le stock de pollution passe en dessous des niveaux critiques ([Cropper, 1976](#)).

La catastrophe environnementale due à la pollution est un problème de changement de régime écologique qui est lié à la notion d'irréversibilité. À notre connaissance, [Tomiyama \(1985\)](#) et [Amit \(1986\)](#) sont les premiers contributeurs à la littérature sur le contrôle optimal lié à ce type de problème de « *switch* » optimal. Ces deux auteurs ont reformulé le problème de « *switch* » optimal comme étant un problème de « *timing* » optimal tout en introduisant le temps de « *switch* » comme une variable de décision explicite. D'autres travaux dans la littérature ont été orientés sur l'environnement déterministe. Dans ce type d'environnement déterministe, [Boucekkine et al. \(2013\)](#) ont proposé une approche de contrôle optimal qui tient compte de deux types de problèmes de « *switch* » optimal. [Boucekkine et al. \(2012, 2013\)](#) ont appliqué cette théorie à la gestion optimale des ressources épuisables soumise à l'irréversibilité écologique et à l'adoption d'un « *back-up* » technologique. Ils utilisent des conditions d'optimalité telles que la continuité de variables et co-variables d'état ainsi que celle de l'hamiltonien.

Bien qu'il existe des seuils de pollution au-dessus desquels les catastrophes environnementales pourraient se produire ([Keller et al., 2008](#)), ces seuils ne sont pas parfaitement connus ([Gjerde et al., 1999](#)). Les perturbations anthropiques des systèmes naturels combinées avec les risques climatiques entraînent le risque du changement climatique qui s'accroît avec l'augmentation de la température. Selon l'IPCC (2014), « *les risques sont considérés comme clés quand il y a une forte probabilité que le danger se produise en raison du changement climatique, dans des circonstances où les sociétés ou les systèmes socio-écologiques exposés sont très sensibles et ont des*

capacités très limitées pour faire face ou s'adapter et par conséquent engendrant des impacts potentiels très importants ». Le rapport indique que les risques d'impacts globaux (à la biodiversité et à l'économie dans son ensemble) sont modérés pour un réchauffement supplémentaire entre 1 à 2°C. De façon plus précise, la perte de la biodiversité (biens et services écosystémiques) pourrait conduire à des risques élevés autour de 3°C de réchauffement supplémentaire, alors que les dommages économiques globaux augmentent avec l'élévation de la température globale. En outre, pour les réchauffements durables au-delà de certains seuils de basculement, la perte quasi-totale de la calotte glaciaire du Groenland se produirait sur plus d'un millénaire ou plus, contribuant jusqu'à 7 m d'élévation globale moyenne du niveau de la mer. Ces risques sont aussi évalués et gérés différemment en ce qui concerne leur ampleur, leur irréversibilité et le temps disponible pour renforcer les capacités d'adaptation nécessaires.

Du point de vue de l'analyse économique, l'abondante littérature sur les options réelles se focalise en partie sur la gestion de l'incertitude environnementale associée à celle des décisions irréversibles tout d'abord. Le terme « valeur d'option » se réfère à des coûts ou à des avantages résultant des irréversibilités et de l'incertitude ([Pindyck, 2007](#)). Par exemple, le fait d'adopter une politique aujourd'hui plutôt que d'attendre demain a un coût d'opportunité négative en raison de son bénéfice non récupérable. Pommeret et Schubert (2009) considèrent dans un modèle d'équilibre général, la technologie de réduction des émissions comme une option réelle où la valeur négative de la pollution modifie à la fois l'aversion au risque et l'élasticité intertemporelle de substitution. Elles trouvent que les préférences plus vertes et les incertitudes plus élevées induisent une adoption anticipée. Par ailleurs, la question sur l'incertitude de catastrophes environnementales remonte à [Cropper \(1976\)](#), qui a utilisé l'exemple d'un accident nucléaire. Tsur et Zemel (1996) se focalisent sur l'épuisement potentiel d'une ressource renouvelable. Ces deux travaux considèrent des problèmes de contrôle optimal lorsque la catastrophe est un événement aléatoire et la fonction objectif est définie en termes d'espérances mathématiques. Ces espérances mathématiques sont dérivées à partir d'une fonction de distribution de probabilité sur la valeur du seuil. Dans ces cas, chaque fois que le stock de pollution radioactive (respectivement des

ressources naturelles) dépasse un (passe respectivement en-dessous d'un) seuil critique, il se produit un événement catastrophique qui réduit l'utilité à zéro et ce pour toujours. Tsur et Zemel (1996) et Nævdal (2006) postulent que l'événement est en partie réversible. En effet, lorsque la pollution atteint le seuil inconnu, la survenance de la catastrophe réduit sensiblement le niveau d'utilité. Néanmoins, l'économie peut se remettre de son impact, même si cela nécessite des coûts considérables (par exemple liés à l'assainissement). Ayong Le Kama et al. (2014) considèrent la catastrophe écologique impliquant particulièrement une dégradation irréversible de la capacité de régénération de l'environnement. Dans cet article, l'incertitude entourant les seuils irréversibles a de fortes répercussions sur le contrôle optimal de la pollution, car elle induit généralement un comportement plus conservateur. Les catastrophes environnementales peuvent également se produire à plusieurs reprises. Tsur et Zemel (1998) considèrent le cas de catastrophes environnementales récurrentes et constatent que les événements réversibles peuvent induire plus de conservation (moins de pollution).

En plus du « *switch* » écologique irréversible, la transition énergétique englobe également le passage à l'énergie renouvelable suite à un long processus. En effet, les politiques énergétiques utilisent des scénarios qui mettent l'accent sur l'adoption de l'énergie renouvelable dans le but de changer radicalement la façon dont l'énergie est produite et de réduire les émissions de CO₂. Cela contribuera à réduire la survenance des catastrophes environnementales dont les conséquences sont désastreuses. La mise en œuvre des politiques de transition énergétique nécessite plusieurs approches qui diffèrent sensiblement d'un pays à un autre. Par exemple en Europe; l'Allemagne, le Royaume-Uni et la France ont pris les devants dans la mise en œuvre des politiques nationales pour faciliter la transition énergétique avec des objectifs ambitieux et politiques (CERRE, 2015). Toutefois, leurs stratégies sont différentes en raison de la différence qui existe entre leur mix énergétique (la grande partie du nucléaire pour la France et le charbon pour le Royaume Uni et l'Allemagne). En outre, la politique de transition énergétique allemande (i.e. Energiewende) est une référence pour les modèles de transition énergétique dans le monde entier en raison de leur stade avancé de pénétration de l'énergie renouvelable avec des niveaux élevés d'efficacité énergétique et de plusieurs tentatives de politiques très

efficaces ([World Energy Council, 2014](#)). La France a récemment adopté une loi sur la transition énergétique (Loi N° 2015-992 composée de 215 articles), qui est appelée « La transition énergétique pour la croissance verte ». Cette loi a été conçue pour diversifier le mix énergétique français et pour contribuer à la lutte mondiale contre le changement climatique. L'objectif est de réduire la consommation finale d'énergie de 50 % d'ici 2050 et la consommation finale d'énergie venant des combustibles fossiles de 30 % d'ici 2030 par rapport à 2012 et de porter la part des énergies renouvelables à 23 % de la consommation finale brute d'énergie. Chaque pays a aussi ses propres spécificités et a besoin de définir de façon optimale sa propre trajectoire de transition énergétique pour un passage structurel vers une économie à faible intensité de carbone.

