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par **Fadoua CHIBA**

## **ENERGY TRANSITION: DIFFICULTIES, IMPLICATIONS AND SOLUTIONS**

sous la direction de **Monsieur le Professeur Sébastien ROUILLON**,  
Professeur d'économie à l'Université de Bordeaux

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# Résumé en Français

En Europe, il existe un consensus fort sur la réalité du changement climatique et l'urgence de l'atténuer. Le secteur de l'électricité est l'un des secteurs les plus polluants en raison de l'utilisation de combustibles fossiles, qui entraîne des émissions de gaz à effet de serre, faisant de la production d'électricité l'une des principales causes du réchauffement de la planète.

Dans ce contexte, l'Union européenne a montré la voie de la transition vers un système énergétique sûr, durable et compétitif. Ces efforts sont illustrés par de nombreuses mesures, telles que le paquet «Énergie et climat» pour 2020 et 2030 et le paquet «Énergie propre pour tous les Européens», adopté le 30 novembre 2016. Ainsi, en 2008, l'Union européenne a adopté sa feuille de route pour la transition énergétique, fixant des objectifs pour 2020, consistant à réduire de 20% les émissions de CO<sub>2</sub>, à augmenter de 20% la part des énergies renouvelables et à améliorer de 20% l'efficacité énergétique.

Dans le cadre de cette thèse, nous nous intéressons principalement à la pénétration des énergies renouvelables sur le marché de l'électricité. Ainsi, à l'aide de modèles théoriques, nous analysons les différents obstacles au développement du secteur des énergies renouvelables et quelques mesures prises pour favoriser leur expansion.

L'augmentation de la part des énergies renouvelables dans le mix énergétique a suscité une vaste littérature. Notre premier chapitre en présente une revue, en mettant en évidence les différentes méthodes utilisées et les hypothèses adoptées.

Cela nous permet de détecter les extensions possibles de la littérature, en termes de problèmes traités et de méthodologies adoptées. De plus, ce premier chapitre nous aide à positionner cette thèse par rapport aux travaux existants et permet de répondre à certaines questions négligées en utilisant des méthodes innovantes.

L'introduction de sources d'énergies renouvelables dans le mix énergétique constitue un défi pour les marchés électriques. En effet, la production d'électricité à partir de sources d'énergies renouvelables dépend des conditions climatiques. Outre les problèmes classiques de transport et de distribution d'électricité, les sources d'énergies intermittentes posent également des problèmes supplémentaires au stade de la production. Dans notre analyse de l'interaction entre les générateurs

conventionnels et intermittents, nous modélisons cette incertitude comme une variable aléatoire reflétant les conditions climatiques.

Le secteur de l'électricité a également attiré une attention considérable dans la réflexion sur l'atténuation du changement climatique. Les politiques publiques engagées pour réduire la part des énergies fossiles dans la production d'électricité sont soit basées sur les taxes, rendant les énergies fossiles plus coûteuses, soit sur des quotas d'émissions échangeables, limitant le recours à ces sources polluantes. Dans cette thèse, nous analysons l'efficacité des outils mis en œuvre.

Dans les chapitres deux et trois, nous examinons comment l'introduction d'une taxe environnementale (chapitre 2) et d'un quota de permis d'émissions (chapitre 3) affectent les investissements dans les technologies renouvelables. Sous l'hypothèse que les dommages environnementaux augmentent plus que proportionnellement avec l'utilisation des énergies fossiles, nous construisons un modèle pour analyser l'efficacité des deux instruments.

Nos résultats montrent que l'intermittence des énergies renouvelables remet en cause les propriétés standard d'efficacité de ces instruments. En effet, sauf à ajuster ex post la taxe et le quota aux conditions météorologiques, ce qui semble techniquement et économiquement impossible, les deux instruments sont incapables de décentraliser l'état optimal. Sous cette contrainte, nous montrons que la puissance installée en technologies renouvelables par rapport à l'optimum de premier rang, pour chaque instrument, dépend des hypothèses adoptées du côté de la demande.

Une autre solution pour faciliter le développement des énergies renouvelables serait d'agir sur la demande. En particulier, le développement des compteurs communicants peut, en théorie, aider à limiter le problème de l'intermittence des énergies renouvelables, en permettant de mettre en place une tarification de l'électricité en temps réel et d'ajuster la demande des consommateurs en fonction de la disponibilité de l'électricité.

Au chapitre 4, nous modélisons un marché électrique simplifié où les facteurs climatiques et/ou sociaux influencent les deux côtés du marché. Dans cette partie de la thèse, nous tentons de rassembler dans un même modèle les deux problématiques du développement optimal des capacités intermittentes et des compteurs intelligents. Cette approche est novatrice car elle permet de

souligner le rôle important joué par la corrélation entre la demande et l'offre intermittente.

Nous proposons également une application numérique calibrée sur le marché électrique français en 2016. Notre principale constatation dans ce chapitre est que la relation entre les capacités intermittentes et les compteurs intelligents dépend de la corrélation entre l'énergie renouvelable et la demande. Par conséquent, toute politique publique susceptible d'influencer positivement cette corrélation doit être encouragée. Cependant, il ressort de notre application numérique qu'une adoption générale des compteurs intelligents ne serait possible que si le coût d'installation et d'exploitation des compteurs intelligents sont très faible. Ce résultat nous pousse à poser des questions sur l'efficacité de la généralisation des compteurs intelligents.

*Dis-moi quel est ton infini, je saurai le sens de ton univers.*

**Gaston Bachelard**

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*Soyons reconnaissants aux personnes qui nous donnent  
du bonheur, elles sont les charmants jardiniers  
par qui nos âmes sont fleuries.*

**Marcel Proust**



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## List of notations

### Chapters 2 and 3:

$\omega$ : Random variable that reflects climatic conditions.

$d(Z)$ : The social damage function.

$C(q)$ : Conventional cost function.

$F(k)$ : The investment cost of building intermittent units.

$S(D)$ : Consumer's surplus of consuming  $D$  kWh of electricity

### Chapter 4:

$x$ : Random variable that reflects climatic conditions.

$t$ : Consumers type and size.

$K$ : The cost of installing and operating traditional meters

$\kappa$ : The cost of installing and operating smart meters.

$\alpha$ : The *expected* market share of the consumers equipped with smart meters.

$I(k)$ : The cost of building intermittent units with capacity.

$\mathcal{S}$ : The set of all consumers' types equipped with smart meters.

$V(\omega)$ : The variance of the capacity factor  $\omega(x)$ .

$V(a)$ : The variance of consumers' demand  $a(x)$ .

$Cov(a, \omega)$ : The covariance between the demand variability and the intermittent electric generation.

$\rho$ : the correlation coefficient between the demand and the electric generation.

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# General introduction

There is now strong evidence that significant global warming is taking place on our planet. Phenomena such as rising global mean sea level, shrinking glaciers and disruptions in many physical and biological systems, confirm the reality of climate change.<sup>1</sup> The majority of climatologists agree that global warming is due to human activities and most major scientific organizations around the world, have issued public statements endorsing this position.<sup>2</sup> For example, the American Meteorological Society stated, "*it is clear from extensive scientific evidence that the dominant cause of the rapid change in climate of the past half century is human-induced increases in the amount of atmospheric greenhouse gases, including carbon dioxide, chlorofluorocarbons, methane, and nitrous oxide*".<sup>3</sup>

Thus, following the evidence of global warming and the urgent need to mitigate it, global environmental awareness has grown, and several measures have been undertaken worldwide to stop it. In the fight against climate change, energy issues are at the top of the agenda at local, national, regional and global levels. Indeed, around two-thirds of global GHG emissions come from energy production and use, which puts the energy sector at the core of efforts to combat climate change. The electricity sector is one of the most polluting sectors because of the use of fossil fuels which leads to harmful greenhouse gas emissions – making electricity production one of the main causes of global warming. This is because electricity is still mainly produced from fossil fuels sources, whose exploitation results in polluting emissions. As we can see on figure 1, coal accounted for 30 % of the OECD emissions, and this consumption of coal is largely due to electricity production.

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<sup>1</sup>Joint science academies' statement: Global response to climate change (2012).

<sup>2</sup>Organizations such as, U.S. National Academy of Science, Académie des Sciences et Techniques du Sénégal, Académie des Sciences, France, Academies of Arts, Humanities and Sciences of Canada, Academy of Athens, hold the position that Climate Change has been caused by human action.

<sup>3</sup>Climate Change: An Information Statement of the American Meteorological Society (2012).



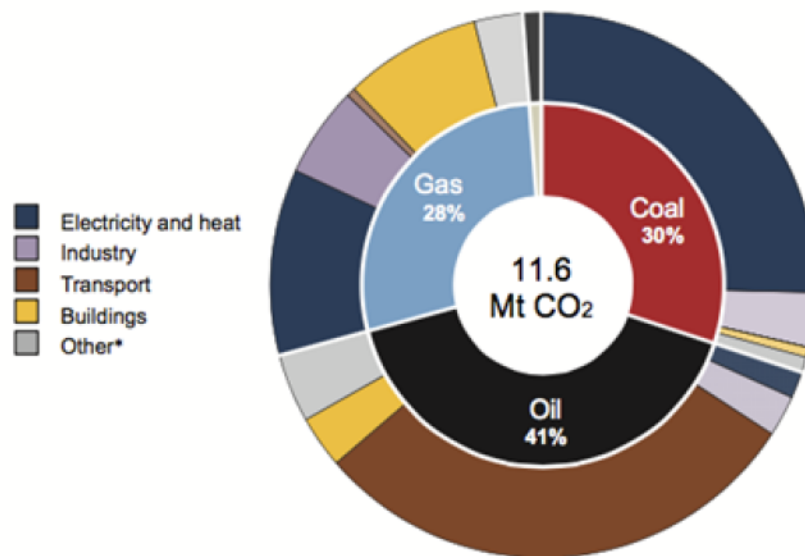


Figure 1: OECD emissions by fuel and sector in 2016. (IEA 2017)

In this context, the European Union (EU) has been showing the way towards the transition to a secure, sustainable and competitive energy system. These efforts are illustrated by many measures, such as the "Energy and Climate" packages, for 2020 and 2030 and the "Clean Energy for All Europeans" package, which was adopted on 30 November 2016. These measures are in line with Commission proposals on the regulatory framework that is needed for a successful energy transition.<sup>4</sup>

*"The energy transition refers to the transition from an energy system that relies primarily on the use of fossil fuels, exhaustible and emitting greenhouse gases (oil, coal and gas), to an energy mix that gives pride of place to renewable energies (such as wind and solar) and energy efficiency"*<sup>5</sup>

By 2020, the EU aims to reduce its greenhouse gas emissions by 20 %, to increase the renewable energy (RE) share to at least 20 % of the energy mix, and to achieve energy savings of at least 20 %.<sup>6</sup> Achieving these goals will allow the EU to help combat climate change and air pollution,

<sup>4</sup><https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte>.

<sup>5</sup><http://www.irena.org/energytransition>

<sup>6</sup><https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte>



decrease its dependence on foreign fossil fuels, and maintain energy affordability for consumers and businesses.

In France, the objectives of the energy transition were formalized by the promulgation, on August 17, 2015, of the Law number 2015-992 on the energy transition for green growth. It identifies 8 main objectives:<sup>7</sup>

- Reduce GHG emissions by 40 % between 1990 and 2030 and divide greenhouse gas emissions by four between 1990 and 2050.
- Reduce the final energy consumption by 50 % by 2050 compared to 2012 levels, with an intermediate target of 20 % by 2030.
- Reduce primary energy consumption of fossil fuels (-30 % by 2030 compared to 2012 levels).
- Increase the share of nuclear power in electricity production to 50 % by 2025.
- Improve the energy performance of buildings.
- Fight against fuel poverty and establish a universal right to have access to energy without excessive cost, depending on household resources.
- Reduce waste production.
- ***Increase the share of RE, in the energy consumption (up to 32 % in 2030).***

Thus, the substitution of RE sources to fossil fuels in electricity production is one of the key technological solutions to fight against global warming. This solution is currently pushed forward by many scientists and policy makers in the debate on greenhouse gas emission reduction.

This is the general context for our thesis. More specifically, we use theoretical models to focus on the penetration of RE on the electricity market, by analyzing the various obstacles to their development and some measures that have been taken to promote their expansion.

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<sup>7</sup><https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte>

RE can be defined as "*energy sources that are continually replenished by nature and derived directly from the sun (such as thermal, photo-chemical, and photo-electric), indirectly from the sun (such as wind, hydro-power, and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and tidal energy). Renewable energy technologies turn these natural energy sources into usable forms of energy, electricity, heat and fuels.*"<sup>8</sup>

Thus, the main advantage of RE is that their exploitation hardly results in GHG emissions. By promoting their development, the adverse effects of electricity production on the environment can be largely reduced. Moreover, the development of the RE sector offers many other advantages, such as local environmental health benefits, improved energy access - especially for rural areas, the diversification of the portfolio of energy resources and technologies, and social and economic development through potential job creation. Indeed, the International Renewable Energy Agency (IRENA) established that the number of jobs in RE rose by 5 % in 2015 to an estimated 8.1 million, plus an additional 1.3 million in large-scale hydro-power. Solar PV was the largest single RE employer, supporting 2.8 million jobs – a figure that has risen by 11 % since 2014.<sup>9</sup> Thus, the penetration of RE helps decrease dependence, reduce the external energy bill, but above all, it lowers our environmental foot-print, while fostering investments, growth, and local jobs creation.

However, the introduction of RE sources into the energy mix is a new challenge for regulators and producers. In addition to the standard issues of transportation and electricity distribution, intermittent energy sources also complicate production stage. This is due to the dependence of electricity production from RE sources on weather conditions. But consumers need electricity to be available constantly and for any level of demand. So, the variability of intermittent energy sources adds more pressures and constraints on the electricity grid. Therefore, it is important to take into consideration the intermittent nature of RE when analyzing its interaction with conventional energy sources on the electricity market.

The effects of RE penetration on the electricity market have generated a vast literature. Our

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<sup>8</sup>Ellabban et al. (2014, p. 781).

<sup>9</sup><http://www.irena.org>

first chapter presents a review of these works, while highlighting the different methods used and the assumptions adopted. This enabled us to detect the possible extensions of the literature, in terms of the problems that are dealt with and the methodologies that are adopted. In addition, this allowed us to position this thesis in relation to existing work and to try to answer some questions such as:

- How to determine the optimal energy mix taking into account the intermittent nature of RE?
- What is the role of demand management in the development of RE sector?
- What environmental policy instruments to use in the context of intermittency?

### **Optimal energy mix:**

It is worth noting that the larger part of the literature is empirical and country specific (Crampes and Ambec, 2012). This includes, among others, Benitez et al. (2008), Bocard (2010), Gowrisankaran et al. (2016), Green and Vasilakos (2011, 2012), Kennedy (2005), Lamont (2008), Menanteau et al. (2003) and Neuhoff et al. (2006). They provide estimates of the social costs and benefits of the penetration of the intermittent renewable technologies for different countries and periods.

However, our work takes a different direction by using stylized micro-economic models to derive some general insights regarding the optimal development of renewable technologies while taking into account their intermittent nature.

The corresponding strand of literature is much less developed including, among others, Ambec and Crampes (2012), Bode (2006), Rouillon (2014) and Twoney and Neuhoff (2010). This literature deals with the issue of competition on an electric market where the electricity is supplied by conventional and renewable generators. Bode (2006) determines the perfect competition equilibrium under several support schemes. Twoney and Neuhoff (2010) use a similar setting, but add the issue of intermittency explicitly. They determine the market equilibrium under perfect, monopolistic and duopolistic competitions, where the incumbent conventional generators exercise market power.

Ambec and Crampes (2012) and Rouillon (2015) consider endogenous energy mix through the possibility of investing in new generating units. Ambec and Crampes (2012) characterize the optimal investment and dispatch between conventional and intermittent generators and discuss its implementability under perfect competition. They consider in turn two polar situations: one where all consumers face prices contingent on the availability of the intermittent source of electricity and another where they all face a uniform price. Rouillon (2015) complements Ambec and Crampes (2012) by assuming that both types of consumers co-exist on the market and by focusing on perfect and monopolistic competitions.

Rouillon (2015) and Ambec and Crampes (2012), are the closest papers to our framework as we model the uncertainty of electricity production from RE sources as a random variable reflecting climatic conditions. Thus, the degree of substitution between power generation units depends on weather conditions. Consequently, capacity and production also vary with climatic conditions. We also adopt the hypothesis of increasing marginal cost with no capacity constraints for the conventional sector. This context corresponds quite well to the current situation of several European countries such as Germany, where there is an over-capacity of conventional units remaining in operation until the end of their scheduled lifetime.

So thanks to simple theoretical models, we show that the optimal capacity of intermittent renewable technologies is decreasing in the variance of the weather conditions. These results are intuitive, as the intermittency of RE constitutes an important obstacle to its development. Indeed, the variability makes the investment in renewable technologies riskier and less profitable. So the more variable the climatic conditions are, the lower the investment in these capacities will be.

### **How to promote the renewable energy sector? Supply-side of the market**

The electricity sector has attracted considerable attention in the debate on climate change mitigation. Consequently, wide range of mechanisms has been undertaken to support the development of RE sources. In this context, policies can be either based on taxation, making fossil fuels more expensive, or on emissions trading permits, limiting the use of these polluting sources.

In this thesis we analyze the effectiveness of the tools implemented by looking at the effects



of the introduction of an environmental tax (chapter 2) and of emission allowance quota (chapter 3) on the investments in renewable technologies.

Environmental taxation is one of the most widespread environmental policy instruments in Europe and has been introduced as a response to increasing environmental degradation. Indeed, the majority of EU member states have implemented carbon taxes at some stage to reduce greenhouse gas emissions (Castiglione et al. 2018). Carbon taxes attribute a value to polluting emissions, thus internalizing a portion of the costs associated with their environmental impact. The effectiveness of environmental taxation has been proved by numerous studies demonstrating the positive impact of taxation both on the quality of the environment (Scott and Eakins, 2004 ; Scrimgeour et al. 2005) and on economic performance (Eurostat, 2013 ; Bento and Jacobsen, 2007 ; Taheripour et al. 2008).

In the context of environmental regulation, emissions trading permits have been accepted, supported and widely applied to different kind of environmental issues in the last decades (Stavins, 2003). For example, to meet its obligations to reduce greenhouse gas (GHG) emissions under the Kyoto Protocol, the European Union (EU) established the first cap-and-trade system for carbon dioxide emissions in the world starting in 2005.

*"The EU emissions trading system (EU ETS) is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest one."* <sup>10</sup>

Emissions trading permits have spread, as they are an efficient way to reduce pollution. They work with a central authority which sets a cap on the total amount of pollutants that can be emitted. The cap is then converted into allowances that give the right to emit a certain amount of pollutants. Permits are allocated to polluters, and can be traded on a secondary market. A market price emerges and buyers pay to increase their emissions, while sellers can earn money by selling their unused allowances. Accordingly, pollution markets can achieve emission reduction targets at the lowest cost to society (Lehmann and Gawel (2013)).

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<sup>10</sup><https://ec.europa.eu/clima/policies/ets>

So far, most of the literature on public policies to green electricity production has ignored the problem of intermittency. For example, Fischer and Newell (2008) and Acemoglu et al. (2012) have looked at pollution externalities in a dynamic framework, and Fullerton and Heutel (2010) in a general equilibrium. They consider exogenous investment in RE technologies. However, in our framework the energy mix is endogenous through the possibility of investing in new generating capacities.

The closest paper to our framework in the literature is Ambec and Crampes (2014). They characterize the optimal dispatch and investment in intermittent and conventional technologies and discuss the efficiency of three public policies: a carbon tax, feed-in tariffs and renewable portfolio standards, under perfect competition. Unlike Ambec and Crampes (2014), we adopt the hypothesis of increasing environmental marginal damage. This assumption is important in that it highlights the additional challenges imposed on regulators due to the introduction of RE sources in the energy mix.

Under the assumption that environmental damage increases more than proportionally with the use of fossil fuels, our results show that the intermittency of RE calls into question the standard properties of efficiency of the latter. Indeed, unless taxation and quota are adapted ex post to weather conditions - which seems technically and economically impossible -, both instruments are unable to decentralize the optimal state. Under this constraint, we show that RE capacities that should be installed under each scheme depends on assumption adopted on the demand-side.

### **Demand-side management**

Another solution to facilitate the development of RE would be to act on demand. In particular, the development of smart meters can, in theory, help to reduce the problem of intermittency of RE, by allowing real-time pricing (RTP). The RTP scheme reflects the marginal value of electricity according to real-time supply. Demand and prices are not predetermined but subject to hourly changes. Accordingly, consumers can vary their demand depending on the availability of electricity.

*Responsive demand refers to changes applied by consumers to their expected load pattern in response to energy price signals for improving the economic efficiency of their energy. The*

*mechanism discourages the energy load when real-time price is high and vice versa.*<sup>11</sup>

Through electricity demand response, smart meters can lead to energy saving measures. Moreover, it can improve the efficiency of the power grid system, and reduce the need for new investments (Hussain and Gao, 2018).

Thus, demand-side management has generated an extensive theoretical literature (Borenstein and Holland, 2003 ; Green and Vasilakos, 2011 ; Joskow and Tirole, 2007 ; Léautier, 2014) dealing with the design of pricing strategies under conditions of imperfect metering of variable demand. The main conclusion of this literature is that as long as some consumers remain on traditional meters and face flat rate tariff, a competitive electricity market will fail to implement the first-best optimum.

The literature has also investigated the possibilities of implementing the second-best optimum when there are price-insensitive retail consumers. Assuming that the retailers can supply linear pricing contracts only, Borenstein and Holland (2003) conclude that the second-best optimum cannot be implemented. On the contrary, Joskow and Tirole (2007) show that it can be implemented if tariffs are composed with a fixed fee and flat rate price. The issue of endogenous investment in metering equipment is evoked in Borenstein and Holland (2003) and Joskow and Tirole (2007), but it is extensively analyzed by Léautier (2014). In a socially optimal allocation, Léautier (2014) shows that the marginal value of an increase in the proportion of consumers on real-time pricing is proportional to the variance of wholesale prices. This determines the consumers incentives to adopt smart meters.

In chapter 4, we model a simplified electric market where both sides of the market are influenced by climatic and/or social factors. In this part of the thesis, we attempt to bring together in the same model the two issues of the optimal development of intermittent capacities and smart meters. This approach is innovative as it allows us to emphasize the important role played by the correlation between demand and intermittent supply. We also give a numeral application calibrated on the French electric market data in 2016. Our main finding in this chapter is that the relation between

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<sup>11</sup>Assessment of demand response and advanced metering. Federal energy regulatory commission reports 2010.

intermittent capacities and smart meters depends on the correlation between renewable energy and demand. Consequently, any public policy that is able to positively influence this correlation should be encouraged. However, it appears from our numeral application that a general adoption of smart meters would be optimal only if the cost of installing and operating the smart meters was unrealistically low. This result pushes us to ask questions about the efficiency of the generalization of smart meters.



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## CHAPTER 1

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State of the art for renewable energy sources

## **Preface**

The substitution of renewable energy sources to fossil fuels in electricity production is one of the key technological solutions to fight against global warming. This solution is currently pushed forward by many scientists and policy makers in the debate on greenhouse gas emission reduction. In this introductory chapter, an overview is given of the various works dealing with the penetration of renewable energies on the electricity market. First of all, we begin by presenting the different sources of energy, the benefits they provide and the obstacles to their development. This allows us to explain the general framework of the subject of the thesis and the importance of the issues dealt with. Then, we summarize the different theoretical and empirical works dealing with the question of the energy mix. Finally, we end the chapter by analyzing the different instruments of environmental policy and the literature on this subject.

## 1.1 Introduction

Environmental awareness and the confirmation of the risk of climate warming have led to significant interest in RE because of the environmental benefits they provide compared to conventional energy sources. Thus, energy issues play an important role at the local, national, regional and global levels in the fight against climate change. In Europe, there is a strong consensus on the reality of climate change and the urgent need to reduce it. The "Clean Energy for All Europeans" package, adopted on 30 November 2016, is in line with the proposals of the Commission on the regulatory framework for energy policy. For example, the EU targets for 2020 aim to reduce greenhouse gas emissions by 20 %, increase the share of RE by 20 % and improve the energy efficiency by 20%.<sup>1</sup>

One of the main advantages of RE is that they have almost no adverse impact on the environment. Indeed, their use does not result in GHG emissions or dangerous waste production. Thus, the penetration of RE helps to reduce not only our energy dependency but also our environmental footprint, while fostering investments, growth and local jobs creation. However, the development of the RE sector is experiencing some difficulties related to the intermittent nature of this energy. Consumers need electricity to be available at all times. So in the absence of large-scale and efficient storage of energy, there is a risk of incompatibility between supply and demand. This is the fundamental difference compared to conventional energies that are available instantly on demand.

Despite these difficulties, the urgent need to mitigate climate change and the growing environmental awareness make the development of the RE sector essential. However, given the intermittent nature of RE, their development cannot happen spontaneously on the market, hence public intervention is needed. Policies can be either based on taxation, making fossil fuels more expensive (price-based tools), or on emissions trading permits, limiting the use of these polluting sources (quantity-based tools).

Another possible solution to develop RE is to act on demand. In this context, the role of smart meters is important, as they allow for real-time electricity pricing, with prices adjusting

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<sup>1</sup><https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte>

frequently to the changes on the market. Thus, consumers can regulate their demand depending on the availability of electricity, which reduces the problem of the intermittency of RE. So if we want to bring about a breakthrough for RE, a series of barriers have to be overcome and proper promotion strategies have to be implemented.

Increasing the share of RE in the energy mix has generated a vast literature. This chapter presents a review of the different works on this topic, while highlighting the different methods that have been used and the assumptions that have been adopted. This enabled us to detect the possible extensions of the literature, in terms of the problems treated and methodologies adopted.

## 1.2 Renewable energy sources

RE can be defined as « *energy sources that are continually replenished by nature and derived directly from the sun (such as thermal, photo-chemical, and photo-electric), indirectly from the sun (such as wind, hydropower, and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and tidal energy)*» (Ellabban et al. 2014, p. 749). They constitute an alternative to traditional, primary, non-renewable energy sources (San Miguel et al. 2010).

### 1.2.1 RE types

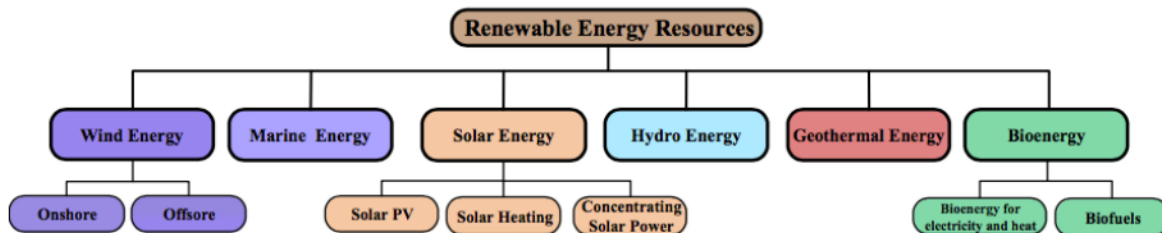


Figure 2: Types of renewable energy sources. (Ellabban et al. (2014))

- **Biomass energy:** Biomass is an industry term that refers to the energy produced through the combustion of organic matter coming from plants and animals. Biomass is a renewable and sustainable source of energy that can be used either directly via combustion to produce heat, or indirectly after converting it into various forms of bio fuel.
- **Geothermal energy:** Geothermal energy is the heat that is obtained from the depths of the Earth as hot water or steam. It is used directly for household heating, for agricultural production, as well as for electrical power production (Boyle, 2004). It is considered as a cost effective, reliable, and environmentally friendly energy source.<sup>2</sup>
- **Hydro-power energy:** is a power that is derived from the energy of moving water. Flowing water releases energy that can be captured and converted into electricity by using turbines. The most prevalent form of hydropower is dams, although newer forms such as the harnessing of waves and tidal power are becoming more common. The hydropower potential is the amount of electrical energy produced in hydropower plants. What can be considered as RE is only the production of electrical power in the power plants naturally fed with water (Hawkins et al., 2003).
- **Marine energy:** Renewable marine energy comes from six distinct sources: waves, tidal range, tidal currents, ocean currents, ocean thermal energy conversion and salinity gradients. Each of them has different origins and requires different technologies for conversion (Ellabban et al., 2014).
- **Solar energy:** Solar energy generation involves the use of the sun's energy to provide hot water via solar thermal systems or electricity with solar PV and concentrating solar power (CSP) systems. These technologies have been successfully used in numerous systems around the world over the last few decades (Byrne et al., 2007).
- **Wind energy:** Wind power is defined by the conversion of wind energy by wind turbines into a useful form. For instance it can be exploited to make electricity, wind mills can be

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<sup>2</sup><https://www.eurobserv-er.org/category/barometer-2017/>

used to produce mechanical power, wind pumps can pump water or power drainage systems. The first wind turbines for electricity generation were developed at the beginning of the 20th century. The technology was gradually improved from the early 1970s. By the end of the 1990s, wind energy had re-emerged as one of the most important sustainable energy resources (Kaygusuz, 2009). Just like hydro-power plants, the potential of wind turbine farms is determined by their capacity to generate electrical power (Burton et al., 2011). Wind energy for electricity production today is a mature, competitive, and virtually pollution-free technology widely used in many areas of the world (Balat, 2009).

### **1.2.2 Renewable energy benefits**

After the oil supply disruptions of the early 1970s, the dependence on foreign oil supplies has kept increasing, which impacts more than just the national energy policy. Thus, from an economic perspective, it is important to reduce the dependency on conventional energy sources and imported fuels. This should contribute favorably to national energy security. It is essential to increase supply diversity and step up the use of RE technologies, which will reduce the vulnerability of energy systems. Indeed, more RE means more diversification of energy supplies and an increased decentralization of energy production (Pach-Gurgul, 2014).

Moreover, investment in RE technologies fosters the creation of new green jobs, especially in rural areas (Longo et al., 2008). Stigka et al., (2014) suggest that the market of RE provides more work positions than the conventional energy market. Indeed, when more people are working, the benefits extend beyond the income earned from those jobs (Akella et al., 2009). So to sum up, investing in RE may contribute to sustainable development, and ensure the balance of the economic, social and natural systems (Varun et al., 2009 ; Stigka et al., 2014). Figure 3 summarizes the main benefits from investing in RE.



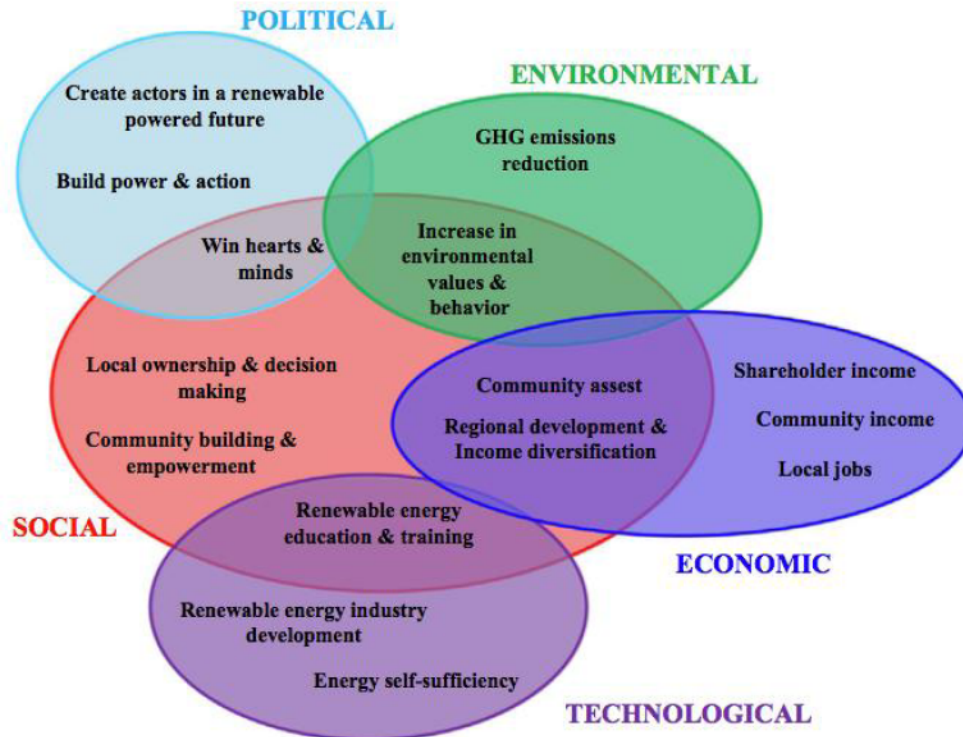


Figure 3: Main benefits of renewable energy. (Ellabban et al. 2014)

### 1.2.3 Barriers to renewable energy development

The identification of the different barriers to the development of RE has begun between the eighties and nineties (Jochem and Gruber, 1990 ; Reddy, 1991 ; Joskow and Marron, 1992 ; Koomey and Sanstad, 1994 ; Jaffe and Stavins, 1994 ; Porter and Van der Linde, 1995 ; Sutherland, 1996). These include cost-effectiveness, technical barriers, and market barriers such as inconsistent pricing structures, institutional, political and regulatory barriers, and social and environmental barriers (Painuly, 2001 ; Mirza et al., 2009). Barriers to RE penetration with special discussions on financial barriers and initiatives to remove them are discussed in Norbert and Painuly (1999), Gutermuth (1998), Taylor and Bogach (1998), Painuly (2001) and Mirza et al. (2009), among others.