Il existe également un ensemble diversifié de mécanismes politiques relatifs à la réglementation pour une transition vers les énergies renouvelables. Plusieurs instruments directs (notamment des incitations fiscales telles que les subventions et les aides à l'investissement, des mandats d'énergies renouvelables, l'accès flexible au réseau avec la facturation nette) et des instruments indirects (taxes environnementales pour sanctionner l'utilisation de combustibles fossiles) contribuent à rendre plus attrayante la production des énergies renouvelables. Les instruments de quantité (à savoir les normes de portefeuille d'énergie renouvelable et des crédits d'énergie renouvelable) et les instruments de prix (par exemple des tarifs garantis ou des enchères) donnent également des incitations pour accroître le déploiement des énergies renouvelables. En outre, différents types de tarif de rachat existent : fixe ou prime, constant ou décroissant au fil du temps, etc. Cependant, après que la trajectoire optimale de transition énergétique a été définie et assortie des réglementations appropriées, en absence de stratégies incitatives il n'est pas évident que la population se conforme à ces réglementations. Dans la section suivante, nous nous focaliserons sur le secteur résidentiel et nous décrirons les comportements des ménages à l'égard de l'adoption de l'énergie renouvelable et de l'investissement dans l'efficacité énergétique.

6.3 Comportements des ménages et transition énergétique

Le secteur résidentiel a un potentiel important pour réduire la demande globale d'énergie, car il en représente une part importante (23 %) (IEA, 2007) et il contribue à hauteur de 17 % aux émissions globales de CO₂ (IEA, 2015d). Les politiques de transition énergétique sont principalement motivées par des décisions politiques nécessitant l'acceptation du public pour leur mise en œuvre. Il est donc important de mieux comprendre les comportements des ménages en matière d'adoption d'énergie propre et d'investissement dans l'efficacité énergétique pour assurer une transition vers une économie verte. Bien que les deux questions soient examinées séparément dans la littérature économique en ce qui concerne le secteur résidentiel, l'économie peut bénéficier de synergies possibles entre les mesures d'efficacité énergétique et d'adoption d'énergie renouvelable. Dans les sections suivantes, nous présentons la revue de littérature sur la demande d'énergie renouvelable (Section 6.3.1) et sur l'investissement dans l'efficacité énergétique (Section 6.3.2). La Section 6.3.3 est consacrée à l'interrelation possible entre les énergies renouvelables et l'efficacité énergétique.

6.3.1 Energies renouvelables et comportements des ménages

La demande d'énergie verte a reçu beaucoup d'attention dans la littérature en raison de la forte contribution de l'énergie issue des combustibles fossiles aux émissions globales de CO₂, principalement responsable du réchauffement climatique. Dans le secteur résidentiel notamment, les études se focalisent essentiellement sur le comportement réel et hypothétique du consommateur pour expliquer la décision d'adoption d'une production d'énergie renouvelable. L'analyse du comportement hypothétique est basée sur des méthodes de préférences déclarées (notamment, l'évaluation contingente ou les choix expérimentaux) dans lesquelles la préférence et les valeurs monétaires pour les énergies renouvelables sont estimées sur un marché hypothétique des énergies renouvelables. Par exemple, la préférence pour les énergies renouvelables peut être estimée en évaluant le consentement du ménage à adopter une énergie renouvelable (Gerpott et Mahmudova, 2010; Ozaki, 2011; Zhai et Williams, 2012 et Sardianou

et Genoudi, 2013), alors que le Consentement A Payer (CAP) pour consommer de l'énergie renouvelable peut servir à estimer les valeurs monétaires associées aux énergies renouvelables (Ek et Söderholm, 2008 ; Zoric et Hrovatin, 2012 et Liu et al., 2013). L'estimation conjointe des préférences et des valeurs monétaires des énergies renouvelables peut également être faite à l'aide des méthodes de préférences déclarées. Le ménage déclare dans un premier temps sa préférence pour l'énergie renouvelable et donne dans un second temps le montant maximal qu'il est prêt à payer pour bénéficier de l'énergie renouvelable (Krishnamurthy et Kriström, 2016 et Shi et al., 2013). Nous tirons trois principaux enseignements de cette littérature empirique.

Primo, le consentement à adopter une énergie renouvelable peut être influencé par les caractéristiques des ménages mais aussi par la norme sociale. En ce qui concerne l'influence des attitudes environnementales du consommateur, Gerpott et Mahmudova (2010) et Ozaki (2011) trouvent des résultats opposés. Les premiers, en utilisant une analyse partielle des moindres carrés sur les données de l'Allemagne, démontrent que les attitudes environnementales ont une forte influence sur le consentement d'un consommateur à adopter une énergie renouvelable. Alors que Ozaki (2011) utilise l'analyse de corrélation pour montrer que les consommateurs pro-environnementaux ne consomment pas nécessairement l'électricité verte. Ceci peut s'expliquer par l'absence de normes sociales fortes et de pertinence personnelle affectant l'adoption des énergies renouvelables, ainsi que par les avantages et les coûts liés à l'énergie renouvelable. L'acceptation sociale est étudiée par Zhai et Williams (2012) qui trouvent qu'elle a une influence positive dans le cas particulier de l'énergie PhotoVoltaïque (PV). De plus, les incitations financières par le biais de l'impôt ou de subventions sont importantes pour promouvoir l'adoption de l'énergie propre. Dans le contexte Grec, Sardanou et Genoudi (2013) trouvent que la déduction fiscale est la mesure de politique financière la plus efficace pour promouvoir l'acceptation des énergies renouvelables par les consommateurs dans le secteur résidentiel.

Secundo, de nombreux travaux ont été réalisés sur le consentement à payer des ménages pour consommer de l'énergie renouvelable. Ek et Söderholm (2008) ont analysé les

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comportements des ménages relativement aux normes incitatives et aux motivations économiques sur le marché suédois de l'électricité verte. Ils montrent que les variables telles que le coût de l'adoption, la responsabilité personnelle, la perception des avantages liés à l'adoption et la norme sociale, sont les déterminants les plus importants du choix des ménages à payer une prime tarifaire pour l'électricité verte. Plus tard, Zoric et Hrovatin (2012) suggèrent que des campagnes de sensibilisation devraient suivre le marketing vert qui ciblerait les plus jeunes, les mieux éduqués et les ménages à revenu élevé. En outre, les ménages peuvent se comporter différemment dans leur évaluation monétaire des énergies renouvelables suivant qu'ils soient dans un pays développé ou dans un pays en développement. Dans le cas spécifique des pays en développement, Liu et al. (2013) ont exploré l'acceptation sociale des énergies renouvelables en milieu rural et constatent que ceux qui résident dans les zones rurales sont généralement favorables au développement d'électricité renouvelable en raison de ses effets positifs sur l'environnement.