- **Institutional barriers:** are those that slow down the penetration of RE . They are numerous

and occur at different levels. Many renewable energy technologies are still in the development stage but there are not enough government incentives to stimulate the adoption of RE by businesses and industries. Institutional barriers include:

- Lack of coordination and cooperation within and between various ministries, agencies and institutes, which restricts the development and commercialization of RE.
- Poorly targeted or poorly implemented environmental regulations that can lead to negative effects on RE development. Indeed, the lack of awareness among regulators restricts technology penetration (Mirza et al., 2009).
- Lack of explicit national policy for renewable energy at end-use level and incomplete transition to cost-based electric tariffs for most residential and some industrial customers.
- Institutional obstacles such as monopolies in the utilities market, so that there is no institutional interest in encouraging competing sources of electricity.
- The absence of a government agency specifically mandated to promote renewable energy development and lack of institutions and mechanisms to disseminate information.
- **Fiscal and financial barriers:** the intermittent nature of RE generation and their site-specific nature make the investment in this sector riskier and less profitable which may disadvantage the investment in intermittent capacities as compared to non-renewable energy sector. Thus, it is difficult to obtain competitive funding due to the lack of familiarity with these technologies, the perception of high risk, and the uncertainty regarding resource assessment (Mirza et al., 2009). However, there is not enough financial support for working capital, maintenance of the equipment or for consumers' service infrastructure. This can hinder the continuity and duration of RE projects (Painuly, 2001).
- **Market-related barriers:** are those that explain why technologies which appear to be cost effective at current prices are not taken up. Market failures are market imperfections (Reddy and Painuly, 2004). For example, there is a gap between market requirements and RD in



RE products. Therefore, products are not correctly developed and continue to depend on the supply-side rather than being responsive to users' needs. This results in a limited market penetration of RE technologies. Moreover, market reforms aiming to set up an electricity market with competitive and reliable power supply tariff rationalization and elimination of subsidies and grants for RE sector may reduce the penetration of renewable energy technologies (Mirza et al., 2009).

- **Information and social barriers:** first, general information and public awareness on new RE technologies are insufficient, and there is limited understanding of the practical problems in the implementation and maintenance of RE projects. In addition, the adoption of RE is generally the result of consumer perceptions of the quality and usefulness of these items when compared to conventional technologies. Thus, since RE technologies are generally perceived as more expensive than conventional ones, their development depends on the propensity of consumers to pay for renewable technologies and their environmental preferences. Nevertheless, even if consumers want to pay more for green electricity, they must be equipped with smart equipment to react to electricity prices (Beck and Martinot, 2004 ; Margolis and Zuboy, 2006).

#### 1.2.4 Status of RE in EU countries

We rely on Agora Energiewende and Sandbag review (2018),<sup>3</sup> to present and summarize the state of the RE in the European power sector in 2017.

With environmental awareness and various regulatory efforts at the European level, the RE sector has experienced a clear evolution in Europe. In 2017 and for the first time, the RE sector generated 30% of the European overall electricity production. Wind, solar and biomass grew to reach 20.9 % of the EU electricity mix. If this rate continues then RE can account for 50 % of the EU electricity mix by 2030. In this context, it is easy to imagine an acceleration of the deployment of RE, which would allow the EU to achieve the 35 % renewable target that is currently under

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<sup>3</sup><https://sandbag.org.uk/wp-content/uploads/2018/01/EU-power-sector-report-2017.pdf>

negotiation. In 2017, renewables generated 30% of Europe’s electricity for the first time. It was a rise of only 0.2% points - from 29.8% in 2016 to 30.0% in 2017 of electricity production (the continuous curve in Figure 4). This was because the huge growth in wind generation was almost completely offset by the lowest hydro electricity generation in a decade. Wind, solar and biomass grew to 20.9% of the EU electricity mix (the dotted line in Figure 4).

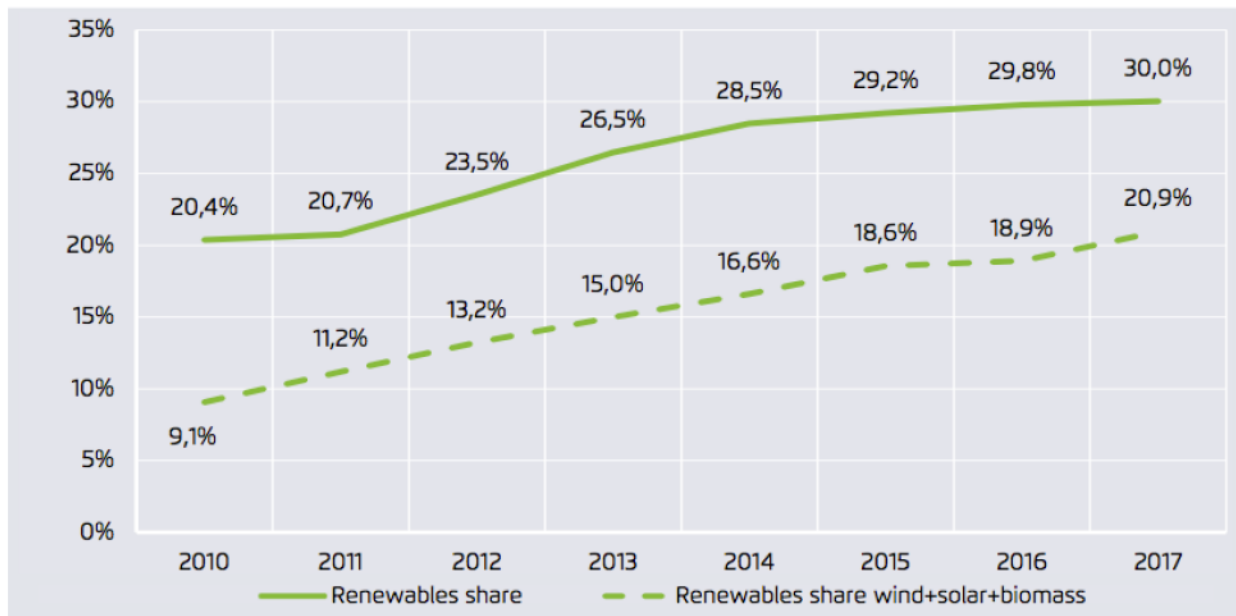


Figure 4: Renewable share of gross electricity production in EU. (Agora Energiewende and Sandbag (2018))

Geographically, the largest part of that increase was located in Germany and the UK alone. The remaining 26 EU countries represent 58 % of the RE growth from 2011 to 2014, but only 43 % from 2014 to 2017. This may be because some Member States have already reached their national 2020 targets under the EU Renewable Energy Directive.<sup>4</sup> However, it can also be due to the high financing costs especially in Central and South-Eastern Europe, which prevent the reduction in the costs of RE technologies from being translated into low-cost RE projects. Figure 5 represents the change in RE generation by EU country between 2011 and 2017.

<sup>4</sup>[https://ec.europa.eu/commission/sites/beta-political/files/report-renewable-energy\\_en.pdf](https://ec.europa.eu/commission/sites/beta-political/files/report-renewable-energy_en.pdf)

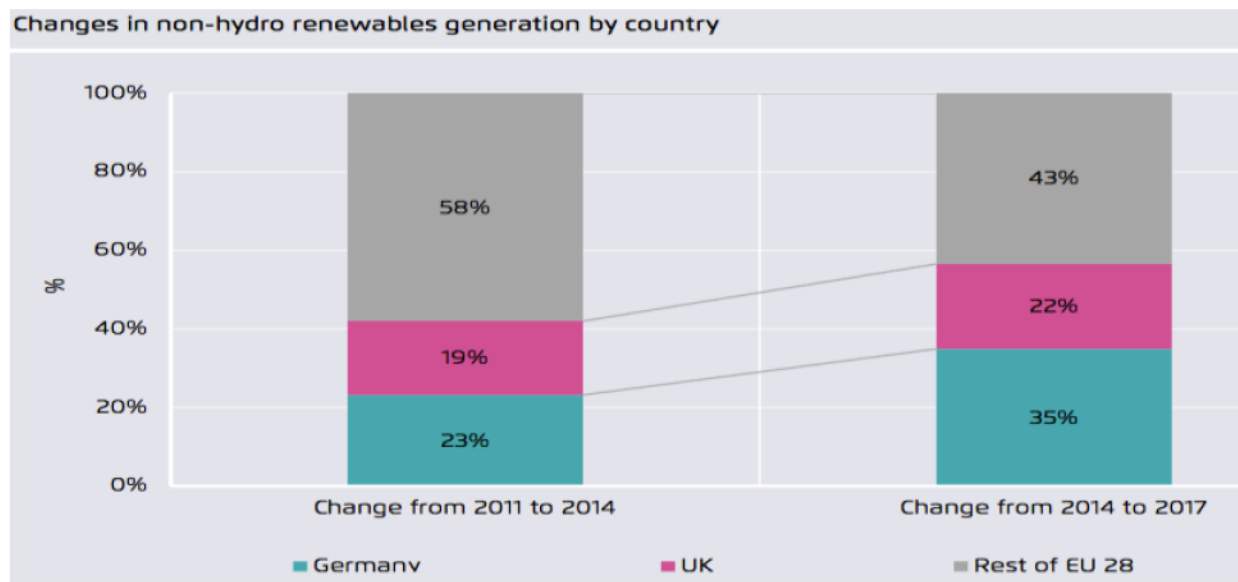


Figure 5: Change in RE production by EU country. (Agora Energiewende and Sandbag (2018))

### 1.3 Literature review on the energy mix

The introduction of a large part of intermittent and non-storable energy sources in the energy mix is a new challenge for operators and regulators in the electricity industry. In addition to transportation and distribution difficulties, they also pose problems at the generation stage. Indeed, the investment in intermittent technologies is mainly influenced by two social objectives.

The first one is the supply of cheap energy because intermittent production units produce electricity at negligible production costs, once the capacities have been installed. Thus, in addition to environmental benefits, switching to RE can help to ensure a reliable, timely and cost-effective power supply (Ellabban et al., 2014).

The second social goal of investing in intermittent technologies is to increase installed electricity generation capacity while limiting the variability of demand and spot prices. However, the intermittent nature of RE can create a contradiction between these two objectives (Lund, 2007 ; Sovacool, 2006 ; Vaillancourt et al., 2008). Indeed, if green electricity production is low when demand is high and vice-versa, investment in new capacities increases the variability of residual

demand, requiring the mobilization of peak-load capacities. Ensuring the continuity of the electricity supply is both necessary and socially useful. It is necessary because consumers who cannot adapt their demand – because they have traditional meters - need electricity to be available at any time and any location. It is socially useful because consumers who can adjust their demand with smart meters prefer not to, due to risk aversion. The undesirable side effects of investing in RE technologies increase with installed capacity (Rouillon, 2014).

This is why there is an extensive literature on the trade-off between the benefits and social costs of investing in RE technologies, and on the analysis of the changes in the electricity market following their deployment in the context of market deregulation.

### **1.3.1 Empirical literature**

Much of this literature is empirical and country specific (Crampes and Ambec, 2012). This literature analyzes the effects of the variability of RE on their economic value. The economic value of RE can be defined as the income that intermittent producers can earn on the market without taking into account subsidy revenues (Joskow, 2011).

The analysis of the effect of RE variability on their economic value is carried out by comparing the actual value of intermittent production and its hypothetical value if the output of this sector was not variable. This difference is often mentioned by the literature as the value factor of RE (Fripp and Wiser, 2008).

#### **- Short term models:**

In order to analyze the effects of the penetration of RE, some studies have used historical data by collecting either hourly electricity prices (Borenstein, 2008 ; Sensfuß, 2008 ; Green and Vasilakos, 2012 ; Fripp and Wiser, 2008), or local electricity prices (Brown and Rowlands, 2009 ; Lewis, 2010). This branch of literature analyzes the variability of wind and solar energy by estimating their marginal economic value. The value factor is calculated as the ratio of the hourly wind-weighted average wholesale electricity price and its time- weighted average (base price).

Borenstein (2008) uses information on solar energy production and spot price data from 2000-



2003 to estimate the real value of the energy produced by photovoltaic panels in California. He finds that the favorable timing of solar energy production increases its value only from 0 to 20 %, but this value could increase to 30 % with the generalization of smart meters. Sensfuß and Ragwitz (2011) estimate that the marginal value of wind in Germany decreased from 1.02 €/MWh to 0.96 €/MWh, between 2001 and 2006, as the wind share increased from 2 to 6 %. Green and Vasilakos (2012) extend the multi-periodic model presented in Forsund et al. (2008) and they include thermal, wind and hydroelectric generation in their analysis over several periods. They review Denmark's different electricity generation and trading patterns between 2001 and 2009 by calculating value factors on a monthly basis. Authors estimate the value factor of the wind during this period at 0.92 €/MWh in western Denmark and 0.96 €/MWh in the East.

Brown and Rowlands (2008) and Lewis (2010) use local electricity prices to estimate grid costs. Brown and Rowlands (2008) study the potential increase in the value of solar electricity in the context of a (decentralized) nodal pricing system instead of a uniform pricing system.<sup>5</sup> They use a hybrid optimization model to analyze solar and electricity market data for locations near Mississauga and Kingston for the period of January 1, 2005 to December 31, 2006. They estimate that the solar value factor is higher in large cities.

The empirical literature that analyzes the ER value factor with exogenous investment in RE, dates back to the 1990s through the work of Grubb (1991), Bouzguenda and Rahman (1993, 1991) among others. More recently, Hirst and Hild (2004) model a small energy system with a short-term unit commitment model. More specifically, the article takes into account different amounts of wind, from 200 to 2000 MW, and integrates them into a unit whose peak demand is less than 5,000 MW. The analysis suggests that modest amounts of wind receive payments that are almost equivalent to the marginal cost of electricity generation. This is because the correlations between

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<sup>5</sup>The theoretical prices of electricity at each node on the network is a calculated "shadow price", in which it is assumed that one additional kilowatt-hour is demanded at the node in question, and the hypothetical incremental cost to the system that would result from the optimized dispatch of available units establishes the hypothetical production cost of the hypothetical kilowatt-hour. This is known as locational marginal pricing (LMP) or nodal pricing and is used in some deregulated markets, most notably in the PJM Interconnection, ERCOT, New York, and New England markets in the USA, New Zealand, and in Singapore.

<https://pocketsense.com/difference-between-nodal-zonal-markets-8620753.html>

wind generation and system load are very low. Braun et al. (2010) use a simple three-technology model to estimate the value of solar energy in Germany. The authors use temperature data for 120 sites in Germany to calculate standardized PV generation time series. Green and Vasilakos (2011) determine the supply function balances to analyze problems of imperfect competition. They report a low wind value factor in the UK of 0.45 to 30 GW of installed capacity. Valenzuela and Wang (2011) and Nicolosi (2011, 2012), show how temporal resolution can influence the results of the economic value of RE penetration. They develop an analytical model to calculate the probability distribution of market prices and wind farm revenues, taking into consideration the availability of production units, the uncertainty of the load and the variability of wind energy production. The proposed stochastic models were also compared to deterministic models in which decommissioned capacities of conventional generating units, average load, and average wind power were used. The results show that wind penetration decreases revenues of wind producers.

As we can see, studies are very broad in scope and report the costs of the profile as one of many outcomes, while others focus on the market value of RE. However, historical market data and dispatch models can only provide estimates of the short-term market value of RE (Hirth, 2013).

#### **- Long-term models:**

The large-scale penetration of RE sources on the market is changing the structure of electricity prices and of the energy mix. In order to include the evolution of the structure of the electricity market and to derive long-term value factors, it is necessary to model the investments endogenously. Much of this discussion in the literature focuses on the marginal value of intermittent technology. From an economic point of view, a technology should penetrate the system as long as its marginal value is greater than its marginal cost.

Kirby et al. (2003) measure the advantage of reliability in terms of a fraction of a peak plant that could be replaced by a wind generator. They found that the capacity credit was about 57 % for photovoltaic and 22 to 26 % for wind in various sites in California. This benefit could be achieved by reducing peak capacity on the system. Although there are a long-term benefits to be gained from intermittent introductions, literature on the subject shows that the marginal benefit

of increasing intermittent capacity decreases as its capacity increases (Bouzeguenda and Rahman, 1993).

Hirst and Hild (2008) and Grubb (1991) also note that the marginal value of RE declines as its capacity increases. Their justification is that RE technology now permits to power cheaper generators and thus it contributes less and less as it enters the system. Lamont (2008) develops an optimization model using data from California. He shows that wind value factor decreases from 0.86 to 0.75 €/MWh when its market share goes from zero to 16 %. Gowrisankaran et al. (2016) build a general model, integrating endogenous demand and possibility of curtailment. Nicolosi (2012) uses a sophisticated model of the European electricity market to estimate wind and solar value factors in Germany. He finds that installed capacity increases to 35 and 9 %, while the value factor decreases by about 0.7€/MWh. Mills and Wiser (2010) develops a similar model and apply it to Californian data to find similar results to those of Nicolosi (2012). They also model concentrated solar energy and find that at high penetration rates, thermal energy storage significantly increases its value.

In summary the results of empirical literature show that the economic value of RE decreases with their penetration.

## **1.3.2 Theoretical literature**

### **1.3.2.1 Supply-side of the market**

Increasing the share of RE in the energy mix is considered to be an effective way to reduce the negative effects of electricity generation on the environment. However, the penetration of RE into the electricity market may face some difficulties that can reduce the development of these sources, such as market power of the incumbent operator and the intermittent nature of RE. There is an extensive literature dealing with the changes in the electric market due to the penetration of renewable technologies in deregulated electricity markets. A good part of this literature focuses on the supply side of the market and on the competition between conventional and renewable technologies including, among others, Joskow (2012), Borenstein (2012), Bode (2006), Lamont (2008), Twomey

and Neuhoff (2010), Green and Vasilakos (2010), Sioshansi (2011), Ambec and Crampes (2012), Rouillon, (2014).

Joskow (2012) and Borenstein (2012) discuss the market and non-market valuation of electricity production from RE, as well as the costs and the subsidies that are available. They analyze the efficiency of using the traditional "levelized cost"<sup>6</sup> calculations to compare conventional and intermittent generating technologies or to compare different intermittent technologies. Under this metric, the technology with the lowest cost per unit of electricity supplied is supposed to be chosen as the technology in which producers will invest to meet additional expected demand for electricity. Although "levelized cost" has been the starting point for cost comparisons since the beginning of electricity generation, Joskow (2012) and Borenstein (2012) demonstrate that this metric is inappropriate for comparing intermittent generating technologies like wind and solar with conventional generating technologies. Indeed, the value of electricity depends on the time and place of production, and the "levelized cost" metric does not take into account differences in the production profiles of intermittent technologies and the associated variations in the market value of the electricity supply. This result highlights the importance of adapting the methods of analysis and comparison between conventional and intermittent production technologies to account for the special characteristics of intermittent technologies and the changes they bring about in the electricity market.

Bode (2006), Lamont (2008) and Twomey and Neuhoff (2010) derive analytical expressions for the market value of RE. Lamont (2008) uses a general functional form for the merit-order curve to develop a theoretical framework to find an expression for the marginal value of an intermittent technology. He shows that the marginal long-term value of an intermittent generator is made up of two components. The first component is strictly a function of the capacity factor of the intermittent generator and the marginal costs on the system as a whole and can be expressed as the base price. The second component is a function of the co-variance of RE production and electricity prices which is itself a function of wind power penetration. Bode (2006) uses a linear functional form for the merit-order curve to dispose the perfect competition equilibrium under several support schemes

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<sup>6</sup>The "levelized cost" is essentially the expected total actual cost per MWh generated over the expected life of the generating unit (Joskow, 2012)



financed either through the general public budget or a RE mark-up charged to the final consumers. The numerical analysis provided in the paper reveals that the consumer's electricity costs may also increase or decrease, depending on the support schemes and assumptions adopted. However, since installed intermittent capacities are assumed to be exogenous, Bode (2006) cannot address the issue of RE intermittency. The main contribution of this part of literature has been to stress the fundamental economic differences between conventional and intermittent technologies.

Twomey and Neuhoff (2010), Green and Vasilakos (2010) and Sioshansi (2011) analyze the market value of RE in the context of market power of conventional generators, applying Cournot theory or supply function equilibrium theory and explicitly add the issue of intermittency to the analysis. Green and Vasilakos (2010) and Twomey and Neuhoff (2010) both examine the issue of market power in the UK market. Twomey and Neuhoff (2010) determine the market equilibrium under perfect, monopolistic and duopolistic competitions, where market power is exercised by conventional generators. They show that, on average, the intermittent generators receive lower prices than conventional generators and that this difference can be exacerbated in the presence of market power. Green and Vasilakos (2010) evaluate the impact of intermittent wind on hourly equilibrium prices and output. They show that in the presence of significant market power, the prices more than doubled and their volatility increased. Using a Stackelberg-type model, Sioshansi (2010) examines the potential effects of large-scale wind and energy storage in the Texas market. He shows that with energy storage, the price of wind energy tends to be below the average price of energy, and that this difference grows with the penetration of wind energy into the market. However, he shows that a more-competitive market can make storage significantly more valuable for wind generators. Summing up, the main finding of this theoretical literature is that market power tends to reduce the value factor of RE. The liberalization of the electricity market and the opening of the electricity market to competition make it possible to reduce the market power of historical operators and accelerate the development of the intermittent sector.

Compared to these papers, Ambec and Crampes (2012) and Rouillon (2014) go one step further, by making the energy mix endogenous through the possibility of investing in new generating

capacities. Ambec and Crampes (2012) characterize the optimal energy mix, emphasizing the availability of the intermittent source as a major parameter for optimal investment in capacity, and they analyze its decentralization through competitive market mechanisms. They consider two polar situations: on the one hand, one where all consumers face prices that are contingent on the availability of the intermittent source of electricity, and on the other hand, one where they all face uniform prices. They show that decentralizing the efficient energy mix requires electricity to be priced contingently on the availability of the intermittent source. But traditional meters impose uniform pricing, which prevents the implementation of the optimal energy mix. The impossibility that is raised by Ambec and Crampes (2012) can be attributed to their implicit assumption that no wholesale spot market exists.

Rouillon (2014) builds on Ambec and Crampes (2012) by adopting the more general assumption that there is a fraction of both types of consumers on the market (traditional and smart meters). Moreover, Rouillon (2014) also deals with monopolistic competitions. The paper shows that under perfect competition the (second-best) optimal allocation can be implemented, provided that the conventional and intermittent generators exchange their electric production on a wholesale spot market. By contrast, if a single incumbent firm owns the conventional generators and has market power, the paper shows that the investment in intermittent technologies will generally be inappropriate.

Thus, theoretical literature agrees on several points. Firstly, it is necessary to adopt the appropriate methods in the comparison between conventional and intermittent technologies, in order to take into account the specific characteristics of intermittent technologies. Secondly, the market power of the incumbent operator presents a major obstacle to the development of the RE sector; so the liberalization of the electricity market and its opening to competition can be an effective solution to this problem. Finally, the development of smart meters can reduce the negative effects of investing in intermittent technologies as they allow consumers to adjust their demand according to the availability of electricity. This reduces the constraint of unresponsive demand and consequently reduces the problem of intermittency.

### 1.3.2.2 Demand-side of the market

Given the increasing share of RE in the energy mix there is a possible solution to the problem of RE intermittency. It is to act on the demand side of the market and on the organizational features that can be used to make the consumers more reactive to the situation of the spot market. Indeed, a major problem in electricity markets is that only part of the consumers can experience and react to real-time pricing (RTP) (Borenstein and Holland, 2003). This is because RTP requires equipping all consumers with connected and communicant meters (Joskow and Tirole, 2006). As long as some consumers still use traditional meters and face flat rate service, a competitive electricity market will fail to implement the first-best optimum (Borenstein and Holland, 2005).

In this context, the role of smart meters is crucial as they allow RTP. Vasconcelos (2008, p. 5) define smart meters as *"modern, innovative electronic devices capable of offering consumers, suppliers, distribution network operators, generators and regulators a wide range of useful information, enabling the introduction of new energy services and new contractual arrangements"*. Indeed, smart meters allow RTP of electricity: electric prices change frequently to reflect the changes in the electricity supply and the cost of the serving load. Thus, consumers can adjust their demands according to the availability of electricity, which reduces the problem of intermittency of RE.

The theoretical literature dealing with the design of pricing strategies under conditions of imperfect metering of a variable electric demand is not very abundant. Borenstein and Holland (2003), Green and Vasilakos (2010), Joskow and Tirole (2007), Leautier (2014), and Chiba and Rouillon (2018) deal with the effect of managing the demand-side of the market on RE penetration.

The general principle of peak-load pricing has been developed by Boiteux, 1949 and recently revisited by Borenstein and Holland (2003) and Joskow and Tirole (2007). Borenstein and Holland (2005) analyze the impact of having a share of non reactive consumers in a competitive electricity market. They show that if some consumers pay fixed tariff, both the first-best and the second-best optimal levels of investment cannot be implemented.

This impossibility that is pointed out in Borenstein and Holland (2005) is due to the fact that there is a missing market in their framework. Indeed, they assume that consumers on flat retail

prices cannot trade with those on RTP or with producers since all electricity transactions must occur at the same price for flat-rate customers. This missing market implies that the competitive equilibrium is not efficient. Conversely, Joskow and Tirole (2007) managed to implement the second-best solution with retail and generation competition, provided that the retailers offer two-part tariffs contracts, with a fixed fee and flat rate price. Then, the variable part of the retail price is chosen optimally which allows for the implementation of the second-best solution. However, they argue that the conditions underlying this result are very strong and would be violated in the presence of price caps and/or market power on the wholesale market, and in the presence of load profiling and/or load profile heterogeneity on the retail market.

Another branch of this literature relies on simulation to analyze the efficiency effects of RTP. Reiss and White (2005) and Allcott (2011) estimate individual price elasticity of customers and make use of it to estimate welfare effects. Reiss and White (2005) examine electricity consumption by San Diego households during the California electricity crisis. They focus on the non-linearity of the pricing schedule and estimate demand for different types of electric appliances. They then estimate the welfare impact of a rate structure change proposed in California. Their results show a strikingly skewed distribution of household electricity price elasticity in the population, with a small fraction of households accounting for most aggregate demand response. Allcott (2011) estimates the demand function from consumers opting for RTP in a pilot program in Chicago. He then estimates the annual short-term consumer surplus increase from RTP, with constant prices and producers' profits. The calculation shows that this RTP program resulted in an annualized consumer surplus gain of about 10 dollars.

Holland and Mansur (2006), Borenstein (2008), Allcott (2012) and Leautier (2014) use existing estimates of price elasticity to assess the welfare impact of RTP. Holland and Mansur (2006) analyze the efficiency, distributional and environmental effects of RTP adoption in the short run. They estimate the short-term welfare impact of exposing some consumers to RTP in the Pennsylvania-New Jersey Maryland market (PJM). The simulations of the PJM electricity market shows that RTP adoption improves efficiency and compresses the distributions of loads and prices. In fact, Holland



and Mansur (2006) show that the annual flat rates and hourly real-time prices decrease with RTP adoption. Allcott (2012) estimates the long-term welfare impact of moving 20 percent of demand to RTP in PJM. He finds that increasing the demand elasticity could increase wholesale electricity prices in peak hours, contrary to predictions from short run models.

The issue of endogenous investment in metering equipment is analyzed in greater details by Leautier (2014). In a socially optimal allocation, he shows that the marginal value of increasing the proportion of consumers in RTP is proportional to the variance of wholesale prices. Then, using data from the French power market, he estimates that, for the vast majority of residential customers whose peak demand is lower than 6 kVA, the net surplus from switching to RTP is lower than 1 €/year for low demand elasticity, and 4 €/ year for high demand elasticity.

In a stylized micro-economic framework, Chiba and Rouillon (2018) attempt to bring together the two issues of the optimal development of intermittent capacities and smart meters. In a social optimum they determine and analyze both the investments in the intermittent technologies and the installation of smart meters. This allows them to emphasize the important role played by the correlation between demand and intermittent supply. The paper challenges the commonly accepted belief that the generalization of smart meters will be needed in response to the penetration of the intermittent generating technologies. Indeed, they show that this holds true only if the electric demand and the intermittent electric generation are negatively correlated or if they are positively correlated but the intermittent capacity is already large enough. In all other cases, intermittent technologies and the installation of smart meters would be substitutes. What we mainly learn from this part of the literature is that despite the many benefits of the widespread use of smart meters, their costs remain the main obstacle to their development.

## **1.4 Public policy**

Since the energy crisis in the 1970s and later the growing concern for climate change in the 1990s, a general scientific consensus now supports greenhouse reduction gas emissions as a neces-

sary measure to fight against climate change. Policymakers and academics agree that the reduction of climate change can be achieved mainly by limiting the production of electricity from fossil fuels. Consequently, incentives to develop RE have been strengthened and RE are receiving increasing support from public authorities because of the social benefits they provide compared to conventional energy sources.

A combination of objectives and energy policies has been adopted in the EU. The 2020 package sets three key targets: a 20 % reduction in GHG compared to 1990 levels, 20 % of EU energy from RE and a 20 % improvement in energy efficiency (European Council, 2009). For 2030 targets are even more ambitious, these include a 40 % reduction in GHG compared to 1990 levels, a 27 % of RE in consumption and 27 % energy savings compared to the usual scenario (European Council, 2014). In its recent Winter Package, the European Commission (2016) recently presented a package of measures which aim is to contribute to a sustainable energy system in its three dimensions. Concerning RE, the package includes a revision of the RE Directive, with cost effective deployment and investor certainty being one of its main objectives. In this context, the EU and its Member States have been and are committed to the deployment of electricity from RE sources. To meet these targets, a wide variety of promotion strategies have been implemented throughout the EU, in recent years. The main target of these strategies is to increase the installed RE capacity in order to enjoy the related environmental and other benefits mentioned above.

From a social perspective, RE are increasingly seen as desirable sources, but their development is slowed down by several barriers (economic, institutional, political and legislative barriers). In response, governments have developed an array of policies to improve the financial situation of RE in order to achieve a more socially optimal investment level.

### **1.4.1 Types of energy policies in the EU**

RE support has been provided with several primary instruments in the EU (Del Rio and Linares, 2014 ; Held et al., 2014). They can be divided into price-based and quantity-based instruments. Table 1 below summarizes the fundamental types of promotion strategies.



	Direct		Indirect
	Price-driven	Quantity-driven	
<b>Investment focused</b>	*Rebates *Tax incentives	*Tradable Green Certificates. *Non-tradable Renewable Portfolio Standards.	*Eco-taxes on electricity produced with non-renewable sources. *Taxes/permits on CO2 emissions.
<b>Generation based</b>	*Feed-in-tariffs. *Rate-based Incentives.	*Competitive bidding process	*Removal of subsidies to fossil and nuclear generation.

Table 1: Fundamental types of promotion strategies. (Held et al. (2006))

### 1.4.2 Regulatory price-driven strategies

In this category of public strategies, there are no quantitative goals. Their main role is to provide financial support to electricity producers. This can be in the form of subsidy per kW of installed capacity or payment per kWh of energy produced. There are a number of variations under this scheme such as:

- **Investment focused strategies:** in this scheme, financial support is provided by investment grants, subsidized loans or tax credits, usually per unit of installed capacity production. To provide incentives for investment the two popular types of strategies are rebates and tax incentives.
- **Rebates:** two large-scale rebate programs for PV and two large-scale rebate programs for wind energy have been implemented in the EU. To promote photovoltaic (PV) in Germany the "1000 roofs program" was launched in 1990. A total of 2250 roofs in Germany were equipped with PV systems, having an average size of 2.6 kW, and a total capacity of about 6 MW. System investment costs were 16700 €/MWh on average, of which the average rebate

capital-subsidy payment was at 70 %. The total installed capacity was 203.6 kW and the average capacity 2.28 kW.

- ***Investment-based*** : different options have been used to promote the generation of electricity from RE with fiscal instruments. For example, lower rates for RE systems and exemptions from income tax dividends for RE-Investment. Both options have similar impacts, acting as investment subsidies for new installations (Faber et al., 2001).