Tertio, certaines études analysent simultanément la préférence et le consentement à payer pour les énergies renouvelables. Par exemple, Krishnamurthy et Kriström (2016) et Shi et al. (2013) se focalisent sur le consentement à accepter et le consentement à payer pour utiliser uniquement les énergies renouvelables et leurs disparités entre les pays de l'OCDE. Les premiers utilisent les données d'enquête EPIC-OCDE de 2011 alors que les derniers utilisent celle de 2007. Ainsi, Krishnamurthy et Kriström (2016) estiment un consentement à payer (CAP) faible qui correspond à 11-12 % de la facture d'électricité actuelle et trouvent un effet ambigu du revenu. De la même façon, Shi et al. (2013) constatent que les variables économiques sont moins importantes, alors que les préoccupations environnementales ou les attitudes poussent les ménages à décider d'entrer sur le marché hypothétique de l'électricité verte. Ils démontrent également que la participation à des organisations environnementales a des effets significatifs sur le CAP pour une utilisation exclusive des énergies renouvelables.

Cependant, la grande faiblesse de cette littérature basée sur l'approche hypothétique réside dans le fait qu'il est simplement demandé aux répondants d'exprimer leurs propres préférences. Cela peut conduire à un biais de surévaluation qui est par ailleurs

source de controverses majeures. Alternativement, l'approche du comportement réel est basée sur des enquêtes réelles et contrairement aux études sur le comportement hypothétique, elles sont peu nombreuses dans le domaine des énergies renouvelables. Pourtant, l'un des avantages de ce genre d'approche est qu'elle peut aider à explorer la façon dont les consommateurs réagissent réellement face aux différents mécanismes de financement pour l'électricité verte. Par exemple, Kotchen et Moore (2007) considèrent le Mécanisme de Contributions Volontaires (MCV) et le Mécanisme de Tarif Vert (MTV) pour financer une nouvelle capacité de production d'énergie propre. Ils démontrent que les deux mécanismes de financement ne sont pas équivalents lorsque la contrainte liée au niveau de la contribution est obligatoire. Arkesteijn et Oerlemans (2005) ont analysé les facteurs qui influencent l'adoption rapide de l'électricité verte par les utilisateurs résidentiels néerlandais en combinant l'approche cognitive et l'approche économique. Ils montrent qu'en plus des variables économiques, les variables qui sont liées à des facteurs cognitifs, des connaissances de base et à des comportements environnementaux réels passés, prédisent fortement la probabilité des ménages à adopter rapidement de l'électricité verte. Cependant, le fait que certaines études se concentrent uniquement sur les consommateurs verts ([Young et al., 2010](#)) constitue la principale limite des enquêtes réelles. Par conséquent, ces études peuvent souffrir de biais de sélection et les implications politiques peuvent ne pas être étendues aux consommateurs qui n'adoptent pas les comportements verts. En outre, les approches hypothétiques et réelles peuvent donner les mêmes résultats pour certaines variables clés. Par exemple, [Roe et al. \(2001\)](#) constatent que l'analyse hypothétique sur la base du CAP et de l'analyse hédonique des primes de prix réels facturés pour l'électricité verte, donnent des valeurs similaires pour les attributs environnementaux clés.

Les variables qui influencent la demande d'énergie verte dans le secteur résidentiel peuvent également influencer la décision du ménage à investir dans l'efficacité énergétique. Dans la section suivante, nous présenterons donc une revue de la littérature sur les facteurs qui influencent la décision du ménage à investir dans l'efficacité énergétique dans le secteur résidentiel.

6.3.2 Efficacité énergétique et comportements des ménages

Les investissements dans l'efficacité énergétique contribuent aussi à la lutte contre le changement climatique en réduisant la demande globale d'énergie. Dans un scénario de politiques de l'Agence Internationale de l'Énergie (AIE), 72 % de la baisse globale des émissions de CO₂ entre 2010 et 2020 proviendra des améliorations de l'efficacité énergétique (Knittel et al., 2014). En effet, l'efficacité énergétique est un moyen relativement moins cher permettant de réduire les émissions de gaz à effet de serre à court et moyen terme (Dietz et al., 2009 et Vandenberg et al., 2007), alors que dans le long terme une transition complète vers une économie sobre en carbone est susceptible d'être très lente (Fouquet, 2010). Ceci justifierait la place importante de l'influence des comportements des ménages sur l'investissement dans l'efficacité énergétique dans la littérature économique. Il est démontré que les facteurs économiques motivent l'efficacité énergétique (Howarth, 1997; Kempton et Neiman, 1986 et et Steg, 2008) et peuvent être utiles dans la conception de politiques fiscales ou de subventions appropriées dans le but de promouvoir les mesures d'économies d'énergie. Par exemple, le fait d'économiser de l'argent ou de réduire la facture énergétique peut être sources d'incitations à investir dans l'efficacité énergétique. Toutefois, le gain potentiel de réduction de la consommation d'énergie peut être entravé par des problèmes tels que la discordance des intérêts (entre propriétaires et locataires), l'incertitude sur le gain et le problème d'aléa moral qui peuvent empêcher les ménages d'adopter ou d'investir dans les mesures d'économie d'énergie.

La réduction de la consommation d'énergie peut aussi conduire à des effets inverses tels que l'effet rebond ou l'effet de reprise (Greening et al., 2000 et Urban et Šcasny, 2012). L'effet rebond peut être résolu en capturant des gains d'efficacité pour les réinvestir dans la réhabilitation du capital naturel (Wackernagel et Rees, 1997) ou en soutenant des actions environnementales à travers le don (Bindewald, 2013). Ainsi, Wackernagel et Rees (1997) suggèrent que les gains d'efficacité devraient être taxés ou retirés du circuit économique. Alternativement, l'effet rebond peut également être résolu à travers les motivations pro-environnementales (Urban et Šcasny, 2012). Néanmoins, il n'y a pas de certitude dans la littérature concernant l'influence de la motivation pro-environnementale

sur les mesures d'économie d'énergie au niveau des ménages. Dans les premiers travaux, la préoccupation environnementale n'a pas d'effet sur la consommation d'énergie et sur les actions d'économie d'énergie (Heslop et al., 1981). Cependant, il y a eu une préoccupation croissante au sujet du changement climatique au cours des dernières années (Capstick et al., 2015) et de nombreux travaux ont montré récemment des effets significatifs des préoccupations environnementales sur les mesures d'économie d'énergie (Barr et al., 2005 et Whitmarsh et O'Neill, 2010). Quelques rares travaux soutiennent encore l'effet limité (Carlsson-Kanyama et al., 2005 et Whillans et Dunn, 2015) ou l'absence d'effet (Steg, 2008) des motivations pro-environnementales. En outre, les préoccupations à la fois économiques et environnementales ont des effets différents lorsque les actions de conservation de l'énergie sont considérées séparément.

En effet, les deux principaux types d'action de conservation de l'énergie sont les investissements d'efficacité qui nécessitent des investissements monétaires et le changement de comportements qui fait référence à des investissements non-monétaires (Jansson et al., 2009). Les investissements monétaires en efficacité énergétique reposant sur des conditions externes (Urban et Šcasny, 2012) telles que les préoccupations économiques, sont moins affectées par des motivations internes (Guagnano et al., 1995) telles que les motivations pro-environnementales. Black et al. (1985) ont trouvé un effet inverse sur les investissements non-monétaires dans l'efficacité. En fin de compte, les préoccupations économiques et environnementales peuvent avoir toutes les deux, des effets ambigus sur les mesures d'économie d'énergie quand elles sont considérées comme le résultat des deux types d'investissement monétaire et non monétaire. En plus des facteurs socio-économiques et démographiques, Urban et Šcasny (2012) ont analysé dans un cadre multi-pays, la façon dont les préoccupations environnementales affectent l'adoption des investissements monétaires et non-monétaires dans l'efficacité énergétique en utilisant les données de l'enquête EPIC de l'OCDE. Ils trouvent un effet positif et significatif pour la motivation pro-environnementale et des effets mitigés pour les autres variables.