- **Generation based strategies:**

- ***Fixed Feed-in-tariffs and premiums:***

Under Feed-in-tariffs (FIT), governmental institutions, utility companies or suppliers have to pay a fixed tariff for a specified period of time (generally about 15 years) to be provided with renewable electricity from eligible producers. These prices are generally offered in a non-discriminatory manner for every kWh of electricity produced and can be differentiated according to the type of technology as well as a number of other project variables (Fouquet and Johansson, 2008 ; Langniss et al., 2009). This enables a greater number of investors to participate and helps to stimulate rapid RE deployment (Klein et al., 2008 ; Lipp, 2007). Under a FIP model a constant premium over and above the average retail price is fixed. The bonus can be designed either to reflect the environmental and social attributes of RE or to approximate RE project costs (Couture and Gagnon, 2010).

The FIT system operates as a subsidy allocated to renewable electricity producers. However, under this strategy, the amount of RE generated is unknown because the marginal cost curve for wind energy generation is usually unknown. Moreover, the cost of subsidizing RE producers is borne by consumers. It is covered either through cross-subsidies among all electricity consumers like in Spain and Italy or simply by customers, who have to buy green electricity like in Germany until 2000, or by the taxpayer, or a combination of both systems like in Denmark (Menanteau et al., 2003).

FIT are increasingly considered as the most effective policy to stimulate rapid development of RE (Klein et al., 2008). They were identified by the literature to have consistently delivered RE supply more effectively and at a lower cost than other policy mechanisms (Menanteau et al., 2003 ; Stern, 2008 ; Lipp, 2007 ; Butler and Neuhoff, 2008 ; De Jager et al., 2008 ; Fouquet and Johansson, 2008). Indeed, according to the European Commission<sup>7</sup> "*well-adapted feed in tariff regimes are generally the most efficient and effective support schemes for promoting renewable electricity.*" Thus, the main advantage of this system, as described in the literature assessments, is its effectiveness in promoting technology development and diffusion. The main disadvantages that are mentioned by the literature are that fixed tariff systems can become very expensive for consumers and the taxpayer. Moreover, RE producers' profits can be high and the system cannot guarantee that an exact amount of renewable electricity will be provided at a certain time. Finally, the incentives for cost reductions are sometimes insufficient (Del Rio and Gual, 2007 ; Diekman, 2008 ; Verhaegen et al., 2009).

So far, FIT have been the primary instrument used in the EU to support RE. This strategy has undergone some changes during the first part of the period (2007-2010). These changes concern their adaptation to existing systems and modifications in their design (Held et al., 2014). However, since 2011 more significant changes can be observed, mostly to move from FIT towards FIP and auction schemes (AURES project, 2016). This is probably related to their low market compatibility, their relatively high support costs and the fact that after the EU Commission Guidelines on Energy and Environmental Protection Aid (2014-2020), auctions for RE have to be implemented in the EU from 2017.

- ***Rate-based Incentives***

Under this program public utilities have to buy PV electricity at full production cost. Such schemes have gained attention mainly in cities where municipal utilities are responsible for power supply and where local politicians have the power to put these "full cost rates" into practice.

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<sup>7</sup><http://ec.europa.eu/economy-finance/publications/pages/publication12574-en.pdf>

### 1.4.3 Regulatory quantity driven strategies

Regulatory quantity-driven strategies are based on a government decision on the desired level of generation or market penetration of electricity from RE. Generally, the price is set through competition between generators. Under these schemes, the policymakers set a desired quota and a target date, to encourage the market penetration of RE (Haas et al., 2011). Examples of regulatory quantity-driven strategies include:

- ***Non-tradable Renewable Portfolio Standards***: under this scheme electricity producers and distribution companies have to generate a certain amount of electricity from new RE sources. This can either be done with the use of certificates, or by generating the required amount of electricity from their own or independent power producers. The disadvantage of this strategy is that quotas are not tradable which leads to market distortions among the utilities, depending on the geographical conditions of the company. Nevertheless, administration costs can be much lower than under a certification system where the certificates are traded. Non-tradable quotas were used in Austria to meet a quota of 4 percent with newer RE installations by 2007.
- ***Competitive bidding processes***: in the case of competitive tenders, the regulator defines a reserved market for a given quantity of RE and calls for tenders are issued for a defined quantity of capacities. Competition between bidders leads to the winners of bid to receive a guaranteed tariff for a specified period of time. Electricity producers are then obliged to buy electricity from the selected electricity producers (Haas et al., 2011). Under competitive bidding processes, competition focuses on the price per kWh. Proposals are ranked in ascending order according to their cost until the amount that had been set is reached. Each RE producers selected obtains a long-term contract to supply electricity at the price defined during the bid. The implicit subsidies that are awarded to the winners of the bid correspond to the difference between the bid price and the electricity price on the wholesale market.

The competitive bidding procedure enables the marginal production costs of all producers to be identified ex-post and the exact amount of renewable electricity defined by the bids is also



known. However, the overall cost of reaching the target cannot be determined and the extra cost is passed on to consumers (Mitchell, 1996).

Competitive bidding systems have been used in the UK under the Non-Fossil Fuel Obligation (NFFO) set up in 1991. Similar schemes existed in France with the Eole 2005 program set up in 1996, in Scotland (Scottish Renewables Order - SRO) and Northern Ireland (NI-NFFO). The main advantages regarding tendering or bidding systems is their economic efficiency in driving down costs. Moreover, they do not cause market distortion because they generally rely on subsidies. But they generate high administration and transaction costs, permit low diffusion of RE and pose difficulties for small and local, developers (Faber et al., 2001).

- ***Tradable Green Certificate (TGC)***: In this type of scheme,<sup>8</sup> a fixed quota of the electricity that is sold by operators on the market has to be generated from RE. The quota is set for the whole country and is then divided among each of the operators. Then, producers, wholesalers, distribution companies or retailers, have to supply or purchase the required amount of electricity. At the date of settlement, they have to submit the required number of certificates to demonstrate compliance with the quota. Compliance can be achieved by producing the required amount of electricity themselves, by purchasing through long term contracts from a specialized RE producer; or by purchasing certificates for specific amounts of green electricity from other operators (Berry and Jaccard, 2001 ; Voogt et al., 2000). The price of the certificates is generally determined by a certificates market. Under the assumption of perfect market conditions this system should lead to minimal generation costs from RE sources.

According to the existing literature, the main advantages of TGC are that they are cost-efficient, ensure a stable development towards deployment objectives and drive innovation and cost-reduction through competition in both electricity and certificate markets (Morthorst, 2000 ; Menanteau et al., 2003 ; Urge-Vorsatz et al., 2004 ; Madlener and Stagl, 2005 ; Ringel, 2006 ; Del Rio and Gual, 2007 ; Verhaegen et al., 2009). TGC schemes have been applied

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<sup>8</sup>In the U.S. and Japan called renewable portfolio standards (RPS).

in six EU countries: Belgium, Italy, Sweden, Poland, Romania and the U.K, and they have recently been combined with FIT for some technologies.

- ***European Union Emission Trading Scheme – EU ETS*** : In order to harmonize the European environmental policy, a European Union Emission Trading Scheme – EU ETS was established by the Directive 2003/87 / EC of 13 October 2003. It aims to promote the reduction of greenhouse gas emissions in economically efficient and effective conditions. It was implemented within the European Union as part of the EU's ratification of the Kyoto protocol. When it was launched in 2005, the EU ETS was the largest carbon credit trading system in the world. Its implementation takes place in several phases:<sup>9</sup>
- From 1 January 2005 to 31 December 2007, a pilot phase supervised by Directive 2003/87 / EC took place. It was about establishing a carbon price and national quotas.
- Phase 2 corresponds to the application of the Kyoto Protocol (from 1 January 2008 to 31 December 2012) and the inclusion of the aviation sector. Quotas are allocated to electricity producers, free of charge. If a company exceeds the quotas, it can either adapt its installation or buy additional allowances from a company that does not need it at market price.
- Phase 3 (2013-2020) is a strengthening of the system with a view to achieving a 20 percent reduction in greenhouse gas emissions by 2020 (compared to 1990 levels). From 2013 the application of the system will be extended, the national emission ceilings will be replaced by a single European ceiling, and the quota will be reduced linearly each year. The quotas will gradually become payable.
- Phase 4 (2021-2030): on November 10, 2017, the Presidency of the Council of Ministers of the European Union and the European Parliament reached an agreement on the reform of the carbon market for the period 2021-2030. This political agreement must now be formally approved by the European Parliament and the Council. As part of the target of reducing European emissions by 40 % from 1990 to 2030, the emissions of the 11 000 power plants

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<sup>9</sup><http://www.consilium.europa.eu/fr/policies/climate-change/reform-eu-ets/>



and large CO<sub>2</sub> emitting industrial sites covered by the European carbon market will have to be reduced by 43 % compared to 2005 levels.

#### **1.4.4 Indirect strategies**

In addition to strategies that directly target the promotion of one or more specific RE technologies, the regulator can also promote their development through indirect strategies. The most important are: Eco-taxes on electricity produced with non-renewable sources; Taxes/permits on greenhouse gas emissions ; Removal of subsidies previously given to fossil and nuclear generation. For the promotion of renewable electricity via energy taxes or environmental taxes, there are two options : the exemption of RE sector from taxes on fossil fuels ; or if there is no exemption for RES, taxes can be partially or entirely refunded.

Both measures lead to improved competitiveness for RES in the market and apply to both existing and new plants. Environmental taxation is one of the most widespread environmental policy instruments in Europe and has been introduced as a response to increasing environmental degradation. Many countries, for example the Netherlands, Norway, Sweden, Denmark, Finland and Switzerland introduced environmental taxes in the early 1990s. Indeed, the majority of EU member states have used carbon taxes at some stage to reduce greenhouse gas emissions (Castiglione et al., 2018). Carbon tax places a value on pollutant emissions, thus internalizing a portion of the costs associated with their environmental impact. The effectiveness of environmental taxation has been confirmed by numerous studies, demonstrating the positive impact of taxation both on the quality of the environment ( Eakin and Barker, 2001 ; Scrimgeour et al., 2005) and on economic performance (Eurostat, 2013 ; Bento and Jacobsen, 2007 ; Taheripour et al., 2008).

#### **1.4.5 Efficiency of promotion strategies**

The review of the effectiveness and efficiency of various promotion strategies for RE, has attracted growing attention in recent years. The impact of the design of direct policy instruments on the market growth and on the policy costs of different support measures have been the focus of

discussion. In measuring the effectiveness of RE policies, most of the literature has used installed capacity as the dependent variable. For example, a large number of country-level case studies have been carried out across different geographies, for various RE technologies and policy instruments (Jacobsson and Lauber, 2006 ; Wustenhagen and Bilharz, 2006 ; Breukers and Wolsink, 2007 ; Lipp, 2007 ; Toke et al., 2008).

A first part of the literature analyzes the effectiveness of one policy instrument in reaching the objectives that had been set. For example, some economic modelers argue that trading schemes such as TGC may be an effective way of minimizing costs (Palmer and Burtraw, 2005), while several authors have suggested that their efficiency and implementation can easily suffer from market power and transaction cost (Jensen and Skytte, 2003 ; Menanteau et al., 2003 ; Verbruggen, 2009 ; Jacobsson et al., 2009 ; Bergek and Jacobsson, 2010).

On the other hand, feed-in tariffs have been applied in 16 countries, either as the only measure or combined with secondary instruments. Even though they have brought about significant new capacity in Germany, they have been criticized for their cost implications especially in the case of PV (Frondel et al., 2008), and their efficiency diverge at country level. Moreover, results show a variety of outcomes according to the country (Rowlands, 2005 ; Campoccia et al., 2009 ; Luthi, 2011 ; Trujillo-Baute et al., 2018). As we can see, academics do not agree on the effectiveness of instruments. Indeed, the results vary according to the methods and measures that are used.

Another strand of literature compares the efficiency of two environmental policies or more. Usually, the comparison opposes the efficiency of price-driven strategies to quantity-driven strategies. This distinction is relevant as both types of instruments have had quite a different impact on the effectiveness and efficiency of RE support schemes (Held et al., 2014 ; Ragwitz et al., 2007 ; IEA, 2011). Mitchell et al. (2006) compare the UK quota obligation system with the German FIT system and focus on the correlation between risks for generators or investors and policy effectiveness. They conclude that the German FIT system provides higher security for investors than the British Renewable Obligation. Lemming (2003) compares the financial risks of TGC and FI systems. He concludes that the TGC systems pose higher financial risks compared to the FIT systems,

which means that investors require more profits under the first system.

As we can see, when it comes to the efficiency of policy strategies, the main conclusion of the literature is that it is variable. Indeed, the literature has consistently shown that the success of RE promotion critically depends on the choice of instruments and design elements (Eickemeier et al., 2011 ; Menanteau et al., 2003 ; Dinica, 2006 ; Ringel, 2006)).

Huber et al. (2007) summarize the effects of different design elements of RE policy instruments. Their main conclusions are that the careful design of strategies is the most important aspect and that the promotion of newly installed capacity rather than already existing ones is crucial for a successful strategy. Haas et al. (2008, p.1034), compare different promotion strategies for RE and conclude that "*promotional schemes that are properly designed within a stable framework and offer long-term investment continuity produce better results*". Meyer (2007) analyses the major lessons learned from wind energy policies in Denmark, Sweden and Spain. His main conclusion is that the lack or delayed development of such a supportive, stable environment explains the different patterns of wind development seen in Sweden and Spain. Nevertheless, he highlights the problems created by liberalized and short-sighted commercial energy markets, especially for wind energy pioneers such as Denmark, Sweden and Spain. His main conclusion is that the lack or delayed development of such a supportive, stable environment explains the different patterns of wind development seen in Sweden and Spain. Nevertheless, he highlights the problems created by liberalized and short-sighted commercial energy markets, especially for wind energy pioneers such as Denmark.

As can be seen from the literature review, the success of any strategy for achieving RE targets depends on its design and implementation. To sum up, the main conclusion is that price-based and quantity-based systems can be comparable from an ideal theoretical point of view. Still, if we take into consideration uncertainty and efficiency to stimulate technical change, both systems are no longer comparable. Menanteau et al., (2003) gave a detailed summary of the effectiveness of these strategies in achieving four main environmental policy objectives. Their main conclusions are that quantity-based approaches are the most effective in controlling the cost of government

incentive policies. However, in terms of installed capacity, price-based approaches have given far better results than quantity-based ones.

These results are consistent with conclusions given by Haas et al. (2011) in a detailed review of promotion strategies for electricity from RE in EU countries. They compare different support schemes. They conclude that "*a well-designed (dynamic) FIT system provided a certain deployment of RE in the shortest time and at lowest costs for society*". They also highlight the superiority of FIT systems to TGC systems and justify it by three main reasons. First of all, FIT systems are easy to implement and can be revised in a very short time to account for new capacities. Secondly, their administration costs are usually lower than TGC systems. Lastly, they allow for a clear distinction between non-harmonized strategies for existing capacities and harmonized strategies for new capacities. However, as mentioned above the success of promotion strategies depends on design and implementation.

After all, there is an important debate on the efficiency of a fully harmonized EU-wide promotion scheme. So far, the majority of the literature on the subject has come to the conclusion that currently a fully European-wide harmonized scheme cannot be recommended (Haas et al., 2011 ; Toke, 2008). Indeed, Toke (2008, p. 670) suggests that: "*A harmonized EU-wide market-based system, would not improve cost-effectiveness, and may serve to reduce, rather than increase, local investment in renewable energy*". However, since the harmonization of environmental policy is still recent, we cannot we can not judge its effectiveness before seeing the results. It is obviously necessary to keep improving and developing promotion schemes for RE.

## **1.5 Conclusion**

In this chapter, we propose a state of the art of the penetration of renewable energies on the electricity market. So we started by defining the different sources of RE, as well as describing the benefits they generate and the obstacles to their development. We have also reviewed the literature dealing with this subject, trying to answer some questions such as what are the methods used by



the literature to deal with the penetration of RE? What are the obstacles to the development of RE?  
How to promote the RE sector?

This enabled us to detect the possible extensions of the literature, in terms of the problems that are dealt with and the methodologies that are adopted. In addition, this allowed us to position this thesis in relation to existing work and to try to answer some neglected questions.

The most important conclusions drawn from our review of the literature is that firstly, the development of the RE is essential to reduce global warming. Secondly, the biggest obstacle to their development is their intermittent nature, it is therefore necessary to promote them to ensure the expansion of this sector. Thirdly, a careful design of strategies is the most important aspect and that the promotion of newly installed capacity rather than already existing ones is crucial for a successful strategy. Finally, acting on the demand-side of the market can also help to mitigate the problem of intermittency.

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## CHAPTER 2

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# Optimal taxation with intermittent energy sources



## **Preface**

The electricity sector has attracted considerable attention in the debate on climate change mitigation. Policymakers around the world have put in place a wide range of mechanisms to support renewable energy sources. In Europe, environmental taxation is one of the most widespread environmental policy instruments. It has been introduced as a response to increasing environmental degradation. In this chapter we examine how the introduction of an environmental tax on polluting emissions from the conventional sector affects investments in renewable technologies. Considering the electricity generation framework, where the pollutant increases linearly and the marginal damage is increasing, a model is proposed to challenge the conventional idea according to which an environmental tax would have a positive impact on investment in renewable energy technologies. We argue that this relationship is more complicated than it is usually thought, because of the intermittency of renewable energy sources.

## 2.1 Introduction

The increasing interest to mitigate global warming by greening the electricity sector have generated an important range of environmental public policy to support renewable energy (RE). Environmental taxation is one of the most widespread environmental policy instruments in Europe and has been introduced as a response to increasing environmental degradation. Many countries, such as the Netherlands, Norway, Sweden, Denmark, Finland and Switzerland introduced environmental taxes in the early 1990s. Indeed, the majority of EU member states have used carbon taxes at some stage to reduce greenhouse gas emissions (Castiglione et al., 2018). Carbon taxes place a value on SO<sub>2</sub> and other emissions, thus internalizing a portion of the costs associated with their environmental impact. The effectiveness of environmental tax has been attested by numerous studies demonstrating the positive impact of taxation both on the quality of the environment (EEA, 2005 ; Scrimgeour et al., 2005) and on economic performance (Eurostat, 2013 ; Bento and Jacobsen, 2007 ; Taheripour et al., 2008).

However, the introduction of RE sources into the energy mix is a new challenge for regulators and producers. In addition to the standard issues of transportation and electricity distribution, intermittent energy sources also present problems at the production stage. This is due to the dependence of electricity production from RE sources on weather conditions. As a consequence, the electricity supply is variable and unpredictable. But consumers need electricity to be available at a given price, anytime and for any level of demand. In the absence of large-scale and efficient energy storage, there is a risk of incompatibility between supply and demand. As black-outs are very costly both economically and politically, electricity production and supply must match the consumers' demand at any time and location. The variability of intermittent energy sources is thus inconsistent with a reliable electricity supply. Therefore, it is important to analyze the effectiveness of environmental taxation in the presence of intermittent sources in the energy mix to take into account the new characteristics of the electricity market.

To address these issues, we extend the model developed in Rouillon (2014), assuming constant

demand and taking into account the environmental damage induced by electricity production from fossil fuels. First, we show that the optimal investment in intermittent renewable technologies can be explicitly calculated. Secondly, we discuss the decentralization of the optimal policy in a competitive market with a tax on pollution. Besides, we show that the intermittency of RE sources coupled with the assumption of increasing environmental marginal damage prevents the tax at a constant rate from implementing the optimal state. Finally, we propose a constrained second-best solution with a tax rate that minimizes the resulting loss. Our results show that the intermittency of RE challenges the standard properties of efficiency of the tax .

The problem of RE intermittency has already been treated by the literature. For example, Ambec and Crampes (2012) study the interaction between a reliable source of electricity production and intermittent sources. They analyze the decentralization of the optimal energy mix, through competitive market mechanisms. They show that this model requires electricity to be priced contingently on the availability of the intermittent source. Rouillon (2014) analyzes the development of intermittent technologies with the competition from incumbent generators, under perfect and imperfect competition, using various assumptions about market power. In contradiction to Ambec and Crampes (2012), he shows that the optimal policy can be decentralized under perfect competition. This is because conventional and intermittent generators exchange their electric production on a wholesale spot market, where the price varies according to the availability of the intermittent source of electricity. This runs contrary to Ambec and Crampes (2012), who implicitly assume that no wholesale spot market exists. However, this literature on intermittency does not consider public policies and environmental externalities. This is an essential feature of the present chapter.

To date, the literature on public policies to green electricity production has ignored the problem of intermittency. For example, Fischer and Newell (2008) and Acemoglu et al. (2012) have looked at pollution externalities in a dynamic framework, and Fullerton and Heutel (2010) in general equilibrium. They have considered two substitutable technologies: pollutant and clean technologies. Compared to this literature, the present chapter provides a new perspective on the question by deriving from a stylized micro-economic framework some general insights into the optimal

development of intermittent technologies to generate electricity. In our chapter, the degree of substitution between power generation units is more precise since it depends on weather conditions. Consequently, installed capacity and electricity production also vary with climatic conditions. This introduces uncertainty in the energy supply which has to satisfy constant demand.

The closest paper to our framework in the literature is Ambec and Crampes (2014). They characterize the optimal dispatch and investment in intermittent and conventional technologies and discuss the efficiency of three public policies: a carbon tax, feed-in tariffs and renewable portfolio standards, under perfect competition. They postulate constant returns-to-scale technologies, with capacity constraints for conventional and intermittent sectors. In contrast, we adopt the hypothesis of increasing marginal cost with no capacity constraints for the conventional sector. This hypothesis is used and explained in Rouillon (2014) and *"is appropriate to represent the initial situation where conventional firms have many production units, using a wide variety of conventional technologies with different marginal costs of electricity generation and where the overall capacity of this set of units is sufficient for demand to avoid the blackout"*. This context corresponds quite well to the current situation of several European countries such as Germany, where there is an over-capacity of conventional units remaining in operation until the end of their scheduled lifetime.<sup>1</sup> Moreover, contrary to Ambec and Crampes (2014), we use the hypothesis of increasing environmental marginal damage. This assumption is important in that it highlights the additional challenges imposed on regulators for the introduction of RE sources in the energy mix. The model gives us insight into how this environmental tax affects investment in capacity production, energy use, electricity supply, environmental pollution and welfare.

The rest of the chapter is organized as follows. We extend the model developed by Rouillon (2014) by introducing environmental damage into the analysis. For convenience, Section 2 summarizes its main features and results. Readers who are familiar with the model can proceed to Section 3, which describes the optimal energy mix and gives some comparative statics results. Section 4 discusses the decentralization of the optimal state in a competitive market with a tax on polluting

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<sup>1</sup><https://www.wwf.fr/vous-informer/actualites/europes-dirty-30-la-politique-climat-de-lunion-europeenne-mise-a-mal-par-le-charbon>

emissions. In section 5, we propose a constrained second-best solution. Finally, section 6 is a conclusion.



## 2.2 The model

We consider a model of energy production and supply with intermittent energy. On the demand side, consumers are equipped with traditional meters and sign fixed-price contracts with retailers on the contract markets. The population size is normalized to 1. Each consumer's inverse demand function is  $P(D)$ . Define  $S(D) = \int_0^D P(s)ds$  the consumer's surplus of consuming  $D$  kWh of electricity. On the supply side, electricity can be produced by means of two technologies. First, using conventional generators, the incumbent firms supply electricity in quantity  $q$ . The cost function  $C(q)$  represents their technology. It is assumed that  $C'(0) = 0$ ,  $C'(q) > 0$  and  $C''(q) > 0$ . The second technology comes from a competitive fringe who seeks to enter the market using intermittent generators. The investment cost of building intermittent units is  $F(k)$ . It is assumed that  $F(0) = 0$ ,  $F'(k) > 0$  and  $F''(k) \geq 0$ .

Uncertainty is essential to address the interaction between the conventional and intermittent generators. The variability of climatic conditions (sun and/or wind) is modeled as a random variable  $\omega$ . It is distributed on  $\omega \in [\omega_0, \omega_1]$ , with cumulative distribution function  $G(\omega)$ . For all  $\omega$ , given the installed capacity  $\bar{\omega}k$ , the intermittent generation will be equal to  $\omega k$ , at a negligible marginal cost. To simplify and normalize the units, it is assumed that  $E[\omega] = 1$ . Accordingly, the variance of  $\omega$  is  $V = E[\omega]^2 - 1 > 0$  and the intermittent generation has a capacity factor of  $1/\bar{\omega}$ .<sup>2</sup>

### Environmental damage

We introduce environmental damage to the model to better analyze the penetration of RE in the electricity market. This is important to address the trade-off between the two externalities that should be internalized, i.e., the variability of intermittent production and polluting emissions from the conventional sector. The electricity production of the conventional sector emits air pollutants ( $SO_2$ ) which cause damages to society. It is assumed that emissions, denoted  $Z$ , are proportional to production. Without loss of generality, we normalize the units so that  $Z = q$ . The damage from pollution depends on total pollution  $Z$  and the social damage function is  $d(Z)$ .<sup>3</sup>

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<sup>2</sup>As in Rouillon (2014), the capacity factor is defined as the ratio of the potential input i.e.,  $\frac{E[\omega k]}{\bar{\omega}k} = \frac{k}{\bar{\omega}k} = \frac{1}{\bar{\omega}}$ .

<sup>3</sup>Since  $Z = q$ , for the rest of the chapter  $d(q)$  replaces  $d(Z)$ .

To simplify, we assume that consumers' demand does not vary with weather conditions. Furthermore, as electricity cannot be stored and the only way to balance supply and demand is to rely on production adjustment or / and price variations.

For the rest of the chapter, we will use the following linear quadratic specification of the model:<sup>4</sup>

$$C(q) = \frac{1}{2}cq^2,$$

$$d(Z) = \frac{1}{2}zZ^2,$$

$$F(k) = \left( \gamma + \frac{1}{2}\delta k \right) k.$$

## 2.3 Optimal policy

The social problem is to choose the consumption of consumers  $D$ , the electric generation of the conventional generators  $q(\omega)$ , for all  $\omega$ , and the capacity of the intermittent generators  $k$ ,<sup>5</sup> to maximize

$$\int_{\omega_0}^{\omega_1} [S(D) - C(q(\omega)) - d(q(\omega))] dG(\omega) - F(k), \quad (1)$$

subject to

$$D = q(\omega) + \omega k, \text{ for all } \omega. \quad (2)$$

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<sup>4</sup>From our assumptions above, all parameters are positive.

<sup>5</sup>For convenience, we will sometimes denote  $k$  as intermittent capacity, with a slight abuse. Strictly speaking, the intermittent capacity is  $\bar{\omega}k$ .

The Lagrangian of this problem writes:

$$L = \int_{\omega_0}^{\omega_1} \begin{bmatrix} S(D) - C(q(\omega)) - d(q(\omega)) \\ -\lambda(\omega)(D - q(\omega) - \omega k) \end{bmatrix} dG(\omega) - F(k), \quad (3)$$

where the Lagrangian multiplier  $\lambda(\omega)$  reflects the implicit price of electricity in the state  $\omega$ .<sup>6</sup>

The optimal solution will be denoted  $D^o$ ,  $k^o$  and  $q^o(\omega)$ , for all  $\omega$ . Rearranging the relevant first-order conditions derived from (3), we can show that the optimal solution satisfies:

$$\lambda(\omega) = C'(q^o(\omega)) + d'(q^o(\omega)), \text{ for all } \omega, \quad (4)$$

$$P(D^o) = \int_{\omega_0}^{\omega_1} (C'(q^o(\omega)) + d'(q^o(\omega))) dG(\omega), \quad (5)$$

$$F'(k^o) = \int_{\omega_0}^{\omega_1} (C'(q^o(\omega)) + d'(q^o(\omega))) \omega dG(\omega). \quad (6)$$

From condition (4), we show that, for every state of nature  $\omega$ , the conventional generators should increase their production as long as their marginal cost is smaller than the price of electricity minus the environmental marginal damage. Conditions (5) shows that, for every state of nature  $\omega$ , consumers should raise their consumption as long as their marginal propensity to pay is larger than the expected electricity price minus the environmental marginal damage. Finally, from condition (6) the intermittent capacities should be increased as long as the investment's cost in the intermittent unit remains smaller than its expected marginal benefit. In the state of nature  $\omega$ , the marginal benefit of investing in the intermittent units is the product of the implicit price of electricity, times the productivity of the marginal generating unit  $\omega$ .<sup>7</sup>

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<sup>6</sup>We suppose that  $\lambda(\omega) > 0$ , for all  $\omega$ .

<sup>7</sup>Most electricity markets have price caps in place. This point is directly related to the possibility of blackouts, i.e. there may not be sufficient conventional capacity to supply residual demand when the spot price is at the price cap. In this case there are two possibilities. The first is the case where the electricity spot price will never exceed the price cap on the optimum trajectory. In this case it has no effect on our results. The second possibility is when the spot price of electricity exceeds the price cap. In this case the ceiling price prevents the realization of the optimal solution.

The optimal dispatch and investment program as well as the comparative statics yield familiar results<sup>8</sup> and some of them must be emphasized. First, the intermittency of RE supply increases the variability of residual demand, requiring the mobilization of expensive peak-load capacity which induces an increase in the price of electricity. Formally, we show in the Appendix that the expected price of electricity is increasing in  $V$ . Moreover, the intermittency of RE constitutes an important obstacle to their development. Indeed, it makes the investment in renewable technologies riskier and less profitable. Thus, the more variable the climatic conditions are, the lower will be the investment in these capacities. Formally, we show in the Appendix that the intermittent capacity  $k^o$  is decreasing in  $V$ .

## 2.4 Competitive equilibrium with emissions tax

In this section, assuming perfect competition, we analyze the impact on electricity production and welfare of a tax on polluting emissions of conventional generators. Assume that the regulator charges conventional generators a tax on their polluting emissions. Let  $T$  denote the tax rate unit of emission that they produce. We consider a market economy with free entry and price-taker producers and retailers. The system of markets is as follows. There is a full set of spot and forward markets. On the spot market, electricity operators sell to retailers at real-time pricing. On the forward market, consumers sign contracts with retailers at fixed prices. Wholesale prices are expected to result from competition among generators, and retail prices would result from competition among retailers serving the final customers. Thus, equilibrium prices are determined by the producers' and retailers' supply functions, as well as by demand from retailers and consumers. This organization of the electricity market is illustrated in Figure 6.

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<sup>8</sup>for more details, see Rouillon (2014) or the summary included in the Appendix for the reader's convenience.

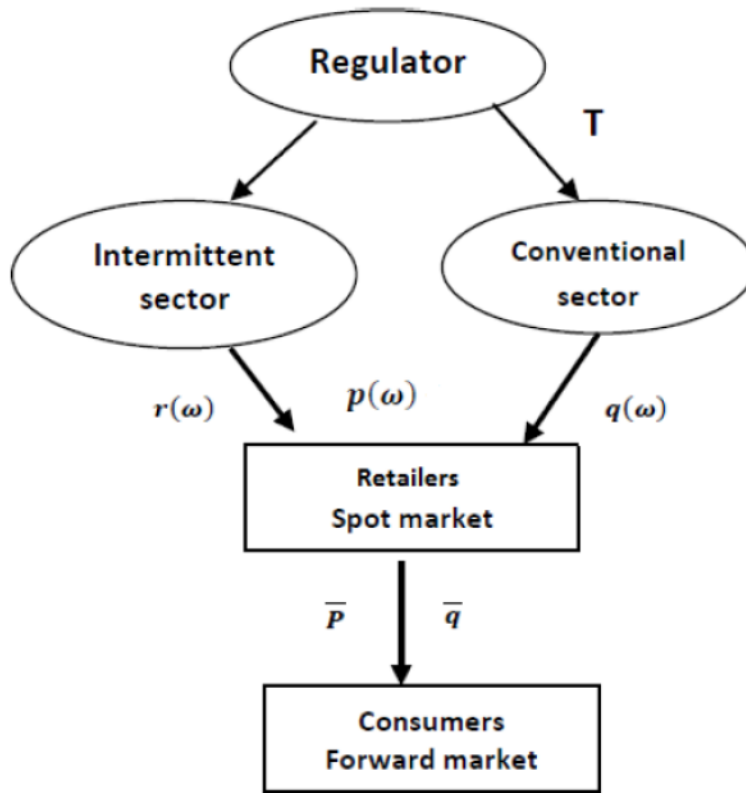


Figure 6: Market design with a tax on polluting emissions

The timing of the decisions is the following. In the first stage, the regulator fixes the tax rate ( $T$ ). In the second stage, the intermittent generators invest in generating units ( $k$ ). In the third stage, consumers sign contracts with retailers (quantities  $\bar{q}$  at price  $\bar{p}$ ). In the fourth stage nature determines the climatic conditions ( $\omega$ ). In the last stage, generating units decide their electricity production on the spot market ( $q(\omega)$  and  $r(\omega)$  at price  $p(\omega)$ ).