6.3.3 Interdépendance entre énergies renouvelables et efficacité énergétique

Les différentes variables qui influent sur la décision des ménages d'adopter l'énergie renouvelable peuvent aussi avoir des effets importants sur les investissements des ménages dans l'efficacité énergétique. Le fait que les recherches se focalisent essentiellement soit sur l'adoption de l'énergie renouvelable, soit sur les investissements dans l'efficacité énergétique peut expliquer les disparités constatées entre les effets des motivations économiques et ceux liés aux préoccupations environnementales. Dit autrement, si les deux décisions sont interdépendantes, elles ne peuvent pas être estimées de manière indépendante. Dans ce cas, les méthodes univariées qui estiment séparément les deux décisions d'adoption de l'énergie renouvelable et de l'investissement dans l'efficacité énergétique produisent des résultats potentiellement biaisés car il peut exister des caractéristiques non observées qui déterminent conjointement les deux décisions. Par exemple, un ménage qui est pro-environnemental peut juger nécessaire d'investir plus dans les énergies renouvelables (resp. dans l'efficacité énergétique) que si il a déjà investi dans l'efficacité énergétique (resp. dans les énergies renouvelables). Dans ce cas, le ménage peut se baser sur sa conscience environnementale pour combiner les deux types d'investissement. Par contre, le ménage qui investit déjà dans l'efficacité énergétique (resp. dans l'énergie renouvelable) peut avoir une capacité financière limitée à investir en plus dans les énergies renouvelables (resp. dans l'efficacité énergétique). Par conséquent, en analysant conjointement les deux décisions possibles: (i) l'adoption de l'énergie renouvelable et (ii) l'investissement dans l'efficacité énergétique, on peut capturer l'interrelation et l'interaction qui pourraient exister entre elles. Une telle investigation a un gain potentiel en termes d'implications politiques dans la mesure où l'adoption de l'énergie renouvelable et les investissements dans l'efficacité énergétique sont tous deux importants pour le marché mondial de l'énergie du futur (Sheffield, 1997) et dans la transition énergétique. À notre connaissance, une telle étude n'a pas encore été faite dans la littérature économique.

6.4 Réseaux intelligents et transition énergétique

Le fait que de nombreuses sources d'énergie renouvelable soient par nature intermittentes et imprévisibles rend leur intégration dans le réseau électrique difficile. Cependant, la transition énergétique conduirait à un changement significatif du réseau de l'électricité afin d'intégrer des énergies propres et renouvelables pour la production d'électricité. Il faudrait alors une nouvelle approche pour gérer efficacement le réseau électrique en tirant pleinement profit des technologies relatives aux réseaux intelligents. Il existe plusieurs définitions du réseau intelligent encore appelé « *smart-grid* ». Selon l'[IEA \(2011\)](#), « *un réseau intelligent est un réseau électrique qui utilise des technologies numériques et d'autres technologies de pointe pour contrôler et gérer le transport de l'électricité à partir de toutes les sources de production afin de répondre aux besoins variables des utilisateurs finaux en électricité* ». Comme décrit dans la figure [6.5](#), le système d'électricité devrait alors se mettre à jour et s'adapter aux nouvelles technologies révolutionnaires pour devenir plus intelligent. Une autre définition de smart-grid vient de l'[European Technology Platform \(2006\)](#) qui a développé le concept de smart-grid en 2006: « *un réseau intelligent est un réseau d'électricité qui peut intelligemment intégrer les actions de tous les utilisateurs connectés (générateurs, consommateurs et ceux qui font les deux) afin de fournir efficacement l'approvisionnement en électricité durable, économique et sûre* ». L'idée principale des réseaux intelligents est donc l'utilisation des technologies de l'information de pointe pour optimiser la production d'électricité, sa distribution et sa consommation. Cela peut contribuer à réduire les émissions globales de CO₂ et peut être mis en place par le biais de la gestion de la demande, les compteurs intelligents, l'efficacité énergétique, l'intégration de l'énergie intermittente renouvelable, le stockage d'énergie, les micro-réseaux électriques, etc. Par exemple, l'[IEA \(2010\)](#) a estimé à travers le scénario « *Energy technology perspectives (ETP) BLUE Map* » que les réseaux intelligents offrent la possibilité de réaliser des réductions d'émissions annuelles nettes de 0,7 à 2,1 Gt de CO₂ d'ici à 2050, y compris les réductions directes et indirectes d'émissions. Dans cette section, nous nous concentrons sur trois niveaux de « *smart-grid* » : (1) la possibilité d'alimenter le réseau d'électricité, (2) les compteurs intelligents et (3) le stockage d'énergie.

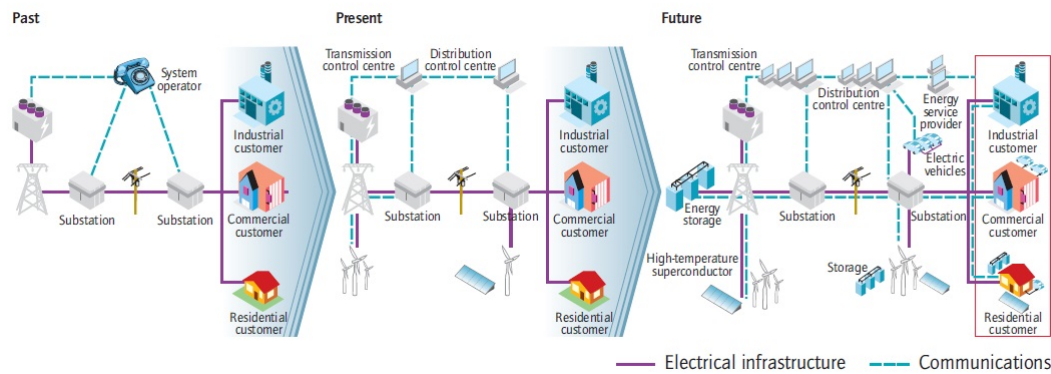


Figure 6.5: *Systèmes électriques intelligents*

Source: IEA, 2011

6.4.1 Alimenter le réseau électrique

Une faible pénétration des énergies renouvelables dans le réseau électrique ne nécessite pas de mettre à niveau les systèmes d'énergie avec des technologies plus intelligentes. Même si l'électricité produite à partir des éoliennes et de l'énergie solaire photovoltaïque est intermittente, il est généralement facile de gérer les fluctuations lorsque leur contribution à la production totale d'électricité est faible. La vente de l'électricité au réseau peut simplement être obtenue par le système de facturation nette (encore appelé le « *net metering* ») du moment où cela n'est pas en conflit avec la législation du pays. Notons que ce système de facturation est autorisé dans l'Union européenne et aux États-Unis, tandis que Hong Kong et certains pays africains ne le pratiquent pas. Lorsque l'éolienne et l'énergie solaire photovoltaïque fournissent une électricité nettement plus importante, le maintien de la fiabilité et de la sécurité des systèmes électriques devient plus difficile et peut provoquer une congestion du réseau. Dans ce cas, en donnant la possibilité aux ménages d'alimenter le réseau électrique avec leur production d'électricité excédentaire peut nécessiter une infrastructure supplémentaire. Bien que dans certains pays (au Royaume-Uni ou en Allemagne par exemple) il est déjà possible pour le ménage de fournir de l'électricité renouvelable au réseau, cela peut ne pas se généraliser.

La littérature sur la pénétration des énergies renouvelables dans le mix énergétique contient deux branches distinctes. D'une part, les modèles macro-dynamiques à

la Hotelling considèrent l'énergie renouvelable comme un flux abondant, régulier et disponible avec certitude. Ils ignorent la variabilité et le problème d'intermittence et se concentrent sur la question des coûts (voir par exemple Hoel et Kverndokk, 1996 ou [Tahvonen, 1997](#)). D'autres recherches étudient la conception du mix électrique (les combustibles fossiles et les énergies renouvelables) lorsque l'intermittence est prise en compte (voir Ambec et Crampes, 2012, 2015) ou lorsque le stockage permet de gérer les demandes d'électricité pendant les périodes de pointe (voir Crampes et Moreaux, 2010) ou de l'excès de production nucléaire pendant les périodes de faible demande ([Jackson, 1973](#)). Dans leur revue de la littérature sur l'économie de l'énergie solaire électrique, [Baker et al. \(2013\)](#) soulignent l'absence d'analyse économique visant l'approvisionnement décentralisé de l'énergie propre par le biais de sources renouvelables. Cependant, les réseaux intelligents et la gestion de la demande d'électricité ont récemment reçu une attention notable que ce soit dans les travaux scientifiques (voir De Castro et Dutra, 2013 ou Hall et Foxon, 2014 et [Bigerna et al., 2016](#)) ou dans les médias (voir [The Economist, 2009](#) ou [The Telegraph, 2015a](#) et [The Telegraph, 2015b](#)). Plus particulièrement, De Castro et Dutra (2013) montrent que les caractéristiques de « biens publics » liées à la fiabilité du réseau électrique sont susceptibles de conduire à un niveau insuffisant de déploiement de réseaux intelligents.

6.4.2 Compteur intelligent

Le compteur intelligent fait partie des technologies liées au réseau intelligent et permet une communication bidirectionnelle entre l'opérateur et le consommateur. Les systèmes électriques sans compteurs intelligents manquent de transparence pour les consommateurs du côté de la distribution. De façon plus précise, la plupart des ménages ne savent pas combien d'électricité ils utilisent avant la réception de leur facture d'électricité. Ils ne savent pas non plus quelle proportion de leur électricité est produite à partir du nucléaire, du charbon, du gaz ou de l'énergie renouvelable et les émissions de CO₂ afférentes. Les compteurs intelligents peuvent alors permettre la tarification en temps réel et la fourniture directe aux appareils intelligents des signaux sur le prix de l'électricité. De ce fait, les consommateurs deviennent plus réactifs aux prix d'électricité en périodes de pointe. Ils peuvent donc prendre de meilleures décisions. Par exemple, il peut permettre

aux consommateurs d'utiliser l'électricité seulement quand il est disponible à partir de sources d'énergie renouvelables en favorisant une forte intégration de l'électricité renouvelable.

Les compteurs intelligents sont largement utilisés en Europe (par exemple, Linky en France). Cependant, Borenstein et Holland (2005) montrent que l'expansion de la tarification en temps réel (RTP) est susceptible de nuire à des clients qui sont déjà sur ce type de tarification tout en profitant aux clients qui restent sur la tarification forfaitaire. Ils démontrent également que des changements progressifs dans l'utilisation de la tarification RTP ont un impact sur l'efficacité du marché qui n'est pas capturé par les ménages qui changent à la tarification RTP. Une externalité qui implique que l'incitation à passer à la RTP ne sera pas en général optimale. Cela suggère que la généralisation des compteurs intelligents peut ne pas être bénéfique pour le ménage. Ceci nécessiterait donc des investigations approfondies sur l'optimalité sociale des compteurs intelligents. En outre, le déploiement de compteurs intelligents peut contribuer à augmenter la substitution entre l'électricité produite ou consommée à des périodes différentes. En ce sens, les ménages peuvent avoir des incitations à consommer ou stocker l'électricité quand celle-ci est moins chère à produire.

6.4.3 Stockage d'énergie

Les systèmes de stockage d'énergie peuvent atténuer le problème de fiabilité relative aux sources intermittentes d'électricité renouvelable en découplant la production et la fourniture d'électricité. Il y a eu un intérêt croissant pour le stockage d'énergie électrique qui est la plupart du temps dominé par le système de stockage hydroélectrique. La capacité globale de stockage d'énergie à grande échelle est d'environ 145 GW, essentiellement de l'hydroélectricité par pompage (97 %) (IEA, 2015c). La problématique de stockage par hydroélectricité est traditionnellement une préoccupation des ingénieurs qui ont produit de nombreux travaux dans des revues techniques sur le sujet, alors que les économistes n'ont pas montré un grand intérêt pour ce sujet (Forsund, 2015). Crampes et Moreaux (2010) fournissent un cadre simple pour évaluer l'efficacité et la répartition optimale du stockage par pompage hydroélectrique. Ils suggèrent que ce système de

stockage ne devrait pas être guidé par le gain de l'électricité produite à partir de sources thermiques ou par l'économie faite sur le coût de l'électricité aux heures de pointe. Dans ce sens, la motivation économique principale est le gain social net obtenu en transférant le surplus social des heures de faible affluence aux heures de forte affluence.

En plus du système de stockage par pompage hydroélectrique, il existe d'autres systèmes de stockage d'énergie qui sont utilisés dans le monde entier. Dans une revue de littérature, [Beaudin et al. \(2010\)](#) indiquent que le défi que représente la question de l'intermittence exige un ensemble de divers systèmes de stockage d'énergie électrique. Ils distinguent les différentes technologies de stockage qui sont: pompage hydraulique, air comprimé, batteries, supraconducteur magnétique, hydrogène, volants d'inertie, condensateurs et super-condensateurs, etc. Dans une revue de littérature récente orientée sur la technologie et se focalisant sur le rôle du stockage de l'énergie dans la transition énergétique, [Gallo et al. \(2016\)](#) ont également constaté qu'il n'y a pas de technologie de stockage d'énergie qui excelle simultanément pour toutes les caractéristiques techniques. Bien que les technologies de stockage d'énergie électrique offrent de nombreux avantages en ce qui concerne la gestion du réseau électrique en présence des énergies renouvelables intermittentes, elles ne peuvent pas se généraliser aussi rapidement que les compteurs intelligents parce qu'elles sont plus chères.

Dans la section suivante, nous présenterons l'organisation générale de la thèse en incluant les différents chapitres, les principaux résultats ainsi que les recommandations politiques.