The market equilibrium is now obtained by working backward in the game tree.



### 2.4.1 Spot market

Let  $\bar{p}$  and  $\bar{q}$ , respectively, be the equilibrium price and the volumes of contracts that the retailers have previously signed with consumers on the forward market. For all  $\omega$ , let  $p^*(\omega)$ ,  $q^*(\omega)$  and  $\omega k^*$ , represent the equilibrium spot price and quantities of electricity from conventional and intermittent sectors in the state  $\omega$ . On the spot market, intermittent generators supply  $\omega k^*$ , and conventional generators produce  $q^*(\omega)$  such that:  $q^*(\omega) = \bar{q}^* - \omega k^*$ .

### 2.4.2 Contract market

The retail sector purchases electricity from generators on the spot market and distributes it to the final customers in the contracts market. Firms in the retail sector are assumed to have no costs other than the wholesale cost of the electricity that they buy for their retail customers. Equilibrium prices in the retail sector are determined by competition among retailers. Each consumer demands  $\bar{q}$  such that  $P(\bar{q}) = \bar{p}$ . Retailers supply  $\bar{q}$  at price  $\bar{p}$ . They anticipate that they will buy their electricity at the spot price  $p(\omega)$ , for all  $\omega$ . Thus, in equilibrium, the price of contracts  $\bar{p}$  must be equal to the expected price of the electricity on the spot markets  $\bar{p} = E[p(\omega)]$ .

This is because if  $\bar{p}$  were greater than the wholesale price, a competing retailer could make profits by undercutting  $\bar{p}$  and attracting more customers. Since charging a price lower than the wholesale price would imply losses, competition forces the flat retail rate to be set to cover exactly the cost of providing electricity to the flat-rate customers. Thus competition among retailers drives  $\bar{p}$  to be equal to the average of the wholesale price.

In the contract market the equilibrium price must verify  $\bar{p}^* = E[p^*(\omega)]$ . Thus  $p^*(\omega)$  is determined by the following condition :

$$C'(q^*(\omega)) = C'(D^* - \omega k^*) = p^*(\omega) - T. \quad (7)$$

Rearrange we obtain:

$$p^*(\omega) = C'(q^*(\omega)) + T, \quad (8)$$

$$P(D^*) = \int_{\omega_0}^{\omega_1} C'(q^*(\omega))dG(\omega) + T, \quad (9)$$

Thus, the tax generates the desired effects, since the aim of such a regulation is to increase the price of fossil fuels, as well as the goods and services which use them for their production and distribution. The increase in prices, proportional to  $SO_2$  content, sends a price signal to producers and consumers, encouraging them to reduce their consumption and to shift towards the products that generate the least  $SO_2$  emissions.

Using the linear-quadratic specification of the model and integrating using  $E(\omega) = 1$ , we show in the Appendix:

$$D^* = \frac{a + ck^* - T}{b + c},$$

and

$$q^*(\omega) = \frac{a + ck^* - T}{b + c} - \omega k^*.$$

Other things equal, it is clear that the conventional generation  $q^*(\omega)$  is decreasing with the tax on polluting emissions. Thus, the tax increases the costs of the conventional sector and therefore reduces its production. It is also useful to observe how the electricity market should adapt in the short term due to the variability of intermittent generation. From the expression of  $q^*(\omega)$ , we see that conventional generators should adjust their supply so as to smooth the variable generation of the intermittent technologies. Formally,  $q^*(\omega)$  is decreasing in  $\omega$ .

### 2.4.3 Investment in intermittent technologies

The intermittent generators anticipate the equilibrium price  $p^*(\omega)$ , for all  $\omega$  and correspondingly choose  $k^*$  to maximize:

$$\pi = \int_{\omega_0}^{\omega_1} p(\omega) \omega k dG(\omega) - F(k).$$

Under the assumption of perfect competition, the equilibrium capacity will satisfy:

$$F'(k^*) = \int_{\omega_0}^{\omega_1} C'(q^*(\omega)) \omega dG(\omega) + T. \quad (10)$$

The introduction of the environmental tax benefits to the intermittent sector by means of two ways. First, the tax makes conventional energy sources more expensive and thus promotes the use of RE. Second, the tax increases the electricity price and consequently boosts the expected benefits of investment in intermittent generations. Formally, the installed intermittent capacity is increasing with the tax  $T$ .

#### **4.4. (In)efficiency of the taxation at the expected environmental marginal damage level**

In this section we analyze a tax effectiveness to implement the first-best solution through the competitive market equilibrium. Let  $\bar{T}$ , be the tax rate equal to the expected environmental marginal damage in a social optimum :

$$\bar{T} = \int_{\omega_0}^{\omega_1} d'(q^o(\omega)) dG(\omega).$$

Under these conditions we propose the following proposition:

##### **Proposition 1:**

*In the presence of intermittent energy sources in the energy mix and the hypothesis of increasing environmental marginal damage, the constant tax rate  $\bar{T}$  does not implement the first-best resource allocation.*

To prove proposition 1, let us first consider the implementation of the optimal demand level with the taxation at the expected environmental marginal damage level  $\bar{T}$ . To do this, we compare

conditions characterizing the optimal and the equilibrium demand levels:

$$P(D^*) = \int_{\omega_0}^{\omega_1} C'(q^*(\omega)) dG(\omega) + T,$$

$$P(D^o) = \int_{\omega_0}^{\omega_1} (C'(q^o(\omega)) + d'(q^o(\omega))) dG(\omega).$$

If we inject the optimal quantities, i.e.,  $q^o(\omega)$  and  $D^o$  and substitute  $T$  by  $\bar{T}$  in the equilibrium condition, we find the same condition characterizing the optimal state:

$$P(D^o) = \int_{\omega_0}^{\omega_1} (C'(q^o(\omega)) + d'(q^o(\omega))) dG(\omega). \quad (11)$$

Thus, the tax rate  $\bar{T}$  implements the optimal quantity on the demand side. Formally, equations (5) and (9) coincide. This is because on the forward market retailers insure consumers, free of charge, against price volatility. Thus, the variability of RE does not represent an externality in this market. However, a necessary condition is that retailers must be risk neutral as long as  $\omega k^o > 0$ .<sup>9</sup> Indeed, risk aversion among retailers would induce a risk premium in the electricity price, which would reduce electricity consumption to below the first-best level.

However, at the expected environmental marginal damage level the taxation  $\bar{T}$  does not implement the optimal level of incentives for investment in intermittent capacities. To show this, we compare conditions characterizing the optimal and equilibrium investment in intermittent generations:

$$F'(k^*) = \int_{\omega_0}^{\omega_1} C'(q^*(\omega)) \omega dG(\omega) + T,$$

$$F'(k^o) = \int_{\omega_0}^{\omega_1} (C'(q^o(\omega)) + d'(q^o(\omega))) \omega dG(\omega).$$

Thus, by injecting the optimal quantities as for  $q^o(\omega)$ ,  $D^o$  and replace  $T$  by  $\bar{T}$  in the condition of the equilibrium investment, we find that it differs from the condition characterizing an optimal

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<sup>9</sup>Since the risk comes from the variability of renewable energies, as long as there is electricity generation from renewable energy, there is uncertainty about the amount of electricity produced and the price of electricity.

outcome:

$$F'(k^o) \neq \int_{\omega_0}^{\omega_1} C'(q^o(\omega))\omega dG(\omega) + \int_{\omega_0}^{\omega_1} d'(q^o(\omega))dG(\omega).$$

As a consequence, the taxation at the expected marginal damage level  $\bar{T}$ , does not implement the optimal state. This result differs from Ambec and Crampes (2015), who decentralize the first-best with a Pigouvian tax. The difference between their and our results stems essentially from our assumption of increasing environmental marginal damage. Indeed, in our context it is not the intermittency of RE in itself that prevents the decentralization of the optimal state, but the interaction between intermittent sources and increasing environmental marginal damage. Thus, the coexistence of these two conditions makes the environmental damage variable dependent upon the state of nature, and also increasing with conventional production.

This is due to the introduction of RE sources which implies that the tax should internalize two market failures that are not corrected by the market. The first one, is the standard externality of pollution caused by electricity production from fossil fuels. To internalize it, the tax sends a price signal to producers and consumers, encouraging them to reduce their consumption and to move towards the products that generate the least polluting emissions. The second market failure is due to RE intermittency. The intermittency of RE sources coupled with the assumption adopted of increasing environmental marginal damage, prevents the tax at the constant rate to internalize simultaneously these two market failures. Thus, with a tax that does not vary, we do not decentralize the optimal state. Choosing a tax rate suitable to different levels of conventional production and pollution requires that the tax rate should vary with climatic conditions. Hence, we make the second proposition:

**Proposition 2:**

*In the presence of intermittent energy sources and increasing environmental marginal damage, the optimal state can be implemented by a tax on pollution only if the tax rate can vary with the availability of renewable energy sources.*

This proposal is consistent with Ambec and Cramps (2015) who suggest that "*The Pigou tax*



rate is easy to compute under our assumption of constant marginal damage due to pollution. It would be more complex under alternative assumptions on environmental damage such as increasing marginal damage. The Pigou tax rate would then vary with the state of nature (whether there is wind or not) or with pollution concentration".

## 2.5 Second-best solution

We have shown in this context that the tax rate equal to the expected marginal damage by emissions in the optimal allocation does not yield the first-best resource allocation. There is still the question of what tax rate minimizes the resulting loss associated with imbalance in incentives to invest in intermittent capacities. To answer this question we use our previous results to determine a constrained second-best tax rate.

The social problem is to choose the consumption of consumers  $D$ , the electric generation of the conventional generators  $q(\omega)$ , for all  $\omega$ , the capacity of intermittent generators,  $k$ , and the tax rate  $T$ , to maximize:

$$\int_{\omega_0}^{\omega_1} [S(D) - C(q(\omega)) - d(q(\omega))] dG(\omega) - F(k), \quad (12)$$

subject to

$$D = q(\omega) + \omega k, \text{ for all } \omega, \quad (13)$$

and<sup>10</sup>

$$F'(k) = P(D) + \int_{\omega_0}^{\omega_1} C'(q(\omega)) (\omega - 1) dG(\omega). \quad (14)$$

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<sup>10</sup>This condition is obtained by equalizing and simplifying the conditions of market equilibrium.

The Lagrangian of this problem writes:

$$L = \int_{\omega_0}^{\omega_1} \begin{bmatrix} S(D) - C(q(\omega)) - d(q(\omega)) - F(k) \\ -\lambda(\omega)(D - q(\omega) - \omega k) \\ -\beta(F'(k) - P(D) - C'(q(\omega))(\omega - 1)) \end{bmatrix} dG(\omega), \quad (15)$$

where the Lagrangian multipliers  $\lambda(\omega)$  and  $\beta$  reflect, respectively, the implicit price of electricity in the state  $\omega$  and the price of incentive constraints for each sub-market.

Let  $q^s(\omega)$ , for all  $\omega$ ,  $D^s$ ,  $k^s$  and  $T^s$ , be the second-best solution. It satisfies the following first order conditions:

$$\lambda(\omega) = C'(q^s(\omega)) + d'(q^s(\omega)) - \beta C''(q^s(\omega))(\omega - 1), \text{ for all } \omega,$$

$$P(D^s) + \beta P'(D^s) = \int_{\omega_0}^{\omega_1} \lambda(\omega) dG(\omega),$$

$$F'(k^s) + \beta F''(k^s) = \int_{\omega_0}^{\omega_1} \lambda(\omega) \omega dG(\omega).$$

### ***Second-best solution vs optimal state***

To compare the second-best solution with the optimal state we rearrange the first-order conditions above to get:<sup>11</sup>

$$P(D^s) - \int_{\omega_0}^{\omega_1} (C'(q^s(\omega)) + d'(q^s(\omega))) dG(\omega) = \Delta, \quad (16)$$

$$F'(k^s) - \int_{\omega_0}^{\omega_1} (C'(q^s(\omega)) + d'(q^s(\omega))) \omega dG(\omega) = \Delta'. \quad (17)$$

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<sup>11</sup>To simplify the presentation we let:

$$\Delta = -\beta \left( \int_{\omega_0}^{\omega_1} (\omega - 1) C''(q^s(\omega)) dG(\omega) + P'(D^s) \right) \text{ and}$$

$$\Delta' = -\beta \left( \int_{\omega_0}^{\omega_1} (\omega - 1) \omega C''(q^s(\omega)) dG(\omega) - F''(k^s) \right).$$

We use the constraint of the market equilibrium and replace it in the first-order conditions to obtain the following:<sup>12</sup>

$$T^s - \int_{\omega_0}^{\omega_1} d'(q^s(\omega))dG(\omega) = \Delta. \quad (18)$$

If we place the optimal quantities on the left side of the conditions above (from (16) to (18)), we find the same conditions characterizing the optimal state. So, the difference between the optimal state and the second-best solution depends on the sign of the term on the right-hand side of each equality. It is necessary to know in what direction the results of the second-best solution diverge from the optimal state. To do this, we analytically resolve the model with its linear quadratic specification.

Using the linear-quadratic specification we can show in the Appendix:

$$q^s(\omega) = \frac{a + (c + z)k^s}{b + c + z - b\frac{z}{b+\delta+Vc}(\omega - 1)} - \omega k^s,$$

$$\beta = -z\frac{k^s}{b + \delta + Vc}V,$$

$$k^s = \frac{\frac{c+z}{b+c+z}a - \gamma}{\frac{s}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV - Vbz\frac{\delta+Vc}{(b+c+z)(b+\delta+Vc)}},$$

$$T^s = z\left(\frac{a + (c + z)k^s}{b + c + z}\right) - k^s - z\frac{k^s}{b + \delta + Vc}V.$$

It is clear that  $\beta$  is decreasing in the environmental marginal damage ( $z$ ) and in the variability of the renewable generation ( $V$ ). This result is intuitive and confirms our previous results. Pollution and intermittency constitute the adverse side of electricity production, since they reduce the social surplus. Hence the following proposition:

**Proposition 3**

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<sup>12</sup>See the Appendix for more details.

*The divergence between the optimal state and the second-best solution increases with the variability of renewable energies and with the environmental marginal damage.*

Under the linear-quadratic specification of the model we show in the Appendix that, for  $b > 0$  and  $z > 0$ :

$$T^s < \int_{\omega_0}^{\omega_1} d'(q^o(\omega))dG(\omega).$$

$$k^s > k^o,$$

and

$$q^s(\omega) < q^o(\omega),$$

The results of the second-best solution seem counter-intuitive since the second-best tax rate should be lower than the expected environmental marginal damage. Surprisingly, not only does it induce a decrease in conventional production but also an increase in investment in the intermittent sector, compared to the optimal state. This result is interesting, since it challenges the often-accepted causal relationship between the rate of environmental tax and investment in intermittent capacities. Indeed, one would expect that the higher the tax rate is, the higher will be the investment in the renewable sector. However, we show that this relationship is more complex than usually thought, due to the intermittency of RE sources.

**Proposition 4:**

*The interaction between constant demand and the intermittency of renewable energy sources implies that the tax rate that minimizes welfare losses and internalizes both the externality of pollution and the market failure of renewable energy intermittency, is below the expected environmental damage at the optimal state and generates greater investment in renewable technologies.*

To explain the mechanism behind these results, consider an example with two states of the world. A case when RE are abundant and the other when they are scarce, with equal probability of 1/2 for each state.

On the one hand, when RE are abundant, conventional generation will decrease.<sup>13</sup> Since we use more clean energy sources and fewer polluting energy sources, the environmental damage will be lower. In this case, the tax should decrease as it is supposed to be proportional to the environmental damage, but it remains constant by hypothesis. So, when there is a lot of RE available the tax remains too high compared to the optimum. Consequently, the price of electricity is maintained above what it should be at the optimum ( $p^*(\omega) > p^o(\omega)$ ). Thus, the difference between the level of the tax rate and the environmental damage level during these periods, represents extra benefits for the intermittent sector. This increases the profitability of investment in intermittent sector and disadvantages conventional sector which does not profit from the price increase since it produces very little during these periods.

On the other hand, we have the inverse phenomenon, when RE are scarce. To compensate, conventional production must be higher and, as a result, the environmental damage is greater. The tax should increase proportionally to the environmental damage, but it remains constant by assumption ( $\bar{T} < \int_{\omega_0}^{\omega_1} d'(q^o(\omega))dG(\omega)$ ). So the constant tax leads to electricity prices that are too low compared to the optimum ( $p^*(\omega) < p^o(\omega)$ ). This disadvantages the conventional sector during these periods, as it sells its electricity production at price lower than it should be.

Investment in intermittent capacities depends on the average selling price of RE, which is equal to the average electricity selling price, weighted by renewable supply. As the selling price is too high when the intermittent sector sells a lot (very windy/sunny) and too low when the sector sells less (no wind/sun), a constant tax rate benefits the intermittent sector on average and supports investment in renewable capacities.

Finally, as there is an over-investment in the intermittent sector, on average, the environmental marginal damage is lower (because with constant demand, less fossil electricity is used), which justifies applying a lower tax rate than the expected environmental marginal damage that would prevail in the optimal state.

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<sup>13</sup>Wind and solar energy have very low marginal costs, their electricity is less costly on the spot market than that from coal or natural gas, and transmission companies buy from them first (Sensfub et al. (2007)).



## 2.6 Conclusion

The penetration of RE in the electricity market could generate many advantages such as reducing dependence to fossil fuels, improving security, creating new investments and jobs and most importantly reducing environmental damage. For these reasons, RE are globally supported by several environmental policy measures to promote their development. Nevertheless, given their intermittent nature, the production of electricity from these sources is variable and unpredictable, which introduces more pressures and problems on the electricity grid. Thus, to tackle the additional challenges induced by the penetration of RE in the electricity market, efficiently and correctly well-designed environmental policy is needed.

In this chapter, we have considered the way a tax on emissions may decentralize the socially optimal outcomes in a competitive market with spot and contract markets. We show that an optimal investment in intermittent technologies can not be implemented under perfect competition if the tax rate is constant. We also find that investment in renewable technologies does not necessary vary in the same way as the tax rate. This result is interesting since it calls into question the often-accepted causal relationship between the rate of environmental tax and investment in intermittent capacities. This result is important from the perspective of policy implications and highlights the need to take into account the intermittency of renewable energies in order to achieve environmental objectives. The model affords us insight into how this environmental tax affects investment in capacity production, energy use, electricity provision, environmental pollution and welfare.

More can be done within our framework. First, other sources of intermittent energy can be considered. The diversification of energy sources is a possible solution to mitigate intermittency. Our model can be extended to accommodate several intermittent sources of energy with heterogeneous costs and occurrences. Another question the model can address is to allow disinvestment in conventional capacity, because what has occurred in many electricity markets is that as renewable capacity increases, coal-fired power plants are “mothballed” or altogether withdrawn from the market.

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# Appendix

## 2.7 Optimal policy

Using the following first order conditions:

$$\int_{\omega_0}^{\omega_1} (P(D^o) - \lambda(\omega)) dG(\omega) = 0,$$

$$\lambda(\omega) - C'(q^o(\omega)) - d'(q^o(\omega)) dG(\omega) = 0, \text{ for all } \omega,$$

$$\int_{\omega_0}^{\omega_1} (\lambda(\omega) \omega - F'(k^o)) dG(\omega) = 0.$$

and considering the linear quadratic specification of the model. The optimal allocation ( $D^o$ ,  $k^o$  and  $q^o(\omega)$  for all  $\omega$ ), satisfies the following system:

$$\int_{\omega_0}^{\omega_1} D^o dG(\omega) = \int_{\omega_0}^{\omega_1} q^o(\omega) dG(\omega) + E(\omega) k^o,$$

$$P(D^o) = a - bD^o = (c + z) \int_{\omega_0}^{\omega_1} q^o(\omega) dG(\omega),$$

$$\gamma + \delta k^o = (c + z) \int_{\omega_0}^{\omega_1} q^o(\omega) \omega dG(\omega).$$

We use the first two equations to get:

$$D^o = \frac{a + (c + z)k^o}{b + c + z},$$

and

$$q^o(\omega) = \frac{a + (c + z)k^o}{b + c + z} - \omega k^o, \text{ for all } \omega.$$

Then substitute  $D^o$  and  $q^o$  into the last two equations and integrate using  $E[\omega] = 1$  and

$E[\omega^2] = V + 1$  to write

$$\gamma + \delta k^o = (c + z) \frac{a + (c + z)k^o}{b + c + z} - (c + z)(V + 1)k^o.$$

Finally solve this system to obtain:

$$k^o = \frac{\frac{(c+z)}{b+c+z}a - \gamma}{\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV}.$$

## 2.8 Comparative statics

Differentiation of  $\omega k^o$  gives:

$$\frac{\partial k^o}{\partial a} = \frac{\frac{c+z}{b+c+z}}{\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV} > 0,$$

$$\frac{\partial k^o}{\partial b} = -\frac{a(c+z)}{(b+c+z)^2} \frac{c+z \frac{a-\gamma}{a} (V+1) + \delta}{\left(\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV\right)^2} < 0,$$

$$\frac{\partial k^o}{\partial \gamma} = -\frac{1}{\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV} < 0,$$

$$\frac{\partial k^o}{\partial \delta} = -\frac{\frac{c+z}{b+c+z}a - \gamma}{\left(\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV\right)^2} < 0,$$

$$\frac{\partial k^o}{\partial s} = \frac{ab}{(b+c+z)^2} \frac{\frac{b\gamma}{a} (V+1) + \delta}{\left(\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV\right)^2} > 0,$$

$$\frac{\partial k^o}{\partial V} = -\frac{b \frac{a(c+z)-\gamma}{b+c+z} c + z}{\left(\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV\right)^2} < 0.$$

The equilibrium price of electricity is:

$$P(D^o) = \frac{a(c+z)}{b+c+z} \frac{\frac{\gamma}{a}b + \delta + \frac{c+z}{b+c+z}bV}{\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV}.$$

Differentiation of  $P(D^o)$  gives:

$$\frac{\partial P(D^o)}{\partial a} = \frac{c+z}{b+c+z} \frac{\delta + \frac{c+z}{b+c+z} bV}{\frac{c+z}{b+c+z} b + \delta + \frac{c+z}{b+c+z} bV} > 0,$$

$$\frac{\partial P(D^o)}{\partial b} = -\frac{a(c+z)}{(b+c+z)^2} \frac{\left(\frac{a-\gamma}{a}s + \delta\right) \delta + (c+z) \frac{(1+V)b(c+z)+2(b+s)\delta}{(b+c+z)^2} bV}{\left(\frac{c+z}{b+c+z} b + \delta + \frac{c+z}{b+c+z} bV\right)^2} < 0,$$

$$\frac{\partial P(D^o)}{\partial \gamma} = \frac{b(c+z)}{b+c+z} \frac{1}{\frac{c+z}{b+c+z} b + \delta + \frac{c+z}{b+c+z} bV} > 0,$$

$$\frac{\partial P(D^o)}{\partial \delta} = \frac{b(c+z)}{b+c+z} \frac{\frac{c+z}{b+c+z} a - \gamma}{\left(\frac{c+z}{b+c+z} b + \delta + \frac{c+z}{b+c+z} bV\right)^2} > 0,$$

$$\frac{\partial P(D^o)}{\partial V} = \frac{b(c+z)}{b+c+z} \frac{b \frac{as}{b+c+z} - \gamma (c+z)}{\left(\frac{s}{b+c+z} b + \delta + \frac{c+z}{b+c+z} bV\right)^2} > 0.$$

## 2.9 Competitive equilibrium

Considering the quadratic specification of the model, the equilibrium outcome for the spot market we have:

$$P(D^*) = a - bD^* = c \int_{\omega_0}^{\omega_1} q^*(\omega) dG(\omega) + T.$$

Substitute  $\int_{\omega_0}^{\omega_1} q^*(\omega) dG(\omega)$  in the last equation we get:

$$a - bD^* = c(D^* - k^*) + T.$$

Solving the system we have:

$$D^* = \frac{a + ck^* - T}{b+c},$$



Using

$$q^*(\omega) = D^* - \omega k^*,$$

we get:

$$q^*(\omega) = \frac{a + ck^* - T}{b + c} - \omega k^*.$$

Finally, on the market of contracts, we have:

$$F'(k^*) = \int_{\omega_0}^{\omega_1} C'(q^*(\omega)) \omega dG(\omega) + T.$$

Using  $E(\omega^2) = (V + 1)$  and  $E(\omega) = 1$ , we get:

$$\gamma + \delta k^* = c \frac{a + ck^* - T}{b + c} - (V + 1) k^* + T.$$

Solving the system we have:

$$k^* = \frac{a \frac{c}{b+c} + T \frac{b}{b+c} - \gamma}{\delta + \frac{c^2}{b+c} V + \frac{bc}{b+c} (V + 1)},$$

and differentiating  $k^*$  with respect to  $T$  we get:

$$\frac{\partial k^*}{\partial T} = \frac{b}{b\delta + c\delta + bc + Vbc} > 0.$$

## 2.10 Second-best solution

The Lagrangian of this problem writes:

$$L = \int_{\omega_0}^{\omega_1} \left[ \begin{array}{l} S(D) - C(q(\omega)) - d(q(\omega)) - F(k) \\ -\lambda(\omega)(D - q(\omega) - \omega k) \\ -\beta(F'(k) - P(D) - C'(q(\omega))(\omega - 1)) \end{array} \right] dG(\omega),$$

where the Lagrangian multipliers  $\lambda(\omega)$  reflects the implicit price of electricity in the state  $\omega$

and  $\beta$  reflects the price of incentive constraint for each sub-market.

Let  $D^s$ ,  $q^s(\omega)$ ,  $k^s$  and  $T^s$  be the solution. It satisfies the first order conditions:

$$\lambda(\omega) - C'(q^s(\omega)) - d'(q^s(\omega)) + \beta C''(q^s(\omega))(\omega - 1) = 0,$$

$$P(D^s) - \int_{\omega_0}^{\omega_1} \lambda(\omega) dG(\omega) + \beta P'(D^s) = 0,$$

$$F'(k^s) - \int_{\omega_0}^{\omega_1} \lambda(\omega) \omega dG(\omega) + \beta F''(k^s) = 0.$$

Rearranging we get:

$$\lambda(\omega) = C'(q^s(\omega)) + d'(q^s(\omega)) - \beta C''(q^s(\omega))(\omega - 1),$$

$$P(D^s) + \beta P'(D^s) = \int_{\omega_0}^{\omega_1} \lambda(\omega) dG(\omega),$$

$$F'(k^s) + \beta F''(k^s) = \int_{\omega_0}^{\omega_1} \lambda(\omega) \omega dG(\omega).$$

By simplifying we can write:

$$P(D^s) = \int_{\omega_0}^{\omega_1} (C'(q^s(\omega)) + d'(q^s(\omega))) dG(\omega) - \beta \left( \int_{\omega_0}^{\omega_1} C''(q^s(\omega))(\omega - 1) dG(\omega) + P'(D^s) \right),$$

$$F'(k^s) = \int_{\omega_0}^{\omega_1} (C'(q^s(\omega)) + d'(q^s(\omega))) \omega dG(\omega) - \beta \left( \int_{\omega_0}^{\omega_1} C''(q^s(\omega))(\omega - 1) \omega dG(\omega) + F''(k^s) \right).$$

To find the expression of  $\beta$  we use the constraint of the market equilibrium, we have:

$$T^s = P(D^s) - \int_{\omega_0}^{\omega_1} C'(q^s(\omega)) dG(\omega).$$

$$T^s = F'(k^s) - \int_{\omega_0}^{\omega_1} C'(q^s(\omega)) \omega dG(\omega),$$

We substitute these conditions in the first-order conditions and we get:

$$T^s = \int_{\omega_0}^{\omega_1} d'(q^s(\omega)) dG(\omega) - \beta \left( \int_{\omega_0}^{\omega_1} (\omega - 1) C''(q^s(\omega)) dG(\omega) + P'(D^s) \right),$$

and

$$T^s = \int_{\omega_0}^{\omega_1} d'(q^s(\omega)) \omega dG(\omega) - \beta \left( \int_{\omega_0}^{\omega_1} (\omega - 1) \omega C''(q^s(\omega)) dG(\omega) + F''(k^s) \right).$$

We equalize the two conditions above and simplify to find the following:

$$\beta = \frac{\int_{\omega_0}^{\omega_1} d'(q^s(\omega)) (\omega - 1) dG(\omega)}{\int_{\omega_0}^{\omega_1} C''(q^s(\omega)) (\omega - 1)^2 dG(\omega) - P'(D^s) + F''(k^s)}$$

### **Analytical resolution of the system with the linear quadratic specification:**

To compare the second-best and the first-best solutions, we have to analytically resolve the model:

$$\int_{\omega_0}^{\omega_1} q^s(\omega) = D^s - k^s,$$

Using the first-order condition we get

$$a - bD^s = (c + z)(D^s - k^s) - b\beta = z \frac{D^s - k^s}{b + \delta + Vc}.$$

Resolve the system, we get:

$$D^s = \frac{a + k^s (c + z) - b \frac{k^s}{b + \delta + Vc} z}{b + c + z - b \frac{z}{b + \delta + Vc}},$$

$$q^s(\omega) = \frac{a + (c + z)k^s}{b + c + z - b \frac{z}{b + \delta + Vc}(\omega - 1)} - \omega k^s,$$

substitute in the equation of  $\beta$  to find:

$$\beta = -z \frac{k^s}{b + \delta + Vc} V < 0.$$

Then substitute the above solutions into the first order condition and integrate using  $E(\omega) = 1$  and  $E(\omega^2) = (V + 1)$  to write:

$$\gamma + \delta k^s = (c + z) \frac{a - bk^s (V + 1)}{b + c + z} + z \frac{k^s}{(b + c + z)(Vc + b + \delta)} V (\delta + Vc).$$

Resolve for  $k$  to find:

$$k^s = \frac{\frac{c+z}{b+c+z}a - \gamma}{\frac{s}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV - Vbz \frac{\delta+Vc}{(b+c+z)(b+\delta+Vc)}}.$$

To determine the second-best tax rate we use:

$$T^s = \int_{\omega_0}^{\omega_1} d'(q^s(\omega))dG(\omega) - \beta \left( \int_{\omega_0}^{\omega_1} (\omega - 1) C''(q^s(\omega)) dG(\omega) + P'(D^s) \right).$$

Comparing conditions (6) and (16) we check:

$$k^s > k^o \iff \frac{\frac{c+z}{b+c+z}a - \gamma}{\frac{s}{b+c+z}b + \delta + \frac{c+z}{b+c+z}bV - Vbz \frac{\delta+Vc}{(b+c+z)(b+\delta+Vc)}} > \frac{\frac{c+z}{b+c+z}a - \gamma}{\frac{c+z}{b+c+z}b + \delta + \frac{c+z}{b+s}bV} \iff b > 0, z > 0.$$

We substitute the solution above and get:

$$T^s = z \left( \frac{a + k^s (c + z) - z \frac{bk^s}{b+\delta+Vc}}{b + c + z - b \frac{z}{b+\delta+Vc}} - k^s \right) - z \frac{k^s}{b + \delta + Vc} bV,$$

$T^s$ , is the tax rate that minimizes the resulting loss associated with imbalance in incentives to invest in intermittent capacities and decentralizes the second-best solution.

Therefore, we deduce that the intermittent capacity in the second-best solution is always smaller than in the optimal state.

Using  $E(\omega) = 1$ , we can write  $\int_{\omega_0}^{\omega_1} q^o(\omega) dG(\omega) = \frac{a-bk^s}{b+c+z}$ . So, we can compare it to  $q^s(\omega)$ .

Knowing that  $k^s < k^o$  we deduce that

$$q^o(\omega) > q^s(\omega)$$

and

$$T^s < d'(q^o(\omega))$$



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## CHAPTER 3

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# Emission permits with intermittent energy sources

## **Preface**

In order to achieve its objectives set by the Kyoto protocol, the European Union has established the first cap-and-trade system for carbon dioxide emissions in the world starting in 2005. It is considered as a cornerstone of the EU's policy to combat climate change and an important measure to reduce greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest one. In this chapter, we are interested in analyzing this environmental policy scheme.

Designed to be compatible with competition mechanisms, marketable pollution permits appear as the appropriate incentive mechanism to promote renewable electricity in the liberalized electric markets. Although they present many theoretical advantages to support renewable energy, their implementation and design raise some difficulties. The chapter looks at the efficiency of pollution permit markets on promoting the investment in renewable energy, considering the electricity generation framework where the pollutant increases linearly, the environmental marginal damage is increasing, and the demand of electricity is variable. We show that the effectiveness of this quantity-based mechanism is essentially dependent on the initial allocation of permits and in the level of investment in renewable technologies.