6.5 Organisation de la thèse

La transition vers les énergies renouvelables implique deux types de préoccupations environnementales. Tout d'abord, les combustibles fossiles sont épuisables et, deuxièmement, leur utilisation génère des externalités négatives à travers des dommages irréversibles sur l'environnement. Il devient alors crucial non seulement de décarboniser les systèmes de production électrique, mais aussi de trouver des stratégies d'économie d'énergie afin de réduire les émissions globales de carbone. En outre, il existe des

possibilités de synergies entre les mesures d'efficacité énergétique et d'adoption de l'énergie renouvelable dans le sens où les premières réduisent la demande d'énergie de sorte que les dernières puissent commencer à réduire les émissions futures de GES. Le principal objectif de cette thèse est d'analyser la transition énergétique optimale sous la contrainte d'une survenance potentielle d'une catastrophe environnementale et de déterminer des stratégies incitatives qui peuvent stimuler la transition énergétique. Cette thèse se compose de quatre chapitres qui indépendamment présentent et discutent les différentes questions relatives à la transition énergétique. Le premier chapitre met l'accent sur la transition énergétique optimale impliquant des décisions à la fois sur l'adoption de l'énergie renouvelable et de l'investissement dans les technologies d'économie d'énergie. Il intègre un seuil déterministe de pollution qui déclenche l'apparition d'une catastrophe environnementale. Le deuxième chapitre étudie la transition optimale vers les énergies renouvelables lorsque l'occurrence de la catastrophe environnementale est incertaine. Le troisième chapitre est consacré à la compréhension du comportement des ménages vis à vis de la transition énergétique. Le quatrième chapitre examine le rôle des réseaux intelligents dans l'intégration de l'énergie renouvelable intermittente afin de faciliter la transition énergétique.

Les deux premiers chapitres de la thèse se focalisent sur la transition énergétique optimale d'une économie à deux secteurs (énergie et produit final) avec des réserves pétrolières épuisables, une source d'énergie renouvelable et une menace de pollution. Dans le premier chapitre, la menace de pollution correspond à un seuil certain de pollution au-dessus duquel une catastrophe environnementale irréversible se produit entraînant la perte d'une partie du capital. La transition énergétique est guidée tant par la décision d'adopter des sources d'énergie plus propres que par l'effet du seuil de pollution. Ce chapitre propose une analyse générale des problèmes de « *switch* » optimal liés à la transition énergétique intégrant : (1) la possibilité d'une catastrophe due à l'accumulation de la pollution; et (2) des régimes technologiques incluant l'adoption de l'énergie renouvelable. Pour ce faire, premièrement nous supposons non seulement que l'économie a besoin de capitaux pour produire de l'énergie propre qui peut être utilisée comme matières premières pour produire du bien final, mais aussi qu'il existe

une complémentarité entre le capital et l'énergie ainsi qu'entre l'énergie propre et l'énergie polluante. Deuxièmement, étant donné les valeurs de base des paramètres, nous montrons numériquement que la trajectoire de transition énergétique la plus rentable peut correspondre à celle où l'économie commence à utiliser les deux types de ressources énergétiques, puis franchit le seuil critique de pollution en perdant une partie de son capital et enfin n'adopte jamais uniquement l'énergie propre. Ce résultat est conforme aux arguments en faveur de l'idée selon laquelle une transition complète vers une économie sobre en carbone est susceptible d'être très lente. Sans les innovations dans le secteur de l'énergie tels que les investissements dans l'efficacité énergétique, et étant donné la nécessité des combustibles fossiles pour produire de l'énergie propre, il est plus rentable de réduire progressivement la dépendance aux combustibles fossiles peu coûteux, que d'utiliser exclusivement de l'énergie propre qui est onéreuse. Troisièmement, nous avons étendu notre modèle pour intégrer l'adoption de technologies d'économie d'énergie, ce qui est très peu étudié dans la littérature économique. Les résultats numériques montrent principalement que cet investissement supplémentaire favorise la transition complète vers l'utilisation unique des énergies renouvelables dans le sens où il reporte la survenance de la catastrophe environnementale, il améliore le bien-être social et il permet une transition énergétique complète. Il est alors avantageux de tirer profit de ces synergies en promouvant conjointement le déploiement de l'énergie propre et des incitations à l'investissement dans les technologies d'économie d'énergie

Le deuxième chapitre considère que les seuils de pollution au-dessus desquels les catastrophes environnementales pourraient se produire sont incertains. La catastrophe environnementale correspond aux fortes inondations générées par le changement climatique après lesquelles (i) la quantité de capital et de ressources sauvée est connue *ex-ante* et (ii) il y a une perte directe d'utilité. Tout d'abord, ce chapitre analyse la transition énergétique optimale comme des problèmes de « *switch* » optimal impliquant deux changements de régimes, l'un d'entre eux étant incertain. De ce fait, nous généralisons le modèle sans incertitude du premier chapitre. Ceci peut être considéré comme une première tentative d'une représentation analytique de la transition énergétique sous la contrainte de risque écologique. Ce nouvel outil de contrôle optimal

est ensuite appliqué pour résoudre le problème de la transition énergétique optimale sous la contrainte de survenance incertaine d'une catastrophe écologique. A cet effet, nous considérons le même modèle à deux secteurs, où l'économie produit de l'énergie et un bien final. L'énergie provient initialement du pétrole et de sources d'énergies renouvelables, et peut éventuellement être produite en utilisant seulement les sources d'énergies renouvelables si les combustibles fossiles sont épuisés. L'utilisation de pétrole à la fois par le secteur de bien final et les ménages a un impact potentiel négatif sur l'environnement à travers un seuil de pollution critique stochastique au-dessus duquel un événement catastrophique se produit. Cet événement résulte en une perte d'utilité pour les ménages et la destruction d'une partie des réserves de capital et de combustibles fossiles (les quantités récupérées étant connues *ex-ante*). Nous résolvons analytiquement le modèle pour les solutions d'équilibre relatives à l'état stationnaire en utilisant la méthode de résolution « *backward* ». Ensuite, la probabilité de survenance de la catastrophe et le temps optimal pour que l'économie n'utilise que les énergies renouvelables sont obtenus numériquement. Nous démontrons qu'il existe des valeurs numériques qui correspondent à un niveau plus élevé de pollution à l'état stationnaire que celui du seuil : la catastrophe environnementale pourrait arriver. Nous montrons aussi des situations dans lesquelles la trajectoire optimale de la transition énergétique correspond à trois phases, commençant par l'utilisation des deux types de sources d'énergie, suivie par la catastrophe, et enfin par l'utilisation unique de l'énergie renouvelable. Enfin, les taux de risque plus élevés génèrent des comportements plus prudents et affectent négativement la pollution, néanmoins le risque de dommages est toujours à la hausse.

Suite aux suggestions du premier chapitre relatives à l'importance des technologies d'économie d'énergie dans la transition complète vers les énergies renouvelables, le troisième chapitre étudie au niveau des ménages, les décisions liées à l'adoption de l'énergie renouvelable et à l'investissement dans l'efficacité énergétique. Il existe des synergies possibles entre les mesures d'efficacité énergétique et l'adoption d'énergie renouvelable. Les premières réduisent la demande d'énergie de sorte que la dernière puisse réduire davantage les émissions futures de GES avec un fort potentiel dans le secteur résidentiel. Plus précisément, ce chapitre explore l'influence des comportements

des ménages sur la transition énergétique par l'adoption de l'énergie renouvelable et l'investissement dans l'efficacité énergétique. Dans le secteur résidentiel, de nombreux travaux ont été réalisés sur la demande d'énergie propre et sur l'investissement dans l'efficacité énergétique. Toutefois, à notre connaissance il n'y a aucune étude spécifique qui étudie l'interaction entre les deux décisions. Ce chapitre comble cette lacune dans la littérature et montre théoriquement dans un premier temps, qu'il existe des interactions (complémentarité ou substitution) entre les deux décisions en fonction d'un seuil relatif à l'effet croisé lié à la motivation environnementale du consommateur. Nous utilisons un modèle simple dans lequel un ménage consacre son budget énergétique à acheter de l'énergie non-propre et à entreprendre des investissements dans l'efficacité énergétique et dans les énergies renouvelables contribuant ainsi à une transition vers une économie sobre en carbone. Dans un second temps, le modèle théorique est suivi par une analyse empirique des interactions entre les deux décisions. Nous explorons si les décisions des ménages à adopter des énergies renouvelables et à investir dans l'efficacité énergétique dans le secteur résidentiel sont liées. Nous utilisons un modèle probit bivarié (biprobit) pour la décision conjointe et nous montrons que les deux décisions sont positivement liées entre elles et ne peuvent être estimées de manière indépendante. De plus, nous étudions les déterminants de l'interaction entre les deux décisions en utilisant le modèle logit ordonné généralisé. L'objectif ici est d'expliquer pourquoi certains ménages décident d'investir à la fois dans l'efficacité énergétique et dans les énergies renouvelables, tandis que d'autres décident d'investir seulement dans les énergies renouvelables ou seulement investir dans l'efficacité énergétique ou de ne rien faire. Le ménage qui adopte uniquement les énergies renouvelables ou qui réduit seulement sa consommation d'énergie, contribue plus à la transition énergétique que le ménage qui n'entreprend aucune action et moins que celui qui entreprend les deux actions. Cette contribution peut servir à définir des politiques incitatives pour stimuler la transition énergétique en prenant en compte les problématiques liées à la pauvreté énergétique, la discordance des intérêts entre le propriétaire et le locataire, les motivations économiques et environnementales, etc. Pour les deux investigations empiriques, nous utilisons les enquêtes sur la politique environnementale et le changement individuel de comportement (EPIC) de l'Organisation de Coopération et de Développement Économiques (OCDE).

Une transition vers l'énergie renouvelable qui dépend des ressources intermittentes générerait un autre défi: la fiabilité et la sécurité des systèmes de production d'énergie. Les technologies liées aux réseaux intelligents offrent de nombreuses solutions pour faire face à ce nouveau défi et pour aider à promouvoir l'intégration des énergies renouvelables dans le réseau d'électricité. Ainsi, dans le quatrième chapitre de la thèse, nous étudions la combinaison efficiente des investissements dans l'énergie intermittente renouvelable (i.e. panneaux solaires) et dans le stockage d'énergie, et évaluons les conséquences de la gestion de la demande en tenant compte de trois niveaux d'équipements du réseau intelligent à savoir : (i) facturation nette ou « *net metering* », (ii) les compteurs intelligents et (iii) le stockage d'énergie. La nouveauté dans notre modèle concerne la flexibilité qu'il attribue au ménage en lui donnant la possibilité de fournir (resp. acheter) de l'électricité au réseau ou de stocker de l'énergie (ou utiliser l'énergie stockée) en plus des installations de production d'énergie renouvelable. De plus, nous analysons les conséquences de stockage d'énergie et d'adoption des compteurs intelligents sur les quantités achetées d'électricité provenant du réseau et sur la consommation d'électricité, l'opportunité d'installer les compteurs intelligents et les conséquences des mesures de restriction pour éviter la congestion du réseau. Notre premier résultat indique qu'il est avantageux d'installer un compteur intelligent permettant au ménage de bénéficier des variations de prix de l'électricité lorsque le prix espéré de l'électricité est suffisamment faible ou élevé. Notre deuxième résultat est que l'objectif de la faible utilisation du réseau grâce à l'installation d'un compteur intelligent ne peut être atteint que si le prix espéré de l'électricité est suffisamment élevé. Dans le cas contraire, la dépendance vis-à-vis du réseau serait plus importante conduisant à plus d'émissions. Ce résultat indique que le niveau du prix de l'électricité doit être soigneusement analysé si le but est de moins dépendre du réseau électrique à travers le déploiement de réseaux intelligents. En outre, on considère le problème de la congestion qui peut survenir lorsqu'il y a trop de ménages qui alimentent le réseau. Notre analyse démontre que les mesures de restriction pour éviter la congestion peuvent décourager les investissements dans les capacités de production d'énergie renouvelable et de stockage d'énergie. Lorsque ces investissements sont découragés, nous montrons que l'électricité produite et introduite dans le réseau par le ménage est réduite à l'extrémité supérieure de la grille de prix. De plus, le ménage n'achète nécessairement pas plus d'électricité venant du réseau.

Plusieurs implications politiques peuvent être tirées des résultats qui ont été suggérés par les quatre chapitres de cette thèse. Le premier chapitre a montré que sans investissement supplémentaire dans les technologies d'économie d'énergie et en raison de la nécessité des combustibles fossiles dans la production d'énergie propre, il est plus rentable de réduire progressivement la dépendance aux combustibles fossiles relativement pas coûteux, que de passer à l'usage exclusif d'énergie propre coûteuse. Les politiques publiques devraient alors favoriser l'innovation qui contribue à augmenter la productivité du capital et du service énergétique dans les secteurs productifs tout en économisant de l'argent et de l'énergie. Comme l'investissement dans les technologies d'économie d'énergie peuvent encourager la transition complète vers les énergies renouvelables, il est donc souhaitable que les politiques publiques cherchent à tirer profit des synergies qui peuvent découler d'un mécanisme conjoint de promotion de l'énergie propre et des incitations à l'investissement dans ces technologies d'économie d'énergie.

Le deuxième chapitre a démontré que l'incertitude joue un rôle important dans la transition énergétique dans la mesure où elle induit un comportement de précaution. Cela amène à penser que lorsque les agents économiques craignent les conséquences négatives du changement climatique dont la survenance est incertaine, ils sont plus favorables à la transition énergétique.

Le troisième chapitre a étudié l'interrelation entre les décisions des ménages à adopter des énergies renouvelables et à investir dans l'efficacité énergétique, et a révélé que leur interrelation est positive. Il faudrait alors considérer les deux décisions lors de la conception des instruments d'incitation pour l'adoption de l'énergie renouvelable et pour les investissements d'efficacité énergétique. Les politiques qui reposent sur des facteurs qui affectent conjointement les deux décisions pourraient bénéficier des synergies qui peuvent exister entre elles. Par exemple, la promotion d'une maison à consommation énergétique nette zéro en investissant aussi bien dans les mesures d'efficacité énergétique que dans les énergies renouvelables, faciliterait davantage l'utilisation unique de sources renouvelables d'énergie dans les bâtiments. La demande d'énergie est ainsi réduite

en raison de gains d'efficacité afin que les besoins énergétiques restants puissent être satisfaits au moyen d'énergies renouvelables.

Certaines problématiques énergétiques ont été traitées dans le troisième essai : (i) la discordance des intérêts ou « *split-incentive* » entre le propriétaire et le locataire, (ii) la pauvreté énergétique et (iii) les facteurs de motivation. Pour résoudre ces problèmes, les politiques suivantes pourraient être envisagées. Premièrement, la réglementation des marchés du logement pourrait aider à résoudre les problèmes de discordance des intérêts entre le propriétaire et le locataire afin de donner des incitations aux locataires d'entreprendre des investissements aussi bien dans l'efficacité énergétique que dans les énergies renouvelables. Des supports financiers permettant de réduire les coûts de démontage et de ré-installation d'équipements d'énergie renouvelable pourraient aussi donner des incitations aux locataires d'entreprendre ces investissements.