### 3.1 Introduction

The electricity sector is one of the most polluting sectors in the world: the use of fossil fuels leads to harmful greenhouse gas emissions (GHG). With the development of environmental awareness, this sector has attracted considerable attention in the debate on climate warming mitigation. Public policies have been launched worldwide to green the electricity production and to replace polluting energy sources by renewable ones. Therefore, there has been a growing focus on the greening of electricity production. This leads us to analyze the efficiency of the tools that have been implemented to achieve environmental goals.

In the context of environmental regulation, emission trading permits have been welcomed and supported (Stavins, 2003) and widely applied to different kind of environmental issues. For example, in order to meet its obligations to reduce GHG emissions under the Kyoto Protocol, the European Union (EU) established the first cap-and-trade system for carbon dioxide emissions in the world starting in 2005. *"The EU emissions trading system (EU ETS) is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest one".*<sup>1</sup>

Emissions trading permits work with a central authority which sets a cap on the total amount of pollutant that can be emitted. The cap is then converted into allowances that give the right to emit a certain amount of pollutant. Permits are allocated to polluters, and can be traded on the market. A market price emerges and buyers pay to increase their emissions, while sellers can earn money by selling their unused allowances. So pollution markets can achieve emission reduction targets for a minimal cost to society.

The interest for emission trading has produced an extensive literature. In particular, Montgomery's paper (1972) provides a rigorous theoretical justification for the way in which pollution permits achieve an effective equilibrium. Montgomery also proves that efficient market equilibrium exists for pollution permits. He shows that the efficient equilibrium achieves the minimal total cost

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<sup>1</sup>Directive (EU) 2018/410.

for all firms and is independent of the initial allocation of permits. Although Montgomery's model is quite general and covers many different scenarios, it cannot be given a temporal interpretation. Many works have pointed some features of permit markets which will prevent them from achieving efficiency. Hahn (1984) and Misiolek and Elder (1989) focus on market power. They find that optimality can be restored by distributing a number of permits to dominant firms. The number of permits must be exactly equal to their emissions. Schwartz and Stahn (2014) analyze the consequences of imperfect competition in an eco- industry on the equilibrium choices of the competitive polluting firms. They show that market power on the eco-industry reduces the welfare with respect to the competitive case. The second-best solution proposed in this paper suggests that to increase welfare under imperfect competition the pollution level should be reduced below the optimal level. Atkinson and Tietenberg (1991) study losses in efficiency due to sequential permit trading. Bohi and Burtraw (1992) and Tschirhart (1984) work on the regulation of permit trade for firms. Zyllicz (1993) writes about the case of interacting pollutants. Tietenberg (1985) characterizes the cheapest allocation of pollution for a uniformly mixed accumulative pollutant, with a single constraint on the total amount of emissions. He states that a permit system could yield this allocation and that the permit price would then rise with the interest rate. He assumes that all permits are issued immediately and that in equilibrium firms will always bank permits. Schennach (2000) explores the consequences of constraints on borrowing. She takes into account an important feature of the Title IV of the US Clean Air Act Amendments of 1990 which prohibits the borrowing of permits. Innes (2003) and Maeda (2004) are among the first studies that explicitly took into account the stochastic nature of emissions in a multi-period setting. Seifert et al. (2008) were the first to develop a dynamic equilibrium model reflecting the main features of the EU ETS, with stochastic emissions and a continuous timeline. As in Seifert et al. (2008), Hintermann (2010) shows that the equilibrium price of allowances shows dependency on time. He identifies that shocks on exogenous variables that influence emissions increasingly affect price permits.

The literature on this topic is extensive and it encompasses hundreds of books and papers. It is out of the scope to review it exhaustively. Here we use a stylized micro-economic framework to

analyze the efficiency of pollution permits to decentralize the optimal development of intermittent power producing technologies. On the demand side of the market, consumers are equipped with smart meters and face prices that vary with climatic conditions. On the supply side of the market we adopt the hypothesis of increasing marginal cost with no binding capacity constraints for the conventional sector. Moreover, we suppose that environmental marginal damage is increasing. This assumption is important in that it allows us to take into account the additional challenges imposed on regulators due to the introduction of renewable energy (RE) sources in the energy mix. To date, the majority of the literature on public policies to green electricity production has ignored the problem of intermittency. In our framework the degree of substitution between the two sources of electricity production depends on weather conditions. It is essential to take uncertainty into account in order to analyze the interaction between conventional and intermittent sectors. It is necessary to reflect the intermittent nature of RE sources, and its consequences on the electricity market.

Integrating RE sources into the electricity mix is no easy task. One reason for this difficulty is that the amount of electricity that is produced from RE varies over time and according to weather conditions, which is not the case with conventional units. So the supply of electricity from renewable sources is highly unpredictable, and yet electricity supply must match demand at all time. Moreover, the recent liberalization of the electricity market and the integration of RE are changing the structure of the electricity market. It is therefore important to analyze the effectiveness of pollution permit markets in achieving environmental objectives in this new context.

The aim of the chapter is to analyze the impact of emission caps on electricity supply in an industry with intermittent sources of energy. To address these issues, we extend the model developed in Rouillon (2014) assuming variable demand and taking into account the environmental damage induced by electricity production from fossil fuels. Then we investigate the efficiency of pollution permits in internalizing the environmental damage in competitive market equilibrium. The analysis shows that a constant emission cap does not implement the optimal state. This is due to the interaction between an electricity production which strongly depends on the availability of intermittent energies and a fixed emission cap that is independent of climatic conditions. Finally, a constrained



second-best solution with an emission cap that minimizes the resulting loss of welfare is proposed. It appears that the interaction between variable demand and intermittent energy production implies that the allocation of pollution permits should be higher than the environmental marginal damage expected at the optimal state and that the investment in renewable technologies should be lower.

The rest of the chapter is organized as follows. We extend the model developed by Rouillon (2014) by introducing environmental damage into the analysis. For convenience, Section 2 summarizes its main features and results. Readers familiar with the model can proceed to Section 3. Section 3 describes the optimal energy mix and gives some comparative statics results. Section 4 discusses the decentralization of the optimal state in a competitive market with an emission cap. In section 5, we propose a constrained second-best solution. Finally, section 6 is a conclusion.

## 3.2 The model

We consider a model of energy production and supply with intermittent energy sources. On the demand side, consumers are equipped with traditional meters and face flat-rate tariffs. The population size is normalized to 1. Each consumer inverse demand function is  $P(D)$ . Define  $S(D) = \int_0^D P(s)ds$  the consumer's surplus of consuming  $D$  kWh of electricity.

On the supply side, electricity can be produced by means of two technologies. First, the conventional sector is composed by many small producers,  $j \in [0, J]$ . Each producer has a production capacity of 1 Mw and its marginal cost is  $c_j$ . Using conventional generators, the incumbent firms supply electricity in quantity  $q$ . The cost function  $C(q)$  represents their technology. It is assumed that  $C'(0) = 0$ ,  $C'(q) > 0$  and  $C''(q) > 0$ . The electricity production of the conventional sector emits air pollutants (SO<sub>2</sub>) which cause damages to society. Let,  $e(\omega) = q(\omega) - a(\omega)$ , be the emissions level. Damage from pollution depends on total pollution  $Z$  and on the abatements efforts  $a$ . The social damage function is  $d(Z)$  and the abatements cost function is  $A(a)$ .

The second technology comes from a competitive fringe, using intermittent generators who seeks to enter the market. The cost of building intermittent units with capacity  $\bar{\omega}k$  is  $F(k)$ . It is assumed that  $F(0) = 0$ ,  $F'(k) > 0$  and  $F''(k) \geq 0$ . Uncertainty is essential to address the interaction between the conventional and intermittent generators. The variability of climatic conditions (sun and/or wind) is modeled as a random variable  $\omega$ . It is distributed on  $\omega \in [\omega_0, \omega_1]$ , with cumulative distribution function  $G(\omega)$ . For all  $\omega$ , given the installed capacity  $\bar{\omega}k$ , the intermittent generation will be equal to  $\omega k$ , at a negligible marginal cost. To simplify and normalize the units, it is assumed that  $E[\omega] = 1$ . Accordingly, the variance of  $\omega$  is  $V = E[\omega]^2 - 1 > 0$  and the intermittent generation has a capacity factor of  $1/\bar{\omega}$ .<sup>2</sup>

Importantly, we assume that electricity cannot be stored and the only way to balance supply and demand is to rely on production adjustment or / and price variations.

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<sup>2</sup>As in Rouillon (2014), the capacity factor is defined as the ratio of the expected output *i.e.*  $\frac{E[\omega k]}{\bar{\omega}k} = \frac{1}{\bar{\omega}}$ .

For the rest of the article, we will use the following linear quadratic specification of the model:<sup>3</sup>

$$P(D) = a - bD,$$

$$C(q) = \frac{1}{2}cq^2,$$

$$F(k) = \left( \gamma + \frac{1}{2}\delta k \right) k,$$

$$d(Z) = \frac{1}{2}zZ^2,$$

$$A(a) = \theta \frac{1}{2}a^2.$$

### 3. Optimal policy

The social problem is to choose the conventional generation and abatement level, respectively,  $q(\omega)$  and  $e(\omega)$ , for all  $\omega$ , the consumption of consumers  $D$ , and the capacity of the intermittent generators,  $k$ , to maximize

$$\int_{\omega_0}^{\omega_1} [S(D) - C(q(\omega)) - d(e(\omega)) - A(a(\omega))] dG(\omega) - F(k), \quad (1)$$

subject to :

$$D = q(\omega) + \omega k, \text{ for all } \omega, \quad (2)$$

and

$$Z(\omega) = e(\omega), \quad (3)$$

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<sup>3</sup>From our assumptions above, all parameters are positive.

Rearrange and integrate the constraint, we get the following problem of maximization:

$$\int_{\omega_0}^{\omega_1} [S(D) - C(q(\omega)) - d(Z(\omega)) - A(q(\omega) - Z(\omega))] dG(\omega) - F(k). \quad (4)$$

Let  $q^o(\omega)$ ,  $a^o(\omega)$  and  $Z^o(\omega)$ , for all  $\omega$ ,  $D^o$  and  $k^o$ , be the optimal solution. Rearranging the first-order conditions, the optimal state is characterized by the following conditions:

$$D^o = q^o(\omega) + \omega k^o, \text{ for all } \omega, \quad (5)$$

$$P(D^o) = \int_{\omega_0}^{\omega_1} (C'(q^o(\omega)) + A'(q^o(\omega) - Z^o(\omega))) dG(\omega), \quad (6)$$

$$d'(Z^o(\omega)) = A'(Z^o(\omega) - q^o(\omega)), \text{ for all } \omega, \quad (7)$$

$$F'(k^o) = \int_{\omega_0}^{\omega_1} P(D^o) \omega dG(\omega). \quad (8)$$

Accordingly, consumers should raise their consumption as long as their marginal propensity to pay is larger than the expected electricity price minus the abatement pollution costs. For every state of nature  $\omega$ , conventional generators should increase their production as long as their marginal cost is smaller than the price of electricity minus the abatement pollution costs. Moreover, they should increase their pollution as long as the cost of pollution remains smaller than the pollution abatement costs. Finally, intermittent capacities should be increased as long as the cost of investing in the intermittent unit remains smaller than its expected marginal benefit. In the state of nature  $\omega$ , the marginal benefit of investing in the intermittent units is the product of the implicit price of electricity plus the environmental marginal damage, times the productivity of the marginal generating unit,  $\omega$ .

Considering the linear-quadratic specification, from (5) to (8), we show in the Appendix:

$$q^o(\omega) = \frac{a - bk^o\omega}{b + c + z\frac{\theta}{z+\theta}}, \quad (9)$$

$$Z^o(\omega) = \frac{\theta}{z + \theta} \frac{a - bk^o\omega}{b + c + z\frac{\theta}{z+\theta}}, \quad (10)$$

$$D^o = \frac{a - bk^o}{b + c + z\frac{\theta}{z+\theta}} + k^o, \quad (11)$$

$$k^o = \frac{a\frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} - \gamma}{b\frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} + \delta + \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)}bV}. \quad (12)$$

$$a^o(\omega) = \frac{z}{z + \theta} \frac{a - bk^o\omega}{b + c + z\frac{\theta}{z+\theta}}. \quad (13)$$

The optimal dispatch and investment program as well as the comparative statics yield familiar results and some results have to be emphasized.<sup>4</sup> Since electricity cannot economically be stored, the variability of RE constitutes a major obstacle to their development. In fact, the intermittency of these energy sources introduces more uncertainty and instability into the power grid, which requires the mobilization of expensive peak load capacity. Formally, we show in the Appendix that the intermittent capacity  $k^o$  is decreasing in  $V$ . Moreover, it is interesting to observe how the electric market should adapt due the variability of the intermittent generation. Using (9), we can see that the conventional generators should adjust their and supply to smooth the variable production of the intermittent units. Formally, when  $b$  and  $k$  are positive,  $q^o(\omega)$  is decreasing in  $\omega$ . Finally, it is clear that the pollution abatement level is decreasing with its marginal cost  $\theta$ . Thus, the higher the pollution abatement costs are, the lower will be the abatement effort level .

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<sup>4</sup>For more details, see Rouillon (2014) or the summary included in the Appendix for the reader's convenience.

### 3.3 Competitive equilibrium with emissions cap

Assuming perfect competition we analyze the impact of emissions cap on electricity production and welfare. Assume that the regulator sets a cap on polluting emissions caused by the electricity production from fossil fuels. Let  $\bar{Z}$  be the maximum level of emissions sets by the regulator and  $p^{SO_2}(\omega)$ , the price of  $SO_2$  in the state of the world  $\omega$ . We consider a market economy with free entry and price-taker producers and retailers. The system of markets is as follows. There is a full set of spot and forward markets. On the spot market, electricity operators sell to retailers at real-time pricing. On the forward market, consumers sign contracts with retailers at fixed prices. Wholesale prices are expected to result from competition among generators, and retail prices would result from competition among retailers serving the final customers. Thus, equilibrium prices are determined by the producers' and retailers' supply functions, as well as by demand from retailers and consumers.

The timing of the decisions is the following. In the first stage, the regulator sets the level of emissions  $\bar{Z}$ . In the second stage, the intermittent generators invest in generating units ( $k$ ). In the third stage, consumers sign contracts with retailers (quantities  $\bar{q}$  at price  $\bar{p}$ ). In the fourth stage nature determines the climatic conditions ( $\omega$ ). In the last stage, generating units decide their electricity production ( $q(\omega)$  and  $r(\omega)$  at price  $p(\omega)$ ) and pollution abatement  $a(\omega)$ , on the spot market

The market equilibrium is now obtained by working backward in the game tree.



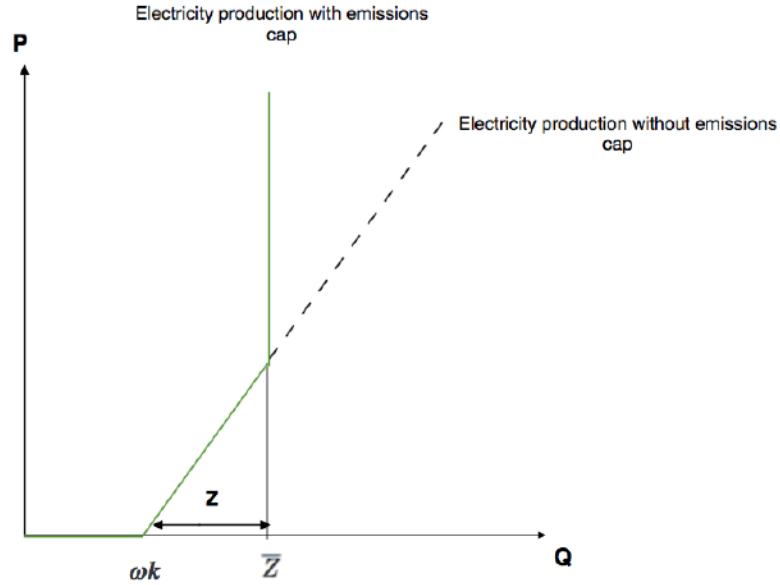


Figure 7: Electricity production with emissions cap

### 3.3.1 Spot and $SO_2$ markets

For all  $\omega$ , let  $p^*(\omega)$  and  $p^{*SO_2}(\omega)$  be respectively the equilibrium spot price of electricity and the price of  $SO_2$  in the state  $\omega$ .

The  $SO_2$  market clearing condition is:

$$Z^*(\omega) = q^*(\omega) - a^*(\omega).$$

The allocation of pollution permits limits the polluting emissions:

$$Z^*(\omega) \leq \bar{Z}^*.$$

On the supply-side of the market, intermittent generators choose  $r(\omega)$  to maximize

$$\pi = p(\omega)r(\omega),$$

subject to  $r(\omega) \leq \omega k$ , and consequently supply  $r^*(\omega) = \omega k^*$ .

Conventional generators choose  $q(\omega)$  to maximize:

$$\pi = p(\omega)q(\omega) - C(q(\omega)) - A(a(\omega)) + p^{SO_2}(\omega) (\bar{Z}^* - e(\omega)),$$

subject to

$$e(\omega) = q(\omega) - a(\omega).$$

Integrating the constraint we get:

$$\pi = p(\omega)q(\omega) - C(q(\omega)) - A(a(\omega)) + p^{SO_2}(\omega) (\bar{Z}^* - q(\omega) + a(\omega)).$$

Thus, conventional generators choose their supply  $q^*(\omega)$  and abatement  $a^*(\omega)$  such that:

$$p^{*SO_2}(\omega) = A'(q^*(\omega) - \bar{Z}^*),$$

$$p^*(\omega) = C'(q^*(\omega)) + p^{*SO_2}(\omega).$$

Integrating the two conditions we get:

$$p^*(\omega) = C'(q^*(\omega)) + A'(q^*(\omega) - \bar{Z}^*). \quad (14)$$

The total electricity produced should match consumers' preferences in the sense that the marginal utility of electricity consumed equals its marginal social cost whatever the state of nature  $\omega$ . If the emissions cap set by the regulator is sufficient to cover the difference between the overall electricity demand and the intermittent generation, then the conventional sector does not have to purchase additional pollution permits and the price of permits will be equal to zero. However, since we suppose that the  $so_2$  constraint is always saturated conventional operators will produce more than the emission cap set by the regulator and must therefore purchase additional pollution permits. Therefore, they should produce as long as their social marginal cost (production marginal costs plus

abatement costs) are lower than the equilibrium price of the market. Thus, the more RE sources are abundant, the lower will be the price of pollution permits.

### 3.3.2 Contract markets

The retail sector purchases electricity from generators on the spot market and distributes it to the final customers in the contracts market. Firms in the retail sector are assumed to have no costs other than the wholesale cost of the electricity that they buy for their retail customers. Equilibrium prices in the retail sector are determined by competition among retailers.

Each consumer demands  $D$  such that  $P(D) = \bar{p}$ . Retailers supply  $\bar{q}$  at price  $\bar{p}$ . They anticipate that they will buy their electricity at the spot price  $p(\omega)$ , for all  $\omega$ . Thus, in equilibrium, the price of contracts  $\bar{p}$  must be equal to the expected price of the electricity on the spot markets  $\bar{p} = E[p(\omega)]$ , with  $p^*(\omega) = C'(q^*(\omega)) + A'(q(\omega) - \bar{Z}^*)$ .

The equilibrium demand on the contract market will satisfy

$$P(D^*) = \int_{\omega_0}^{\omega_1} \left( C'(q^*(\omega)) + A'(q(\omega) - \bar{Z}^*) \right) dG(\omega) \quad (15)$$

### 3.3.3 Investment in intermittent technologies

The intermittent generators anticipate the equilibrium prices  $p^*(\omega)$  for all  $\omega$  and correspondingly choose  $k^*$  to maximize:

$$\pi = \int_{\omega_0}^{\omega_1} p(\omega)r(\omega)dG(\omega) - F(k),$$

with

$$r(\omega) = \omega k.$$

Under the assumption of perfect competition, the equilibrium capacity will satisfy:

$$F'(k^*) = \int_{\omega_0}^{\omega_1} p^*(\omega) \omega dG(\omega), \quad (16)$$

with

$$p^*(\omega) = C'(q^*(\omega)) + p^{so_2}(\omega).$$

Intermittent generators should increase their capacity as long as their marginal cost of investment is smaller than their expected marginal profit of investment. The  $so_2$  price is included to the electricity price, as a result, the expected benefits of investment in intermittent technologies also increase. Thus, regulation both reduces the competitiveness of the conventional sector and promotes the investment in the intermittent sector.

Using the linear quadratic specification of the model, we can show in the Appendix:

$$q^*(\omega) = \frac{a - bk\omega + \theta\bar{Z}}{b + c + \theta},$$

$$a^*(\omega) = \frac{a - bk\omega + \theta\bar{Z}}{b + c + \theta} - \bar{Z},$$

$$D^* = \frac{a - bk^* + \theta\bar{Z}}{b + c + \theta} + k^*,$$

$$k^* = \frac{a - \gamma - b \frac{a + \theta\bar{Z}}{b + c + \theta}}{\delta + b \frac{c + \theta}{b + c + \theta} (V + 1)}.$$

### 3.3.4 (In)efficiency of emissions cap to implement the optimal state

Comparing the conditions characterizing the optimal state (from (5) to (8)) and those of the market equilibrium (from (14) to (16)), we can see that the emissions cap  $\bar{Z}$  does not decentralize

the optimal state.

Indeed, it is straightforward that no market equilibrium can decentralize the optimal state. First, this impossibility is because in the optimal state conventional production and emissions,  $q^o(\omega) = Z^o(\omega)$ , vary with climatic conditions while it is a constant in the market equilibrium. Indeed, the intermittency of RE sources implies that the total electricity output vary with climatic conditions. In contrast, since the regulator sets the emission cap  $\bar{Z}$  and distributes pollution permits before knowing the state of nature  $\omega$ , it is impossible to vary  $\bar{Z}$  according to climatic conditions. Thus, the impossibility of implementing the first-best state through the competitive market mechanisms is the result of the contradiction between an electricity production which strongly depends on the availability of intermittent energies, and a fixed emissions cap regardless of the state of nature.

**Proposition 1:**

*In the presence of intermittent energy sources in the energy mix, the fixed emissions cap  $\bar{Z}$  does not implement the first-best resource allocation.*

## 5. Second-best solution

While it is clear that a fixed emissions cap  $\bar{Z}$  does not yield the first-best resource allocation, there is still the question of which emission cap level minimizes the resulting loss of welfare. To answer this question we use our previous results to determine a constrained second-best solution.

Assume that the regulator fixes  $\bar{Z}$  under constraint of the market equilibrium. The social problem is to choose the consumers' consumption  $D$ , the electric generation and pollution level of the conventional generators, respectively,  $q(\omega)$  and  $Z(\omega)$ , for all  $\omega$ , and the capacity of the intermittent generators  $k$  to maximize:

$$\int_{\omega_0}^{\omega_1} [S(D) - C(q(\omega)) - d(Z(\omega)) - A(q(\omega) - Z(\omega))] dG(\omega) - F(k),$$

subject to

$$D = q(\omega) + \omega k,$$

$$Z(\omega) = \bar{Z} = q(\omega) - a(\omega),$$

$$F'(k) = \int_{\omega_0}^{\omega_1} P(D) \omega dG(\omega).$$

and

$$p^{SO_2}(\omega) = A'(q(\omega) - \bar{Z}).$$

Rearrange and eliminate the last constraint because there is always  $p^{SO_2}(\omega)$  to satisfy it (provided it is positive). Finally, we get the following problem of maximization

$$\int_{\omega_0}^{\omega_1} [S(\bar{Z} + a(\omega) + \omega k) - C(\bar{Z} + a(\omega)) - d(\bar{Z}) - A(a(\omega))] dG(\omega) - F(k), \quad (17)$$

subject to

$$F'(k) = \int_{\omega_0}^{\omega_1} P(\bar{Z} + a(\omega) + \omega k) \omega dG(\omega). \quad (18)$$

Let  $D^s$ ,  $q^s(\omega)$ , for all  $\omega$ ,  $\bar{Z}^s$  and  $k^s$ , be the second-best solution. Rearranging the relevant first-order conditions, we can show that the second-best solution satisfies:

$$\int_{\omega_0}^{\omega_1} P(\bar{Z} + a(\omega) + \omega k) dG(\omega) = \int_{\omega_0}^{\omega_1} (C'(\bar{Z} + a(\omega)) + d'(\bar{Z})) dG(\omega), \quad (19)$$

$$P(\bar{Z} + a(\omega) + \omega k) = C'(\bar{Z} + a(\omega)) + A'(a(\omega)), \quad (20)$$



$$F'(k) = \int_{\omega_0}^{\omega_1} P(\bar{Z} + a(\omega) + \omega k) \omega dG(\omega). \quad (21)$$

***Second-best solution vs optimal state:***

In order to compare the second-best solution and the optimal state, we compare the conditions (19) and (21) with conditions (5) and (8). We show in the Appendix that  $k^s < k^o$ . Therefore, we deduce that the intermittent capacity in the second-best solution is always smaller than in the optimal state.

Using  $E(\omega) = 1$ , we can write  $\int_{\omega_0}^{\omega_1} q^o(\omega) dG(\omega) = \frac{a-bk^o}{b+c+z}$ . So, we can compare it to  $q^s(\omega)$ .

Knowing that  $k^s < k^o$ , we deduce that the number of permits that must be distributed in the second-best solution is greater than the environmental marginal damage expected at the optimal state. Hence the following proposition:

**Proposition 2:**

*To reduce the problem of variability of RE sources when demand is variable, regulator should act on the demand and the supply sides of the electricity market at the same time. First, the investment in renewable capacity should be below the optimal level. Second, the allocation of pollution permits should be greater than the expected pollution at the first-best optimum.*

By applying these two environmental policies at the same time, the regulator can reduce the negative effects of the variability of RE sources on the electricity grid by acting on both the demand-side and the supply-side of the market. In fact, on the one hand, decreasing the investment in renewable capacity reduces the sources of variability of the electricity production. Therefore, it reduces the pressure on the electricity grid. On the other hand, this will also reduce the overall capacity of electricity production. This is where the role of smart meters is important that it allow consumers to vary their demand according to availability of electricity. On the other hand, increasing the allocation of pollution permits allows the conventional producers to increase their production when RE are scarce, in order to smooth the overall electricity supply. Thus, the use of conventional units, which are polluting but reliable, remains socially indispensable to ensure the balance between supply and demand in the electricity market.

### 3.4 Conclusion

In this chapter we have investigated the optimal development of the intermittent technologies to generate electricity, given the competition of incumbent generators using the conventional technologies. We also analyze the efficiency of the emission allowance markets in decentralizing the socially optimal outcomes through the mechanisms of competitive market. We have shown that the optimal investment in the intermittent technologies cannot be implemented under perfect competition if the emission cap is at a constant level.

This result is due to the contradiction between an electricity production which strongly depends on the availability of intermittent energies and a fixed emissions cap regardless of the state of nature. Thus, to fight against the adverse side of investing in RE, it is necessary to act on both the supply and the demand of electricity.

Indeed, we have shown that the second-best solution can be implemented but, first it requires to invest less in renewable capacities compared to the optimal level. This is because in our framework consumers are equipped to vary their demand according to climatic conditions. Second, it requires increasing the emissions cap above the expected pollution level at the first-best optimum to allow more conventional production when RE are not available.

Thus, it remains socially indispensable to keep some conventional capacities in reserve for topping when RE are scarce to ensure the balance between supply and demand in the electricity market.

Several extensions of this model are expected. First, other sources of intermittent energy can be considered. The diversification of energy sources is a possible solution to mitigate intermittency. Our model can be extended to accommodate several intermittent sources of energy with heterogeneous costs and occurrence. Another question the model can address is to allow the disinvestment in conventional capacity. Finally and more evident, is to have heterogeneous consumers to be more realistic.

## 3.5 Appendix

### 3.5.1 Optimal policy

Rearrange and integrate the constraints, we get the following problem of maximization:

Let  $q^o(\omega)$ ,  $a^o(\omega)$  and  $Z^o(\omega)$ , for all  $\omega$ ,  $D^o$  and  $k^o$ , be the optimal solution. Rearranging the first-order conditions, the optimal state is characterized by the following conditions:

$$D^o = q^o(\omega) + \omega k^o, \text{ for all } \omega,$$

$$P(D^o) = \int_{\omega_0}^{\omega_1} (C'(q^o(\omega)) + A'(q^o(\omega) - Z^o(\omega))) dG(\omega),$$

$$d'(Z^o(\omega)) = A'(Z^o(\omega) - q^o(\omega)), \text{ for all } \omega,$$

$$F'(k^o) = \int_{\omega_0}^{\omega_1} P(D^o) \omega dG(\omega).$$

Using the linear specification of the model we get:

$$a - b \int_{\omega_0}^{\omega_1} (q^o(\omega) + k^o) = c \int_{\omega_0}^{\omega_1} q^o(\omega) dG(\omega) + \theta \int_{\omega_0}^{\omega_1} (q^o(\omega) - Z^o(\omega)) dG(\omega),$$

$$zZ^o(\omega) = \theta(q^o(\omega) - Z^o(\omega)), \text{ for all } \omega,$$

$$\gamma + \delta k^o = \int_{\omega_0}^{\omega_1} (a - b(q^o(\omega) + k^o\omega)) \omega dG(\omega).$$

To determine the optimal solution we use the first two equations to calculate:

$$q^o(\omega) = \frac{a - bk^o\omega}{b + c + z\frac{\theta}{z+\theta}},$$

$$Z^o(\omega) = \frac{\theta}{z + \theta} \frac{a - bk^o\omega}{b + c + z\frac{\theta}{z+\theta}},$$

$$D^o = \frac{a - bk^o}{b + c + z\frac{\theta}{z+\theta}} + k^o$$

Using ,  $a^o(\omega) = q^o(\omega) - Z^o(\omega)$ , we get

$$a^o(\omega) = \frac{z}{z + \theta} \frac{a - bk^o\omega}{b + c + z\frac{\theta}{z+\theta}}.$$

Then substitute into the last equation and integrate (using  $E(\omega) = 1$  and  $E[\omega^2] = (V + 1)$ ) to calculate:

$$k^o = \frac{a \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} - \gamma}{b \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} + \delta + \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} bV}.$$

### 3.5.2 Second-best solution

Rearrange and eliminate the last constraint because there is always  $p^{SO2}(\omega)$  to satisfy it (provided it is positive). Finally, we get the following problem of maximization

$$\int_{\omega_0}^{\omega_1} [S(\bar{Z} + a(\omega) + \omega k) - C(\bar{Z} + a(\omega)) - d(\bar{Z}) - A(a(\omega))] dG(\omega) - F(k),$$

subject to

$$F'(k) = \int_{\omega_0}^{\omega_1} P(\bar{Z} + a(\omega) + \omega k) \omega dG(\omega).$$

Let  $D^s$ ,  $q^s(\omega)$ , for all  $\omega$ ,  $\bar{Z}^s$  and  $k^s$ , be the second-best solution. Rearranging the relevant first-order conditions, we can show that the second-best solution satisfies:

$$\int_{\omega_0}^{\omega_1} P(\bar{Z} + a(\omega) + \omega k) dG(\omega) = \int_{\omega_0}^{\omega_1} (C'(\bar{Z} + a(\omega)) + d'(\bar{Z})) dG(\omega),$$

$$P(\bar{Z} + a(\omega) + \omega k) = C'(\bar{Z} + a(\omega)) + A'(a(\omega)),$$

$$F'(k) = \int_{\omega_0}^{\omega_1} P(\bar{Z} + a(\omega) + \omega k) \omega dG(\omega).$$

Using the linear-quadratic specification we have:

$$a - b(Z + a(\omega) + \omega k) = c(Z + a(\omega)) + \theta(a(\omega)),$$

$$\gamma + \delta k = a - b \left( \frac{\theta(a - bk)}{\theta(b + c + z) + z(b + c)} + z \frac{a - bk(V + 1)}{\theta(b + c + z) + z(b + c)} + (V + 1)k \right).$$

Solve the system we get:

$$\bar{Z} = \frac{\theta}{z + \theta} \frac{a - bk}{b + c + z \frac{\theta}{z + \theta}},$$

$$q^s(\omega) = \frac{a - bk^s \omega}{b + c + z \frac{\theta}{z + \theta}},$$

$$k^s = \frac{a \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} - \gamma}{\frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} b + \delta + bV}.$$

### Justification proposition 2:

Comparing conditions (27) and (28) with conditions (12) and (13) we check:

$$k^s < k^o \iff \frac{a \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} - \gamma}{\frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} b + \delta + bV} < \frac{a \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} - \gamma}{b \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} + \delta + \frac{\theta(c+z)+cz}{\theta(b+c+z)+z(b+c)} bV} \iff b > 0.$$

Therefore, we deduce that the intermittent capacity in the second-best solution is always smaller than in the optimal state.

Using  $E(\omega) = 1$ , we can write  $\int_{\omega_0}^{\omega_1} q^o(\omega) dG(\omega) = \frac{a - bk^s}{b + s}$ . So, we can compare it to  $q^s(\omega)$ .

Knowing that  $k^s < k^o$ , we deduce that the number of permits that must be distributed in the second-best solution is greater than the environmental marginal damage expected at the optimal state.

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## CHAPTER 4

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Intermittent electric generation technologies  
and smart meters: substitutes or complements



## Preface

Demand management can be an efficient solution to fight against the problem of renewable energy intermittency. This solution can be set up thanks to the generalization of smart meters. Thanks to these technologies, consumers can vary their demand according to the availability of electricity. Consequently this would reduce pressure on the power grid and improve its efficiency. In the present chapter, we propose a framework designed to determine and analyze in a social optimum, both the investments in the intermittent technologies and the installation of smart meters. Thus, in the proposed model, both sides of the market are influenced by climatic and/or social factors such as temperature, sun, wind, holidays, etc. Thus, we calculate the investment in intermittent technologies and smart meters in a social optimum. We find that the optimal penetration of smart meters is increasing in the volatility of the electric spot price. As a consequence, intermittent capacities and smart-meters are complement, only if the correlation existing between intermittent energy and demand is negative or if the capacity of intermittent generators is large enough. Otherwise, larger intermittent capacities actually help to decrease the volatility of the electric spot price, making smart-meters less useful. We also give a numeral application, calibrated to represent the French electric market in 2016 and policy objective for 2030. We show in particular that a general adoption of smart meters would be optimal only if the cost of installing and operating smart meters was unrealistically low.

## 4.1 Introduction

The energy transition aims to prepare for the post-carbon era and to establish a robust and sustainable energy model, facing the challenges of energy supply, depletion of fossil resources and environmental protection. In France, the main objectives of the Energy Transition for Green Growth Act is to increase the share of renewable energy up to 23% of gross final energy consumption in 2020 and to 32% of gross final energy consumption in 2030.<sup>1</sup>

In this chapter, we model a simplified electric market with, on the demand-side, consumers on either smart or traditional meters and, on the supply-side, producers using either conventional or intermittent electric generators. Both sides of the market are influenced by climatic and/or social factors (temperature, sun, wind, nebulosity, business cycles, holidays, and so on). All consumers share the same (inverse) demand curve, up to a scaling factor (i.e., the consumer's size). The demand variability is formalized by assuming that the intercept of the (inverse) demand curve is a random variable with known distribution. The consumers can chose either to be equipped with a smart or a traditional meter. Facing real-time pricing, the consumers on smart meters are induced to adapt their demand to the short term position of the electric market. The consumers equipped with traditional meters face flat tariff and their demand is insensitive to the short term position of the electric market. The producers using conventional generators supply a reliable and predictable quantity of electricity, at an increasing marginal cost. Their technology is assumed given . The producers using intermittent generators supply an unreliable and unpredictable quantity of electricity, at a negligible marginal cost. Their production is limited by a capacity constraint, which is endogenously determined by way of investment in new generating units. The marginal cost of building new capacities is assumed increasing, to account for the fact that the implantation sites will be used in a decreasing order of efficiency.

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<sup>1</sup>See: <https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte> (visited November 28th, 2017).

See: <https://www.legifrance.gouv.fr/affichCode.do?idSectionTA=LEGISCTA000031749063&cidTexte=LEGITEXT000023983208&dateTexte=20160421> (visited November 28th, 2017).

Our framework is designed to determine and analyze in a social optimum, both the investments in the intermittent technologies and the installation of smart meters. The model is kept simple enough in order to allow for the derivation of a closed form solution and for the disambiguation of most comparative statics results. Roughly speaking, the social objective can be represented and summarized along two dimensions, which are to provide electricity at the lowest cost possible, while limiting the volatility of the spot price as much as possible. With this reading in mind, consider first the policy of investing in intermittent generating units. Provided that the renewable technologies are socially efficient, it will directly help to reduce the electric spot price. However, the belief is commonly accepted that, in counterpart, it will increase the volatility of the electric spot price (Wozabal et al., 2014). In fact, our analysis challenges and clarifies this point, by emphasizing the role played by the correlation existing between the electric demand and the intermittent electric supply. We show that the common belief holds true only if the electric demand and the intermittent electric generation are negatively correlated (*i.e.*, on average, the electric demand is smaller during sunny and/or windy hours) *or* if they are positively correlated, but the intermittent generating capacity is already large enough. Otherwise, the development of the intermittent generating technologies allows to reduce both the level and the volatility of the electric spot price.<sup>2</sup> Consider now the policy of installing smart meters. It will clearly help to smooth the electric demand, by encouraging equipped consumers to react to the electric spot price. However, it has no (direct) effect on the cost of producing electricity. Now, the belief is commonly accepted that the penetration of smart meters will *indirectly* reduce the electric spot price, by inducing a larger intermittent generating capacity in a social optimum. Anew, our analysis shows that this insight is correct only if the electric demand and the intermittent electric generation are negatively correlated *or* if they are positively correlated but the intermittent capacity is already large enough. In other words, cases exist such that the deployment of smart meters induce a smaller optimal intermittent generating capacity, thus increasing the average electric spot price.

This being said, our most important results are the following. In a social optimum, the con-

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<sup>2</sup>Wozabal et al. (2014) give empirical supports of these results in the case of the German electric spot market.

sumers equipped with traditional meters should always face a tariff equal to the *expected* real-time price paid by the consumers equipped with smart meters. The optimal penetration of smart meters is increasing in the volatility of the electric spot price. This is quite intuitive, as smart meter are actually used to smooth it. As a consequence, given that increasing the capacity of intermittent generating units may either increase or decrease the volatility of the electric spot price, depending on the correlation existing between the electric demand and the availability of the renewable energies, the capacity of intermittent technologies and the penetration of smart meters may in theory be either complements or substitutes. In practice, it is commonly accepted that the generalization of smart meters will be needed in response to the penetration of the intermittent generating technologies. We show that this holds true only if the electric demand and the intermittent electric generation are negatively correlated *or* if they are positively correlated but the intermittent capacity is already large enough. In all other cases, the capacity of intermittent technologies and the installation of smart would be substitutes.

In this chapter, we also complement our theoretical findings by a numerical application, in order to give some idea of the magnitude of the mechanisms at stake. Though mainly illustrative, the numerical example is meant to reflect the French electric market in 2016 (RTE, 2016). Under our benchmark parametrization, which in particular presumes no correlation between demand and intermittent energy, we find that the optimal intermittent capacity will be increasing in the market share of smart meters (i.e., from 51257 MW to 54647 MW). As a result, the average real-time price will be slightly decreasing in the market share of the smart meters (i.e., from 33.65 €/MWh to 32.31 €/MWh). The optimal market share of smart meters is rapidly decreasing in the cost of installing and operating smart meters (i.e., from 100 % for an annualized cost of smart meters of 0.5 €/year, to 46 % for an annualized cost of 30 €/year). This confirms that a general adoption of smart meters would be optimal only if the cost of installing and operating smart meters was unrealistically low (Léautier, 2014).

This chapter is part of a rapidly growing body of literature, dealing with the changes of the electric market due to the deployment of the renewable and digital technologies, in the policy



context of market deregulation. We will not try to give an exhaustive survey of this literature, as this is far beyond the scope of this chapter. Instead, we limit our presentation to a selection of papers which we consider as close to our framework, in order to emphasize our contribution.

Firstly, it is worth remarking that the larger part of the literature is empirical and country specific (Crampes and Ambec, 2012). This includes, among others, Benitez et al. (2008), Bocard (2010), Gowrisankaran et al. (2016), Green and Vasilakos (2010, 2011), Kennedy (2005), Lamont (2008), Menanteau et al. (2003), Musgens and Neuhoff (2006, 2007), and Neuhoff et al. (2006, 2007). They provide estimates of the social costs and benefits of the (either optimal or equilibrium) penetration of the intermittent renewable technologies for generating electricity, for different countries and periods. Setting aside secondary differences, the common background can be summarized as follows. Observed electric demands and wind outputs data are combined to build a *residual load duration curve* (Kennedy, 2007), thus accounting for the interaction between the electricity demand and the renewable energy availability. Then, screening curves are used to derive the (either optimal or equilibrium) mix of generating technologies and electric dispatch, in order to satisfy the demand at all times. Some notable departures from this benchmark framework can be found in Benitez et al. (2008), Bocard (2010), Gowrisankaran et al. (2016), Green and Vasilakos (2010, 2011), Musgens and Neuhoff (2006, 2007), and Neuhoff et al. (2006, 2007). Benitez et al. (2008), and Musgens and Neuhoff (2006, 2007) set up inter-temporal models in order to formalize hydropower storage. Gowrisankaran et al. (2016) construct a quite general model, incorporating endogenous demand, with a possibility of curtailment, and a risk of outage of generating units. Green and Vasilakos (2010, 2011) determine supply function equilibria, in order to analyze issues of imperfect competition. Neuhoff et al. (2006, 2007) deal with spatial variation in wind output and transmission constraints within the grid.

This article takes a different direction, by using a stylized microeconomic framework to derive general insights regarding the optimal development of intermittent technologies to generate electricity and smart meters. The corresponding strand of literature is much less developed, including Ambec and Crampes (2012), Bode (2006), Borenstein and Holland (2000), Green and Vasilakos

(2010), Joskow and Tirole (2007), Léautier (2014), Rouillon (2015), and Twoney and Neuhoff (2010). For the sake of our presentation, these papers are divided below in two subsets, by distinguishing between those that focus on the supply size of the market and on the competition between conventional and renewable technologies, and those that focus on the demand side of the market and on the organizational features that can be used to make the consumers more reactive to the situation of the spot market.

A first strand of the theoretical literature (Ambec and Crampes, 2012 ; Bode, 2006 ; Rouillon, 2014 ; Twoney and Neuhoff, 2010) deals with the issue of competition on an electric market where the electricity is supplied by conventional generators and renewable generators. Bode (2006) determines the perfect competition equilibrium under several support schemes, financed either through the general public budget or a renewable energy mark-up charged to the final consumers. Implicitly, it is assumed that all consumers pay their electricity at the spot price and the installed renewable capacity is exogenous and not subject to intermittency. The main finding is that the final cost to the consumers may increase or decrease, depending on the support schemes and assumptions. Twoney and Neuhoff (2010) use a similar setting, but add the issue of intermittency explicitly. They determine the market equilibrium under perfect, monopolistic and duopolistic competitions, where the exercise of market power is by the incumbent conventional generators. They show that the average price received by intermittent generators are lower than for conventional generators. Indeed, the conventional generators, having increasing marginal costs, always set the market price, as marginal generators. Therefore, the latter will be lower (higher) in the periods of high (low) renewable energy. Moreover, Twoney and Neuhoff (2010) find that the difference can be exacerbated in the presence of market power. Ambec and Crampes (2012) and Rouillon (2015) go one step further, by making the energy mix endogenous through the possibility of investing in new generating capacities. Ambec and Crampes (2012) characterize the optimal investment and dispatch between conventional and intermittent generators and discuss its implementability under perfect competition. They consider in turn two polar situations, one where all consumers face prices contingent on the availability of the intermittent source of electricity (first-best optimum) and another where they



all face a uniform price (second-best optimum). Rouillon (2015) complements Ambec and Crampe (2012), by assuming that both types of consumers co-exist on the market and by dealing with perfect and monopolistic competitions. Under perfect competition, it is shown that the (second-best) optimal policy is implementable, provided that the conventional and intermittent generators exchange their electric production on a wholesale spot market. By contrast, if a single incumbent firm owns the conventional generators and has market power, the paper shows that the investment in the intermittent technologies will in general be inappropriate.

Another strand of the theoretical literature (Borenstein and Holland, 2003 ; Green and Vasilakos, 2010 ; Joskow and Tirole, 2006 and 2007 ; Léautier, 2014) deals with the design of pricing strategies under conditions of imperfect metering of a variable electric demand. A major problem in electricity markets is that only a fraction of the consumers face and react to real-time pricing (Borenstein and Holland, 2003). The reason is because generalizing real-time pricing requires to equip all consumers with connected *and* communicant meters (Joskow and Tirole, 2006). As long as some consumers remain on traditional meters and face flat rate service, a competitive electricity market will fail to implement the first-best optimum (Borenstein and Holland, 2003). Indeed, in the short run, reallocation of electric consumption between consumers on real-time pricing and flat rate will be socially worth each time they pay different prices. In the long run, the equilibrium spot price will fail to provide adequate incentives to invest in the generating technologies. The literature also investigated the conditions such that an electricity market can implement the second-best optimum, given the existence of price-insensitive retail consumers. Borenstein and Holland (2005) obtain an impossibility, assuming that the retailers can supply linear pricing contracts only. On the contrary, Joskow and Tirole (2007) show that the second-best optimum can be implemented, provided that the retailers offer two-part tariffs contracts, with a fixed fee and flat rate price. However, they argue that the conditions underlying this result are very strong and, in particular, would be violated in the presence of price caps and/or market power on the wholesale market, and in the presence of load profiling and/or load profile heterogeneity on the retail market. Though evoked in Borenstein and Holland (200) and Joskow and Tirole (2007), the issue of endogenous investment in meter-

ing equipment is analyzed in greater details by Léautier (2014). In a socially optimal allocation, Léautier (2014) shows that the marginal value of increasing the proportion of consumers on real-time pricing is proportional to the variance of wholesale prices. This determines the consumers' incentives to adopt smart meters.

To the best of our knowledge, this work is the first attempt to bring together, in a stylized microeconomic framework, the two issues of the optimal development of intermittent capacities and smart meters just surveyed above. The closest papers are Léautier (2014) and Rouillon (2015). The reason why it is interesting to deal with both issues in the same setting is because it allows to emphasize the important role played by the correlation between demand and intermittent supply. As said above, this challenges from the theoretical viewpoint the commonly accepted belief, namely that intermittent capacities and smart meters should necessarily develop in parallel. Although this belief may be true from the empirical viewpoint, this nevertheless drives us to encourage any policy that could increase the correlation between demand and intermittent energy supply. We think that many policies have the potential to influence the correlation between demand and intermittent energies, such as, for example, the introduction of daylight saving time (Havranek et al, 2016), the development and organization of prosuming consumers (Parag et al, 2016), the choice of the renewable energy mix (Torres et al, 2016), and so on. Such policies would be socially worth and would in fact render the need for smart metering even less urgent.

The outline of this chapter is as follows. Section 2 sets out the model. Section 3 deals with the normative analysis. It determines the optimal allocation and gives its comparative statics. Section 4 discusses the development of numerical simulations for the French market, and presents the main empirical results. Section 5 concludes.

## 4.2 The model

Consider a simplified electricity system without network constraints. The natural and social factors influencing the electric demand and supply (temperature, sun, wind, nebulosity, business cycles, holidays, and so on) are indexed by a random variable  $x$ , with cumulative distribution  $F(x)$ .<sup>3</sup> The population of consumers is normalized to one. The *aggregate* demand writes  $D(p) = (a(x) - p) / b$ , where  $a(x) > 0$ , for all  $x$ , and  $b > 0$ .<sup>4</sup> Define  $\bar{a}$  and  $V(a)$ , respectively, the expected value and the variance of  $a(x)$ .<sup>5</sup> Each consumer is characterized by his type  $t \in [t_0, t_1]$ . The consumers' types are assumed to be positive and distributed according to the cumulative distribution  $G(t)$  within the population.<sup>6</sup> The demand function of a consumer with type  $t$  is  $tD(p)$ . Since, by assumption, the population is normalized to one and the aggregate demand is equal to  $D(p)$ , the average type needs to be normalized to one. Formally,  $\int_{t_0}^{t_1} t dG(t) = 1$ . The consumers can be equipped with either smart or traditional meters. Let  $\mathcal{S} \subseteq [t_0, t_1]$  be the set of all consumers' types equipped with smart meters. Facing real-time pricing, the consumers with types  $t \in \mathcal{S}$  can adapt their demand to the short term position of the electric market. We will denote by  $p(x)$  the real-time price of electricity in the state  $x$ . The consumers with types  $t \notin \mathcal{S}$  are equipped with traditional meters. Facing a flat tariff, their demand is insensitive to the short term position of the electric market. We will denote by  $P$  the flat price of electricity. The cost of installing and operating the smart and traditional meters are  $K$  and  $\kappa$  respectively, with  $K > \kappa$ .<sup>7</sup> The incumbent plants supply electrical energy in quantity  $q$ , using conventional generators (i.e., hydro, nuclear, coal, gas, oil). The cost function  $C(q)$  represents their technology. It is assumed that  $C'(0) = 0$ ,

<sup>3</sup>The use of a uni dimensional index to represent all factors influencing the electricity market is made for the sake of notation convenience. It entails no loss of generality.

<sup>4</sup>For the sake of notation simplicity, we make here a slight abuse of notations, since  $D(p)$  actually is a function of  $x$ .

<sup>5</sup> $\bar{a} = \int_{-\infty}^{+\infty} a(x) dF(x)$  and  $V(a) = \int_{-\infty}^{+\infty} (a(x) - \bar{a})^2 dF(x)$ .

<sup>6</sup>We assume that  $dG(t) > 0$  if and only if  $t \in [t_0, t_1]$ .

<sup>7</sup>If  $K \leq \kappa$ , then our analysis shows that all consumers should always be equipped with smart meters.

$C'(q) > 0$  and  $C''(q) > 0$ .<sup>89</sup> New plants, using intermittent generators (i.e., solar and wind), seek to enter the market. The cost of building intermittent units with capacity  $k$  is  $I(k)$ . It is assumed that  $I(0) = 0$ ,  $I'(k) > 0$  and  $I''(k) \geq 0$ . Given the installed capacity  $k$ , the intermittent generation will be equal to  $\omega(x)k$  in the state  $x$ , at a negligible marginal cost. Define  $\bar{\omega}$  and  $V(\omega)$ , respectively the expected value and the variance of the capacity factor  $\omega(x)$ .<sup>10</sup> Also, define  $Cov(a, \omega)$ , the covariance between the demand variability and the intermittent electric generation.<sup>11</sup> We let  $\rho$  denote the correlation coefficient, defined by  $\rho = Cov(a, \omega) / \sqrt{V(a)V(\omega)}$ .

To simplify the analysis, only interior solutions will be considered and the following linear-quadratic specification of the model:<sup>12</sup>

$$C(q) = \frac{1}{2}cq^2,$$

$$I(k) = \left( \gamma + \frac{1}{2}\delta k \right) k,$$

will be used in some parts of the chapter.<sup>13</sup>

<sup>8</sup>This assumption is used in Twoney and Neuhoff (2010). It is appropriate to represent the initial situation where the incumbent firms own many generating units, using a large variety of conventional technologies (hydro, nuclear, coal, gas, oil), with different marginal costs of generating electricity, and where the overall capacity of this set of generating units is sufficient to match the demand and to prevent black-out. This picture fits quite well the current situation of several countries in Europe, where there exists an overcapacity of conventional units remaining in operation till the end of their programmed lifetime.

<sup>9</sup>To simplify, following Ambec and Crampes (2012), we assume implicitly that the cost function  $C(q)$  includes the environmental damages related to electricity production. This justifies a scenario where the renewable technologies are socially efficient.

<sup>10</sup> $\bar{\omega} = \int_{-\infty}^{+\infty} \omega(x) dF(x)$  and  $V(\omega) = \int_{-\infty}^{+\infty} (\omega(x) - \bar{\omega})^2 dF(x)$ .

<sup>11</sup> $Cov(a, \omega) = \int_{-\infty}^{+\infty} (a(x) - \bar{a})(\omega(x) - \bar{\omega}) dF(x)$ .

<sup>12</sup>From our assumptions above, all parameters are positive.

<sup>13</sup>As mentioned previously, the social cost of CO2 emissions is implicitly included in  $C(q)$ . With the linear-quadratic specification, it thus contributes to the value of parameter  $c$ . To justify this, recall that, as peaking technologies are in general more intensive in CO2 emissions, the system-wide CO2 emissions intensity increases with the convention production. To simplify, assume that the latter can be approximated linearly by  $\eta q$ . Then, the total CO2 emissions of producing  $q$  units of conventional electricity are equal to  $\eta q^2$ . Moreover, letting  $\tau$  represent the social cost of CO2 emissions, the social cost of producing  $q$  units of conventional electricity is equal to  $\tau \eta q^2$ . In this setting, the cost function writes  $C(q) = (c_0 + 2\eta\tau)q^2/2$ , with  $c = c_0 + 2\eta\tau$ .



### 4.3 Optimal policy

The social problem is to determine the metering equipments of the consumers, the generating capacity of the intermittent units, and the demand and supply of electricity in every states of the world, so as to maximize the *expected* social surplus.

In order to solve it, some more notations need to be introduced. Denote by  $S(p)$  the *indirect* aggregate gross surplus when the price of electricity is  $p$ .<sup>14</sup> Then the *indirect* gross surplus of a consumer with type  $t$  facing the price  $p$  is  $tS(p)$ . Moreover, let  $\phi(t)$  be a variable formalizing the meter's equipment of a type  $t$  consumer, such that  $\phi(t) = 1$  if  $t \in \mathcal{S}$  and  $\phi(t) = 0$  if  $t \notin \mathcal{S}$ .<sup>15</sup>

The social problem is to choose  $p(x)$ , for all  $x$ ,  $P$ ,  $q(x)$ , for all  $x$ ,  $k$  and  $\phi(t)$ , for all  $t$ , to maximize the *expected* social surplus

$$\int_{-\infty}^{+\infty} \left[ \int_{t_0}^{t_1} \begin{pmatrix} \phi(t) (tS(p(x)) - \kappa) \\ + (1 - \phi(t)) (tS(P) - K) \end{pmatrix} dG(t) - C(q(x)) - I(k) \right] dF(x), \quad (1)$$

subject to the market clearing condition

$$\int_{t_0}^{t_1} \begin{pmatrix} \phi(t)tD(p(x)) \\ + (1 - \phi(t))tD(P) \end{pmatrix} dG(t) = q(x) + \omega(x)k, \text{ for all } x. \quad (2)$$

The Lagrangian for this problem writes

$$L = \int_{-\infty}^{+\infty} \left[ \int_{t_0}^{t_1} \begin{pmatrix} \phi(t) (tS(p(x)) - \lambda(x)tD(p(x)) - \kappa) \\ + (1 - \phi(t)) (tS(P) - \lambda(x)tD(P) - K) \end{pmatrix} dG(t) \right. \\ \left. + \lambda(x)q(x) - C(q(x)) + \lambda(x)\omega(x)k - I(k) \right] dF(x) \quad (3)$$

where  $\lambda(x)$  is the multiplier associated with the market clearing condition.

<sup>14</sup>By definition,  $S(p) = \int_0^d D^{-1}(z) dz$  where  $d = D(p)$ . It is immediate to calculate that  $S(p) = (a(x)^2 - p^2)/(2b)$ . Again, we make here a slight abuse of notations, since  $S(p)$  actually is a function of  $x$ .

<sup>15</sup>For technical reason, we will admit that  $\phi(t)$  can take any value between 0 and 1.

The optimal solution will be denoted  $p^0(x)$ , for all  $x$ ,  $P^0$ ,  $q^0(x)$ , for all  $x$ ,  $k^0$  and  $\phi^0(t)$ , for all  $t$ . Below, we let  $\alpha^0 = \int_{t_0}^{t_1} t\phi^0(t)tdG(t)$ , which gives the *expected* market share of the consumers equipped with smart meters (see footnote 16). In order to better explain the properties of the optimal solution, we construct and discuss it step by step below. The first-order conditions and comparative statics are derived in the appendix.

### 4.3.1 Optimal dispatch

Let us consider as given here, the intermittent units' capacity (i.e.,  $k^0$ ) and the consumers' metering equipment (i.e.,  $\alpha^0$  and  $\phi^0(t)$  for all  $t$ ). The regulator's problem then reduces to finding prices  $p(x)$ , for all  $x$ , and  $P$ , and conventional units' electric generations  $q(x)$ , for all  $x$ , in order to maximize the *expected* social surplus.

Figure 8 below illustrates the determination of the market equilibrium and the calculus of the resulting *ex post* social surplus in a given state  $x$ . The *aggregate* demand of the consumers on smart meters (resp., traditional meters) is  $\alpha^0 D(p(x))$  (resp.,  $(1 - \alpha^0)D(P)$ ). The corresponding (inverse) demand curves are shown in Parts (a) and (b) of Figure 8. Part (c) depicts the *aggregate* supply curve by the conventional and intermittent generating units. It is obtained by translating to the right the marginal cost curve  $C'(q(x))$ , by the quantity  $\omega(x)k^0$  generated by the intermittent generating units. By construction, the market equilibrium is obtained when the spot price  $p(x)$  and the conventional generation  $q(x)$  satisfy  $p(x) = C'(q(x))$  and  $\alpha^0 D(p(x)) + (1 - \alpha^0)D(P) = q(x) + \omega(x)k^0$ . The resulting *ex post* social surplus is the sum of the consumers' gross surplus (i.e., the trapezes in Parts (a) and (b) of Fig.8), less the cost of electric generation (i.e., the triangle in Part (c) Fig.8).



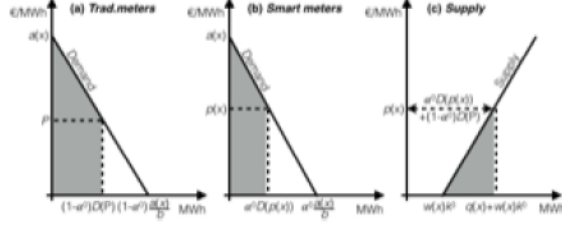


Figure 8: Short term market equilibrium

Rearranging the relevant first-order conditions derived from (3), we can show that the optimal solution satisfies

$$p^0(x) = C'(q^0(x)), \text{ for all } x, \quad (4)$$

$$P^0 = \int_{-\infty}^{+\infty} C'(q^0(x)) dF(x), \quad (5)$$

together with the market clearing condition (2).

In other words, the consumers equipped with the smart meters should always face a price equal to the *ex post* marginal cost of generating electricity. The consumers equipped with the traditional meters should face a price equal to the *expected* marginal cost of generating electricity.

Using (4) and (5), it is immediate that<sup>16</sup>

$$P^0 = \int_{-\infty}^{+\infty} p^0(x) dF(x),$$

meaning that the flat tariff paid by the consumers equipped with traditional meters should simply reflect the *expected* real-time tariff paid by the consumers equipped with smart meters. Therefore, the fact that the consumers equipped with smart meters adapt their demand to the short term positions of the electric market, whereas the consumers equipped with traditional meters do not, is

<sup>16</sup>Joskow and Tirole (2007) and Léautier (2014) obtain the more general result that  $P^0 = \left[ \int_{-\infty}^{+\infty} D'(p^0(x)) p^0(x) dF(x) \right] / \left[ \int_{-\infty}^{+\infty} D'(p^0(x)) dF(x) \right]$  (when there is no rationing). Here, our expression simplifies because the slope of the demand function is constant (i.e.,  $D'(p) = -1/b$ ).

no justification to discriminate their tariffs on average. This may come as a surprise, because the consumers on traditional meters are actually responsible for a dead weight loss each time the flat tariff differs from the real-time tariff.

Using the linear-quadratic specification of our model, we can show that

$$p^0(x) = c \left( \frac{\bar{a} - b\bar{\omega}k^0}{b + c} + \frac{1}{b + \alpha^0 c} (a(x) - \bar{a}) - \frac{bk^0}{b + \alpha^0 c} (\omega(x) - \bar{\omega}) \right), \quad (6)$$

$$P^0 = c \frac{\bar{a} - b\bar{\omega}k^0}{b + c}, \quad (7)$$

$$q^0(x) = \frac{\bar{a} - b\bar{\omega}k^0}{b + c} + \frac{1}{b + \alpha^0 c} (a(x) - \bar{a}) - \frac{bk^0}{b + \alpha^0 c} (\omega(x) - \bar{\omega}), \quad (8)$$

where<sup>17</sup>

$$\alpha^0 = \int_{t_0}^{t_1} t \phi^0(t) dG(t)$$

represents the *expected* market share of the consumers equipped with smart meters.

It is immediate to show that the optimal flat tariff  $P^0$  is increasing in  $\bar{a}$  and  $c$ , and decreasing in  $b$  and  $\bar{\omega}$ . More interestingly, we note that increasing the intermittent capacity  $k^0$  decreases it, whereas increasing the ratio  $\alpha^0$  of the demand of the consumers on smart meters has no impact.<sup>18</sup>

From this, we can calculate the *ex post* fluctuations of the real-time price around its expected value

$$p^0(x) - P^0 = \frac{c}{b + \alpha^0 c} ((a(x) - \bar{a}) - bk^0 (\omega(x) - \bar{\omega}))$$

---

<sup>17</sup>Formally,  $\alpha^0$  is equal to the *expected* demand of the consumers on smart meters (i.e.,  $\int_{-\infty}^{+\infty} \left[ \int_{t_0}^{t_1} \phi^0(t) t D(p^0(x)) dG(t) \right] dF(x)$ ) over the *expected* aggregate demand (i.e.,  $\int_{-\infty}^{+\infty} \left[ \int_{t_0}^{t_1} (\phi^0(t) t D(p^0(x)) + (1 - \phi^0(t)) t D(P^0)) dG(t) \right] dF(x)$ ). We can simplify it, using  $\int_{t_0}^{t_1} t dG(t) = 1$ , and (6) and (7), which implies that  $\int_{-\infty}^{+\infty} D(p^0(x)) dF(x) = \int_{-\infty}^{+\infty} D(P^0) dF(x)$ .

<sup>18</sup>The latter confirms result 1 in Léautier (2014).

and its variance<sup>19</sup>

$$V(p^0) = \left( \frac{c}{b + \alpha^0 c} \right)^2 \left( V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \right). \quad (9)$$

The volatility of the real-time price primarily comes from the demand variability (i.e.,  $V(a)$ ), the renewable energy intermittency (i.e.,  $V(\omega)$  and  $k^0$ ) and their correlation (i.e.,  $\rho$ ). Clearly, the price volatility is decreasing in  $\rho$ . However, the comparative statics with respect to  $V(a)$ ,  $V(\omega)$  and  $k^0$  is ambiguous, depending on the correlation existing between the shocks  $a(x)$  and  $\omega(x)$ . Let  $\underline{k}$  be the intermittent capacity minimizing  $V(p^0)$ . It is not difficult to show that it is equal to 0 if  $\rho \leq 0$  and to  $(\rho/b)\sqrt{V(a)/V(\omega)}$  otherwise. It can then be seen that the price volatility is increasing in  $V(\omega)$  and  $k^0$ , if and only if the optimal capacity  $k^0$  is larger than the capacity  $\underline{k}$  minimizing  $V(p^0)$ . Also, we can also prove that  $V(p^0)$  is increasing in  $V(a)$  if and only if  $\rho^2 k^0 < \underline{k}$ . The transmission of the shocks (i.e.,  $a(x)$  and  $\omega(x)$ ) to the spot prices depends on the elasticities of demand (i.e.,  $\alpha^0$  and  $b$ ) and supply (i.e.,  $c$ ).<sup>20</sup> The volatility of the spot prices is increasing in  $c$  and is decreasing in  $\alpha^0$ . The comparative statics with respect to  $b$  is ambiguous, basically because a more elastic demand has countervailing effects on the spot prices. More precisely, it amplifies the shocks on  $a(x)$  and attenuates the shocks on  $\omega(x)$ . Overall, we are able to show that the real-time price volatility is increasing in  $b$  as long as  $k^0 \geq \underline{k}$ .<sup>21</sup>

Figure 9 illustrates our discussion above. Assuming that  $\rho > 0$ , it represents the variance of the real-time price  $V(p^0)$ , as a function of the optimal capacity of intermittent generating units  $k^0$ . Then,  $V(p^0)$  is decreasing for  $k^0 < \underline{k}$ , is increasing for  $k^0 > \underline{k}$ , and has a minimum equal to  $(1 - \rho^2)(c/(b + \alpha^0 c))^2 V(a)$  for  $k^0 = \underline{k}$ . Remark that this minimum is decreasing in  $\rho$  and vanishes when  $\rho = 1$ . Finally, also note that the penetration of intermittent generating units actually helps

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<sup>19</sup> $V(p^0) = \int_{-\infty}^{+\infty} (p^0(x) - P^0)^2 dF(x)$ .

<sup>20</sup>For all  $x$ , the aggregate demand is  $\alpha^0 D(p^0(x)) + (1 - \alpha^0)D(P^0) = (a(x) - \alpha^0 p^0(x) - (1 - \alpha^0)P^0) / b$ . The derivative of the demand function with respect to  $p^0(x)$  is thus equal to  $\alpha^0 / b$  (in absolute value), showing that the reactivity of the aggregate demand to shocks depends on both  $\alpha^0$  and  $b$ .