Deuxièmement, les politiques ciblant les investissements dans l'efficacité énergétique devraient être améliorées. Dans de nombreux pays, les soutiens financiers aux mesures d'économie d'énergie sont surtout rentables pour les ménages plus aisés. Comme le ménage doit d'abord investir avant de demander le remboursement et étant donné que les ménages les plus pauvres sont financièrement limités, ces investissements ne sont pas abordables pour eux. Par conséquent, il serait nécessaire de mettre en place des subventions vertes qui devraient être des éco-prêts sans intérêt ciblant uniquement les ménages énergiquement pauvres.

Troisièmement, il pourrait être d'un grand intérêt de profiter des organisations caritatives locales et environnementales existantes pour communiquer avec leurs membres sur l'importance de la transition énergétique. Ces membres ont une grande prédisposition à mieux comprendre la contribution cruciale de la transition énergétique dans la protection de l'environnement. En outre, les scientifiques et les autorités nationales ou locales sont les plus appropriés pour communiquer sur la transition énergétique. Par conséquent, ils devraient être plus impliqués dans la sensibilisation et les résultats académiques devraient être aussi plus vulgarisés.

Enfin, nos résultats sur les réseaux intelligents pourraient servir de base à la conception de politiques environnementales telles que les subventions à l'endroit des micro-réseaux (ou « *micro-grid* ») ou des réseaux intelligents. Ils indiquent que la conception du système de tarification dynamique devrait être telle que le prix espéré de l'électricité soit suffisamment élevé pour induire moins de dépendance sur le réseau électrique par l'utilisation de compteurs intelligents conduisant à moins d'émissions. Ils suggèrent également que les mesures de restrictions sur l'alimentation du réseau pourraient être utilisées pour traiter le problème de congestion du réseau comme une alternative à l'approche de gestion des prix.

Cette thèse n'est pas sans limites. Dans les deux premiers essais, nous avons pu donner une vue générale de la transition énergétique avec le risque de dommages climatiques, sous contrainte du caractère épuisable des ressources non renouvelables et en tenant compte des problèmes de « *switch* » optimal. Néanmoins, cela a nécessité d'autres hypothèses strictes telles que la complémentarité entre les sources d'énergie propre et polluante dans la consommation intermédiaire et finale. Cette hypothèse ne nous a pas permis de mettre l'accent sur la transition énergétique en tant que processus de substitution progressive de l'énergie propre à l'énergie polluante. Une alternative consisterait à incorporer des phases intermédiaires de substitution progressive entre les sources d'énergie suivant la phase de complémentarité entre l'énergie propre et l'énergie polluante. Cela pourrait changer la trajectoire optimale de transition énergétique et donc nécessiterait une recherche approfondie. En outre, il existe de nombreux facteurs qui n'ont pas été pris en compte dans l'étude de l'influence du comportement des ménages sur la transition énergétique. Par exemple, le fait de vivre dans un appartement sans balcon ou de disposer d'un espace limité sur le toit, etc., peuvent limiter la possibilité du ménage à installer des équipements d'énergie renouvelable. Aussi les variables liées aux caractéristiques de la résidence, tels que l'âge de l'habitation ou le type d'isolation pourraient influencer la décision du ménage à investir dans l'efficacité énergétique. Malheureusement, ces variables ne sont pas renseignées dans l'enquête EPIC-OCDE que nous avons utilisée et ceci nécessiterait des recherches plus approfondies avec de nouvelles bases de données. En ce qui concerne

l'étude sur les réseaux intelligents, nous pourrions évaluer la pertinence des smart-grids dans le cas où il existe un risque de coupure d'électricité comme rencontré tant dans les pays développés comme les Etats-Unis que dans les pays en développement comme l'Inde. En outre, nous pourrions explorer des cas dans lesquels les panneaux solaires et les technologies de stockage d'énergie sont tellement chers que leurs investissements sont bénéfiques uniquement si ils sont complétés par d'autres technologies supplémentaires liées aux réseaux intelligents.

La thèse est organisée comme suit.

Chapitre 1 : La transition énergétique sous la contrainte d'irréversibilité: une approche à deux secteurs

Chapitre 2 : La transition énergétique sous la contrainte du risque d'une catastrophe environnementale: une approche à deux secteurs

Chapitre 3 : L'investissement dans l'efficacité énergétique, l'adoption de l'énergie renouvelable et le comportement des ménages : cas des pays de l'OCDE

Chapitre 4 : Production d'électricité renouvelable intermittente avec les réseaux intelligents

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Abstract: The transition to renewable energy involves two kinds of environmental concerns. First, fossil fuels are exhaustible and second, their use generates negative externalities through irreversible environmental damage. Furthermore, there are possible synergies between energy efficiency measures and renewable energy adoption in the sense that the former reduces the energy demand so that the latter can begin to cut future greenhouse gases emissions. The main objective of this dissertation is to analyze the optimal energy transition under certain and uncertain occurrence of environmental catastrophe and to determine incentive-based instruments at the household level in order to boost the energy transition. The dissertation consists of four chapters that independently present and discuss different issues of energy transition. The first chapter focuses on the optimal energy transition involving decisions about both renewable energy adoption and investment in energy saving technologies, when there is a certain pollution threshold that triggers the occurrence of environmental catastrophe. The second chapter investigates the optimal transition to renewable energy under uncertain occurrence of environmental catastrophe. The third chapter is devoted to understanding household behavior regarding energy transition. The fourth chapter explores the role of smart-grids in integrating intermittent renewable energy to facilitate the energy transition.

Keywords : Renewable energy; uncertainty; irreversibility; energy efficiency; household behaviours; smart grids.

Résumé : La transition vers les énergies renouvelables implique deux types de préoccupations environnementales. Les combustibles fossiles sont épuisables et leur utilisation génère des externalités négatives à travers des dommages environnementaux irréversibles. En outre, il existe des possibilités de synergies entre les mesures d'efficacité énergétique et l'adoption de l'énergie renouvelable dans la mesure où les premières réduisent la demande d'énergie de sorte que la dernière puisse commencer à réduire les émissions futures de gaz à effet de serre. L'objectif principal de cette thèse est d'analyser la transition énergétique optimale dans un contexte de survenance certaine et incertaine d'une catastrophe environnementale et de déterminer les instruments incitatifs au niveau des ménages en vue de stimuler la transition énergétique. La thèse est composée de quatre chapitres qui traitent indépendamment des différentes questions de la transition énergétique. Le premier chapitre met l'accent sur la transition énergétique optimale impliquant des décisions à la fois sur l'adoption de l'énergie renouvelable et de l'investissement dans les technologies d'économie d'énergie, quand il y a un seuil de pollution certain qui déclenche une catastrophe environnementale. Le deuxième chapitre étudie la transition optimale vers les énergies renouvelables quand la survenance de la catastrophe environnementale est incertaine. Le troisième chapitre cherche à comprendre le comportement des ménages par rapport à leurs décisions d'adopter simultanément les énergies renouvelables et à investir dans l'efficacité énergétique. Finalement, le quatrième chapitre examine le rôle des réseaux intelligents dans l'intégration de l'énergie renouvelable intermittente afin de faciliter la transition énergétique.

Mots clés : Energie renouvelable ; incertitude ; irréversibilité ; efficacité énergétique ; comportements des ménages ; Smart grids.