<sup>21</sup>Note that the comparative statics derived here treats  $\alpha^0$  and  $k^0$  as parameters, although they are endogenously determined in an optimal solution. This is clearly for the sake of simplicity. We will provide a numerical illustration below, in order to fully describe the optimal behavior of all endogenous variables at the same time.

limiting the variance of the real-time price as long as  $k^0 \leq 2\underline{k}$ ; it becomes detrimental only for  $k^0 > 2\underline{k}$ .

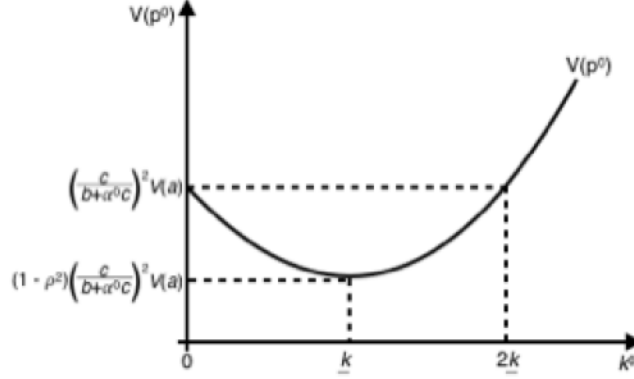


Figure 9: Variance of the real-time price (when  $\rho > 0$ )

### 4.3.2 Intermittent capacity

Let us consider as given here, the real-time price and flat tariff (i.e.,  $p^0(x)$  for all  $x$  and  $P^0$ ), and the consumers' metering equipment (i.e.,  $\alpha^0$  and  $\phi^0(t)$  for all  $t$ ). The social problem then becomes to determine the investment in the intermittent technologies, in order to maximize the *expected* social surplus.

Rearranging the relevant first-order conditions derived from (3), we can show that the optimal solution satisfies

$$I'(k^0) = \int_{-\infty}^{+\infty} C'(q^0(x)) \omega(x) dF(x). \quad (10)$$

Accordingly, the intermittent capacity should be increased as long as the cost of investing in the marginal intermittent unit remains smaller than its *expected* marginal benefit. In the state  $x$ , the marginal benefit of intermittent units is the product of the marginal cost of generating electricity from the conventional generators,  $C'(q^0(x))$ , times the production of the marginal generating unit,  $\omega(x)$ .

Using the linear-quadratic specification of our model, for an interior solution, we can show that<sup>22</sup>

$$k^0 = \frac{\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma + \frac{c}{b+\alpha^0 c}\rho\sqrt{V(a)V(\omega)}}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)}. \quad (11)$$

Accordingly, the optimal capacity of intermittent generating units depends on the demand's level, variability and reactivity (i.e.,  $\bar{a}$ ,  $V(a)$ ,  $b$  and  $\alpha^0$ ), the cost of electric generation by conventional units (i.e.,  $c$ ), the cost of building and operating renewable generating units (i.e.,  $\gamma$  and  $\delta$ ), the availability and variability of intermittent energy (i.e.,  $\bar{\omega}$  and  $V(\omega)$ ), and the correlation between demand and renewable energy (i.e.,  $\rho$ ). Clearly, the optimal capacity of intermittent units is increasing in  $\bar{a}$  and  $\rho$ , decreasing in  $\gamma$  and  $\delta$ , and is increasing in  $V(a)$  if and only if  $\rho$  is positive. The comparative statics with respect to  $\alpha^0$ ,  $b$ ,  $c$ ,  $\bar{\omega}$  and  $V(\omega)$  is ambiguous. However, we are able to show that the optimal capacity of intermittent generating units is decreasing in  $b$  if  $\rho$  is positive, increasing in  $\bar{\omega}$  if and only if  $k^0 < \bar{a}/(2b\bar{\omega})$  and increasing in  $V(\omega)$  if and only if  $k^0 < \underline{k}/2$ .

Figure 10 is useful to understand the comparative statics of  $k^0$  with respect to  $\alpha^0$ .<sup>23</sup> It inventories the two reasons for investing in the intermittent generating technologies, from which the optimal strategy derives. The first rationale is to supply low cost electricity (i.e., merit order argument). It is represented by the horizontal dashed line, plotting the capacity  $\bar{k}$  that would be worth investing in the renewable generating units if the renewable energy was continuously available at its average value (i.e., if  $\omega(x) = \bar{\omega}$  for all  $x$  and  $V(\omega) = 0$ ).<sup>24</sup> The second rationale is to limit the variability of the dispatchable generation (i.e., intermittency argument). It is represented by the broken dashed line, depicting the capacity  $\underline{k}$  that would minimize the variance of the real-time price of electricity.<sup>25</sup> In Figure 10, we let  $\rho^0$  be the value of the coefficient of correlation  $\rho$  such that these two lines intersect (i.e.,  $\bar{k} = \underline{k}$ ).<sup>26</sup> For all  $\alpha^0$ , the optimal capacity  $k^0$ , given by (11),

<sup>22</sup>An interior solution is obtained as long as  $\gamma < \bar{a}\bar{\omega}c/(b+c) + \rho\sqrt{V(a)V(\omega)}/(b+\alpha^0 c)$ . Otherwise the optimal capacity in intermittent units is null.

<sup>23</sup>Here again, for the sake of simplicity, we treat  $\alpha^0$  as a parameter, although it is endogenously determined. Below, a numerical illustration is provided to complete the analysis.

<sup>24</sup>Using (11) and substituting  $V(\omega) = 0$ , we get  $\bar{k} = \left(\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma\right) / \left(\frac{c}{b+c}b\bar{\omega}^2 + \delta\right)$ .

<sup>25</sup>Recall that  $\underline{k}$  is null if  $\rho \leq 0$  and equal to  $(\rho/b)\sqrt{V(a)/V(\omega)}$  otherwise.

<sup>26</sup>It is easily calculated that  $\rho^0 = b\bar{k}\sqrt{V(\omega)/V(a)}$ . Note that we implicitly assume in Figure 9 that  $\rho^0 < 1$ .



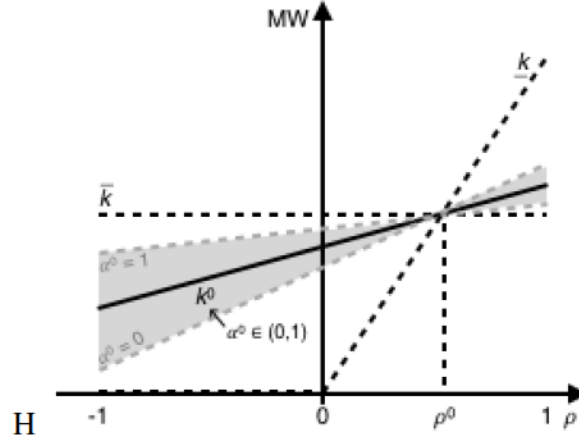


Figure 10: Optimal capacity

lies within the shaded area, bounded by the two dashed frontiers in gray, corresponding to the limit cases where  $\alpha^0 = 0$  and  $\alpha^0 = 1$ . Finally, the optimal capacity  $k^0$  is represented by the plain line, for a given  $\alpha^0$  strictly between 0 and 1. As it can be seen, for all  $\alpha^0$ , it always lies between the two dashed lines  $\underline{k}$  and  $\bar{k}$  and intersects them both when  $\rho = \rho^0$ . Moreover, as the market share of smart meters  $\alpha^0$  increases from 0 to 1, it rotates clockwise around this intersection point. In other words, it gets closer to the horizontal dashed line plotting the capacity  $\bar{k}$ . This should not come as a surprise, as the development of smart meters helps to limit the variability of the generation of the conventional units. Increasing the market share of smart meters thus justifies to put more weight on the other objective (i.e., merit order argument). This means that  $k^0$  is increasing in  $\alpha^0$  when  $\rho < \rho^0$ , is decreasing in  $\alpha^0$  when  $\rho > \rho^0$ , and does not depend on  $\alpha^0$  when  $\rho = \rho^0$ .

### 4.3.3 Metering equipments

Let us finally consider as given, the real-time price and flat tariff (i.e.,  $p^0(x)$  for all  $x$  and  $P^0$ ), and the capacity in intermittent units (i.e.,  $k^0$ ). The social problem then boils down to determining the consumers' metering equipment, in order to maximize the *expected* social surplus.

Using the relevant first-order conditions derived from (3), we can show that the optimal solu-



tion satisfies<sup>27</sup>

$$\phi^0(t) = 1 \quad \text{iff} \quad \begin{aligned} & \int_{-\infty}^{+\infty} p^0(x) t (D(P^0) - D(p^0(x))) dF(x) \\ & - \int_{-\infty}^{+\infty} t (S(P^0) - S(p^0(x))) dF(x) \end{aligned} \geq K - \kappa. \quad (12)$$

This inequality emphasizes three terms, listing the different benefits and costs from equipping with a smart meter a consumer with type  $t$ . Supplying a consumer on a smart meter saves costs of generating electricity, because the latter has an incentive to reduce his demand when the price/marginal cost of electricity is high (upper part on the left-hand side of the inequality). However, in counterpart, a consumer on a smart meter incurs a welfare loss, because he bears the risk of price volatility (lower part on the left-hand side of the inequality). Finally, the installation and operation of the smart meter is more costly *per se* (right-hand side of the inequality).

By definition of  $D(p)$  and  $S(p)$ , this condition simplifies to<sup>28</sup>

$$\frac{t}{2b} V(p^0) \geq K - \kappa. \quad (13)$$

Assuming that the equality occurs for an interior solution (i.e.,  $t_0 < t^0 < t_1$ ), we can define the optimal marginal consumer's type

$$t^0 = \frac{2b(K - \kappa)}{V(p^0)}, \quad (14)$$

such that every consumer with types  $t > t^0$  (resp.,  $t \leq t^0$ ) should be equipped with smart (resp. traditional) meters. The corresponding optimal *expected* market share of the consumers equipped with smart meters is

$$\alpha^0 = \int_{t^0}^{t_1} t dG(t). \quad (15)$$

Clearly, as it is decreasing in  $t^0$ , it is immediate from above that the optimal *expected* market share of the consumers equipped with smart meters is decreasing in  $b$  and  $K - \kappa$ , and is increasing

<sup>27</sup>Remember that  $\phi(t)$  can only take values 0 or 1.

<sup>28</sup>Moreover, recall that from (4) and (5), we have  $P^0 = \int_{-\infty}^{+\infty} p^0(x) dF(x)$ .

in  $V(p^0)$ . These findings are quite intuitive. Smart meters are worthwhile if the consumers are sufficiently reactive (i.e.,  $b$  is small), if installing and operating them is not too costly (i.e.,  $K - \kappa$  is small) and if there exists enough price fluctuations (i.e.,  $V(p^0)$  is large).

At that point, our understanding of the factors influencing the optimal *expected* market share of the consumers equipped with smart meters is partial. Indeed, in an optimal allocation, the variance of the real-time price  $V(p^0)$ , satisfying (9), is itself a function of  $\alpha^0$  and most parameters of the model. However, accounting for all these indirect effects, we are still able to show that  $\alpha^0$  is increasing (resp., decreasing) in all parameters that increase (resp., decrease) the variance of the real-time price, either directly or indirectly.

Accordingly, the optimal *expected* market share of the consumers equipped with smart meters  $\alpha^0$  is increasing in  $V(a)$ ,  $V(\omega)$  and  $c$ , and decreasing in  $\rho$ . It is increasing (resp., decreasing) in  $k^0$  if the intermittent capacity  $k^0$  is larger (resp. smaller) than the intermittent capacity  $\underline{k}$  minimizing the variance  $V(p^0)$  of the real-time price. Finally, the comparative statics with respect to  $b$  is essentially ambiguous.<sup>29</sup>

## 4.4 Numerical illustration

To complete our analysis, we now provide a calibration of our model. Although it is mainly for illustrative purpose, the proposed calibration is meant to reflect the French electric market in 2016. We use the annual report of Réseau de Transport de l'Electricité (RTE, 2016), which operates the French power transmission system. In 2016, the electric aggregated consumption was equal to 480.32 TWh. The hourly consumption was equal to 54681.29 MWh, with a standard deviation equal to 11531.66 MWh. The average price of electricity on the spot market was 36.75 €/MWh. The electric generation from intermittent energy sources decomposed to 20.92 TWh for wind energy and 8.26 TWh for solar energy, with installed capacities of 11670 MW and 6772 MW

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<sup>29</sup>Again, for the sake of simplicity, the comparative statics derived here treats  $k^0$  as a parameter, although it is endogenously determined in an optimal allocation. The numerical illustration in Section 4.

respectively. Overall, the aggregated hourly generation from intermittent energy sources was equal to 3321.8 MWh, with a standard deviation equal to 2055.13 MWh. Accordingly, one can calculate a capacity factor equal to 18.01 %, with standard deviation equal to 11.14 %.<sup>30</sup> We also rely on estimates of the price elasticity of demand for electricity. EPRI (2008) reviews 18 studies giving estimates of the price elasticity of demand for electricity under a variety of conditions. They find that the elasticity of electricity demand is comprised between 0.2 and 0.6, in the short run, and between 0.7 and 1.4, in the long run. Recently, Lijesen (2012), dealing more specifically with *real-time* price elasticities, obtains smaller estimates between 0.01 and 0.1. Finally, in 2016, the share of renewable energies in the the electric consumption attained 21.08 %.<sup>31</sup> Our calibration is made to comply with the French energy laws, prescribing a renewable energy target of 32 % of final energy consumption by 2030,<sup>32</sup> and a smart meter target of 100 % for sites with peak demand smaller than 36 kVA by 2024.<sup>33</sup>

Using this piece of information, we calibrate our model by assuming that the equilibrium of the *regulated* electric market in 2016 is best described by the assumption of perfect competition. Accordingly, the optimal solution calculated previously must both fit the current data and meet the French target for renewable energy. Table 1 below lists our benchmark calibration. The details and calculus can be found in the appendix.

$\bar{a}$	$V(a)$	$b$	$c$	$\gamma$	$\delta$	$\rho$	$\bar{\omega}$	$V(\omega)$
146.113	531.917	0.002	0.000715	5	0.000011	0	0.180121	0.012418

Table 2 Benchmark calibration

<sup>30</sup>The capacity factor is equal to the hourly output of 2611.63 MWh over the potential output of 14412 MWh. Its standard deviation is equal to the hourly standard deviation equal to 1589.99 MWh over the potential output of 14412 MWh.

<sup>31</sup>In 2016, the generation from hydroelectricity and biomass were equal to 63.36 TWh and 8.71 TWh respectively.

<sup>32</sup>See: <https://www.ecologique-solidaire.gouv.fr/loi-transition-energetique-croissance-verte> (visited November 28th, 2017).

<sup>33</sup>See: <https://www.legifrance.gouv.fr/affichCode.do?idSectionTA=LEGISCTA000031749063&cidTexte=LEGITEXT000023983208&dateTexte=20160421> (visited November 28th, 2017).

A sensibility analysis will complete this benchmark calibration, by varying the parameters  $b$  and  $\rho$ .<sup>34</sup> A robustness check with respect to the parameter  $b$  is needed due to the lack of consensus about the price elasticity of demand for electricity. Moreover, this factor is critical in our model, since the reactivity of the consumers to real-time prices directly influences the social benefit of smart meters. We will consider values of  $b$  between 0.001 and 0.005, corresponding to price elasticities between 0.1 and 0.7 approximately.<sup>35</sup> A sensibility analysis with respect to the parameter  $\rho$  is interesting to better highlight the role of intermittent energy sources within the electric system. We will consider values of  $\rho$  between -1 and 1.<sup>36</sup> Indeed, the commonly accepted belief is that the penetration of intermittent technologies causes adverse effects to the electric system. Our analysis has made clear that this is so only if we presume a negative correlation between demand and intermittent energy sources or if the intermittent capacity is sufficiently large. Otherwise, the wind and solar energies could in fact supply valuable hedging services. This leads to encourage any public policies capable of increasing the correlation between intermittent energy sources and demand.<sup>37</sup>

Figure 11 represents the optimal capacity of intermittent generating units, as a function of the expected market share of the consumers on smart meters.<sup>38</sup> The main curve plots  $k^0$  for the benchmark specification (i.e.,  $b = 0.002$  and  $\rho = 0$ ).<sup>39</sup> We verify that it is increasing in the market share of the smart meters (i.e., from 51257 MW to 54647 MW). From our previous analysis, we know that it would actually be increasing (resp., decreasing) for any  $\rho < \rho^0$  (resp.,  $\rho > \rho^0$ ). Here, we can calculate that  $\rho^0 \simeq 0.65$ . The horizontal dashed line represents the capacity that would be worth investing provided the renewable energies were perfectly dispatchable (i.e.,  $\bar{k}$ ). Here, we

<sup>34</sup>Importantly, it must be noted that the whole set of parameters is automatically updated after varying them, following the same calibration process just described (Cf Tables in appendix).

<sup>35</sup>See the appendix for the calculus of the price elasticity of demand in our model.

<sup>36</sup>Of course, we are perfectly aware that considering the whole range  $\rho \in [0, 1]$  is quite unrealistic. However, as noted by Ambec and Crampes (2012, footnote 6, page 322), both cases of positive and negative correlation are possible. For example, Torres et al. (2016) obtain correlation coefficients varying between -0.79 and 0.71, depending on considered scenarios (capacities and energy mix). Finally, we find interesting to think of  $\rho$  also as a policy instrument.

<sup>37</sup>Examples of policies that can influence the correlation between demand and intermittent energies are the introduction of daylight saving time (Havranek et al, 2016), the development and organization of prosuming consumers (Parag et al, 2016), the choice of the renewable energy mix (Torres et al, 2016), and so on.

<sup>38</sup>See equation 11.

<sup>39</sup>More generally, for any  $\rho$ , the optimal capacity would lie in the shaded area, between the lower and upper boundaries (dashed lines in gray) respectively corresponding to  $\rho$  equal to  $-1$  and  $1$ .



can obtain that  $\bar{k} = 67038$  MW. From Figure 9, we know that it would also coincide with the optimal capacity of intermittent technologies provided that  $\rho = \rho^0$ . Figure 11 also highlights the potentially large influence of the correlation between demand and intermittent energy sources on the optimal capacity of intermittent units. This can be seen by comparing the lower and upper boundaries (dashed lines in gray), plotting the capacity that would be optimal if  $\rho$  was equal to  $-1$  or  $1$  respectively. The gap varies from 48720 MW when  $\alpha^0 = 0$ , to 38255 MW when  $\alpha^0 = 1$ .<sup>40</sup>

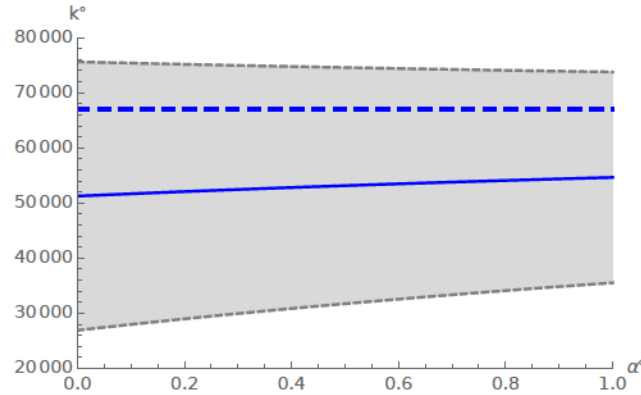


Figure 11: Optimal capacity of intermittent units (Units: %; MW)

Figure 12 depicts the expected real-time price, as a function of the expected market share of the consumers on smart meters.<sup>41</sup> Equation (7) implies that this relation is only indirect, through the variations of the optimal capacity of intermittent generating units. Thus, the underlying mechanisms are exactly the same as above in Figure 10 and corresponding comments. In Figure 11, the main curve plots  $P^0$ , assuming that the capacity of intermittent generating units is set optimally for the benchmark specification (i.e.,  $k^0$  calculated for  $b = 0.002$  and  $\rho = 0$ ).<sup>42</sup> The latter being increasing with  $\alpha^0$ , we observe that  $P^0$  is slightly decreasing in the expected market share of the smart meters (i.e., from 33.65 €/MWh to 32.31 €/MWh). From our theoretical analysis, we know

<sup>40</sup>In the appendix, we observe qualitatively the very same behaviors in Figures 2(a) and 2(b), dealing with the case where  $b = 0.001$  and  $b = 0.005$ . The differences are only to be found in the magnitude of the variations of the optimal capacity of intermittent units.

<sup>41</sup>See equation 7.

<sup>42</sup>More generally, for any  $\rho$ , the expected real-time price in the optimal outcome would lie in the shaded area, between the lower and upper boundaries in dashed gray lines, respectively corresponding to  $\rho$  equal to  $1$  and  $-1$ .

that it would actually be decreasing (resp., increasing) for any  $\rho < \rho^0$  (resp.,  $\rho > \rho^0$ ). The upper dashed line plots the expected real-time price that would prevail with the intermittent capacity set equal to zero. The gap with the main curve thus gives the reduction of the expected real-time price due to the optimal investment in the intermittent technologies. It varies from 4.86 €/MWh if  $\alpha^0 = 0$ , to 5.18 €/MWh if  $\alpha^0 = 1$ . Finally, the lower dashed line plots the expected real-time price that would prevail with the intermittent capacity set equal to  $\bar{k}$ . Recalling that  $\bar{k}$  is the capacity that would be worth investing provided the renewable energies were perfectly dispatchable, the gap with the main curve provides a measure of the expected marginal cost of intermittency (i.e., the cost of optimally reducing the intermittent capacity for the sake of limiting the volatility on the spot market). It varies from 1.50 €/MWh when  $\alpha^0 = 0$ , to 1.18 €/MWh when  $\alpha^0 = 1$ .

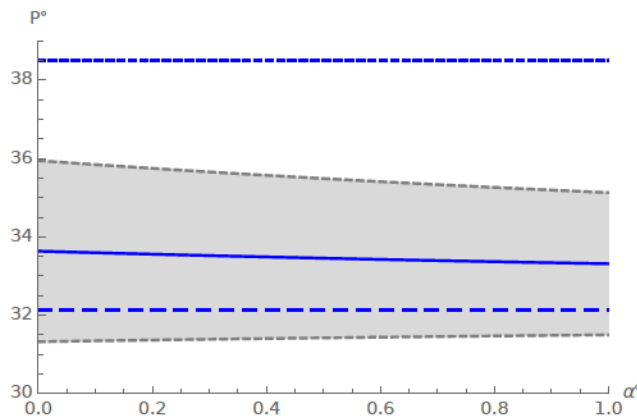


Figure 12: Expected real-time price (Units: %; €/MWh)

Figure 13 represents the variance of the real-time price, as a function of the expected market share of the consumers on smart meters.<sup>43</sup> Equation (9) implies that this relation is both direct and indirect. It is direct because the consumers on smart meters react to real-time price fluctuations in the opposite direction; it is indirect because installing smart meters induces variations of the optimal capacity of intermittent units, which can either increase or decrease the real-time price volatility, depending on the assumptions. In Figure 14, the main curve plots  $V(p^0)$ , assuming that the capacity of intermittent generating units is set optimally for the benchmark calibration (i.e.,  $k^0$

<sup>43</sup>See equation (9).



calculated for  $b = 0.002$  and  $\rho = 0$ ).<sup>44</sup> We verify that it is decreasing in the expected market share of the consumers on smart meters. In the appendix, we prove that this would hold true for any  $\rho$ . This means that the direct effect discussed above (i.e., consumers' reactivity) always dominates the indirect effect (i.e., variations of the optimal intermittent capacities). The lower dashed line plots the variance of the real-time price that would prevail with the intermittent capacity set equal to zero. The gap with the main curve thus measures the increase of the variance of real-time price due to the optimal investment in the intermittent technologies. It varies from 16.70 (€/MWh)<sup>2</sup> if  $\alpha^0 = 0$ , to 10.30 (€/MWh)<sup>2</sup> if  $\alpha^0 = 1$ . Finally, the upper dashed line represents the variance of the real-time price that would prevail with the intermittent capacity set equal to  $\bar{k}$ . Anew, knowing that  $\bar{k}$  gives the capacity that would be worth investing provided the renewable energies were perfectly dispatchable, the gap with the main curve illustrates the optimal trade-off between low cost energy and intermittency, which induces to restrict the use of intermittent technologies compared to  $\bar{k}$ .

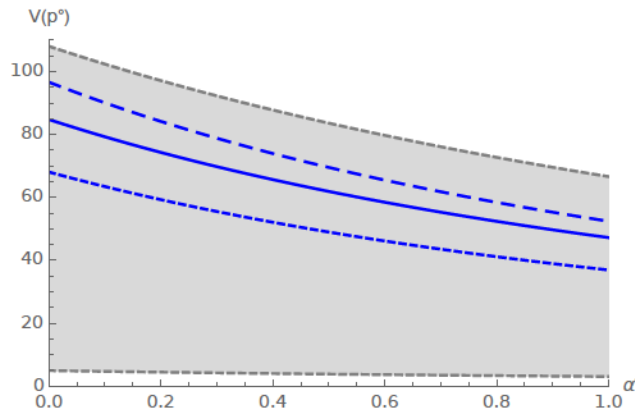


Figure 13: Variance of the real-time price (Units: %; (€/MWh)<sup>2</sup>)

In Figures 11 to 13, the expected market of the consumers on smart meters has been treated as a parameter, in order to better highlight its role in the optimal outcome. To complete the analysis, we now deal with its optimal determination.

<sup>44</sup>More generally, for any  $\rho$ , the variance of the real-time price in the optimal outcome would lie in the shaded area, between the lower and upper boundaries in dashed gray lines, corresponding to  $\rho$  equal to  $-1$  and  $1$  respectively.

To do so, some additional piece of information is needed in order to calibrate the distribution of the consumers (i.e.,  $G(t)$ ). We use the following data initially collected by Léautier (2014):

- (i) the large non residential sites represent 0.1 % of all sites and 42 % of total demand;
- (ii) the medium non residential sites represent 1 % of all sites and 15 % of the total demand;
- (iii) the small non residential sites represent 13 % of all sites and 10 % of total demand;
- (iv) the residential sites represent 86 % of all sites and 32 % of total demand.

Now, assume that the consumers' types are distributed according to the Pareto distribution

$$G(t) = 1 - (t_0/t)^\mu, \text{ for all } t \geq t_0,$$

with parameters  $t_0 > 0$  and  $\mu > 1$ .<sup>45</sup> Then, the average type is equal to  $\mu t_0 / (\mu - 1)$ . In our model, it must be normalized to one by assumption. Also, the associated Lorenz curve writes

$$L(f) = 1 - (1 - f)^{1-1/\mu},$$

where  $f$  is the percentage of consumers consuming  $L(f)$  percent or less of the aggregate electric consumption. Below, we calibrate the Pareto distribution, by finding parameters  $t_0$  and  $\mu$  such that the Lorenz curve approximately fits the data collected by Léautier (2014). We retain the calibration  $t_0 = 1/6$  and  $\mu = 6/5$ . Figure 14 represents the position of the Lorenz curve with respect the three points derived from Léautier (2014).

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<sup>45</sup>Note that  $t_1 = \infty$  with the Pareto distribution.

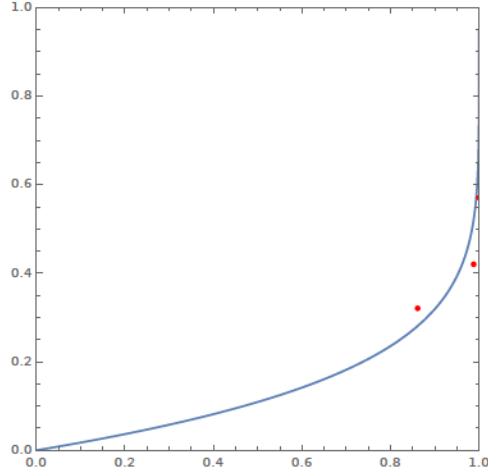


Figure 14: Lorenz curve (Units: %; %)

Figure 15 represents the optimal expected market share of the consumers on smart meters, as a function of the extra cost of installing and operating a smart meter, instead of a traditional meter.<sup>46</sup> The main curve plots  $\alpha^0$  for the benchmark calibration (i.e.,  $b = 0.002$  and  $\rho = 0$ ), assuming that the capacity of intermittent generating units is set optimally.<sup>47</sup> We see that a general adoption of smart meters (i.e.,  $\alpha^0 = 1$ ) is optimal only if  $K - \kappa$  is less 0.5 €/year. However, as smart meters become more costly, their optimal deployment decreases to reach 46 % when  $K - \kappa$  is equal to 30 €/year. The dashed curve depicts the expected market share of smart meters that would be optimal, in a situation with no capacity of intermittent generating units. Since it lies below the main curve, we conclude that under the benchmark specification, the investment in the intermittent technologies justifies to use smart meters more extensively. However, it must be noted that this result is not general. Indeed, we could display cases, for  $\rho$  large enough, such that the main curve would be below the dashed curve (e.g, the dashed gray lines, corresponding to  $\rho$  equal to  $-1$ ). In other words, smart meter and intermittent technologies can be either complements or substitutes, depending on the correlation between demand and intermittent energies.

<sup>46</sup>In our model,  $K$  and  $\kappa$  are the cost of installing and operating the smart and traditional meters, for the whole population, over one period of time. Here, for the sake of interpretation, we normalize the units by first dividing  $K$  and  $\kappa$  by 36.6 millions sites and then multiplying them by 8760 hours per year. Accordingly, the x-axis in Figure 5 gives the extra cost of a smart meter, for one site over one year.

<sup>47</sup>More generally, for all  $\rho$ , the curve plotting the optimal expected market share of the consumers on smart meters lies between the lower and upper boundaries in dashed gray lines, corresponding to  $\rho$  equal to 1 and  $-1$  respectively.

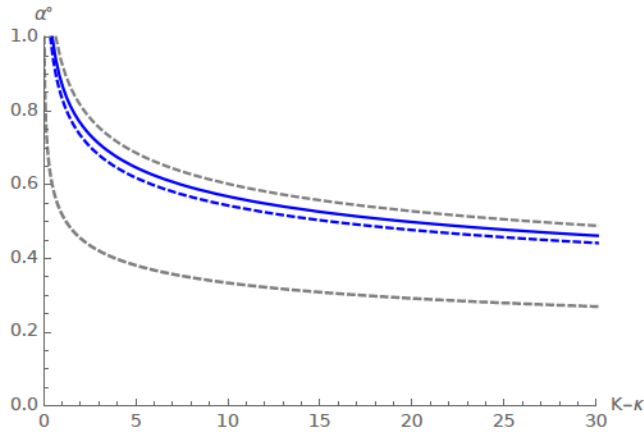


Figure 15: Expected market share of smart meters (Units: €/year; %)

## 4.5 Conclusion

In this chapter, we bring together, in a stylized microeconomic framework, the issues of the determination of the development of intermittent capabilities and smart meters in a social optimum. Dealing with both issues at the same time allows in particular to highlight the role played by the correlation existing between demand and intermittent supply within the electric system. Our results challenge and clarify two commonly accepted beliefs. The first one is that the penetration of intermittent technologies necessarily causes negative externalities to the electric system. The second one is that the intermittent capacities and smart meters should necessarily be developed in parallel. Our analysis makes clear that this is so only if the electric demand and the intermittent electric generation are negatively correlated *or* if they are positively correlated but the intermittent capacity is already large enough. Otherwise, the development of the intermittent generating technologies may be a win-win policy, by allowing to reduce both the level and the volatility of the electric spot price. Then, the capacity of intermittent technologies and the installation of smart meters would be substitutes rather than complements. This leads to encourage any public policies capable of increasing the correlation between intermittent energy sources and demand. Finally, using data from the French power market, we show that a general adoption of smart meters would be optimal only if the cost of installing and operating smart meters was unrealistically low (0.5 €/year). This

finding is important from a policy perspective as it casts doubt on the economic value of the general deployment of smart meters.

## 4.6 Appendix

### 4.6.1 Lagrangian and first-order conditions

The social problem is to choose  $p(x)$ , for all  $x$ ,  $P$ ,  $q(x)$ , for all  $x$ ,  $\phi(t)$ , for all  $t$ , and  $k$  to maximize the *expected* social surplus

$$\int_{-\infty}^{+\infty} \left[ \int_{t_0}^{t_1} \left( \begin{array}{l} \phi(t) (tS(p(x)) - \kappa) \\ + (1 - \phi(t)) (tS(P) - K) \end{array} \right) dG(t) - C(q(x)) - I(k) \right] dF(x),$$

subject to the market clearing condition

$$\int_{t_0}^{t_1} \left( \begin{array}{l} \phi(t)tD(p(x)) \\ + (1 - \phi(t)) tD(P) \end{array} \right) dG(t) = q(x) + \omega(x)k,$$

for all  $x$ .

The lagrangian for this problem writes

$$L = \int_{-\infty}^{+\infty} \left[ \int_{t_0}^{t_1} \left( \begin{array}{l} \phi(t) (tS(p(x)) - \lambda(x)tD(p(x)) - K) \\ + (1 - \phi(t)) (tS(P) - \lambda(x)tD(P) - \kappa) \end{array} \right) dG(t) \right. \\ \left. + \lambda(x)q(x) - C(q(x)) + \lambda(x)\omega(x)k - I(k) \right] dF(x),$$

where  $\lambda(x)$  is the multiplier associated with the market clearing condition.

Denoting  $\alpha = \int_{t_0}^{t_1} \phi(t)t dG(t)$ ,<sup>48</sup> the derivatives of the lagrangian are:<sup>49</sup>

$$\frac{\partial L}{\partial p(x)} = \frac{\alpha}{b} (p(x) - \lambda(x)) dF(x)$$

$$\frac{\partial L}{\partial P} = \frac{1 - \alpha}{b} \int_{-\infty}^{+\infty} (P - \lambda(x)) dF(x)$$

<sup>48</sup>Remark that  $\alpha \in [0, 1]$ .

<sup>49</sup>The derivatives simplify using  $S'(p) = -p/b$  and  $D'(p) = -1/b$ .



$$\frac{\partial L}{\partial q(x)} = (\lambda(x) - C'(q(x))) dF(x)$$

$$\frac{\partial L}{\partial \phi(t)} = dG(t) \int_{-\infty}^{+\infty} \begin{pmatrix} \lambda(x)t (D(P) - D(p(x))) \\ -t(S(P) - S(p(x))) \\ -(K - \kappa) \end{pmatrix} dF(x)$$

$$\frac{\partial L}{\partial k} = dG(t) \int_{-\infty}^{+\infty} (\lambda(x)\omega(x) - I'(k)) dF(x)$$

From this, we can show that the optimal solution satisfies the following conditions:

$$p^0(x) = C'(q^0(x)), \text{ for all } x,$$

$$P^0 = \int_{-\infty}^{+\infty} C'(q^0(x)) dF(x),$$

$$I'(k^0) = \int_{-\infty}^{+\infty} C'(q^0(x)) \omega(x) dF(x),$$

$$\phi^0(t) = 1 \quad \text{iff} \quad \frac{t}{2b} \int_{-\infty}^{+\infty} (p^0(x) - P^0)^2 dF(x) > K - \kappa.$$

### Comparative statics of $V(p^0)$ (Equation (9))

We derive here the comparative statics of

$$V(p^0) = \left( \frac{c}{b + \alpha^0 c} \right)^2 \left( V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \right).$$

Let us define below

$$\underline{k} \equiv \max \left\{ 0, \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} \right\}.$$

We show below that  $\underline{k}$  is the investment in the renewable generating units that minimizes  $V(p^0)$ . Considering  $\alpha^0$  and  $k^0$  as given, we can calculate that

$$\frac{\partial V(p^0)}{\partial \bar{a}} = 0,$$

$$\frac{\partial V(p^0)}{\partial V(a)} = \left( \frac{c}{b + \alpha^0 c} \right)^2 \frac{b}{\rho} \sqrt{\frac{V(\omega)}{V(a)}} \left( \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} - \rho^2 k^0 \right) \begin{matrix} \geq 0 \\ \leq 0 \end{matrix} \Leftrightarrow \rho^2 k^0 \begin{matrix} \leq \underline{k} \\ \geq \underline{k} \end{matrix},$$

$$\frac{\partial V(p^0)}{\partial b} = -2 \frac{c^2}{(b + \alpha^0 c)^3} \left( \begin{matrix} V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \\ + (b + \alpha^0 c) bk^0 V(\omega) \left( \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} - k^0 \right) \end{matrix} \right) < 0 \text{ if } k^0 \leq \underline{k},$$

$$\frac{\partial V(p^0)}{\partial c} = \frac{2bc}{(b + \alpha^0 c)^3} \left( V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \right) > 0,$$

$$\frac{\partial V(p^0)}{\partial \bar{\omega}} = 0,$$

$$\frac{\partial V(p^0)}{\partial V(\omega)} = \left( \frac{bc}{b + \alpha^0 c} \right)^2 k^0 \left( k^0 - \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} \right) \begin{matrix} \geq 0 \\ \leq 0 \end{matrix} \Leftrightarrow k^0 \begin{matrix} \geq \underline{k} \\ \leq \underline{k} \end{matrix},$$

$$\frac{\partial V(p^0)}{\partial \rho} = -2 \left( \frac{c}{b + \alpha^0 c} \right)^2 bk^0 \sqrt{V(a)V(\omega)} < 0,$$

$$\frac{\partial V(p^0)}{\partial \alpha^0} = -2 \left( \frac{c}{b + \alpha^0 c} \right)^3 \left( V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \right) < 0,$$

$$\frac{\partial V(p^0)}{\partial k^0} = 2 \left( \frac{bc}{b + \alpha^0 c} \right)^2 V(\omega) \left( k^0 - \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} \right) \begin{matrix} \geq 0 \\ \leq 0 \end{matrix} \Leftrightarrow k^0 \begin{matrix} \geq \underline{k} \\ \leq \underline{k} \end{matrix}.$$

Remark that the last result means that  $V(p^0)$  is minimized when  $k^0 = \underline{k}$ .

## 4.7 Comparative statics of $k^0$ (Equation (11))

We derive here the comparative statics of

$$k^0 = \frac{\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma + \frac{c}{b+\alpha^0 c}\rho\sqrt{V(a)V(\omega)}}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)}.$$

Let us first define

$$\bar{k} = \frac{\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma}{\frac{c}{b+c}b\bar{\omega}^2 + \delta}.$$

Note that  $k^0$  coincides with  $\bar{k}$  when  $V(\omega) = 0$ . Taking  $\alpha^0$  as given, we can calculate that

$$\frac{\partial k^0}{\partial \bar{a}} = \frac{\frac{c}{b+c}\bar{\omega}}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} > 0,$$

$$\frac{\partial k^0}{\partial V(a)} = \frac{\frac{c}{b+\alpha^0 c}\frac{1}{2}\rho\sqrt{\frac{V(\omega)}{V(a)}}}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} \geq 0 \Leftrightarrow \rho \geq 0,$$

$$\begin{aligned} \frac{\partial k^0}{\partial b} = & - \frac{\frac{c}{(b+c)^2}\bar{a}\bar{\omega} \left( \frac{\bar{a}\bar{\omega} - \gamma}{\bar{a}\bar{\omega}} c\bar{\omega}^2 + \delta \right) + \frac{c}{(b+c)^2}\bar{a}\bar{\omega} \frac{c}{(b+\alpha^0 c)^2} V(\omega) \left( (1 - \alpha^0)b^2 + \alpha^0 \frac{\bar{a}\bar{\omega} - \gamma}{\bar{a}\bar{\omega}} (b+c)^2 \right) + \frac{c}{(b+\alpha^0 c)^2} \rho \sqrt{V(a)V(\omega)} \left( (b^2 + 2bc + \alpha^0 c^2) \frac{c}{(b+c)^2} \bar{\omega}^2 + \delta + cV(\omega) \right)}{\left( \frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega) \right)^2} > 0 \text{ if } \rho \geq 0, \end{aligned}$$

$$\begin{aligned} \frac{\partial k^0}{\partial c} = & \frac{\frac{b}{(b+c)^2}\bar{a}\bar{\omega} \left( \frac{\gamma}{\bar{a}} b\bar{\omega} + \delta \right) - \frac{b}{(b+c)^2}\bar{a}\bar{\omega} \frac{b}{(b+\alpha^0 c)^2} V(\omega) \left( (1 - \alpha^0)c^2 - \frac{\gamma}{\bar{a}\bar{\omega}} (b+c)^2 \right) + \frac{b}{(b+\alpha^0 c)^2} \rho \sqrt{V(a)V(\omega)} \left( (1 - \alpha^0)c^2 \frac{b}{(b+c)^2} \bar{\omega}^2 + \delta \right)}{\left( \frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega) \right)^2}, \end{aligned}$$

$$\frac{\partial k^0}{\partial \gamma} = - \frac{1}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} < 0,$$

$$\frac{\partial k^0}{\partial \delta} = -\frac{\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma + \frac{c}{b+\alpha^0 c}\rho\sqrt{V(a)V(\omega)}}{\left(\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)\right)^2} < 0,$$

$$\frac{\partial k^0}{\partial \bar{\omega}} = \frac{c}{b+c}2b\bar{\omega}\frac{\frac{\bar{a}}{2b\bar{\omega}} - k^0}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} \geq 0 \Leftrightarrow k^0 \leq \frac{\bar{a}}{2b\bar{\omega}},$$

$$\frac{\partial k^0}{\partial V(\omega)} = \frac{bc}{b+\alpha^0 c}\frac{\frac{1}{2}\frac{\rho}{b}\sqrt{\frac{V(a)}{V(\omega)}} - k^0}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} \geq 0 \Leftrightarrow k^0 \leq \frac{k}{2},$$

$$\frac{\partial k^0}{\partial \rho} = \frac{\frac{c}{b+\alpha^0 c}\sqrt{V(a)V(\omega)}}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} > 0,$$

$$\frac{\partial k^0}{\partial \alpha^0} = \left(\frac{c}{b+\alpha^0 c}\right)^2 \frac{\left(\frac{c}{b+c}b\bar{\omega}^2 + \delta\right)bV(\omega)}{\left(\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)\right)^2} \left(\frac{\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma}{\frac{c}{b+c}b\bar{\omega}^2 + \delta} - \frac{\rho}{b}\sqrt{\frac{V(a)}{V(\omega)}}\right) \geq 0 \Leftrightarrow \bar{k} \geq \underline{k}.$$

Note that the comparative statics with respect to  $c$  is very ambiguous and cannot be easily characterized.

## 4.8 Justification of Figure 1

We derive here the calculus which justify Figure 1.

We first verify that

$$\bar{k} \geq \underline{k} \Leftrightarrow \rho \leq \rho^0 \equiv b\sqrt{\frac{V(\omega)}{V(a)}\frac{\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma}{\frac{c}{b+c}b\bar{\omega}^2 + \delta}}.$$

Indeed,  $\underline{k}$  is equal to  $\bar{k}$  when  $\rho = \rho^0$  and is increasing in  $\rho$ .<sup>50</sup>

<sup>50</sup>Note that  $\bar{k}$  does not vary with  $\rho$ .

We have shown in a previous appendix that

$$\frac{\partial k^0}{\partial \alpha^0} \begin{matrix} \geq \\ < \end{matrix} 0 \Leftrightarrow \bar{k} \begin{matrix} \geq \\ < \end{matrix} \underline{k}.$$

Given that

$$\bar{k} \begin{matrix} \geq \\ < \end{matrix} \underline{k} \Leftrightarrow \rho \begin{matrix} \leq \\ \geq \end{matrix} \rho^0,$$

it is equivalent to

$$\frac{\partial k^0}{\partial \alpha^0} \begin{matrix} \geq \\ < \end{matrix} 0 \Leftrightarrow \rho \begin{matrix} \leq \\ \geq \end{matrix} \rho^0.$$

Finally, let us show that  $k^0$  always lies between  $\underline{k}$  and  $\bar{k}$ . To see it, first substitute  $\rho = \rho^0$  into

$$k^0 = \frac{\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma + \frac{c}{b+\alpha^0 c}\rho\sqrt{V(a)V(\omega)}}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)}$$

to verify that

$$k^0 = \underline{k} = \bar{k}$$

in this case. If  $\rho > \rho^0$ , we have just shown that  $k^0$  is decreasing in  $\alpha^0$ . Remarking that

$$\lim_{\alpha^0 \rightarrow -b/c} k^0 = \frac{\rho}{b} \sqrt{\frac{V(w)}{V(a)}}$$

and

$$\lim_{\alpha^0 \rightarrow \infty} k^0 = \frac{\frac{c}{b+c}\bar{a}\bar{\omega} - \gamma}{\frac{c}{b+c}b\bar{\omega}^2 + \delta},$$

we get in particular  $\bar{k} < k^0 < \underline{k}$  for all  $0 \leq \alpha^0 \leq 1$ . Likewise, if  $\rho < \rho^0$ , we can show that  $\underline{k} < k^0 < \bar{k}$ .<sup>51</sup>

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<sup>51</sup>When  $\rho < 0$ , to show that  $k^0 > \underline{k}$ , we use the fact that  $k^0 > 0$  (interior solution) and  $\underline{k} = 0$ .

## Comparative statics of $\alpha^0$ (Equations (9), (14) and (15))

We derive the comparative statics of

$$\alpha^0 = \int_{t^0}^{t^1} t dG(t),$$

given that

$$t^0 = \frac{2b(K - \kappa)}{V(p^0)}$$

and

$$V(p^0) = \left( \frac{c}{b + \alpha^0 c} \right)^2 \left( V(a) - 2bk^0 \text{Cov}(a, \omega) + (bk^0)^2 V(w) \right).$$

As  $V(p^0)$  is itself a function of  $\alpha^0$ , this system defines  $\alpha^0$  implicitly. In order to ease the presentation, we proceed in two steps below.

Let us first consider  $V(p^0)$  as a parameter. Total differentiation then directly yields after arrangement

$$d\alpha^0 = \left( -\frac{db}{b} - \frac{d(K - \kappa)}{K - \kappa} + \frac{dV(p^0)}{V(p^0)} \right) (t^0)^2 dG(t^0), \quad (16)$$

which implies that  $\alpha^0$  is decreasing in  $b$  and  $K - \kappa$ , and is increasing in  $V(p^0)$ .

Let us now take into account the variations of  $V(p^0)$ . Using the comparative statics of  $V(p^0)$  calculated in a previous appendix, total differentiation yields

$$\begin{aligned} dV(p^0) = & -2 \left( \frac{c}{b + \alpha^0 c} \right)^3 \left( V(a) - 2bk^0 \rho \sqrt{V(a)V(w)} + (bk^0)^2 V(w) \right) d\alpha^0 \\ & + 0 d\bar{a} + \left( \frac{c}{b + \alpha^0 c} \right)^2 \frac{b}{\rho} \sqrt{\frac{V(w)}{V(a)}} \left( \frac{\rho}{b} \sqrt{\frac{V(a)}{V(w)}} - \rho^2 k^0 \right) dV(a) + \dots \end{aligned}$$



Substituting this into (16), we obtain

$$\Delta d\alpha^0 = -\frac{db}{b} - \frac{d(K - \kappa)}{K - \kappa} + 0 d\bar{a} + \left(\frac{c}{b + \alpha^0 c}\right)^2 \frac{b}{\rho} \sqrt{\frac{V(\omega)}{V(a)}} \left(\frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} - \rho^2 k^0\right) dV(a) + \dots$$

where we let

$$\Delta \equiv \frac{1}{(t^0)^2 dG(t^0)} + 2 \left(\frac{c}{b + \alpha^0 c}\right)^3 \left(V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega)\right) > 0.$$

From this, we can finally calculate that

$$\frac{d\alpha^0}{d\bar{a}} = 0,$$

$$\frac{d\alpha^0}{dV(a)} = \frac{1}{\Delta} \left(\frac{c}{b + \alpha^0 c}\right)^2 \frac{b}{\rho} \sqrt{\frac{V(\omega)}{V(a)}} \left(\frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} - \rho^2 k^0\right) \geq 0 \Leftrightarrow \rho^2 k^0 \leq \underline{k},$$

$$\frac{d\alpha^0}{db} = -\frac{1}{\Delta} \left(\frac{1}{b} + 2 \frac{c^2}{(b + \alpha^0 c)^3} \left( \begin{array}{l} V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \\ + (b + \alpha^0 c) bk^0 V(\omega) \left(\frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} - k^0\right) \end{array} \right)\right) < 0 \text{ if } k^0 \leq \underline{k},$$

$$\frac{d\alpha^0}{dc} = \frac{1}{\Delta} \frac{2bc}{(b + \alpha^0 c)^3} \left(V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega)\right) > 0,$$

$$\frac{d\alpha^0}{d(K - \kappa)} = -\frac{1}{\Delta} \frac{1}{K - \kappa} < 0,$$

$$\frac{d\alpha^0}{d\omega} = 0,$$

$$\frac{d\alpha^0}{dV(\omega)} = \frac{1}{\Delta} \left(\frac{bc}{b + \alpha^0 c}\right)^2 k^0 \left(k^0 - \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}}\right) \geq 0 \Leftrightarrow k^0 \geq \underline{k},$$

$$\frac{d\alpha^0}{d\rho} = -\frac{2}{\Delta} \left( \frac{c}{b + \alpha^0 c} \right)^2 b k^0 \sqrt{V(a)V(\omega)} < 0,$$

$$\frac{d\alpha^0}{dk^0} = \frac{2}{\Delta} \left( \frac{bc}{b + \alpha^0 c} \right)^2 V(\omega) \left( k^0 - \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} \right) \geq 0 \Leftrightarrow k^0 \geq \underline{k}.$$

## 4.9 Proof that $V(p^0)$ is decreasing in $\alpha^0$ (Equations (9) and (11))

We prove here that the use of smart meters always reduces real-time price volatility, even when accounting for both its direct (i.e.,  $k^0$  assumed given) and indirect (i.e.,  $k^0$  varying with  $\alpha^0$ ) effects on  $V(p^0)$  (see Figure 4). Indeed, consider the system

$$V(p^0) = \left( \frac{c}{b + \alpha^0 c} \right)^2 \left( V(a) - 2bk^0 Cov(a, \omega) + (bk^0)^2 V(\omega) \right)$$

and

$$k^0 = \frac{\frac{c}{b+c} a\bar{\omega} - \gamma + \frac{c}{b+\alpha^0 c} \rho \sqrt{V(a)V(\omega)}}{\frac{c}{b+c} b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c} bV(\omega)}.$$

We wish to determine the sign of

$$\frac{dV(p^0)}{d\alpha^0} = \frac{\partial V(p^0)}{\partial \alpha^0} + \frac{\partial V(p^0)}{\partial k^0} \frac{\partial k^0}{\partial \alpha^0}.$$

Using

$$\frac{\partial V(p^0)}{\partial \alpha^0} = -2 \left( \frac{c}{b + \alpha^0 c} \right)^3 \left( V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \right),$$

$$\frac{\partial V(p^0)}{\partial k^0} = 2 \left( \frac{bc}{b + \alpha^0 c} \right)^2 V(\omega) \left( k^0 - \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} \right)$$

and

$$\frac{\partial k^0}{\partial \alpha^0} = \left( \frac{c}{b + \alpha^0 c} \right)^2 \frac{bV(\omega)}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} \left( k^0 - \frac{\rho}{b} \sqrt{\frac{V(a)}{V(\omega)}} \right),$$

we can write that

$$\begin{aligned} \frac{dV(p^0)}{d\alpha^0} &= -2 \left( \frac{c}{b + \alpha^0 c} \right)^3 \left( V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \right) \\ &\quad + 2b \left( \frac{c}{b + \alpha^0 c} \right)^4 \frac{\left( bk^0 V(\omega) - \rho \sqrt{V(a)V(\omega)} \right)^2}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} \end{aligned}$$

Noting that

$$2b \left( \frac{c}{b + \alpha^0 c} \right)^4 \frac{(bk^0 V(\omega) - Cov(a, w))^2}{\frac{c}{b+c}b\bar{\omega}^2 + \delta + \frac{c}{b+\alpha^0 c}bV(\omega)} < 2 \left( \frac{c}{b + \alpha^0 c} \right)^3 \frac{(bk^0 V(\omega) - Cov(a, w))^2}{V(\omega)},$$

we obtain that

$$\frac{dV(p^0)}{d\alpha^0} < -2 \left( \frac{c}{b + \alpha^0 c} \right)^3 \left( \begin{array}{l} V(a) - 2bk^0 \rho \sqrt{V(a)V(\omega)} + (bk^0)^2 V(\omega) \\ - \left( bk^0 V(\omega) - \rho \sqrt{V(a)V(\omega)} \right)^2 / V(\omega) \end{array} \right).$$

Rearranging the terms under brackets, we can rewrite this as

$$\frac{dV(p^0)}{d\alpha^0} < -2 \left( \frac{c}{b + \alpha^0 c} \right)^3 V(a) (1 - \rho^2) \leq 0,$$

since  $-1 \leq \rho \leq 1$ .

## 4.10 Calibration

Here we explain how we calibrate the parameters  $\bar{a}$ ,  $V(a)$ ,  $b$ ,  $c$ ,  $\gamma$ ,  $\delta$ ,  $\rho$ ,  $w$  and  $V(w)$ . We use the following data set (see main text for sources):<sup>52</sup>

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<sup>52</sup>Note that the notations used here are specific to this appendix. They should not be confused with the notations used in the main text.

	Notation	Value
<b><i>Initial situation (2016):</i></b>		
- Average hourly consumption :	$D_0$	54681.29 MWh
- Variance of hourly consumption:	$V(D_0)$	$(11553.66)^2 \text{ MWh}^2$
- Average real-time price:	$P_0$	36.75 €/MWh
- Intermittent power capacity:	$k_0$	11670 + 6772 MW
- Average capacity factor:	$w_0$	0.180121
- Variance of the capacity factor:	$V(w_0)$	$(0.111437)^2$
- Average biomass production:	$q_0^B$	991.73 MWh
- Average hydraulic production:	$q_0^H$	7213.06 MWh
- Share of smart meters:	$\alpha_0$	0
<b><i>Objectives (2030):</i></b>		
- Ratio for renewable energy:	$\tau_1$	0.32
- Share of smart meters:	$\alpha_1$	1

The parameters  $\bar{a}$ ,  $V(a)$ ,  $c$ ,  $\bar{w}$  and  $V(w)$  are chosen such that the initial situation determines a market equilibrium under perfect competition:

$$D_0 = \frac{\bar{a} - P_0}{b},$$

$$V(a) = b^2 V(D_0),$$

$$P_0 = c \frac{\bar{a} - b\bar{w}k_0}{b + c},$$

$$\bar{w} = w_0,$$

$$V(w) = V(w_0).$$

The parameters  $\gamma$  and  $\delta$  are chosen such that the optimal outcome comply with the policy objectives:<sup>53</sup>

$$\bar{\omega}k^0 + q_0^B + q_0^H = \tau_1 \frac{\bar{a} - P^0}{b},$$

with  $k^0$  satisfying (11) when  $\alpha^0 = \alpha_1$ .

As one can see, we have three degrees of freedom (i.e., 6 equations and 9 parameters). In our calibration, the parameter  $\gamma$  is set equal to 5, representing an *annual* amortized cost of a generating unit of 1 MW equal to  $5 \times 8760 = 43800$  €/year. Then, we solve the system to determine  $\bar{a}$ ,  $V(a)$ ,  $c$ ,  $\delta$ ,  $\bar{\omega}$  and  $V(\omega)$ , as functions of  $b$  and  $\rho$ . In the benchmark calibration, we set  $b = 0.002$  and  $\rho = 0$ . We also consider alternative calibrations where  $b = 0.001$  and  $\rho = 0$ , on the one hand, and  $b = 0.005$  and  $\rho = 0$ , on the other hand. The corresponding scenarios are shown the the following table:

	$\bar{a}$	$V(a)$	$b$	$c$	$\gamma$	$\delta$	$\rho$	$\bar{\omega}$	$V(\omega)$
Benchmark	146.113	531.917	0.002	0.000715	5	0.000011	0	0.180121	0.012418
Low elast.	91.431	132.979	0.001	/	/	0.000014	/	/	/
High elast.	310.156	3324.48	0.005	/	/	0.000009	/	/	/

Table 2 Alternative calibrations

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<sup>53</sup>Note that we assume implicitly that the biomass and hydraulic productions will remain constant in the period.

## 4.11 Sensibility analysis

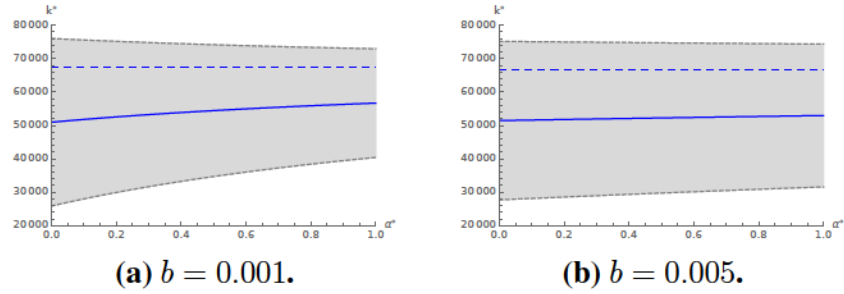


Figure 16: Optimal capacity of intermittent units (Units: %; MW)

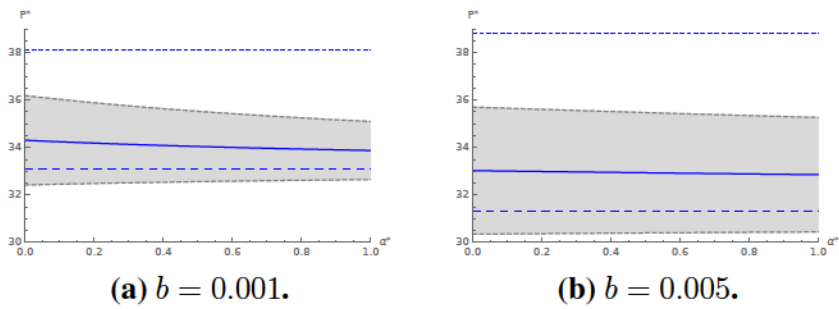


Figure 17: Expected real-time price (Units: %; €/MWh)

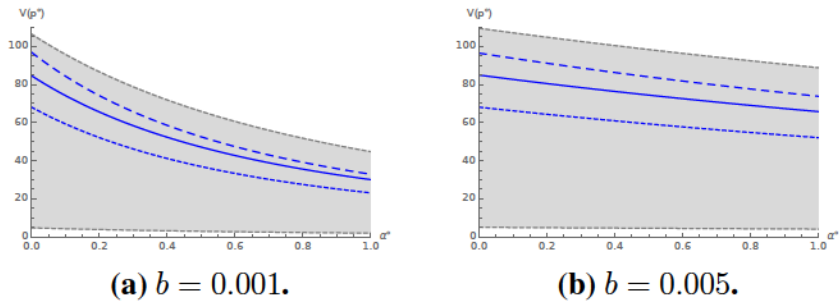


Figure 18: Variance of the real-time price (Units: %;  $(\text{€/MWh})^2$ )



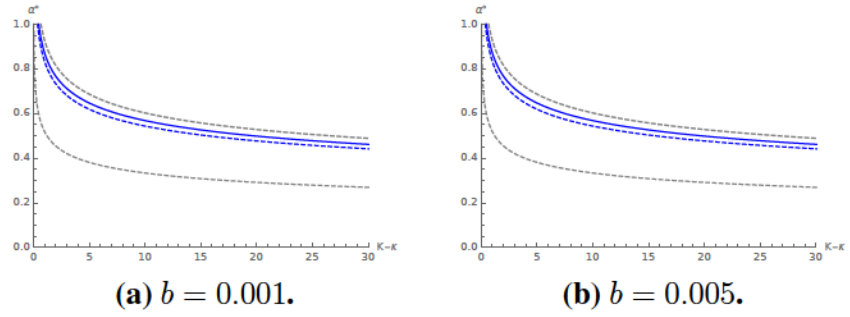


Figure 19: Expected market share of smart meters (Units: €/year; %)

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## General conclusion

## **Main results of the thesis**

In this thesis we focus on the development of the renewable energy sector by analyzing the obstacles that slow down its development, the measures that have been undertaken to overcome them, as well as the changes it brings to the electricity market. Thus, using theoretical models that take into account the specific characteristics of the electricity market, we model uncertainty as a random variable reflecting climatic conditions to provide some general insights on the optimal development of renewable energy technologies. Firstly, chapter 1 takes stock of the different characteristics of renewable energy sources, the difficulties that they face and the many advantages that their development provides. We also studied the literature dealing with the penetration of renewable energy on the electricity market. Therefore, we present a review of the different works on this subject, by identifying the questions that have been treated, the methods that have been used as well as the hypotheses that have been adopted. This enabled us to consider the possible extensions of the literature and to position this thesis in relation to existing work by trying to answer some neglected questions. The main conclusions of this chapter are that the difficulties encountered by the renewable energy sector are mainly related to their intermittent nature. In fact, the intermittency of renewable sources adds more constraints on the electricity grid and increases the risk of imbalance between supply and demand in the electricity market. However, despite these difficulties, all the literature agrees that it is essential to develop the renewable energy sector.

Indeed, the penetration of renewable energies on the electricity market provides economic benefits (job creation, energy security, new investments, among others), social benefits (by increasing the sources of electricity production) but above all, and most importantly, environmental benefits (by reducing global warming).

That is why a number of environmental policy measures have been adopted around the world to promote the renewable energy sector. These policies can be either based on taxation, making fossil fuels more expensive, or on emissions trading permits, limiting the use of these polluting sources. In chapter 2 we look at the effects of the introduction of an environmental tax on the optimal investment in renewable energy technologies. To this end, we have developed a theoret-

ical model that integrates the environmental damage caused by conventional generators' power generation in the context of constant demand.

Under the assumption that environmental damage increases more than proportionally with conventional production, our results show that the intermittency of renewable energy challenges the standard proprieties of efficiency of the environmental tax. Indeed, it appears that in the context of intermittency, a constant tax rate does not allow for the achievement of the optimality. In this context, our results suggest that the tax rate should be below the expected pollution at the optimum but, surprisingly, it generates greater investment in renewable technologies. In Chapter 3 we use the same framework as for the environmental tax, but with variable demand. We analyze the efficiency of an emission allowance permits in achieving optimality. We show that the effectiveness of this quantity-based scheme is essentially dependent on the initial allocation of permits. In fact, our results suggest that to reduce the problem of variability of renewable sources, their installed capacities should be reduced compared to the optimum. However, the allocation of pollution permits should be greater than the expected pollution at the first-best optimum. In addition to reducing the production of electricity from polluting sources, either by making them more expensive or by limiting their use in the electricity production, there is also another solution to promote the development of renewable energies. This solution is to act on demand through the generalization of smart meters. Indeed, thanks to these technologies, consumers can adjust their demand according to the availability of electricity. Consequently pressure on the power grid can be reduced and the efficiency of the network can be improved. In the last chapter we propose a framework designed to determine and analyze both the investments in intermittent technologies and the installation of smart meters in a social optimum. In this model, both sides of the market are influenced by climatic and/or social factors such as temperature, sun, wind, and holidays, among others.

This approach was innovative as it emphasized the role played by the correlation between electric demand and intermittent electric supply. Our analysis challenges and clarifies the commonly accepted view that investing in the renewable energy sector will increase the volatility of the electric spot price. Moreover, we show that depending on the correlation existing between electric

demand and the availability of renewable energies, the investment in intermittent technologies and the installation of smart meters can either complete or replace one another.

### **Environmental Policy Implications**

First, increasing the share of renewable energy sources in the energy mix is a new challenge for producers and regulator. So it is necessary to carefully design strategies that take into consideration the intermittency of renewable energy and its implications on the electricity market, in order to ensure the good development of this sector. As we have shown in chapter two and three, the intermittency of renewable energy challenges the standard proprieties of efficiency of the environmental tools. It is therefore important to find the right combination of policy schemes to achieve environmental goals. Secondly, the widespread belief according to which the penetration of renewable technologies causes adverse effects on the electric system constitutes an obstacle to their development. However, our analysis has made clear that this is not always true. It depends on the correlation between demand and intermittent energy sources. This shows the need to encourage any public policies that can increase the correlation between demand and intermittent energies. For example, the daylight saving time that is used in France and in other European countries can positively influence this correlation. Moreover, another efficient way to improve the correlation between renewable energy and demand could be to encourage consumers to produce electricity as well, through solar panels for example. Finally, we show that the general adoption of smart meters would be optimal only if the set up and maintenance costs of smart meters were unrealistically low. This leads us to wonder about the economic value of the generalization of smart meters.

### **Research Perspectives**

We have mainly three expected extensions to the models used in the present thesis. The first one is to consider different sources of renewable energy. Indeed the diversification of energy sources can help to mitigate the problem of intermittency. Thus, we can consider various intermittent sources, different locations, costs and variable availability, and analyze their interaction with the conventional sector. In many electricity markets, coal-fired power plants are withdrawn from the

market because they are very pollutant. So another question that we can address is disinvestment in conventional capacity to better reflect the actual context of the electricity market. Finally, it would be interesting to compare various environmental policy schemes on the same model. This could allow us to give some policy recommendations for the choice of instruments in the context of intermittency.



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